DUCKWEED

One of the Best Kept Secret of Urban Agriculture

a compilation - version 1

from various internet websites

Back to contents

Productive use of livestock wastes; a manual for the use of biodigester effluent and ponds for duckweed production

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Introduction

The two products from the anaerobic biodigestion of livestock wastes are:

- Biogas which is rich in methane (55-65%) and used mainly for cooking
- Effluent which is the residue coming out of the biodigester and which contains all the plant nutrients present in the original manure

This section of the manual deals with the utilization of the effluent as a fertilizer for crop plants. Since the effluent is voluminous (about 98% water) it is an advantage if it is used as close as possible to the site of production. For this purpose it is necessary to select crop plants which have a rapid growth rate (and therefore high capacity to extract nutrients from the medium in which they are growing) and good nutritive value.

For this purpose it has been found that duckweed (Lemnaceaea) is the most appropriate because it:

- Has a rapid rate of growth (doubles its biomass in 24 hours)
- Is palatable and has high digestibility for monogastric animals (dry matter digestibility over 65% in pigs according to Rodriguez and Preston 1996a)
- Its protein content is almost doubled (from 20-22% to 35-40%) when grown in nutrient-rich water (Leng et al 1995; Rodriguez and Preston 1996b; Nguyen Duc Anh et al 1997)

The products of the biodigester

These are:

- Biogas
- The effluent

The biogas flows by tube from the biodigester to the reservoir situated as close as possible to where it will be used, usually near the kitchen.

The effluent is produced daily in accordance with the schedule of charging the biodigester. The volume that comes out is equal to the volume that goes in. The residence time (time taken on average for the "digesta" to pass from the entrance to the exit) will vary usually within the range of 10 to 40 days depending on the quantity of manure and water put into the biodigester. The greater the input volume the shorter the residence time. It is desirable that the residence time is at least 20 days so as to secure inactivation of pathogenic organisms and parasites.

There should be a pit to receive the effluent large enough to hold at least the output of two days. Normally it is not necessary to line the pit as the floor and walls soon become impervious. If the topography permits a pipe should be laid to take the effluent from the receiving pit to the duckweed ponds.

Photo 1. Methane for cooking

Photo 2. Effluent as source of nutrients

Photo 3. A pipe connects the effluent pit with the duckweed ponds

Photo 4. Entry of the pipe bringing the effluent to the duckweed ponds

Using the effluent from the biodigester

When manure and water enter the biodigester a similar volume of effluent is forced out of the exit pipe.

It is usually adequate to have an unlined pit as very quickly this becomes impervious to filtration.

A pipe from this pit then connects directly to ponds used to cultivate duckweed.

When duckweed is fertilized with biodigester effluent its crude protein content can be between 35 and 40% in the dry matter, making it a valuable supplement for pigs and poultry.

In order to maintain a nitrogen content in the pond water of about 20mg/litre, the volumes of effluent to be added can be calculated from the table below:

- At the beginning when the pond is prepared and filled with water the first time
- Every day (to compensate for the nitrogen removed in the duckweed assuming a daily harvest of 100 g/m² pond surface/day)

The calculations are based on a pond of 20m² area and 20 cm depth of water. For ponds with different dimensions the data should be adjusted accordingly.

Effluent daily (litres)
area, m*m 20
depth,m 0.2

	dry matter content of effluent (%)					
N in effluent DM (%)	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**
0.5	288	144	96	72	58	48
1	144	72	48	36	29	24
1.5	96	48	32	24	19	16
2	72	36	24	18	14	12
2.5	58	29	19	14	11	10

3	48	24	16	12	10	8

Effluent at beginning (litres)
Pond area, m*m 20
Pond depth,m 0.2

	dry matter content of effluent (%)					
N in effluent DM (%)	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**
0.5	3200	1600	1067	800	640	533
1	1600	800	533	400	320	267
1.5	1067	533	356	267	213	178
2	800	400	267	200	160	133
2.5	640	320	213	160	128	107
3	533	267	178	133	107	89

Moving the effluent from the biodigester

The simplest way of moving the effluent is with buckets.

Photo 5. When manure and water enter the biodigester a similar volume of effluent is forced out of the exit pipe.

Photo 6. Taking the effluent with a bucket

Photo 7.Carrying the effluent to the duckweed ponds

Photo 8. Applying the effluent to the duckweed ponds

If the topography permits a more convenient method is to lay a pipe (5 cm id is enough) connecting the effluent pit with the duckweed pond and in turn to have each duckweed pond connected in series to the next one.

Photo 9. .A pipe linking the biodigester outlet with the ponds

Photo10. Pipe located between two ponds to allow the flow of the effluent

Photo 11. Ponds linked in series

Using a pump to manage the effluent

In this example the duckweed ponds surrounding the biodigester are at a higher elevation than the outlet pit.

A 1/4 HP electric pump has the inlet pipe connected directly to the effluent pit and the outlet at the highest point of the slope. In a matter of minutes the effluent is pumped into the duckweed ponds

Photo 12. The system: a pen with 24 hens, a pen with 4 pigs, a 6 m

long biodigestert and 6 duckweed ponds (each 6 m*m), 3 ponds on each side of the biodigester and cassava planted around the ponds and biodigester

Photo 13. The pit full of effluent after washing the pen

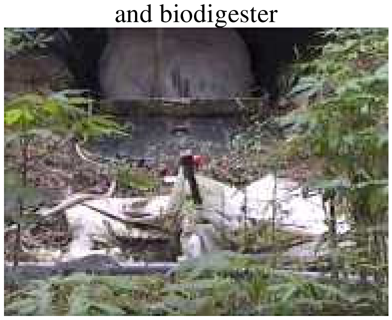


Photo 14.A punp located next to the pit

Photo 15. Taking the cover off the pump

Photo 16. The pit holding the pump

Photo 17. The pump is located at a lower level than the effluent in the exit pit. This avoids the need to "prime" the pump

Photo 18. PVC pipes in the form of a "T" link the pump to the ponds on two sides of the biodigester

Photo 19. The PVC pipe connected to the pond on the left side of the biodigester

Photo 20. The PVC pipe connected to the pond on the right side of the biodigester

Photo 21. Pumping the effluent

Photo 22. A pipe connects two ponds

Photo 23. The effluent pit being emptied

The duckweed ponds

If water is not a limiting resource the most appropriate way of using the effluent from the biodigester is for the cultivation of duckweed (Lemnaceae).

Where there is a high clay content in the soil the floor and wall of the pond soon become impervious to filtration of water. But in sandy soil it is necessary to line the ponds with a mixture of soil and cement. For a pond 40cm deep and with an area of 20 m², the required overall quantities are 25 kg of cement and 300 kg of soil.

Smaller mixes of 30 kg soil, 2.5 kg cement and 1.5 kg water are prepared and a thin layer of the mixture is applied to the floor of the ponds and to the walls.

After two days the ponds can be filled with water and seeded with duckweed

Inoculating the pond with duckweed

The duckweed pond is connected by a pipe with the exit of the biodigester.

The inoculum of duckweed is prepared and distributed on the pond surface at the rate of 400 g/m².

Photo 24 . Mixing the soil and cement

Photo 25 Putting the mixture on the walls of the pond

Photo 26 . Putting the mixture on the bottom of the pond

Photo 27. The pond ready and full of water (next day)

Photo 28. Adding duckweed seed

Harvesting duckweed

Each pond is harvested daily. It is a simple operation requiring a bamboo pole slightly shorter than the width of the pond and a plastic basket.

Beginning at the mid-point of the pond the duckweed is pushed steadily to the narrow end of the pond and then scooped out of the water with the basket. It is left to drain for few minutes before being weighed and taken to the animals.

These ponds are producing about 100 g fresh duckweed/m^2/day which is equivalent to about 6 tonnes protein/ha/year.

Photo 29. A bamboo stick : the tool to harvest

Photo 30. Preparing to harvest

Photo 31. Usually every day 50 % of the area of the pond is harvested

Photo 32. Pushing the duckweed with the bamboo stick

Photo 33. Pushing the duckweed to one corner of the pond

Photo 34. Collecting the duckweed with a porous plastic container

Photo 35. The density of duckweed in the pond after harvesting

Duckweed as a feed for chickens

Duckweed has a balance of essential amino acids slightly superior to soya bean meal (Rusoff et al 1980).

Rice bran and cassava root meal are dry, powdery materials. Duckweed by contrast is very wet (94-96% moisture..!!). Mixing fresh duckweed with either rice bran or cassava root meal, or with a combination of the two, produces a feed with a crumbly texture that is more readily accepted by chickens than any one of the ingredients given separately.

Proposed combinations (all on fresh basis) that will give at least 10% protein in dry matter (suitable for growing and laying chickens) are:

- one part rice bran; one part duckweed
- four parts duckweed: one part cassava root meal
- two parts duckweed: one part cassava root meal: one part rice bran

Photo 36 . Harvesting duckweed every day

Photo 37. Mixing duckweed with rice bran

Photo38. The hens prefer the mixture rather than each feed given in separate containers

Photo 39. Fresh duckweed to supplement the diet of scavenging hens

Photo40. Duckweed as protein supplement for chicks

Duckweed as a feed for "local" pigs

The same principles apply as for chickens and the same mixtures of duckweed with cassava root meal and rice bran can be used.

Photo 41 . Rice bran

Photo 42. Fresh duckweed

Photo 43. Mixing fresh duckweed with rice bran

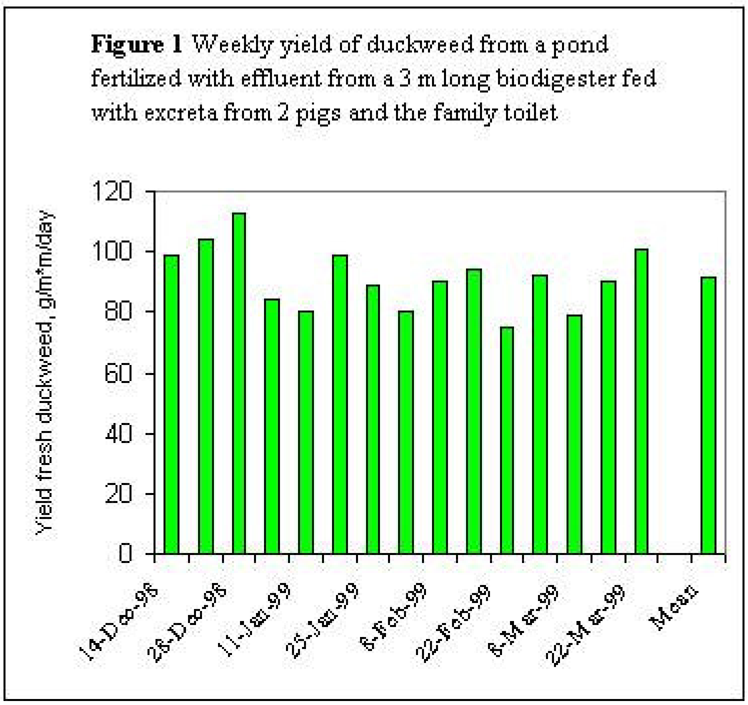
Photo 44. Feeding the mixture to a pregnant Mong Cai sow

Photo 45. Fresh duckweed as a source of protein for Mong cai sows

Duckweed also an alternative for landless farmers

Photo 46. Small biodigester (3 m long) linked to the toilet and a pig pen (2 pigs) and connected to a duckweed pond

The pond has an area of 16 m² and the average daily yield over 3 months of observations was 91 g/m² (Figure 1), equivalent to 1.5 kg fresh duckweed daily. This is sufficient to provide the supplementary protein for 15 chickens.



Photos by Lylian Rodriguez

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Back to top

Duckweed Aquaculture

A NEW AQUATIC FARMING SYSTEM

FOR DEVELOPING COUNTRIES

Paul Skillicorn, William Spira

and William Journey

THE WORLD BANK

EMENA TECHNICAL DEPARTMENT

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DUCKWEED AQUACULTURE

Table of Contents

List of Figures

Caption

Foreword

Although duckweed species are familiar to most people who have seen the tiny aquatic plants covering stagnant water bodies, few people realize their potential. Until a few years ago, man made little use of duckweed species. Their unique properties, such as their phenomenal growth rate, high protein content, ability to clean wastewater and thrive in fresh as well as brackish water, were only recognized by a few scientists.

Prior to 1988 duckweed had been used only in commercial applications to treat wastewater in North America. In 1989 staff of a non-governmental organization based in Columbia, Maryland, The PRISM Group, initiated a pilot project in Bangladesh to develop farming systems for duckweed and to test its value as a fish feed. An earlier project in Peru investigated the nutritional value of dried duckweed meal in poultry rations.

The results of the pilot operations were extremely promising; production of duckweed-fed carp far exceeded expectations, and dried duckweed meal provided an excellent substitute for soy and fish meals in poultry feeds. Duckweed could be grown using wastewater for nutrients, or alternatively using commercial fertilizers.

During start-up of the pilot operations it also became apparent how little is known about the agronomic aspects of producing various species of the duckweed family, and exactly why it is so effective as a single nutritional input for carp and other fish.

Although these pilot operations were located in South Asia and Latin America, the results suggested that the plant would be important as a source of fish and poultry feed and simultaneously as a wastewater treatment process in selected areas of the Middle East, particularly in Egypt and Pakistan.

Technical and agronomic information about duckweed culture and feed use, and details of farming duckweed and fish in a single system, are not easily available to the general public, let alone to fish farmers in developing countries. The pilot operations in Bangladesh demonstrated that duckweed and fish culture can succeed commercially, although such ventures would initially require technical assistance and information. In many other areas of the world pilot operations linked to applied research may be required to review production parameters before commercial operations should be initiated. This Technical Study was therefore designed to bring together, in one publication, relevant information on duckweed culture and its uses to make people worldwide aware of the potential of this plant, to disseminate the currently available technical and agronomic information, and to list those aspects that require further research, such as duckweed agronomy, genetics and use in animal feeds.

This Technical Study is aimed at the following audiences: (a) established fish farmers who would like to experiment with duckweed as a fish feed, and staff of agricultural extension services involved in fish culture; (b) scientists of aquaculture research institutes who may initiate pilot operations and applied research on duckweed; (c) staff of bilateral and multilateral donor agencies who may promote funding for duckweed research and pilot operations; and (d) wastewater specialists in governments and donor agencies who may promote wastewater treatment plants based on duckweed in conjunction with fish culture.

The information in this technical study comes from many sources; the contribution of the staff of the Mirzapur experimental station in Bangladesh and its director Mohammed Ikramullah, in particular, is acknowledged. Paul Skillicorn and William Spira of the PRISM Group, and William Journey wrote the text. Viet Ngo of the Lemna Corporation and Richard Middleton of Kalbermatten Associates provided technical material relating to wastewater treatment applications. The draft was reviewed by a Bank technical committee comprising Messrs. Grimshaw, Khouri, Leeuwrik, van Santen and Macoun. Professor Thomas Popma of the International Center for Aquaculture at Auburn University provided technical support, and illustrations were provided by Ms. S. Gray of Auburn.

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Preface

The purpose of this booklet is to present a group of tiny aquatic plants commonly known as "duckweeds" as a promising new commercial aquaculture crop. Duckweed species are members of the taxonomic family *Lemnaceae*. They are ubiquitous, hardy, and grow rapidly if their needs are met through sound crop management. Aquaculture systems are many times more productive than terrestrial agriculture and have the potential to increase protein production at rates similar to increases of terrestrial carbohydrate crops realized during the Green Revolution. Section 1 presents basic information on duckweed biology.

This paper summarizes current knowledge, gained from practical experience from the beginning of 1989 to mid-1991 in an experimental program in Mirzapur, Bangladesh, where duckweed cultivation was established and fresh duckweed fed to carp and tilapia. In the Mirzapur experimental program a farming system was developed which can sustain dry-weight yields of 20 - 35 metric tons per hectare per year (ton/ha/year), which is a rate exceeding single-crop soybean production six to tenfold. Section 2 discusses duckweed farming issues in detail.

Like most aquatic plants, duckweed species have a high water content, but their solid fraction has about the same quantity and quality of protein as soybean meal. Fresh duckweed plants appear to be a complete nutritional package for carp and tilapia ponds. Duckweed-fed fish production does not depend on mechanical aeration and appears to be significantly more productive and easier to manage than traditional pond fish culture processes. Section 3 addresses the important issues in duckweed-fed fish production.

The economics of duckweed farming and duckweed-fed fish production and institutional factors that are likely to affect its widespread adoption as a commercial crop are discussed in Section 4.

Section 5 summarizes the use of duckweed for stripping nutrients from wastewater. The bio-accumulation of nutrients and dissolved solids by duckweed is highly effective. World-wide applications of duckweed-based technologies for wastewater treatment and re-use are being implemented in both idustrialized and developing countries.

Section 6 provides other potential commercial applications of duckweed: (1) in its dried form as the high protein component of animal feeds; and (2) as a saline-tolerant aquaculture crop. It also contains a discussion of key research issues and constraints inhibiting the potential for duckweed as a commercial crop.

The paper concludes with a selected bibliography covering important duckweed-related research. This is an impressive body of literature covering the entire spectrum from microbiology to poultry research. The work described here did not attempt to repeat experimentation of earlier researchers, nor did it originate any basic duckweed production or application concepts. The concepts presented here do, however, represent the first attempt to synthesize a complete commercial paradigm for cultivating and using duckweed.

Section 1 - Biology of Duckweed

Duckweed species are small floating aquatic plants found worldwide and often seen growing in thick, blanket-like mats on still, nutrient-rich fresh and brackish waters. They are monocotyledons belonging to the botanical family *Lemnaceae* and are classified as higher plants, or macrophytes, although they are often mistaken for algae. The family consists of four genera, *Lemna, Spirodela, Wolffia*, and *Wolffiella*, among which about 40 species have been identified so far.

All species occasionally produce tiny, almost invisible flowers and seeds, but what triggers flowering is unknown. Many species of duckweed cope with low temperatures by forming a special starchy "survival" frond known as a **turion**. With cold weather, the turion forms and sinks to the bottom of the pond where it remains dormant until rising temperatures in the spring trigger resumption of normal growth.

Morphology Duckweed species are the smallest of all flowering plants. Their structural and functional features have been simplified by natural selection to only those necessary to survive in an aquatic environment. An individual duckweed frond has no leaf, stem, or specialized structures; the entire plant consists of a flat, ovoid frond as shown in figure 1. Many species may have hair-like rootlets which function as stability organs.

Species of the genus *Spirodela* have the largest fronds, measuring as much as 20 mm across, while those of *Wolffia* species are 2 mm or less in diameter. *Lemna* species are intermediate size at 6 - 8 mm. Compared with most plants, duckweed fronds have little fiber -- as little as 5 percent in cultured plants -- because they do not need structural tissue to support leaves or stems. As a result virtually all tissue is metabolically active and useful as a feed or food product. This important characteristic contrasts favorably with many terrestrial crops such as soybeans, rice, or maize, most of whose total biomass is left behind after the useful parts have been harvested.

Distribution Duckweed species are adapted to a wide variety of geographic and climatic zones and can be found in all but waterless deserts and permanently frozen polar regions. Most, however, are found in moderate climates of tropical and temperate zones. Many species can survive temperature extremes, but grow fastest under warm, sunny conditions. They are spread by floods and aquatic birds.

Duckweed species have an inherent capability to exploit favorable ecological conditions by growing extremely rapidly. Their wide geographic distribution indicates a high probability of ample genetic diversity and good potential to improve their agronomic characteristics through selective breeding. Native species are almost always available and can be collected and cultivated where water is available, including moderately saline environments.

Growth conditions The natural habitat of duckweed is floating freely on the surface of fresh or brackish water sheltered from wind and wave action by surrounding vegetation. The most favorable circumstance is water with decaying organic material to provide duckweed with a steady supply of growth nutrients and trace elements. A dense cover of duckweed shuts out light and inhibits competing submerged aquatic plants, including algae.

Duckweed fronds are not anchored in soil, but float freely on the surface of a body of water. They can be dispersed by fast currents or pushed toward a bank by wind and wave action. If the plants become piled up in deep layers the lowest layer will be cut off from light and will eventually die. Plants pushed from the water onto a bank will also dry out and die. Disruption of the complete cover on the water's surface permits the growth of algae and other submerged plants that can become dominant and inhibit further growth of a duckweed colony.

To cultivate duckweed a farmer needs to organize and maintain conditions that mimic the natural environmental niche of duckweed: a sheltered, pond-like culture plot and a constant supply of water and nutrients from organic or mineral fertilizers. Wastewater effluent rich in organic material is a particularly valuable asset for cultivating duckweed because it provides a steady supply of essential nutrients and water.

In this case there is a coincidence of interests between a municipal government, which would treat the wastewater if it could afford to do so, and nearby farmers, who can profitably do so.

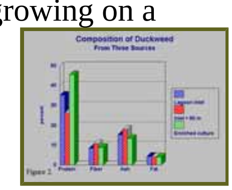
Production rates Duckweed reproduction is primarily vegetative. Daughter fronds bud from reproductive pockets on the side of a mature frond. An individual frond may produce as many as 10 generations of progeny over a period of 10 days to several weeks before dying. As the frond ages its fiber and mineral content increases, and it reproduces at a slower rate.

Duckweed plants can double their mass in less than two days under ideal conditions of nutrient availability, sunlight, and temperature. This is faster than almost any other higher plant. Under experimental conditions their production rate can approach an extrapolated yield of four metric tons/ha/day of fresh plant biomass, or about 80 metric tons/ha/year of solid material. This pattern more closely resembles the exponential growth of unicellular algae than that of higher plants and denotes an unusually high biological potential.

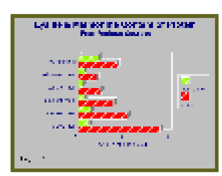
Average growth rates of unmanaged colonies of duckweed will be reduced by a variety of stresses: nutrient scarcity or imbalance; toxins; extremes of pH and temperature; crowding by overgrowth of the colony; and competition from other plants for light and nutrients.

Actual yields of fresh material from commercial-scale cultivation of *Spirodela*, *Lemna*, and *Wolffia* species at the Mirzapur experimental site in Bangladesh range from 0.5 to 1.5 metric tons/ha/day, which is equivalent to 13 to 38 metric tons/ha/year of solid material.

Nutritional value Fresh duckweed fronds contain 92 to 94 percent water. Fiber and ash content is higher and protein content lower in duckweed colonies with slow growth. The solid fraction of a wild colony of duckweed growing on nutrient-poor water typically ranges from 15 to 25 percent protein and from 15 to 30 percent fiber. Duckweed grown under ideal conditions and harvested regularly will have a fiber content of 5 to 15 percent and a protein content of 35 to 45 percent, depending on the species involved, as illustrated in figure 2. *[see next footnote]* Data were obtained from duckweed colonies growing on a wastewater treatment lagoon and from a duckweed culture enriched with fertilizer.



Duckweed protein has higher concentrations of the essential amino acids, lysine and methionine, than most plant proteins and more closely resembles animal protein in that respect. Figure 3 *[see next footnote]* compares the lysine and methionine concentrations of proteins from several sources with the FAO standard recommended for human nutrition.



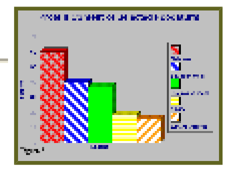
[Footnote: Source: Mbagwu and Adeniji, 1988.]

[Footnote: Source: Mbagwu and Adeniji, 1988.]

Cultured duckweed also has high concentrations of trace minerals and pigments, particularly beta carotene and xanthophyll, that make duckweed meal an especially valuable supplement for poultry and other animal feeds. The total content of carotenoids in duckweed meal is 10 times higher than that in terrestrial plants; xanthophyll concentrations of over 1,000 parts per million (ppm) were documented in poultry feeding trials in Peru and are shown in figure 4. *[see next footnote]* This is economically important because of the relatively high cost of the pigment supplement in poultry feed.

[Footnote: Source: Haustein et al, 1988.]

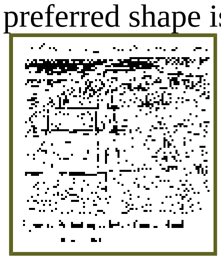
A monoculture of Nile tilapia and a polyculture of Chinese and Indian carp species were observed to feed readily on fresh duckweed in the Mirzapur experimental program. Utilizing duckweed in its fresh, green state as a fish feed minimizes handling and processing costs. The nutritional requirements of fish appear to be met completely in ponds receiving only fresh duckweed, despite the relatively dilute concentration of nutrients in the fresh plants. The protein content of duckweed is compared with several animal feed ingredients in figure 5.

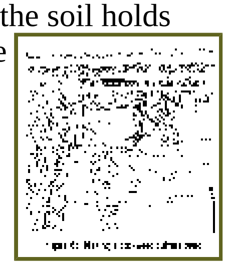


Section 2 - Duckweed Farming

Duckweed farming is a continuous process requiring intensive management for optimum production. Daily attention and frequent harvesting are needed throughout the year to ensure the productivity and health of the duckweed colonies. Harvested plant biomass must be used daily in its fresh form as fish feed or dried for use in other animal feeds. However, the high intensity of duckweed cropping can increase the productivity of both land and labor resources, especially where land is scarce and agricultural labor is seasonally underemployed.

Land For long term water impoundment and year-round cropping to be practical, land for culture plots dedicated to duckweed farming should be able to retain water and should be protected against flooding. Uncultivated marginal land is a good first choice to cultivate duckweed. Such strips of land may be found along roads and paths and would not normally be cultivated because of their elevation or shape. The preferred shape is a channel, as shown in figures 6 and 7. Almost any land is suitable if the soil holds water well, even if it is waterlogged or salinized. One exception may be alkaline soils. Initially these soils may raise the pH of the water and reduce duckweed growth. However, with time the pH should reduce to more favorable levels.





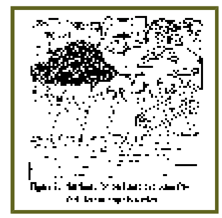
Water management Ideally water should be available year-round. Although some locations may have access to surface water, most farmers will need to install some form of pumped groundwater supply. Groundwater, surface water irrigation, or wastewater are all potential sources of water for duckweed cultivation.

A complete cover of duckweed can reduce the rate of evaporation by about one-third compared to open water. Annual water loss due to evapotranspiration is likely to range from 800 to 1,200 mm in the tropics and semitropics. In general, duckweed can be cultivated wherever irrigation resources can sustain rice production.

In addition to replenishment of water losses, crop water management is concerned with buffering extremes of temperature, nutrient loadings, and pH. The depth of water in the culture plot determines the rate at which it will warm up in the sun and cool off at night. The freshening effect of cool groundwater can relieve heat stress quickly, or dilute a plot with an oversupply of nutrients, high pH, or high ammonia concentration. Duckweed species will grow in as little as one centimeter of water, but good practice is to maintain a minimum of 20 cm or more to moderate potential sources of stress and to facilitate harvesting.

Acute temperature stress can be managed by spraying water on the crop, physically immersing the crop, inducing better mixing, or flooding the plot with cooler water. Shading with vegetation, such as bamboo and banana trees, or taro plants, can also moderate temperature extremes.

Nutrient sources Hydroponic farming of a continuous crop, such as duckweed, converts substantial amounts of fertilizer into plant biomass. As duckweed colonies grow they convert nutrients and minerals dissolved in the water column into plant tissue. The nutrient removal rate is directly proportional to the growth rate. When plants are harvested, nutrients, and trace minerals are removed from the system and a dynamic nutrient and mineral sink is established, thus forming the basis for a highly effective wastewater treatment technology. To cultivate duckweed farmers will need a dependable source of either commercial mineral or organic fertilizers throughout the year, as illustrated in figure 8.



Empirical testing of nutrients for duckweed cultivation, carried out over the past two years in the Mirzapur experimental program in Bangladesh, has produced some insight into appropriate fertilizer application schedules.

Nitrogen Ammonium ion is the preferred form of nitrogen for duckweed species. The main source of ammonium for wild colonies of duckweed is from fermentation of organic material by anaerobic bacteria. Duckweed plants reportedly utilize all available ammonium before beginning to assimilate nitrate, and appear to grow more quickly in the presence of ammonium than with nitrate. In contrast to duckweed unicellular algae prefer nitrate.

Urea contains approximately 45 percent nitrogen and is the most commonly available and lowest cost nitrogenous fertilizer. Urea is the most efficient form of nitrogen supply to terrestrial crops, but its volatility in water and its elevating effect on pH makes it problematic for hydroponic applications. When applied to water with a pH above 7.0, nitrogen losses through ammonia volatility can often exceed 50 percent. For example, urea is applied to the duckweed crop in Bangladesh at the rate of 20 kilograms per hectare per day (kg/ha/day), which is equivalent to 9.0 kg/ha/day of nitrogen. Assuming a 50 percent loss before the crop is able to utilize the nitrogen, 4.5 kg/ha/day is then available to support growth. This is enough nitrogen to sustain a yield of at least 1,000 kg/ha/day of fresh duckweed and is adjusted seasonally as growth rates accelerate in moderate temperatures.

Ammonium nitrate contains about 38 percent nitrogen and is marginally more expensive to produce than urea. It contains slightly less nitrogen than urea, but compared with urea, ammonium nitrate is significantly more stable in water. It does not undergo any biochemical conversion process when it is put into water and has no immediate effect on the water's pH. The recommended application rate for ammonium nitrate to sustain biomass production of 1,000 kg/ha/day in Bangladesh is 10 kg/ha/day. Ammonium nitrate can be explosive and it is hygroscopic. However, its chief disadvantage is that it is not widely available in many poorer countries.

Nitric acid can be used as an occasional treatment to lower a high pH quickly and as a nitrogen fertilizer, but it is expensive and may not be readily available.

***Phosphorus* - Triple super phosphate** (TSP) is a good source of both phosphorus and calcium.

Phosphorus is essential for rapid growth and is a major limiting nutrient after nitrogen. For example, a ratio of TSP to urea of 1 : 5 worked satisfactorily in the Mirzapur experimental program. Duckweed colonies do not appear to respond to additional TSP above this threshold, and doubling the supply results in only marginally increased productivity. The major disadvantage of TSP is that it raises the pH of the culture pond slightly, but alternative forms of phosphorus are too expensive to consider.

Potassium Vigorously growing duckweed is a highly efficient potassium sink, but little is required to maintain rapid growth. **Muriated potash** (MP) is a commercial source of potassium widely available in most countries. As with phosphorus, duckweed growth is not particularly sensitive to potassium once an adequate threshold has been reached. A 1 : 5 ratio for MP to urea was found to be satisfactory in the Mirzapur experimental program.

Trace minerals Duckweed species need many other nutrients and minerals to support rapid growth. The absolute requirement for each trace element is extremely small and may seem insignificant. However, with hydroponic culture, large quantities of plants are produced in a limited space and the trace minerals available from soil leaching are soon removed. Under these circumstances, the farmer is obliged to supply trace minerals to ensure optimum growth. Fortunately, **unrefined sea salt** contains all needed trace minerals. Unlike most plants, duckweed species tolerate relatively high concentrations of salts, up to almost the mid-range of brackish water, or about 4000 mg/liter total dissolved solids. An adequate rate of sea salt application for cropping in Bangladesh was determined empirically to be 9.0 kg/ha/day when used with urea as the nitrogen source.

Organic wastes As detailed in Section 5 a variety of waste organic material can supply duckweed with growth nutrients. The most economical sources are wastewater effluents from homes, food processing plants, or livestock feedlots. Solid materials, such as manure from livestock, night soil from villages, or food processing wastes, can also be mixed with water and added to a pond to approximate the nutrient content of raw wastewater. Wastewater containing untreated nightsoil should undergo primary treatment to reduce pathogens. This treatment may consist of a few days tetention in an anaerobic pond or longer periods in a facultative pond environment. These ponds should be designed on a site-specific basis to optimize their treatment effectiveness.

Fertilizer application Nutrients are absorbed through all surfaces of duckweed fronds. There are at least three methods of fertilizer application: broadcasting, dissolving in the water column of the plot, and spraying a fertilizer solution on the duckweed mat. Efficient crop management strategy seeks to minimize fertilizer losses, particularly nitrogen, while also maintaining the pH of the water in the range of six to eight.

Duckweed can survive across a pH range from five to nine, but grows best in the 6.5 to 7.5 range. When the pH is below 7.0, ammonia can be kept in its ionized state as ammonium ion, which is the preferred form of nitrogen for the plants. An alkaline pH shifts the ammonium-ammonia balance toward the unionized state and results in the liberation of free ammonia gas, which is toxic to duckweed.

Table 1 gives a fertilizer application schedule developed for duckweed cultivation in the Mirzapur experimental program in Bangladesh. Recommended urea application rates, because of ammonia volatility, are approximately double that of ammonium nitrate. Replenishment rates given below are based on existing production rates. It should not be inferred, however, that high fertilizer application will necessarily generate high duckweed production. Production may be constrained by many other factors, including temperature, pH, and the presence of algae.

Table 1. Daily Fertilizer Application Matrix (kg/ha)

	Daily production of fresh plants per hectare					
Fertilizer	*500kg*	*600kg*	*700kg*	*800kg*	*900kg*	*1,0*
Urea	10.00	12.00	14.00	16.00	18.00	[illegible]
TSP	2.00	2.40	2.80	3.20	3.60	
Muriated Potash	2.00	2.40	2.80	3.20	3.60	
Crude Sea Salt	4.50	5.40	6.30	7.20	8.10	

Fertilizer to support duckweed cropping in the Mirzapur experimental program in Bangladesh costs about $1,800/ha/year based on these application rates and 1992 fertilizer prices. (See Annex 1 for a breakdown of costs and returns for duckweed cropping.)

Crop management Duckweed species are robust in terms of survival, but sensitive in terms of thriving. They can survive and recover from extremes of temperature, nutrient loadings, nutrient balance, and pH. However, for duckweed to thrive these four factors need to be balanced and maintained within reasonable limits.

Crop management is concerned with **when** to fertilize, irrigate, harvest, and buffer; **how much** to fertilize and to harvest; and with **which** nutrients to supply. Good crop management will maintain a complete and dense cover of duckweed, low dissolved oxygen, and mid-range pH. The complete crop cover suppresses algae growth, which minimizes CO_2 production from algal respiration and its elevating effect on pH.

A dense crop cover also reduces dissolved oxygen in the water column and suppresses nitrifying bacteria. An increase in anaerobic bacteria enhances the denitrification process and swings the nitrogen balance further in favor of ammonium over nitrate. This tends to lower pH as ammonium ions are assimilated by duckweed. The ability to form a mat over the surface of the water is one of the competitive advantages of duckweed.

An optimum standing crop density is a complete cover, which still provides enough space to accommodate rapid growth of the colony. A base *Spirodela* stocking density of 600 g/m² of has been shown, in the Mirzapur experimental program, to yield daily incremental growth of between 50 to 150 g/m²/day. This is equivalent to a daily crop production rate of 0.5 to 1.5 tons of fresh duckweed per hectare.

Containment and wind buffering Crop containment to prevent dispersal by water or wind currents is essential to the success of any duckweed cultivation. Crop containment is a function of three basic factors: wind diffusion, pond size, and floating barrier grid-size. The larger the pond and the greater the average wind speed, the smaller the recommended grid-size. The smaller the floating grid-size, the greater the investment costs. Higher costs may be justified on retrofitted ponds or deep ponds with large-scale prodution.

An efficient design balances the three variables to develop a least-cost system, which is an improved approximation of the ideal natural environment. The duckweed crop should cover the surface of the water completely without significant crowding on the leeward perimeter of each grid unit. Large diameter bamboos, contained by vertical bamboo guides, served adequately as grid barriers in Bangladesh, as shown in figures 7 and 9. Sealed PVC or polyethylene pipes, similarly guided, will last longer than

bamboo, but are significantly more expensive. A commercially available grid system which can incorporate baffles for flow control

has been developed by the Lemna Corporation. This product is designed to accommodate efficient mechanical harvesting systems.

Duckweed cropping systems should include terrestrial and other emergent aquatic plants as collateral crops for two important reasons: (1) co-cropping increases overall cropping intensity, and (2) the co-crop plants buffer against high wind and high temperatures. Bamboo, for example, grows well in a wet environment and has market value as a structural material. Planted along the perimeter of a duckweed culture plot, bamboo will diffuse the wind and filter sunlight during hot, dry weather. When the more moderate and cloudy monsoon season begins, the bamboo crop can be thinned to allow more light on the duckweed crop and sold to increase cash flow. Co-cropping is illustrated in figure 9.

Rooted aquatic crops do not have to be as tall as perimeter crops to buffer against the wind. There are, therefore, more options from which to choose for such crops. The leaves of taro are good as a green vegetable and the tuber competes favorably with potato in many countries. Planted about one meter apart in the water column of duckweed culture plots, the "black taro" variety shades a portion of the pond surface and benefits from nutrients in the water column. The "giant swamp taro" is reported to grow well in brackish water. Other candidate crops such as lentils, bananas, and squash thrive on the levees because water and nutrient constraints are removed. The choice of co-crops should be based on local market demand and the relative need for wind and temperature buffering.

Seeding duckweed Currently, the only source of duckweed to begin cultivation is from colonies growing wild, as illustrated in figure 10. Seed stock should be taken from all available native species of duckweed growing near the planned farmstead or in the same region. These species will be well adapted to the local climate and water chemistry. If duckweed is to be cultivated on salinized soil, then the best place to get seed stock is from a brackish wetland.

Figure 10: Collecting duckweed seedstock

Frequently, two or more duckweed species will be found growing together in wild colonies. Polyculture increases the range of environmental conditions within which the crop will grow. Seasonal variations produce changes in species mix and dominance because different species have different growth optima. It should be recognized that seed stock taken from different colonies of the same species will be slightly different genetically from the others and are likely to be adapted to a slightly different set of environmental conditions.

The collected duckweed seed stock should be put into containment plots at a density of 600 to 900 g/m² (wet weight). The newly seeded crop may require a week or more to recover from the shock of handling and may grow slowly, if at all, during this period. The relatively dense cover will prevent significant algae growth during the recovery time. Too thin a cover will allow algae to compete for nutrients in the water column.

Stress management The mat of duckweed floating on the surface of a pond heats up in the sun much faster than the water column below it. The temperature differential several centimeters below the mat can be as great as 8 degrees C. As surface temperatures rise above 33° C, duckweed shows signs of heat stress which, if unrelieved, can damage the colony.

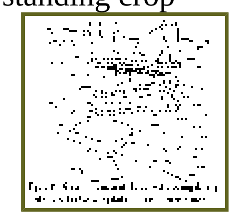
There are two basic approaches to relieving heat stress: (1) passive measures such as shading and self-selection by different species, and (2) active processes such as pond mixing, addition of cool water, immersion, and spraying of plants. The passive methods are significantly more efficient from a financial standpoint since active methods are more labor intensive. Large overhanging plants, such as bamboo and banana trees, for example, can provide marketable products as well as shade for duckweed during periods of intense sunlight, high temperature, and wind.

Crowding reduces crop growth rates and increases the average age of the frond population, which can weaken the resistance of the colony to attack by predators such as aphids, snails, or fungi. An aquatic fungus of the genus *Pithium* is known to attack crowded duckweed colonies. Crowding also lowers the nutritional value of the crop by lowering the average protein content and increasing the proportion of fiber and ash. Control of crowding by regular harvesting is essential to maintaining the health of the colony and the quality of the harvested product.

Unicellular algae are the primary competitors of duckweed for nutrients and are among the few plants that will grow faster. One of the essential crop management techniques is to maintain a sufficiently dense crop cover to suppress algae by cutting off light penetration into the water column. Algae dominance will result in a swing toward high pH and production of free ammonia, which is toxic to duckweed. While precise mechanisms are not known, there is evidence to suggest that species of microscopic algae may also reduce duckweed growth by inhibiting nutrient uptake.

Harvesting The standing crop density, or the weight of fresh plant biomass per square meter, will determine the amount and timing of harvests. The current standing crop density is compared to a "base" density in order to calculate the amount to be harvested. As the standing crop's density increases, crowding begins to inhibit the doubling rate of the colony. However, higher standing crop density is positively related to absolute biomass productivity. This is due to the fact that more fronds will produce more biomass even if each individual frond experiences a slightly longer doubling time. The positive correlation between crop density and total crop production peaks at some "optimal" density and gradually declines as increasing density inhibits cloning. Clearly, optimal standing crop densities will be site-specific and will need to be defined in detail through practical experience.

Measurement of standing crop density is done with a calibrated, fine mesh screen of 0.25 m² that is used to lift a section of the duckweed mat growing on the culture plot. The procedure is to gently slide the screen beneath the surface and to pick up exactly the amount of duckweed above the screen, shake it gently to drain excess water, and weigh the fresh plants, as illustrated in figure 11. The standing crop density per square meter for that plot can then be estimated at four times the weight recorded.



Daily harvesting of the incremental growth of the duckweed plot - averaging approximately 100 g/m²/day - is recommended, not only to achieve the best production rate, but to maintain a healthy standing crop. Harvesting can be mechanized or done by hand with a dip net, as illustrated in figure 12.

Fresh duckweed plants contain 92 to 94 percent water and can be stored temporarily in a cool, wet place, such as a small tank or pool. The fresh material will begin to ferment in high temperatures after a few hours, but will keep for several days, if kept cool and damp.

Duckweed dried to a whole meal with a residual moisture content of 10 percent can be stored without deterioration for at least five years without special precautions, if protected from sunlight and changes in humidity. Exposure to direct sunlight will degrade the pigments and, therefore, the overall nutritional value, but not the protein. Sealable, opaque plastic bags are recommended for long-term storage. Protection from humidity, insects, and vermin in an opaque, sealable plastic bag is recommended as for any feedstuff. (See figure 13). Passive solar drying, spreading the fresh material on the bare ground, or on a grassy pasture, is the simplest form of post-harvest processing. However,

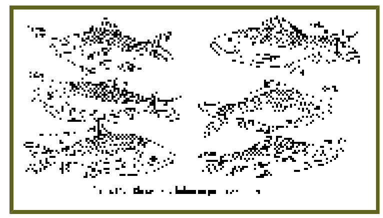
exposure of fresh duckweed to the sun's ultraviolet light degrades beta carotene and other pigments, and reduces their concentrations. Pigment losses of about one-third to one-half may be expected after two days in the sun.

Dried duckweed is a light, fluffy material whose density must be greatly increased to be handled efficiently and transported at affordable cost. The dried whole meal can be pelletized in standard commercial equipment without the need of a binder.

Section 3 - Duckweed-Fed Fish Production

Introduction

Carp species are the most widely cultivated family of freshwater fish. Their tolerance of wide differences in pond temperature and chemistry, their ease of management, and their high growth rates have made them a favorite of fishery development programs worldwide. Several Chinese and Indian carp varieties are illustrated in figure 14.



Carp production is a function of three basic variables: (1) availability of food, (2) fish seed stock, and (3) oxygen. Carp production can be enormous when constraints on all three variables are lifted simultaneously. Cage fish production in fast-moving and, therefore, oxygen-saturated wastewater streams in Indonesia can support several times the density of fish compared to still ponds. In ponds where artificial aeration cannot be supplied, efficient culture techniques realize up to 8 metric tons/ha/year.

Polyculture increases the efficiency of carp production by maintaining top-feeding, mid-feeding, and bottom-feeding carp species in the same pond to extend productivity throughout all three zones. Carp polyculture is designed to make maximum use of all available oxygen and available nutrients.

Importance of oxygen Efficient use of available oxygen is a key to maximum carp production. It supports the fish and their food, and it supports the denaturing of toxins, such as ammonia, which can limit productivity. Even brief periods of anoxia can be disastrous to the fish crop in a pond that has slipped out of control. Even without fish kills, frequent oxygen deprivation leaves fish weakened and susceptible to disease.

The traditional model of carp polyculture is conceptually elegant, and a great deal is known about the nutritional value of supplementary inputs. However, to achieve the highest productivity from a carp pond still involves a high degree of art. High production with current techniques requires a delicate and precarious balancing act between fish density, feed, fertilizer inputs, and the amount of dissolved oxygen in the pond.

More efficient culture of top-feeders Another limitation of existing carp polyculture methodology has been underutilization of plant-eating top-feeders that have the highest production rates among all carp species. Since current approaches to carp polyculture focus on the use of plant material that is scavenged and of marginal economic utility, the problem has been both plant selection and availability. Grass carp consume plant material so rapidly that available wild stocks of nutritious, fresh material are quickly depleted in the pond if stocking rates exceed 3 to 4 percent. Duckweed farming has the effect of creating a parallel industry to produce nutritious green fodder for top-feeding carp and other fish varieties that feed on these nutritious plants.

Review of conventional carp polyculture

The Chinese are credited with developing carp polyculture, a methodology which evolved from the observation that the three-dimensional space in a fish pond contains several discrete feeding zones, only a few of which are accessible by any single fish species. Noting that carp are selective in their feeding habits led the Chinese to the practice of combining species with complementary feeding habits to take advantage of all the feeding zones and the diversity of natural sources of fish food in the pond.

Chinese carp polyculture recommends the use of at least four species of carp: a green plant feeder which feeds at the surface; two middle-feeders, one for zooplankton and a second for phytoplankton; and one bottom-feeding omnivore. The art of a Chinese carp polyculture has been to balance species to prevent overpopulation in feeding zones and the loss of productivity from competition. Middle-feeding plankton-eaters are usually the largest fraction of the species mix, accounting for up to 85 percent in some systems.

Fertilization In conventional carp polyculture fertilization is the primary mechanism for feeding fish. Solid food is put into the pond to sustain the grass carp. Fertilization takes several forms: direct application of inorganic fertilizers; direct application of manure and compost, and the indirect fertilization effects of fish fecal matter.

Fertilization stimulates growth of phytoplankton which is, in turn, consumed by filter-feeding carp. These fish, therefore, can feed more and grow faster as long as pond oxygen is high. Over-fertilization can, however, quickly destabilize a pond by depletion of oxygen due to: (1) high densities of phytoplankton which respire at night and use up oxygen; (2) high densities of fish which respire at all times, and (3) aerobic bacterial metabolism of excess organic material and mineral fertilizers in the pond which also uses up oxygen.

Heavy blooms of phytoplankton may also result in a net productivity loss by shading the pond bottom and effectively shutting down that zone. Photosynthetic activity ceases, temperature gradients are exaggerated, mixing slows, and the zone becomes increasingly anoxic.

Compost and manures, as well as commercial fertilizers, are acceptable inputs to carp polyculture. The correct type and quantity of fertilizer to apply depends on pond chemistry as well as on fish density, and these requirements vary seasonally and with locality. Managing pond fertility consists of estimating how much a given amount of fertilizer will contribute to overall biochemical oxygen demand (BOD) in addition to the BOD contribution of fish and feed wastes.

Supplementary feeding Nutritious solid feed costs more than fertilizer, manures, or compost, and is typically less available. Direct feeding of fish is considered supplementary in the conventional carp polyculture model because higher fish densities can be maintained through supplementary feeding. Such feed is usually high in carbohydrate because natural food is high in protein and because carbohydrate is less expensive than protein.

Fish farmers must adjust feed inputs in response to key environmental variables. Fish feed consumption varies with fish size and water temperature. Carp may not feed at all during the coldest months, but in the summer can eat as much as their own weight daily and even waste food. Uneaten or poorly digested feed results not only in lost productivity, but also contributes to oxygen depletion. Several light feedings daily are, therefore, preferred to one large feeding.

Feeds are usually blended from a variety of vegetable and animal products. Fish grow best on a balanced diet with a balanced amino acid profile. The protein constituent of feed is usually derived from a variety of sources. Pelleted feeds for fish simplify feed management but typically add significantly to operating costs.

Production constraints Intensification of pond fish culture requires an increase in the density of fish in the pond, provision of more food to sustain them, and better utilization of available dissolved oxygen. A typical semi-intensive system may rely on high-quality manure and supplementary feeding, but will not have mechanical aeration.

Intensification of production demands more capital and labor, and significantly more sophisticated management skills to handle increasingly restrictive production constraints. The farmer must acquire needed inputs in a timely manner. These include the right species mix of fingerlings, pre-mixed pelleted feeds, sufficient fertilizers of the right type, and technical assistance.

Most farmers do not maintain all the ingredients needed to prepare a complete feed on-site or the equipment to blend and pellet it. They must, therefore, have guaranteed primary and alternative market sources at all times, which is not a simple management activity.

In an intensified production system the fish compete for an increasingly uncertain oxygen supply with other fish and with the other sources of oxygen demand already described. The chief concern of the fish farmer is management of risk associated with the pond's oxygen budget: the risks of disease, of depressed growth, and of fish kills.

Typical carp yields in Asia A well managed, semi-intensive carp polyculture farm in Asia produces between 2 and 8 metric tons/ha/year. Carp production in Bangladesh averages approximately 50 kg/ha/year for all fished inland ponds. Traditional pond fisheries average 500 kg/ha/year while improved fisheries, practicing some variation of carp polyculture, show average annual yields of approximately 2.5 metric tons/ha/year. Aeration is needed to exceed the best yields, but is generally beyond the means of most carp producers.

Duckweed-fed carp polyculture

Practical objectives The fish production methodology discussed in this study extends carp polyculture by: (1) making more efficient use of top-feeding carp varieties that live in the more highly oxygen-saturated surface zone of ponds; (2) making more efficient use of bottom-feeders to extract marginal nutrients from fish fecal matter before they can contribute to pond BOD; and (3) simplifying pond management to a single input -- duckweed, a floating biomass feed.

A duckweed-fed fish pond appears to provide a complete, balanced diet for those carp that consume it directly, while the feces of duckweed-feeding species, consumed directly by detritus feeders, or indirectly through fertilization of plankton and other natural food organisms, provide adequate food for remaining bottom and mid-feeding carp varieties.

Early results suggest that the duckweed carp polyculture methodology permits increases in carp polyculture production to between 10 and 15 metric tons/ha/year in non-aerated ponds, and it also increases the financial and economic viability of the production system.

Logic of Duckweed-fed Carp polyculture

The logic which led to experiments with duckweed-fed carp polyculture at the Mirzapur experimental site in Bangladesh was as follows:

If the nutrients could be distributed properly among a mix of carp species, then duckweed could be a complete nutritional package for the polyculture.

If a high percentage of organic nutrients entering the pond could be converted to fish flesh before they contribute to biochemical oxygen demand, then pond water quality would be better and greater fish densities could be supported.

If duckweed were a complete nutrient package for the polyculture, then fertilizer and other feed inputs could be eliminated, simplifying management of the nutrition of the polyculture.

If the first three assumptions were validated, then fish farmers could secure local supplies of complete fish feed through the farming of duckweed.

Basic hypotheses about duckweed-fed carp polyculture The departure from conventional polyculture methodology is exemplified by the switch from fertilizer to feed as the primary input. This would appear to contradict the traditional logic which suggests that:

$$fertilizer, \rightarrow plankton_{feed} \rightarrow fish$$

is more efficient with respect to inputs than:

$$duckweed_{feed} \rightarrow fish$$

which would indeed be the case, if there were no oxygen constraint. Considering oxygen as a constraint, however, it is useful to extend the model as follows:

$$\mathbf{[oxygen_{avail}]}\ fertilizer_{chem} \rightarrow plankton_{feed} \rightarrow fish \rightarrow fecesfert \rightarrow NH_3, planktonfeed \rightarrow fish \rightarrow feces_{fert} \rightarrow NH_3, plankton_{feed} .....\mathbf{[oxygen_{min}]}$$

is less efficient with respects to inputs and oxygen than:

$$duckweed_{feed} \rightarrow fish \rightarrow feces_{feed} \rightarrow fish \rightarrow \mathbf{[oxygen_{avail}]}\ feces_{fert}$$

$$\rightarrow plankton_{feed} \rightarrow fish \rightarrow feces_{fert} \rightarrow NH_3, plankton_{feed} \rightarrow fish \rightarrow feces_{fert}$$

$$\rightarrow NH_3, plankton_{feed} \rightarrow .....\mathbf{[oxygen_{min}]}$$

In the duckweed model, the entire cycle of:

$$duckweed_{feed} \rightarrow fish \rightarrow feces_{feed} \rightarrow fish \rightarrow$$

takes place ahead of the existing oxygen constraint. The second round of fecal input from bottom-feeding carp is then roughly analogous to the chemical or organic fertilizer input to conventional carp polyculture, but at a lower level.

The fish farmer must, of course, balance this potential increase in productivity against his increased costs. Technological inputs in the duckweed model do not differ from conventional non-aerated carp polyculture. The additional cost of a duckweed system is, therefore, roughly equal to the price of duckweed inputs.

A more careful analysis should also consider increased incremental costs for fingerling inputs, as well as decreased expenses for fertilizer and manure, which a farmer would otherwise expect to incur following conventional carp polyculture methodology. For simplicity, however, unadjusted duckweed procurement costs are used to estimate the cost of converting to a duckweed polyculture system.

Because the feces of top-feeders and first-round bottom-feeders provide the manure normally purchased to meet the needs of middle and second-round bottom-feeders, the farmer has only to calculate the profit for the incremental production of top-feeders (grass carp, catla, and mirror carp) and bottom-feeders (mrigal and mirror carp) to determine his marginal benefit.

Experience in the Mirzapur experimental program in Bangladesh has been that a grass carp/mrigal combination produces 1 kg of fish for between 10 to 12 kg of fresh duckweed, or about $0.30 to $.40 *[see next footnote]* worth of duckweed consumed. That amount of fish brought approximately $1.50 at the wholesale price. The farmer is, in effect, making a large profit on his "fertilizer production engine".

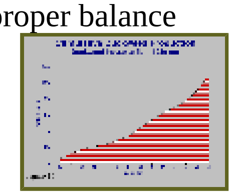
[Footnote: All dollar amounts are US$]

Carp stocking strategy In the Mirzapur experimental ponds, grass carp (*Ctenopharyngodon idella*) is the primary consumer of duckweed in the polyculture. However, both catla (*Catla catla*) and mirror carp (*Cyprinus carpio*) also compete aggressively for available duckweed feed and consume it directly. Top-feeders directly absorb about 50 percent of duckweed nutrients in their digestive systems. Their feces contain the balance of the original duckweed nutrients and furnish a relatively high quality detritus for bottom-feeders.

Bottom-feeding species comprise a relatively high 30 percent of the polyculture. The purpose is to increase the probability that feces from the entire fish population will be digested several times, not only to convert the maximum amount of nutrients into fish flesh, but to moderate biochemical oxygen demand in the pond. Mrigal (*Cirrhinus mrigala*) is a bottom-feeder and is tolerant of the low oxygen levels at the bottom. Although they grow more slowly than the other varieties, they keep the pond bottom clean.

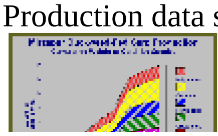
Rohu (*Labeo rohita*) and silver carp (*Hypothalmichthys molitrix*) are two phytoplankton-feeding species used in the duckweed-fed polyculture at a total of 40 percent of the species mix, or approximately half of the typical Chinese carp polyculture. The objective in the Mirzapur experimental program was to match the fish population to the expected lower availability of phytoplankton. Maintaining a proper balance

between middle-feeders and phytoplankton production achieves a higher efficiency in fish flesh production and reduces fluctuations in dissolved oxygen caused by excessive densities of green algae.

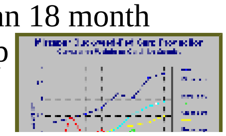


Carp fry and fingerlings feed on zooplankton. Fingerlings will also eat *Wolffia* as soon as their mouths are big enough. The traditional use of duckweed in Asia has been to feed fish fingerlings.

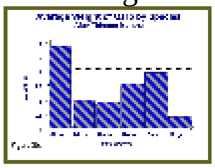
Production data shown in figures 15, 16, 18, 19, and 20, refer to the first 12 months (of an 18 month



cycle) of carp polyculture production at the Mirzapur experimental carp pond, a 2.2 hectare pond stocked with approximately 50,000 carp in



September 1989. As of April 1991 approximately 18 tons of the original fish had been harvested. An estimated three to five tons, primarily mirror carp, were stolen, and an estimated five tons of the original fish were left in the pond. A further 30,000 fingerlings were stocked in the pond in September 1990. Harvesting of these fish, along with the remaining original fish, began in April 1991. Although total pond productivity can only be estimated, it appears to be around 10 tons per hectare per year.



Duckweed feed Duckweed is not a supplementary feed in the Mirzapur polyculture, it is the main source of nutrition. Feeding a carp polyculture with duckweed simplifies nutrition to a single input and the feeding schedule to a single issue: feeding the carp as much as they will eat. Any uneaten duckweed will be visible floating in the feeding station and the farmer can respond by reducing the volume on the following day.

Fish are fed duckweed throughout the day. Freshly harvested duckweed is brought in baskets to the pond and distributed evenly among several "feeding stations" consisting of 4 m² open-bottom enclosures, as illustrated in figure 17. Feeding stations provide access by the fish to the duckweed and prevent it from dispersing over the pond surface. The feeding station can be a floating enclosure anchored near the shore. Six feeding stations per hectare were installed at the Mirzapur experimental site and appeared to provide sufficient access to food for all fish.

Judging from carp production rates in the Mirzapur experimental program, approximately 10 to 12 kg of fresh, cultured duckweed is converted into 1 kg of fish. Precise confirmation of this figure awaits controlled experimentation.

Fertilization of the pond Fertilization of a duckweed-fed fish culture is indirect and gradual, resulting from bacterial decomposition of fish feces, dead algae, and other fermenting organic material in the pond. The issue of pond fertility is removed from the farmer's management tasks. Fertilization of the base of the food web in the fish pond is automatically regulated by the consumption of fresh duckweed by the fish and its subsequent entry into the pond water where it will ultimately decompose.

Oxygen regime In the Mirzapur experimental model, several carp species acquire a significant percentage of their nutritional requirements through direct consumption of duckweed. This allows maintenance of higher stocking densities while also reducing production of algae that contributes to depletion of oxygen during nocturnal respiration. The result is a pond environment that has generally higher concentrations of dissolved oxygen with a lower amplitude of diurnal oxygen fluctuation. This means more fish, healthier fish, and more confident farmers.

The dawn-dissolved oxygen concentration in a 0.5 ha pond at the Mirzapur experimental site, stocked with 30,000 fish fed entirely on duckweed, was monitored over a six-month period. It did not go below 4 milligrams per liter (mg/l) until the fish density increased to an estimated 20 metric tons/ha and the temperature began to rise with the advent of spring in Bangladesh. Feeding was curtailed to reduce pond BOD, and the stock of fish was reduced by harvesting until only about 15 metric tons/ha remained. This again prevented dawn-dissolved oxygen levels from dropping below 4 mg/l.

Management and productivity compared to the traditional Chinese model The Mirzapur duckweed-fed carp polyculture model has an 18-month cycle. Fingerlings are introduced in August and September, harvesting begins in March and continues for approximately one year. A second 18-month cycle begins the following year and continues concurrently for six months. After the initial six months, the model allows year-round harvesting.

In the Mirzapur experimental system, duckweed is the single nutrient input. It floats and is visible until eaten. This minimizes ambiguities concerning the level of feeding needed to support efficient fish growth. Fish regulate their feeding by eating until they are satiated. The farmer has a simple visual signal to regulate the feed supply and will supply just enough to guarantee a small daily residual floating in the feeding station. Over-feeding and over-fertilization are two problems typical of the traditional model which are avoided in the duckweed-fed polyculture. However, for this model to be risk-free it is essential that optimal stocking rates be known precisely, which is not yet the case.

Duckweed species grow faster in warm weather when fish need more feed and more slowly in cold weather when the fish also do not require as much feed. In general a farmer should design a duckweed supply capability to fulfill his peak needs and should dry excess biomass for use as an animal feed ingredient. Current production rates suggest that one hectare of duckweed production can support two hectares of carp polyculture.

The first annual cycle of carp production in Bangladesh produced slightly more than 10 metric tons/ha/year. This yield occurred in spite of the fact that, for the first three months, duckweed production constraints prevented the fish from receiving enough duckweed feed for optimal growth.

Empirical results so far in Bangladesh suggest that a polyculture stocked at about 30,000 fish per hectare may be fed as much duckweed as they will eat daily, regardless of the season. Furthermore, a yield of between 10 to 15 tons/ha/year appears to be sustainable before biological constraints become the limiting factors.

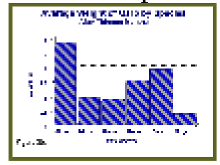
The Mirzapur duckweed-fed fish polyculture requires daily labor over the entire season. Carp are fed daily and duckweed is harvested daily to maintain the best production rates. The duckweed farmer's family is the most cost-effective source of labor and can be gainfully employed year-round. Hired labor is usually necessary at critical times, such as weekly harvests and pond-cleaning.

Crop and oxygen monitoring Unicellular algae, or phytoplankton, grow extremely rapidly in response to nutrient availability, sunlight, and warm temperatures. These algae are harvested for food by filter-feeding species of carp and other phytoplankton-feeding fish. An oversupply of phytoplankton can deplete the dissolved oxygen in the pond to dangerously low levels for the fish. Sudden die-off of phytoplankton and its subsequent decay results in a dramatic increase in BOD that can also deplete oxygen to dangerously low levels.

Direct monitoring of pond-dissolved oxygen levels is impractical for most small farmers in countries such as Bangladesh. Equipment is too expensive to enable widespread use and not sufficiently robust for continuous use. However, monitoring of pond oxygen can be performed during harvesting. Fish with adequate oxygen exhibit considerable vigor during harvesting. When oxygen levels fall below 4 mg/l the reduction of jumping during harvesting is striking. If farmers harvest twice a week, observation of fish behavior during harvesting should provide feedback in time to reduce feed inputs, to introduce fresh water, or to further reduce stock, all of which can have immediate impact on pond-dissolved oxygen levels.

Fish quality, health, and security Duckweed-fed carp raised in the Mirzapur experimental program have so far appeared to be healthy and well-nourished. However, the bottom-feeding mrigal, the slowest growing of the species in the polyculture, averaged 0.45 kg in one year of growth. In this duckweed-fed system mrigal feed primarily on detritus provided by the fecal matter of the top-feeders, which has only a fraction of the nutrients of fresh duckweed. The relatively poor production of mrigal is attributable to the strategy of stocking them in relatively high numbers so that fecal matter from top-feeders would be more likely to be consumed before contributing to pond BOD.

Figure 20 demonstrates the average weight of fish caught 13 months after being placed in the Mirzapur experimental pond. Silver carp experienced the best growth at 2.75 kg/year, followed by catla and rohu. The relatively poor growth of grass carp attests to their high stocking density and a shortage of duckweed during the first several months of production. Grass carp production during the second production cycle (not reported here), when duckweed inputs were not constrained, was considerably higher with individual fish reaching 4 kg within six months.



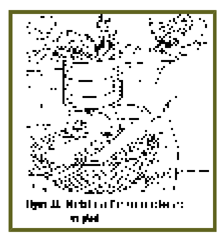
Mirror carp growth was, in fact, better than indicated. Only a few, stunted mirror carp remained in the pond at the end of one year. Mirror carp are easily caught from the pond perimeter by throw net, and most were stolen by intruders before action was taken to increase pond security. Once the value of the fish in the Mirzapur experimental ponds became known, it became necessary to employ nighttime guards. Management of the security force is an added concern and operating cost.

Fish mortality has not been an issue so far in the Mirzapur experimental program. There have been no fish kills or outbreaks of disease. Water quality appears to be good and the fish appear to be in good health, even at relatively high densities for the semi-intensive system.

Harvesting Regular and frequent harvests are prescribed for duckweed-fed fish culture. The catch is sorted by size, counted, and weighed. The intermediate size fish are returned to the pond for further growth. These data help the farmer to track the growth rate of his fish and to estimate the quantity and quality of future harvests.

Routine harvesting of duckweed-fed carp began approximately six months after the Mirzapur polyculture pond was stocked. Bi-weekly harvesting was the preferred pattern, following a simple protocol to take the largest fish (75 to 100 percentile) and the smallest (0 to 25 percentile) in each species. The rationale is the assumption that the largest fish will have a declining growth rate and that the small fish are simply poor performers. This protocol was particularly difficult to follow with respect to mrigal which, because of their small size, became entangled in the nets. Fish damaged in this manner were removed from the pond regardless of size.

As the carp were harvested, they were counted, each variety weighed separately, and the data recorded in order to analyze the efficiency of the farming operation and to maintain the desired ratios of species in the pond. This is illustrated in figure 21.



Care was taken not to deplete top-feeders and bottom-feeders -- the fertilizer and food engines -- disproportionately. Fortunately, several species of carp, not considered to be macrophyte feeders (mirror carp and catla, in particular), also competed vigorously for supplies of fresh duckweed, which is apparently a learned behavior.

Markets Duckweed-fed fish from the Mirzapur experimental site had a clear quality edge in the local market. Aesthetically, fresh, green duckweed contrasted favorably with manure and other less appealing inputs to a conventional pond fishery. The consumer's perception appeared to be that because duckweed-fed fish are reared on fresh vegetables and live in higher quality water, they "smell, feel, and taste" better than fish reared conventionally.

Duckweed-fed tilapia

Tilapia species are of African origin but have been introduced to most tropical and subtropical regions. (See figure 22). Tilapia are hardy, grow fast, and can tolerate low pond oxygen levels better than most fish. They are warm water fish which do not grow below 16° C and do not survive temperatures below 10° C. Unlike carp, they have no "floating" intramuscular bones, making it easier for the diner to separate bones from flesh.

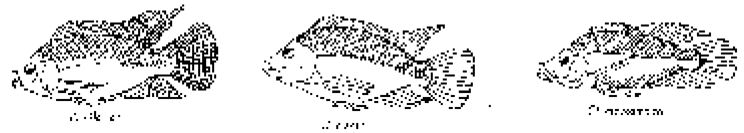


Figure 22. Major Tilapia Species

Most species of tilapia tolerate brackish water well. Adult tilapia are primarily herbivorous, occasionally omnivorous, and some species are used to control aquatic weeds. Fry feed primarily on plankton. At least one species, *Oreochromis niloticus*, is reported to be extremely flexible in its feeding habits, readily consuming *Lemna* and *Wolffia* species along with phytoplankton and detritus.

Tilapia are well-equipped to feed on duckweed. They have grinding plates in their pharynx, a highly acidic stomach, and a long intestine to absorb digested nutrients. Duckweed supplies the high protein diet they need for rapid growth. The maceration and digestion of duckweed by macrophyte-feeding tilapia requires less energy expenditure than a diet of more fibrous plants.

Because the Nile tilapia appears to be able to harvest food from all of the space and food niches in a pond, it was tested in the Mirzapur experimental program as an alternative to the duckweed-fed carp polyculture. The single-species culture appears to benefit from duckweed as the single nutritional input in much the same way as the carp polyculture because the nutrients appear to be distributed similarly. Production at Mirzapur in a 0.6 hectare pond totaled 4.5 tons in one year of continuous operation. As management of the pond improved, and the stocking balance between recruits, juveniles, and mature fish became more efficient, productivity rates improved. Local pond managers now believe that they should be able to average at least 10 tons/ha/year for mixed (sizes) tilapia harvest.

Because of their fecundity, tilapia require special management to keep their population stable and to maintain even growth. They mature at about three months and breed prolifically in the pond at intervals of three to six weeks. The additional fish population, called recruits, leads quickly to extreme competition for food and, hence, a stunted population. There are three basic approaches to management of tilapia populations: monosex culture, intensive culling and inclusion of predators. Frequent, intensive harvesting to remove market-size fish and recruits is highly labor intensive and can stress the fish population. It is, however, a relatively simple technique available to the small farmer.

Predatory fish can be included with the tilapia culture to control recruits and allow the production of market-size fish. Predator species include the clarias catfish, notopterus, snakehead, and others, many of which have high market value. The principle constraints with this method are the difficulty of obtaining stocks of predator species and determining efficient stocking densities.

The tilapia culture strategy investigated at the Mirzapur experimental site is conceptually similar to duckweed cultivation. The concept is to determine an efficient "standing crop" and to maintain it with bi-weekly harvests. Tilapia are categorized either as recruits, adolescents, or adults. During harvests, estimates are made of the total amount of tilapia in the pond and their distribution among the three categories. For example, the standing crop today is 10 tons and, numerically, 60 percent of the fish are recruits, 30 percent are adolescents, and 10% are adults. To bring the standing crop back to the empirically derived "normative" size and balance, the harvesting heuristic should then specify a harvest profile by weight: harvest 400 kg - 50 kg of recruits, 150 kg of adolescents, and 200 kg of adults. Current harvest profiles will rely more on intuition than formula until efficient harvesting algorithms are developed.

Tilapia recruits, although very small, fetch a surprisingly high market price in rural markets in Bangladesh. They are purchased by people unable to afford fish in the size range prevalent in the market (0.5 - 1 kg). Where tilapia above 250 g can command up to $2.00 per kg in rural markets, mixed adolescents, and recruits can bring up to $1.00 per kilogram. This mechanism allows even the poorest people to include some fish in their diet. With production costs averaging between $0.40 - $0.50 per kg in Bangladesh, farming duckweed-fed tilapia is highly profitable.

Section 4 - Economic and Institutional Issues

Introduction of duckweed cropping is likely to be attended with "teething problems" influenced by several factors in unfamiliar combinations. Duckweed is not only a novel crop, but a highly intensive one. It appears to be "multipurpose" in the sense that it may be farmed in several possible settings with different economic and financial implications, and it is an aquaculture crop. With the exception of the Mirzapur experimental program, there are no attempts on record to develop full-scale cropping systems. There are currently no institutions equipped to provide extension support to duckweed farmers, and a market for duckweed does not yet exist.

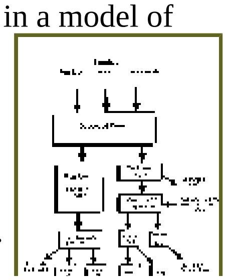
Nevertheless, the success of the experimental work suggests that duckweed cropping should be introduced to a wider audience of farmers, especially those in tropical and semitropical developing countries.

A logical first step would be to develop institutional centers capable of assimilating existing knowledge concerning duckweed, adapting this knowledge to specific local conditions and expanding it through research. These research and demonstration centers should also be supported by extension and credit institutions capable of delivering information and financial support directly to duckweed and duckweed-fish farmers. Pending the development of markets for duckweed as an end-product, mechanisms should be developed to link duckweed production with some end-use. Currently there are only three: direct fish or poultry production, and production of blended animal feeds.

The remainder of this section will discuss key institutional issues at the farm level and beyond, which should be addressed to facilitate introduction of duckweed production and duckweed-fed fish production elsewhere. The research center model, best exemplified by the various CGIAR facilities worldwide, needs little elaboration. The discussion will concentrate, therefore, on farm level linkages, extension, credit, and pricing issues that are basic to duckweed production.

Linkage of duckweed and fish production

Duckweed cannot be stored for more than two or three days in its green state and at temperatures above 20° C. Until adequate cold storage or drying technologies have been developed, this limitation prevents formation of a conventional duckweed market where supply and demand can determine an equilibrium price. Protection of both duckweed and fish producers' interests, therefore, assumes some formal linkage between duckweed and fish production. Figure 23 illustrates product flows and linkages in a model of duckweed production and utilization. Several simple models are discussed below.



Demand models The simplest duckweed/fish production paradigm is a demand model, in which the fish producer expresses demand for duckweed with an offer to pay a floor price for all the supply brought to him. This mechanism was tried in Khulna, Bangladesh, to foster the collection of naturally occurring duckweed from village ponds.

It had the effect of stimulating deliveries of fresh duckweed by villagers while wild stocks lasted. But, having depleted existing duckweed stocks, villagers did not, as expected, request technical assistance to develop and maintain duckweed culture ponds. Supplies of duckweed quickly dropped to levels insufficient to maintain a duckweed-fed carp fishery, and an increase in the offering price had little effect on supply.

A more active model in which duckweed farmers are provided with technical assistance and investment capital, in addition to a floor price offer, is likely to produce better results. Without guarantees on either side, however, duckweed producers retain little pricing leverage and remain vulnerable to arbitrary termination, while fish farmers are vulnerable to supply uncertainties.

Two-unit linkage Paired linkage between a duckweed farmer and fish farmer, reinforced by formal short-term agreements specifying mutual obligations with respect to price and supply, is more satisfactory, both from a productivity as well as an equity point of view. By enabling formal negotiation, this mechanism allows better distribution of benefits between the two parties. However, simple linked production may not provide an adequate buffer against fluctuations in duckweed supply and demand.

Group linkage Close linkage between and among two producer groups appears to provide the best circumstance for duckweed/fish production. Pooling of supply and demand is the major difference between this and the paired producer model. The supply buffer can also be augmented in a group context by guaranteeing adequate substitution, for example, water hyacinth, in the event duckweed production does not meet some specified minimum. Fish producers should also provide guarantees for floor price and minimum quantity purchases. The possibility of substitution within each group -- duckweed production for fish production and vice versa -- provides dynamic tension to price negotiations and therefore higher returns to duckweed producers.

Vertical Integration Vertical integration is a logical response to the uncertain relationship between duckweed producers and fish producers, but it is unclear at this point whether farmers will prefer separate or integrated operations. Because duckweed production has significantly lower net returns than does fish production, fish farmers who could vertically integrate may find it more attractive to devote all their production capacity to fish farming while working to stimulate production of their duckweed requirements among neighboring farmers. Entry into duckweed production by fish farmers may also be inhibited by the need to hire labor and somewhat lower productivity compared with an owner-operated duckweed farm. Poorly paid hired laborers are unlikely to sustain either the level of effort, or to develop the sensitivity to crop fluctuations that are essential to maintain high duckweed productivity. On the other hand, a fish farmer would be more likely to add duckweed production than a duckweed farmer to add fish production.

For most duckweed farmers, moving to a vertically integrated production model is unlikely because of significantly increased risk and the requirement to defer gratification. To achieve such production integration, duckweed producers must also gain access to adequate land area, infrastructure, and working capital to sustain at least six months of production. It is likely that they would also have to forgo the daily salary-like cash reinforcement derived from duckweed production contracted to a nearby fish farming operation.

Linkage catalysts Duckweed production is technically complex and there are large requirements for working capital for joint duckweed and fish production. It is critically important to coordinate between both production elements, yet there are few operating production centers that can serve as models for aspiring producers. For these reasons, it is important to develop an effective institutional framework for stimulating and managing duckweed and duckweed-fed fish production.

It is unlikely that farmers or groups of farmers will band together of their own volition in a coordinated duckweed/fish venture. An external catalytic agent is required. This can take many institutional forms: government extension services, private voluntary agencies, producer cooperatives, or agribusiness. The agency's primary responsibility should be to ensure smooth coordination between duckweed and fish producers. Also, the agency should ensure that adequate supplies of working capital and technical assistance are available. Efficient duckweed production requires continuous supervisory, technical, and financial reinforcement.

Technical assistance and extension issues

Unlike traditional crops which need only sporadic attention, duckweed cultivation, and duckweed-fed fish culture are both continuous production processes. Duckweed production, in particular, departs significantly from the conventional agricultural paradigm of *planting* -> *fertilizing/crop maintenance* -> *harvesting* -> *processing* -> *storage* -> *sale* spread over a growing season ranging from two months to two years. All of these elements are compressed into a daily cycle in duckweed farming. Adapting to farming as a continuous process is likely to demand a difficult conceptual adjustment on the part of most farmers.

Receiving daily payment for daily production is strong reinforcement for good practice. A farmer who fails to fertilize, maintain, or harvest his crop adequately will experience an immediate drop in production and, consequently, in income. He would not have to wait for three months before facing the consequences of his action. Feedback is immediate and has a salutary reinforcing effect on both quality and level of effort.

The duckweed-fed fish culture model discussed here has also been structured as a continuous production process. Feeding with duckweed is continuous throughout the day, while guarding and monitoring of the fish crop continues both day and night. Only harvesting is conducted periodically.

The role of a village level extension agent is to ensure: (1) that each participating farmer is trained in the latest duckweed or fish farming techniques; (2) that he understands the continuous nature of the production processes; (3) that he continues to engage in good practice; and (4) that he continues to receive immediate payment for his daily product. This suggests that extension support for duckweed and duckweed-fed fish production should also, as with the processes being supported, become a continuous process. And it suggests that duckweed extension should have some financial and commodity exchange capability.

Building these elements into existing extension systems, whether government or private, is likely to be difficult. Extension, credit, and commodity exchange capabilities are more appropriately built into duckweed research and demonstration centers. These centers of applied research could then evolve into integrated centers for duckweed research and dissemination.

Credit requirements

Credit support for duckweed and duckweed-fed fish farming is essential. Both are intensive processes that need a steady flow of investment. Credit for these linked processes is characterized by two features: (1) it is appropriately disbursed continuously in small, productivity-based increments, and (2) it is considerably greater than the credit required for comparable conventional farming processes. Where wastewater is the source of water and growth nutrients for duckweed production, lower recurrent costs mean that credit requirements will be about half those for hydroponic culture of duckweed.

The performance of agricultural credit programs to small farmers worldwide is poor. Loan amounts seldom match real requirements; disbursements are slow; recovery rates are low; and where recovery is mandatory, as in the United States, small-farmer bankruptcies are commonplace. While a discussion on the reasons for this poor performance is beyond the scope of this paper, common belief holds that, beyond the more frequently cited structural deficiencies of the credit institutions themselves, a primary failing of agricultural credit programs is the inability of farmers to manage their credit. Experience shows that farmers are likely to consume directly a significant portion of the credit they receive, and the greater the amount of disbursement, the higher the proportion of consumption.

The amount of working capital required for linked duckweed and fish production is high by most comparable standards. Fertilizer inputs to duckweed production are higher than for other crops. Similarly, duckweed input requirements to a carp fishery are higher than those of comparable fish feeds. Both require daily inputs and, therefore, a continuous flow of cash. Assuming that the duckweed farmer will be paid immediately for his daily product, credit requirements for working capital may then be focused directly on the fish farmer. At the beginning of his production cycle, he must have access to sufficient working capital to enable daily procurement of duckweed supplies for six to seven months. At a price of $0.03/kg for fresh duckweed, a farmer growing one hectare of carp will require between $1,500 and $1,600 for a year's supply of duckweed. This is for most Bangladeshi farmers more than their expected household income for a year. The likelihood of their retaining the money over six months and spending it for duckweed procurement is, therefore, very low, and a phased supply of incremental installments is needed.

In the case of duckweed/fish production the risk for farmers can be reduced through close technical and managerial involvement by the credit institution. A village-based agent should manage the exchange of duckweed between duckweed farmers and fish producers, and should also arrange direct payment to duckweed producers on behalf of fish farmers. Direct payments to fish farmers should be for (1) salaries of external labor employed directly in fish production, and (2) sustenance allowances to fishery owners.

Credit institutions should serve as exchange agents in the final disposition of fish. Income from fish sales should flow through the credit institution before net payments are made to fish producers. In performing these exchange services credit institutions should add value to the production processes by improving both production and marketing efficiencies, and by continuously reinforcing good practice through technical assistance and efficient timing of financial inputs.

Pricing issues

Current experience suggests that at a price of 1.0 Taka, or about $0.03 per kg, a duckweed farmer in Bangladesh can expect to net less than one-third of what a fish farmer can earn from the same amount of land. Close linkage of duckweed and fish production is likely to place continued upward pressure on the price of fresh duckweed. This upward pressure is moderated by a general acceptance that fish farmers deserve a higher return because they accept greater risk and make higher capital investments. Upward pressure on the price of duckweed is also relieved slightly by the threat that fish farmers might decide to vertically integrate their operations by producing duckweed themselves.

Where extension-credit institutions provide linkage services between duckweed and fish producers, provision should be made for a mechanism to negotiate the price of duckweed when fluctuations are justified to distribute profits from linked production more equitably.

As a market for dried duckweed meal is gradually established, pricing of fresh duckweed will be influenced more by market prices of dried duckweed meal and protein extract. And these will, in turn, be tied closely to prices of competitive products derived from soybean and fish.

Profitability

The projected rates of return on investments in duckweed-fed carp production and duckweed production compare favorably with alternative investments in the agricultural sector in Bangladesh. Annexes 1 and 2 estimate the profitability in Bangladesh of five-year investments in duckweed-fed carp culture and duckweed production respectively.

The profitability of duckweed production is especially sensitive to two factors, (1) the cost of fertilizer, and (2) the sale price of fresh duckweed. Where all fertilizer and most water are obtained from a domestic wastewater stream, the internal rate of return on duckweed production escalates from 44 percent to 63 percent. A 30 percent increase in the price of fresh duckweed brings the internal rate of return up to 74 percent.

The profitability of duckweed-fed fish production is most sensitive to the price of fresh fish, and the cost of investment capital, but reasonably insensitive to the price of fresh duckweed. A 30 percent decrease in the price of fish reduces the internal rate of return to 45 percent. However, a 30 percent increase in the price of duckweed only reduces the internal rate of return from 85 percent to 80 percent.

Section 5 - Duckweed-based Wastewater Treatment Systems

[Press Here for *"A Wastewater Treatment Primer*"]

Effective treatment of nightsoil and wastewater, at both the village and urban level, remains an elusive objective in most developing countries. While there are many reasons for this, experts generally agree that the overriding factor is cost. Conventional treatment systems, which generally rely on heavy aeration are prohibitively expensive to install, and both difficult and costly to operate and maintain. If affluent cities such as Sydney and San Diego cannot afford to make the billion dollar investments required to provide effective treatment of their wastewater, what prospects are there for Calcutta or Lima? And if Lima and Calcutta, which have viable municipal governments, cannot afford wastewater treatment how can it be accomplished in small towns and villages which have essentially no tax base?

Duckweed-based wastewater treatment systems provide genuine solutions to these problems. They are inexpensive to install as well as to operate and maintain. They do not require imported components. They are functionally simple, yet robust in operation; and they can provide tertiary treatment performance equal or superior to conventional wastewater treatment systems now recommended for large-scale applications. Finally, and perhaps most importantly, duckweed wastewater treatment systems have the potential, by turning wastewater into valuable duckweed meal, to return a net profit against both capital and recurrent costs. This being the case, it suggests that in future, cities like Lima and Calcutta cannot afford **not** to treat their wastewater.

Duckweed wastewater treatment systems remove, by bioaccumulation, as much as 99% of the nutrients and dissolved solids contained in wastewater. Duckweed systems distinguish themselves from other efficient wastewater treatment mechanisms in that they also produce a valuable, protein-rich biomass as a bi-product. Providing accumulated toxin and heavy metal levels are not high, *[see next footnote]* the harvested duckweed biomass may be used as the sole feed input for fresh-water pisciculture, and as up to 40% of poultry feed. This biomass might also be useful for a variety of other domestic animals.

[Footnote: Algae are the major constituent of TSS in the final effluent of most wastewater treatment systems.]

Duckweed wastewater treatment systems are, at their core, lagoon systems. They differ from conventional lagoon systems, however, in that they (a) achieve a significantly higher level nutrients removal from the wastewater stream; and (b) work to prevent rather than to encourage algal growth.

The effect is to produce a high-quality effluent which can halt or significantly reduce the continual influx of harmful substances (nitrogen, phosphorus, etc.) into receiving bodies of water (rivers, lakes or seas). Unlike conventional lagoon systems, duckweed wastewater treatment systems also have a low algal content - thereby meeting the most stringent discharge requirements for suspended solids. Duckweed system discharge contains few organic compounds and may therefore be chlorinated without significant production of carcinogenic trihalomethane compounds. Finally, because they are more efficient than conventional lagoon systems duckweed systems occupy less (expensive) land to achieve a higher level of treatment.*[See next footnote]*

[footnote: An unlikely occurrence in village, small town and urban periphery systems.]

The section which follows describes the pilot duckweed wastewater treatment plant at the Mirzapur experimental site which has been in operation since July 1990. Results have been impressive. Treating an average flow of 125 m³/day of hospital, school, and residential wastewater produced by a population of between 2,000 and 3,000 persons, the 0.6 hectare plant produces a final treated effluent which exceeds the highest quality standards mandated in the United States. *[See next footnote]* Table 2 shows typical influent, primary effluent and duckweed system effluent data for the Mirzapur experimental wastewater treatment plant:

[Footnote: The wastewater effluent from the Kumudini Hospital complex, with BOD of 120 mg/l, is not typical of most developing country wastewater streams. The collection system at the complex does not capture a significant portion of the discharge from the complex - particularly kitchen wastes, and hostel septage - and the water discharge from the hospital itself is significantly higher than average institutional discharge in developing countries. This contributes to both a low flow and a relatively low BOD.]

Table 2. Quality of final treated effluent for March 23, 1991: Mirzapur Experimental Site

Treatment Phase	*BOD_5 (mg/l)*	*NH_3 (mg/l)*	P (mg/l)	Turbidity (FTU*
Raw Influent	120	39.40	1.90	113
Primary	60	32.20	2.00	85
Duckweed	1	0.03	0.03	10
US Summer Standards: Washington D.C. area	10	2.00	1.00	20**

** This turbidity unit standard is roughly equivalent to total suspended solids (TSS) times two. ** Standards for the Patuxent Valley in Maryland, north of Washington D.C.. TSS standards of 10 mg/l are shown in FTU units (20) for comparability.*

Many other wastewater treatment facilities designed solely for municipal treatment in the U.S. and elsewhere have produced better than secondary effluent quality for flows ranging from a few hundered cubic meters per day to over 30,000 m^3/day.*[See next footnote]* Even higher flow rates are being designed for large cities with hundreds of thousands of inhabitants. These systems have been designed to conform to all standards of design and operation imposed by the U.S. Environmental Protection Agency and other similar regulatory agencies in various countries.

[Footnote: The Lemna Corporation, St. Paul, Minnesota, U.S.A.]

The basic mechanism employed by the duckweed wastewater treatment system is to farm various duckweed species on the wastewater requiring treatment. The rapidly growing plants act as a nutrient sink, absorbing primarily nitrogen, phosphorus, calcium, sodium, potassium, magnesium, carbon and chloride from the wastewater. These ions are then removed permanently from the effluent stream as the plants are harvested.

Depletion of nutrients causes diminished duckweed growth. The starved plants then begin processing increasingly greater amounts of water as they search for growth nutrients. In the process, they absorb virtually every chemical present in the wastewater stream. The small volume of plants harvested during this polishing process may contain unacceptably high levels of toxins and heavy metals when influent contains a significant volume of factory discharge. If so, they should be disposed of as green manure for crops not used as food or forage.

Maintenance of efficient duckweed growth requires even distribution of a thick layer of plants across the entire lagoon surface. This has the additional effect of shading the water below from sunlight and preventing growth of algae. *[See next footnote]*

[Footnote: Algae are the major constituent of TSS in the final effluent of most wastewater treatment systems.]

Harvested duckweed plants contain up to 45% protein by dry weight and may be used without further processing (i.e., drying) as a complete feed for fish. Dried duckweed meal can provide the protein constituent of various mixed animal feeds. The vitamin A and pigment content of duckweed have proven particularly valuable in poultry diets. *[see next footnote]*

[Footnote: This has been shown during 4 years of research on the nutritional value of Lemnaceae conducted by The PRISM Group in collaboration with the Agricultural University of Peru and the Ralston Purina company. See Haustein et al].

A typical duckweed wastewater treatment plant will yield a daily harvest of up to one ton of duckweed plants (wet weight) per hectare. This can, in turn, produce up to 100 kilograms of fish or 90 kilograms of dried, high-protein duckweed meal each day.

The duckweed wastewater treatment process is described in greater detail below:

Primary System

The primary phase of the duckweed wastewater treatment system receives all the raw wastewater influent. Like any primary treatment process, the principal objective is to separate floating material and achieve significant solids removal through sedimentation - all at a low capital cost.

Duckweed systems should also work to maximize release of nutrients from sedimented solids through anaerobic digestion of primary sludge. This process also produces significant release of methane which can be collected for subsequent use or simply vented.

Sedimentation Achieving efficient sedimentation is important to prevent degradation of initial duckweed treatment runways. Septage and influent wastewater must also be introduced with minimal aeration to maintain anaerobic conditions and to avoid odor nuisance. This is easily achieved using a deep tank or pit, and is enhanced by maintaining methane storage under slight pressure. A deep, reinforced circular tank with a vertical, centrally located, low-pressure, large diameter inflow pipe will achieve efficient settling while also maintaining anaerobic conditions within the tank. *[See next footnote]*

[Footnote: Where cost factors prevent construction of deep, enclosed sedimentation/digestion chambers and odor control is not considered to be a high priority, reasonably efficient sedimentation can still be achieved using two deep, open earthen tanks. Inflow should be designed to minimize turbulence and aeration.]

Twin primary tanks are usually necessary. Both tanks should be located side-by-side with the first tank being built approximately 30 cms above the second tank to enable gravity flow-through. Initially, both systems should be operated in series, with the second tank receiving the effluent from the first tank. As sedimentation increases in the first tank, efficiency will also drop and an increasing volume of sediment will be passed through, and be trapped by, the second tank. When total fluid volume in the first tank has been reduced by 50% it should be bypassed, with all influent flows passing only through the second primary tank. The first tank should then be drained and sludge removed by whatever mechanism is most safe and efficient given local circumstances.

The cleaned tank (#1) should be brought back into service as soon as possible. Eventually, the second tank (#2) will also require desludging. This will, of course, require bypassing the tank, with direct discharge of primary effluent from tank #1 into the duckweed plug-flow system.

Sludge disposal Sludge should be analyzed for toxin and heavy metal concentrations prior to project implementation. If found to meet established criteria, the project should include a mechanism for composting sludge and either using it directly or selling it as garden manure. Sludge should otherwise be disposed of in a manner which will minimize entry of toxins or heavy metals into the human food chain. The most profitable application is likely to be use as a fertilizer in a nearby agroforestry project.

Primary treatment must deal with two types of floating material, plastic and flotsam carried on the raw influent, and scum-like material floated from the bottom in anaerobic systems. Flotsam is easily removed through course screens. Scum is easily trapped by releasing effluent from the primary tanks 0.5 meters below the surface. The resulting crust of floating material will also serve to minimize surface aeration and reduce odor in open-cut primary systems.

Odor control Both primary settling tanks should be covered if possible. The resulting odor reduction will have a significant salutary effect on acceptance of the facility by persons having occasion to live or work near the facility.

Efficient operation of the primary facility dictates maintenance of an anaerobic system. As such, generation of a significant volume of methane and hydrogen sulfide is inevitable. These gases should be trapped under an airtight cover and either used as biogas or flared-off.

Bad smells are the most frequently cited objections of people living in the vicinity of wastewater treatment facilities. Designed and operated correctly, a duckweed primary system should issue no objectionable odors. In fact, a well landscaped duckweed wastewater treatment makes an excellent park. The Mirzapur facility is favored by local couples as a meeting place.

Costs System cost is an important consideration in the design of a primary process for a duckweed wastewater treatment system. Should cost prove to be a significant constraint it is possible to achieve effective primary treatment with two simple open-cut facultative lagoons. Unlike the closed system described above, open systems may present significant public relations problems to the operating agency.

Duckweed Plug Flow System

The essential element of a duckweed wastewater treatment facility is the duckweed system itself. It consists of a shallow, lined *[see next footnote]* pond system designed to allow effective cultivation of duckweed plants **and** incremental treatment of a wastewater stream. As such, the system must enable efficient harvesting and maintenance of the duckweed crop while also preventing short-circuiting of the wastewater flow.

[Footnote: Lining is essential to both prevent water loss and protect aquifers. Unlike the multilayer linings strictly mandated for landfill sites in North America and Europe, a relatively inexpensive clay lining will usually suffice.]

The duckweed plug flow system may be thought of as containing two distinct elements: (a) the duckweed farm; and (b) the wastewater polishing facility. Under circumstances where wastewater consists primarily of domestic sewage, these two elements may be indistinguishable.

Duckweed Farm The principal objective of the duckweed farm is to produce as much usable, harvested duckweed as possible while also maximizing **net** returns from the process. In so doing, the objective of achieving maximum removal of nutrients from the wastewater stream is also achieved.

Like all biological systems, duckweed plants prefer certain growth conditions over others. Maintenance of these conditions is important in achieving both efficient plant growth and effective wastewater treatment.

While duckweed species are known to survive under widely varying conditions of both water temperature and chemistry, their rate of growth is quite sensitive to variations of both. *[see next footnote]*

[Footnote: Refer to Chapters one and two for specific information on optimal conditions for duckweed cultivation.]

Recirculating systems The ultimate treatment objective of removing all nutrients from wastewater inevitably leads to duckweed starvation at some stage in the treatment process. This eventually leads to virtual cessation of plant growth. At the other extreme, high loadings of nutrients (ammonia in particular), surfactants *[see next footnote]* and compounds with herbicidal properties can have a similar effect but is easily prevented. This is achieved by recirculating a portion of the final treated effluent. Systems should therefore be designed to begin and end at a proximate location. This makes recirculation a simple matter of lifting treated effluent about six inches and pumping it a short distance. A simple rule of thumb for dilution of primary effluent is to ensure that BOD_5 at the head of the first duckweed treatment runway is maintained under 80 mg/l.

[Footnote: Surfactants are a product of soap and detergent in effluent streams. In high concentrations they can "dissolve" duckweeds' protective waxy coating, leaving plants more vulnerable to fungal

infection.]

The objective of maximizing minimum surface temperatures and minimizing maximum surface temperatures is served by increasing system depth and stimulating system mixing. An additional consideration dictating system depth is total detention time (approximately 20-30 days to achieve acceptable pathogen reduction).

Experience suggests that systems with a maximum operational depth of 1.0 meter can provide acceptable temperature buffering and detention time without incurring unacceptably high costs. *[see next footnote]*

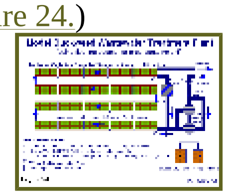
[Footnote: Depths of between one half and three meters are also acceptable. For example, a circumstance with relatively low BOD and high land costs and a requirement to maximize pathogen removal would be designed with deep runways and low recirculation. Similarly, a situation with high BOD and inexpensive land might be better served by an extensive, relatively shallow system with high rates of recirculation.]

Distributing and containing duckweed plants Among factors affecting duckweed growth, unconstrained access to the pond surface ranks as the most important. Plants should be distributed across the entire surface to make full use of the productive potential of that surface. They should also be distributed in a manner which does not constrain their growth. Increasing the base population of plants in a given area increases the multiplicative potential of that population. There is, however, a point of diminishing returns, where the inhibitive effect of crowding on plant reproduction outweighs the increased productive potential of a higher base population.

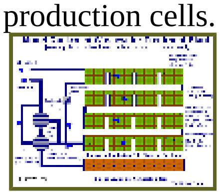
Efficient distribution of duckweed plants across the entire available growing surface requires that plants be contained in relatively small, discrete cells. This is achieved by two means: (a) placing an interlocking floating grid over the ponds or runways used for growing duckweed; or (b) building containment cells with low earthen berms and bunds. Choice of containment system is primarily a function of land, labor and material costs but is also influenced by factors such as prior circumstance *[see next footnote*] and choice of system operation intensity.

[Footnote: A duckweed system "retrofit" on an existing lagoon will typically use an extensive floating grid for containment.]

Floating containment structures should be UV resistant and sufficiently robust to survive 5 or more years of heavy harvesting activity by self-propelled mechanical harvesters. Where capital is constrained containment booms can be fashioned from large diameter bamboo or some other inexpensive floating material. They will, however, require frequent replacement, and will probably cost more in the long run than barriers made from extruded plastic. The size of the grid is determined by mean ambient wind conditions and the maximum projected system flow velocity. Cell sizes on existing PRISM and Lemna Corporation wastewater treatment systems range between 25 sq. m to 50 sq. m. (see figure 24.)



Alternatively, low earthen berms are also effective in creating efficient duckweed production cells. This system, depicted in Figure 25, allows use of perimeter harvesting with a variety of hand tools and small mechanized harvesters. Berm systems have the additional advantage of providing increased area for collateral crops which can significantly boost total system profitability.



Harvesting Having determined the standing crop density which realizes the highest duckweed productivity, efficient management dictates maintenance of a steady state system at that density. Each cell should be harvested back to the target density. Optimal system densities on existing duckweed systems range from 400 to 800 grams of duckweed per square meter.

The choice of harvesting technique is dictated by system configuration as well as the cost of labor and capital. The most simple harvesting mechanism involves scooping of plants from the pond surface using handtools. This mechanism is facilitated by a facility design which enables harvesting from a perimeter surface - typically a narrow plug flow system. Larger, broader pond-based systems require harvesting from self-propelled craft. These may be either engine driven, or powered by the harvestors themselves. In most developing country applications, systems should be designed to enable labor-intensive perimeter harvesting.

Regular harvesting is important not only because it generates a valuable biomass byproduct, but also because bioaccumulation remains the principal mechanism of wastewater treatment, and harvesting ensures that the accumulated nutrients and toxins are permanently removed from the wastewater being treated. Harvesting is also important to maintain a healthy, productive crop. Younger plants not only maintain a better nutrient profile (i.e., they contain more protein and less fiber), but they also reproduce and grow more quickly than older plants.

Algae Shade A significant benefit of duckweed systems over other lagoon-based wastewater treatment systems is that they are capable of efficient removal of influent suspended solids **and** they prevent formation of algal suspended solids which are the bane of lagoon system effluent. This is achieved through the simple mechanism of shading. A dense layer of floating duckweed plants prevents sunlight from reaching algae populations distributed throughout the water column. Unable to photosynthesize they simply die and precipitate to the pond bottom.

Systems with enclosed primary treatment units maintain algae inhibition from the outset and will provide marginally better total suspended solids (TSS) removal than systems with open primary lagoons. In either case, duckweed wastewater treatment systems can consistently bring total final effluent TSS to below 5 mg/liter.

Nutrient Uptake Efficiency Duckweed plants are remarkably efficient at removing elements which are, for them, growth nutrients. These include some organic compounds, as well as ions of elements such as nitrogen, phosphorus, potassium, magnesium, calcium, sodium, chlorine, boron, and iron, among others. Duckweed can directly absorb and metabolize both complex carbohydrates such as sucrose, fructose and glucose, as well as organic nitrogenous compounds such as urea and most amino acids. While growth nutrients remain, duckweed plants are disposed to absorb them to the exclusion of other elements present in the wastewater column. As such, **well-fed** duckweed plants cannot be considered ideal engines for **complete** treatment of wastewater *[see next footnote]* with high toxin and heavy metal content.

[Footnote: Duckweed wastewater treatment systems are, nevertheless, capable of efficient toxin and heavy metals removal in a polishing process (described under "Duckweed Wastewater Polishing") which exploits the plants' unique uptake characteristics under nutrient-deprived circumstances.]

Safety of Harvested Duckweed Plants Duckweeds' predilection for exclusive uptake of nutrients is important in enabling the safe utilization of plants harvested from urban wastewater. Testing, over the years, of many duckweed plant samples harvested from **nutrient rich** urban wastewater has consistently failed to find any heavy metals or known toxins in concentrations approaching USFDA (United States Food and Drug Agency) food standards prohibiting human consumption. *[see next footnote]*

[Footnote: Haustein, A., R. Gilman, P. Skillicorn, 1987, The Safety and Efficacy of Sewage-grown

Duckweed as feed for Layers, Broilers and Chicks, report to USAID Science Advisor.]

Duckweed Wastewater Polishing

Duckweed plants do, nevertheless, provide a complete wastewater treatment engine. Starved duckweed plants - i.e., plants unable to find sufficient nutrients to maintain rapid growth - undergo a remarkable metamorphosis: plant protein drops below 20%; fiber content goes up; roots become long and stringy; fronds become larger and discolored; and, most importantly, the plants begin processing huge amounts of water in their search for sustaining nutrients. In the process, they absorb - as ash in the case of metals - virtually everything still present in the wastewater.

Polishing units, necessarily, form the final stage of a duckweed wastewater treatment system. In instances where analysis of wastewater indicates heavy concentrations of toxins and heavy metals, the beginning of the polishing zone should be explicitly indicated. Plants harvested from the zone should then be disposed of in an appropriate manner. Most wastewater does not, however, contain significant concentrations of either toxins or heavy metals, and polishing zones may simply be considered to be the latter reaches of a continuous duckweed treatment process. Harvest volume and plant quality will be somewhat lower than that achieved from the bulk of the farming zone, but polishing plants need not be excluded from the main harvest.

Pathogen removal

Pathogen reduction in any lagoon system relies on two simple mechanisms: sedimentation and die-off. Parasites and parasite ova precipitate with other suspended solids and are trapped in the bottom sediment. Other pathogens, suspended in water, simply die as a function of time and temperature. A sufficient detention time must be provided to ensure die-off of pathogens adequate to meet effluent discharge or reuse standards. Recirculation in duckweed systems adds *dilution [see next footnote]* as a third pathogen reduction mechanism.

[Footnote: Dilution is the principal treatment mechanism of sewage outfalls. The huge volume of essentially sterile seawater into which the wastewater is discharged, quickly reduces seawater pathogen counts below the threshhold for human infection. This is, unfortunately countered by the ability of mollusks and other coastal shellfish to concentrate and incubate some human pathogens - notably ***Vibrio cholerae****.]*

As with any organic surface area enhancing material introduced into wastewater, duckweed plants do marginally concentrate pathogens on their surfaces. As such, pathogens will, inevitably, be harvested along with the duckweed crop. If harvested plants are used green as fish feed, these bacteria experience even greater dilution and faster die-off in the fish pond. The small number of surviving pathogens consumed by fish will be digested in their guts. In instances where plants are processed and dried, desiccation will achieve even more rapid die-off. No viable human pathogens could be cultured from dried sewage-grown duckweed meal in 4 years of testing. *(See next footnote)*

[Footnote: Haustein, A., R. Gilman, P. Skillicorn, 1987, The Safety and Efficacy of Sewage-grown Duckweed as feed for Layers, Broilers and Chicks, report to USAID Science Advisor. This research, conducted in collaboration with enteric disease experts from The Johns Hopkins University, examined both wet and dried Lemnaceae harvested from the San Juan wastewater lagoons located in Lima, Peru, for presence of various human enteric pathogens.]

The unique ability of duckweed systems to directly uptake complex organic compounds, combined with their inhibition of algae, provides another important potential benefit. Chlorination of treated duckweed system effluent should result in no significant production of carcinogenic trihalomethane *(See next footnote)* compounds. Therefore, while chlorination of wastewater effluent is generally not recommended, it may, if required by local regulation, be used to remove residual bacteria from treated duckweed system effluent.

[Footnote: Trihalomethanes have been identified to be among the most potent known organic compound carcinogens .]

Final Effluent Discharge Under most circumstances the final effluent from duckweed wastewater treatment systems will be superior to the receiving stream or waterbody. Duckweed system runoff may therefore be used as input to virtually any water-intensive operation - irrigation, factory use and cooling systems, among others. Providing thorough filtration *(see next footnote)* and some form of disinfection is performed - either chlorination, ozone or ultraviolet treatment - treated effluent from a duckweed system may potentially be used as input to municipal water supply systems. In water constrained areas such as the Middle East, the Caribbean and the west coast of South America, this represents a viable, ecologically superior alternative to desalination and costly dam and aqueduct projects.

[Footnote: Simple slow sand filters have been shown to provide excellent removal of organic compounds and are now routinely recommended as pretreatment for water treatment plants that draw from surface water sources.]

Commercial Systems

In the United States, Minnesota-based Lemna Corporation has developed a commercial process approved by the U.S. Environmental Protection Agency for funding in numicipal applications, which it has now applied, under varying conditions, in over sixty distinct locations throughout the United States, Europe and Latin America. The Lemna Corporatio treatment system consists of a sophisticated interlocking network of floating booms and hydraulically-driven mechanical harvesters to enable the growth and harvesting of duckweed on vast open ponds. These treatment facilities routinely achieve secondary to tertiary effluent standards for municipal waste streams in climates varying for sub-arctic to tropical. Lemna Corporation systems compete favorably against mechanical wastewater treatment systems *(see next footnote)* on both capital costs and treatment efficiency. In addition, the operating requirements are much less demanding than those of conventional systems, resulting in substantially lower energy and labor costs.

[Footnote: Aerated lagoons, activated sludge, or high rate algae systems.]

In general, care must be taken to ensure that the design, construction and operation of any wastewater treatment system conforms to the local regulations and design standards. This ensures protection of public health, public safety *and* the environment. To this end, it is advisable to retain the services of professionals in the wastewater treatment field to advise and assist in such design and construction programs.

Section 6 - Alternative Uses for Duckweed, Constraints, and Future Research

Developing alternative uses for duckweed

Use of duckweed is currently restricted to processes that can utilize freshly harvested plants. Further, transportation and storage constraints dictate that these processes be near the duckweed farm. Nutritionally, duckweed is an excellent substitute for soybean meal and fish meal in a variety of products. However, the economic potential of the duckweeds may not be fully realized until they can be economically reduced to a dried, compact commodity. This requires drying, and either pelleting, or powdering.

All drying technologies consume large amounts of energy, which is expensive, except waste heat and solar energy. Desiccating duckweed, which may contain from 92 to 94 percent moisture, using purchased energy - either gas, oil, electricity or biomass - is not economically feasible. If duckweed is to become a traded commodity, drying must be achieved through efficient application of either solar or waste process heat.

Duckweed plants have a waxy coating on their upper surface that is a good binding agent for pelleting. Dried meal, fed through conventional pelleting equipment, either alone or in combination with other feed ingredients, produces an excellent pellet. Duckweed in the form of pellets or dried meal can been stored without difficulty for five or more years. Evidence suggests that it is not attacked preferentially by weevils, mice, rats, or other vermin.

Duckweed as poultry and other animal feed Feeding trials reported in the literature and carried out recently in Peru have demonstrated that duckweed can be substituted for soy and fish meals in prepared rations for several types of poultry: broilers, layers, and chicks. Cultured duckweed can be used as the protein component in poultry diets. Acceptable levels of duckweed meal in the diets of layers range up to 40 percent of total feed. Duckweed-fed layers produce more eggs of the same or higher quality as control birds fed the recommended formulated diets. Levels of up to 15 percent duckweed meal produce growth rates in broilers which are equal to those produced by control feeds. Diets for chicks, consisting of up to 15 percent duckweed meal, are suitable for birds under three weeks of age. Duckweed meal will almost certainly find as large a range of animal feed applications as soybean meal.

Duckweed as a mineral sink Duckweed is a crop whose micronutrient requirements are substantial, so much so, in fact, that waterlogged, salinized soils, which are an important constraint on irrigated agriculture worldwide, may be a favorable environment for duckweed cropping. Duckweed has the potential, thereby, to become the building block for integrated farming in those areas. Several types of saline environments that may be converted to duckweed cropping have considerable economic potential: (1) waterlogged, salinized irrigation command areas; (2) coastal wetlands; and (3) saline groundwater for irrigation or potable use.

Alternative solutions to these problems are engineering-intensive and typically require large capital investments. Investigation to develop alternative duckweed systems to substitute for these expensive investments is an important area of future duckweed research.

Constraints and research needs

It has long been evident that duckweed has the potential to become a major protein commodity. Researchers worldwide have replicated experiments demonstrating the remarkable productivity of duckweed. Similarly, numerous studies have demonstrated the value of duckweed as a feed for poultry, fish, and other animals. However, duckweed has not yet been accepted as a commercial crop. But the major problem has been the economics of desiccation. No conventional drying technology has been able to produce a dried duckweed commodity without incurring a significant financial loss.

The Mirzapur experimental program in Bangladesh represents the first effort to apply existing knowledge on duckweed growth and cultivation to develop a practical farming system. By closely tying a viable and efficient duckweed end-use (feeding fish) to duckweed production, the Mirzapur experimental program has shown that duckweed farming can be profitable. Together, these two processes represent a farming system which, in its first full production cycle, is already competitive with any crop now grown in Bangladesh. The Mirzapur duckweed/carp polyculture ponds are currently the most productive non-aerated carp ponds in Bangladesh.

In the Mirzapur experimental program both duckweed farming and duckweed/carp polyculture have borrowed heavily from the existing literature to achieve their early success. This success has also highlighted a number of important areas for additional research.

Duckweed production The most important immediate research priority to advance duckweed production is to determine fertilizer requirements, particularly nitrogen and trace elements. The current practice of using of urea and unrefined sea salt is clearly inadequate. Exhaustive trials are needed, first to determine nutrient requirements and then to determine efficient sources for those minerals.

Farming-systems research should examine a variety of collateral crops which can provide efficient sun and wind buffering while maximizing total system income. Taro, for instance, works well as a buffer and provides excellent financial returns, but cannot reproduce efficiently in water 20 to 50 cm deep.

Much more work is required to understand circumstances which favor one species of duckweed over another. Although *Wolffia* species are seldom found to be dominant in the wild, it has now been successfully cultivated for two years, both singly and in combination, with other species. Based on current information, *Wolffia* appears to be the most productive of the three genera available in Bangladesh.

Genetic improvement Little has yet been done to assess and harness genetic variance both within and among duckweed species. Studies are needed to develop strains that are more tolerant of variations in pH and temperature. Recent advances in recombinant technology point to the possibility of developing optimized strains in the near future. By virtue of their structural simplicity and their ability to clone, the duckweed family is one of the most amenable of the higher plants to genetic engineering.

Duckweed wastewater treatment Duckweed-based wastewater treatment systems have demonstrated great efficiency in treating domestic wastewater and also have done so at a net profit. Research needs to be conducted to optimize pond design in balance with the agronomic requirements for duckweed production. For example, not enough is known about the capability of duckweed to remove heavy metals and toxins from certain types of wastewater. Answers to these questions, as well as more precise information on nutrient uptake rates, are necessary to develop standardized engineering guidelines for duckweed-based wastewater treatment facilities.

Drying Duckweed will not become a traded commodity until it can be economically dried. Several solar drying methodologies have already shown considerable promise. These and other inexpensive drying technologies should be further developed to enable commercial-scale drying. Care should be taken to ensure that beta-carotene and xanthophyll are not degraded during drying.

Derived products Researchers have demonstrated the ability to extract the protein fraction of wet duckweed through coagulation. If this process is refined and can be made cost-competitive with soy protein, the potential applications for duckweed protein are very great. High concentrations of beta carotene and xanthophyll suggest that duckweed could become a significant source of vitamin A and pigment.

Duckweed and fisheries Evidence so far suggests that duckweed serves as a complete nutritional package for carp polyculture and can significantly increase total system productivity. The various hypotheses underlying the duckweed/carp polyculture model presented in this paper now require careful testing to explain their fundamental mechanisms. There is clearly room to optimize the model. Questions such as species mix for the polyculture, timing of harvests, length of cycle, and timing of fingerling inputs, and quantity of feed application require more precise answers.

Annexes

Investment Scenarios

Annex 1 estimates the profitability in Bangladesh of five-year investments in one hectare of duckweed-fed carp culture. ***Annex 2*** analyzes costs and returns of the unit of duckweed production (0.5 hectare) necessary to support one hectare of duckweed-fed fish production. Both scenarios assume a sale price for fresh duckweed of $0.03/kg, 7 percent yearly inflation, and a 10 percent discount rate. The investment scenario for fish production assumes a sale price of $1.50/kg for fresh carp. The projected rates of return on both investments compare favorably with any alternative investments in the agricultural sector in Bangladesh.

Land costs for the fish culture scenario are assumed to be significantly higher ($5,000/ha versus $3,000/ha) than for the duckweed scenario. This reflects an assumed use of marginal, unimproved land for duckweed production and use of existing, highly valued fish ponds for duckweed-fed fish production.

For simplicity, both scenarios assume that all capital, including working capital, will be provided by the farmer in year zero. For that reason "cost of capital" is not included as a line item under "recurrent costs". Substitution of debt for direct investment will greatly enhance the farmer's rate of return for each scenario.

The profitability of duckweed production is especially sensitive to two factors: (1) the cost of fertilizer, and (2) the sale price of fresh duckweed. Where all fertilizer and most water are obtained from a domestic wastewater stream, the internal rate of return on duckweed production jumps from 23 percent to 52 percent. A 30 percent increase in the price of fresh duckweed brings the internal rate of return up to 55 percent.

The profitability of duckweed-fed fish production is most sensitive the price of fresh fish, and the cost of investment capital, but reasonably insensitive to the price of fresh duckweed. A 30 percent decrease in the price of fish reduces the internal rate of return to 16 percent, but a 30 percent increase in the price of duckweed only reduces the internal rate of return by 6 percent to 44 percent.

Annex 1. Investment Scenario for Duckweed-Fed Fish Production: 1.0 Hectares for 5 Years

COSTS(US$)	Year_0	Year_1	Year_2	Year_3	Year_4	Year_5
Capital Costs						
Land	$5,000					
Pond Rehabilitation	$5,714					

Water Supply	$1,500					
Equipment	$857					
Total Fixed Costs	$13,071					
Total Working Capital	$4,200					
Total Capital Requirements	$17,271					
Recurrent Costs						
Duckweed - fresh feed		$3,100	$3,317	$3,549	$3,798	$4,0
Fingerlings		$457	$498	$523	$560	$5
Pond Preparation		$429	$459	$491	$526	$5
Water		$571	$611	$654	$699	$7
Labor		$712	$762	$815	$872	$9
Miscellaneous		$57	$611	$654	$699	$7
Total Recurrent Costs		$5,840	$6,249	$6,686	$7,154	$7,6
INCOME						
Sale of Fish		$15,000	$16,050	$17,174	$18,376	$19,6
NET INCOME	($17,271)	$9,160	$9,801	$10,487	$11,221	$12,0
CALCULATIONS (5-Year investment)						
Internal Rate of Return	50%					
Net Present Value	$20,141					
Breakeven Point	1.8	years				
ASSUMPTIONS (per year)						
Labor	2,601	hours				
Water	60,000	m^3				
Fingerlings	20,000					
Production	10	tonnes				

Annex 2. Investment Scenario for Duckweed Production: 0.5 Hectares for 5 Years

COSTS(US$)	Year_0	Year_1	Year_2	Year_3	Year_4	Year_5
Capital Costs						
Land	$1,500					
Earthworks	$714					
Water Supply	$714					
Equipment	$286					
Total Fixed Costs	$3,285					
Total Working Capital	$486					
Total Capital Requirements	$3,771					
Recurrent Costs						

Fertilizer		$866	$927	$991	$1,061	$1,1
Supplies		$71	$76	$81	$87	$9
Bamboo, etc..		$171	$183	$196	$209	$2
Water		$286	$306	$327	$350	$3
Labor		$548	$586	$627	$671	$7
Miscellaneous		$0	$0	$0	$0	$
Total Recurrent Costs		$1,942	$2,078	$2,223	$2,379	$2,5
INCOME						
Sale of Duckweed		$3,142	$3,362	$3,597	$3,849	$4,1
NET INCOME	($3,771)	$1,200	$1,284	$1,374	$1,470	$1,5
CALCULATIONS (5-Year investment)			Hydroponic (fertilizer)		With Wastewater	
Internal Rate of Return			23%		52%	
Net Present Value			$2,712		$4,757	
Breakeven Point			2.9	years	1.8	years
ASSUMPTIONS (per year)						
Fertilizer						
Urea			3,120	kgs		
TSP			624	kgs		
Potash			624	kgs		
Salt			1,404	kgs		
Water			30,000	m^3/yr		
Labor			2000	hrs		
Production (wwt)			110	tonnes		

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DUCKWEED AQUACULTURE is a special publication of the Agriculture Division of the Technical Department of the Europe, Middle East, and North Africa Regional Office of the World Bank, 1818 H Street, N.W., Washington, D.C., USA. (Facsimile: (202) 477-0712, Telex: WUI 64145 WORLDBANK, RCA 248423 WORLDBK).

This publication is based primarily on a study performed at the Mirzapur Experimental Duckweed Site by The PRISM Group of Columbia, Maryland, USA. The study describes current knowledge about farming aquatic plants of the family Lemnaceae, the common duckweeds, their potential as a protein-rich animal feedstuff, and their value as a low cost, low energy wastewater treatment technology.

Figures

Figure 1

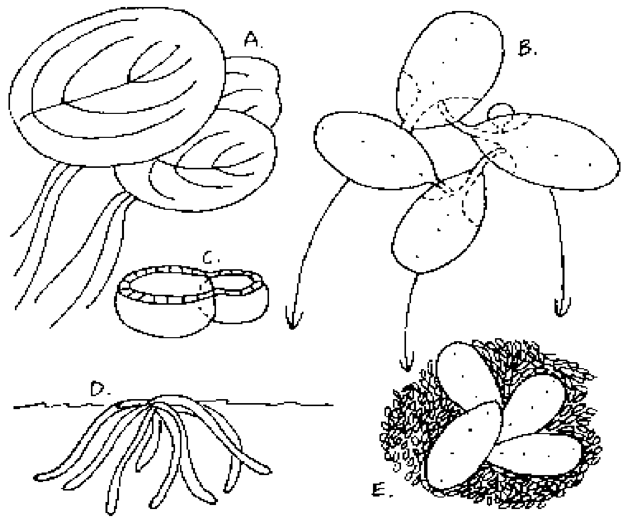

Figure 1. Duckweed, the smallest flowering plants.
Genera: A. Spirodela B. Lemna C. Wolffia
D. Wolfiella E. Lemna with Wolffia

Figure 2

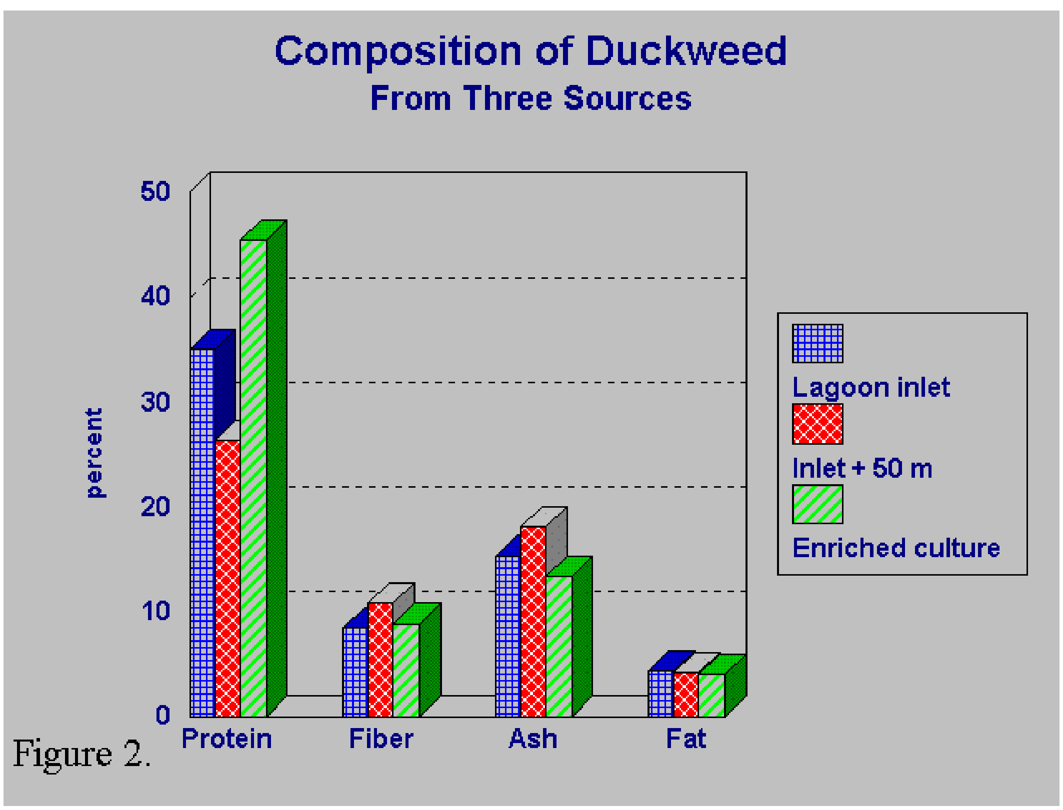

Figure 2.

Figure 3

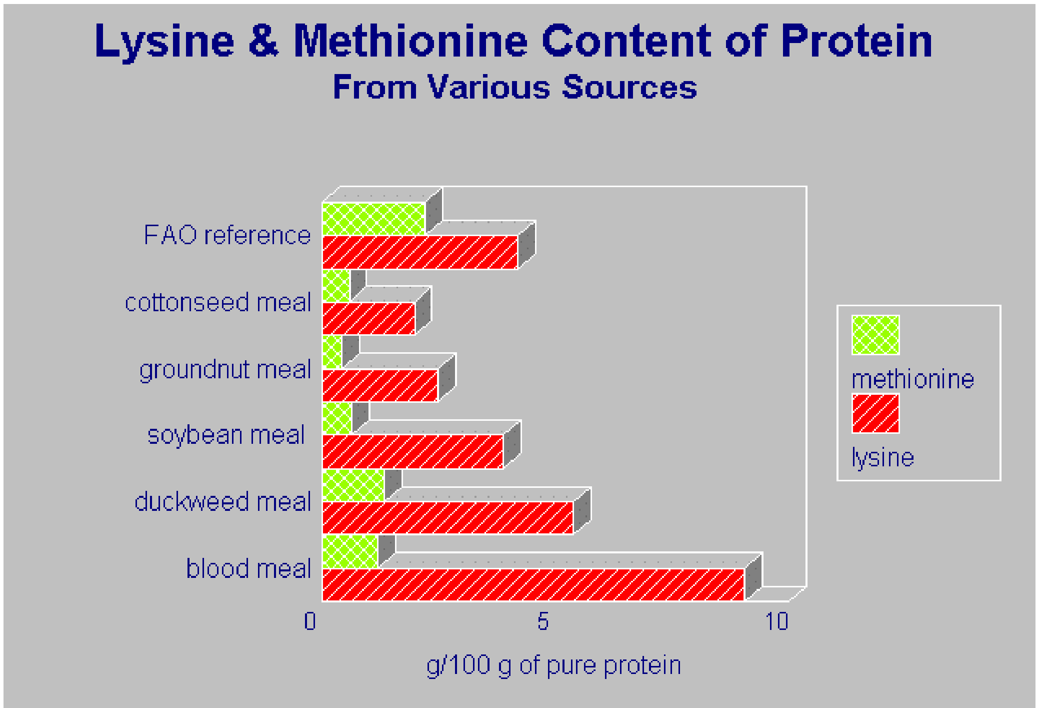

Figure 3.

Figure 4

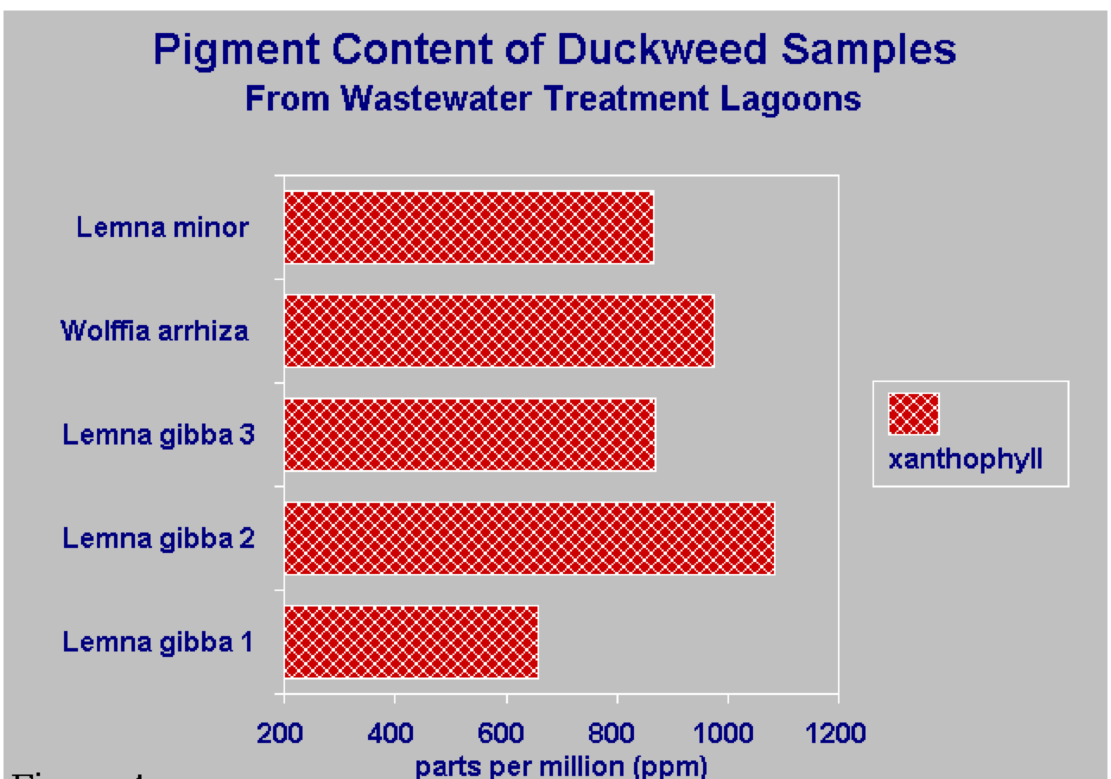

Figure 4.

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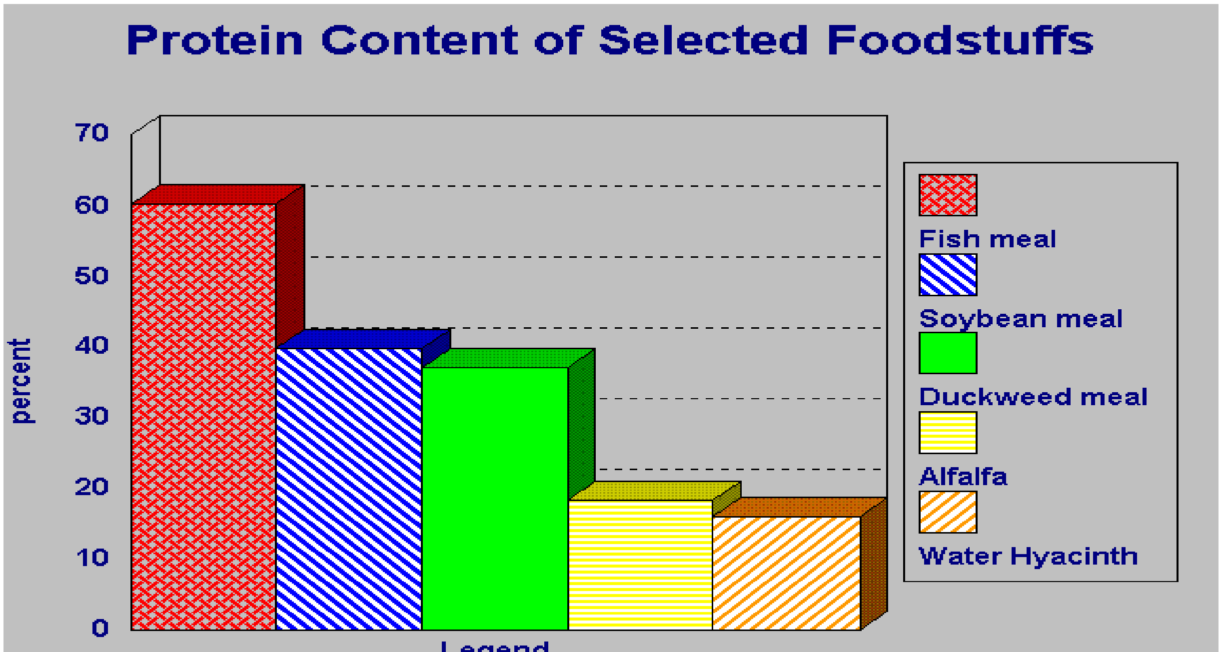


Figure 5.

Figure 6

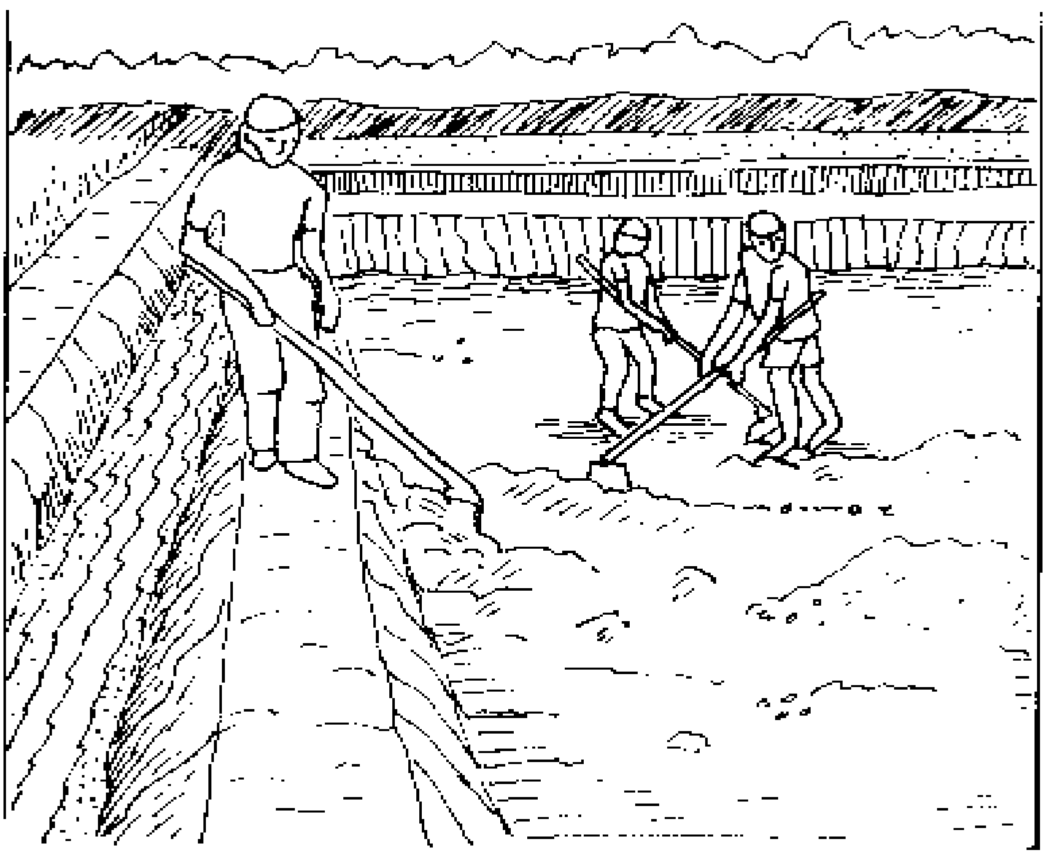


Figure 6: Making a duckweed culture pond

Figure 7

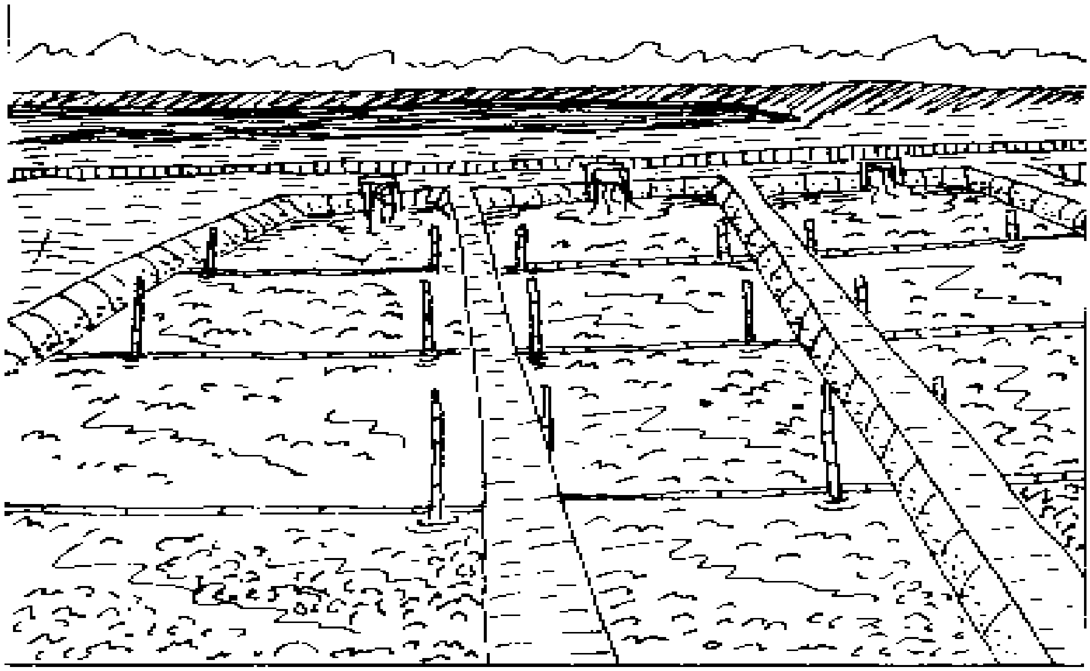


Figure 7. Protecting duckweed from wind and wave action

Figure 8

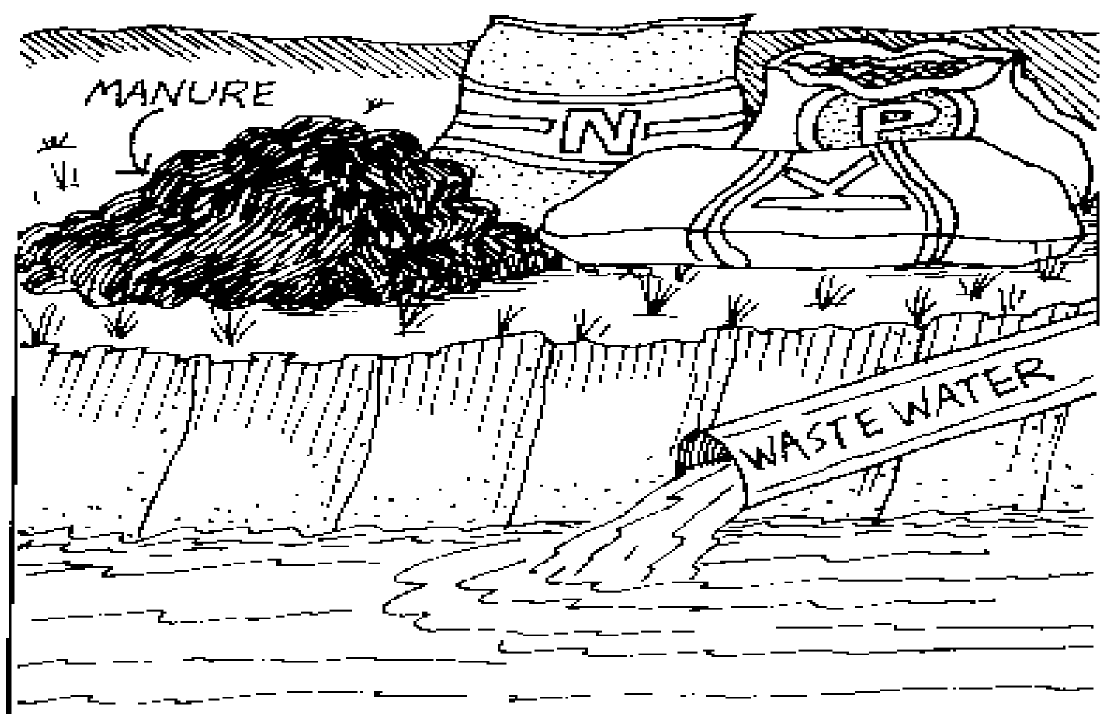


Figure 8. Nutrients for duckweed can come from fertilizer or organic wastes

Figure 9

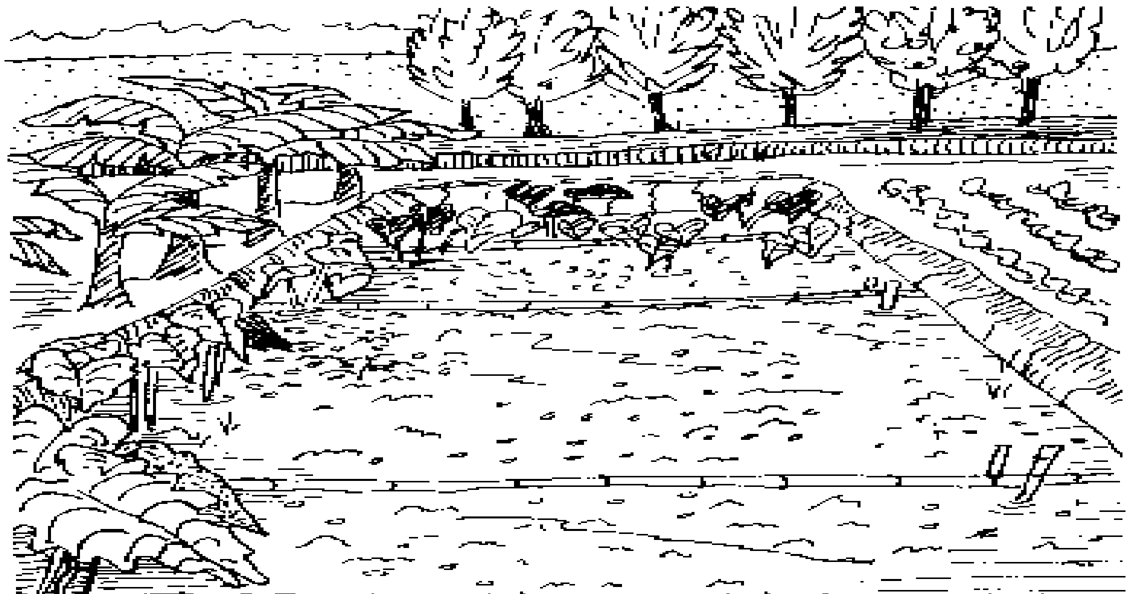


Figure 9. Co-cropping with terrestrial plants mimics duckweed's natural environment and increases cropping intensity

Figure 10

Figure 10: Collecting duckweed seedstock

Figure 11

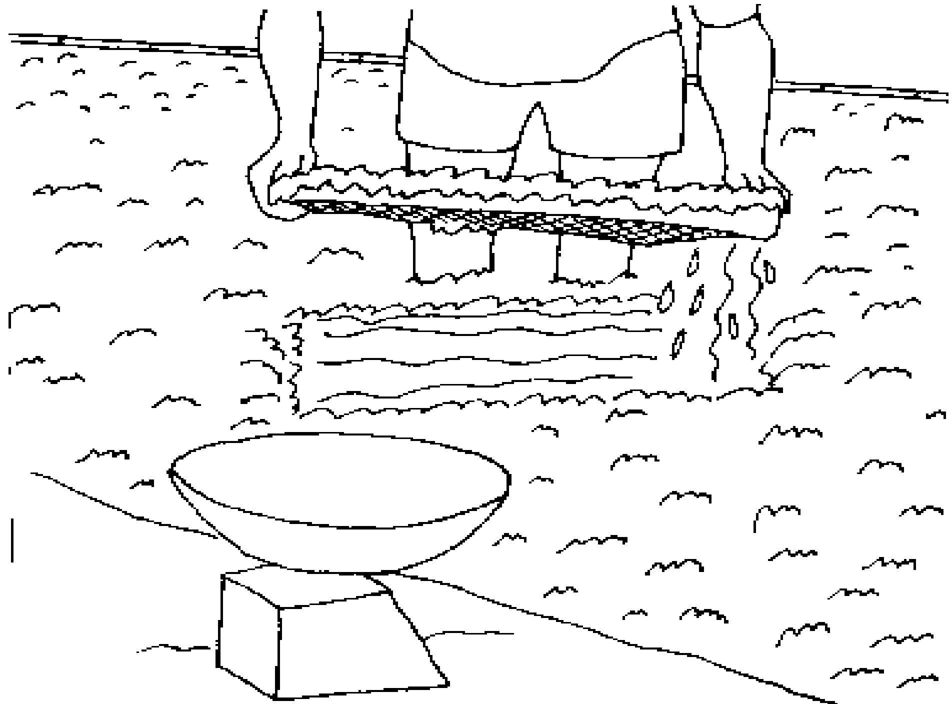


Figure 11. Growth in excess of the optimal stocking density should be harvested regularly to promote rapid growth

Figure 12

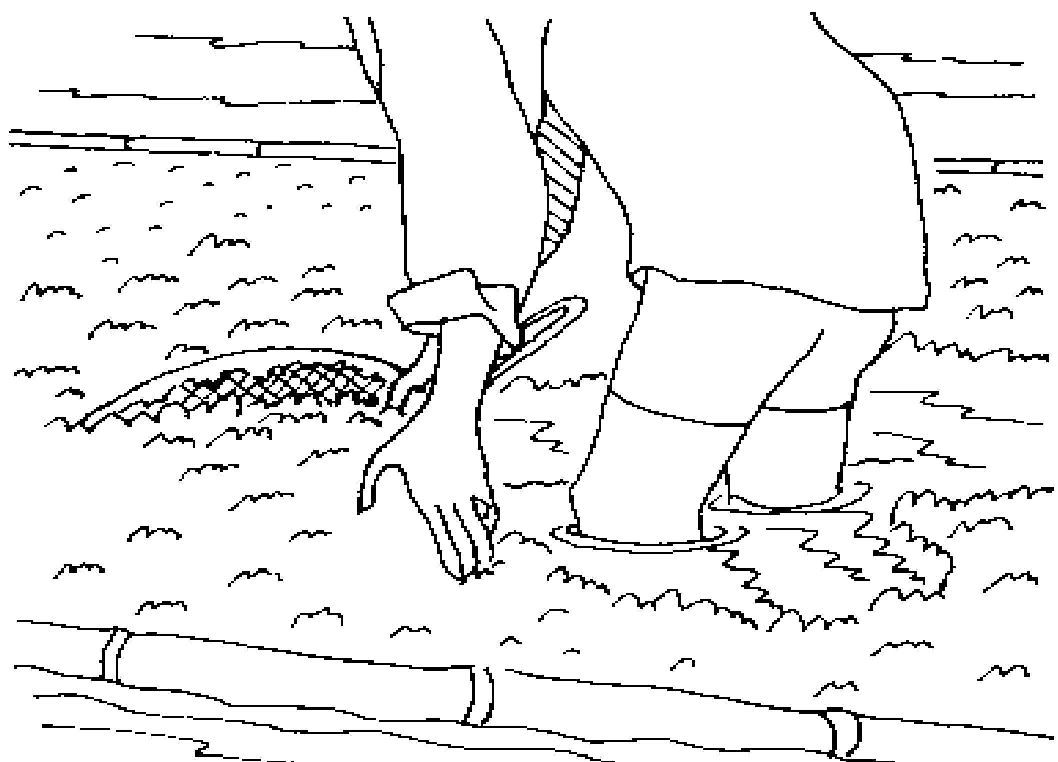


Figure 12. Harvesting by skimming with a dip net

Figure 13

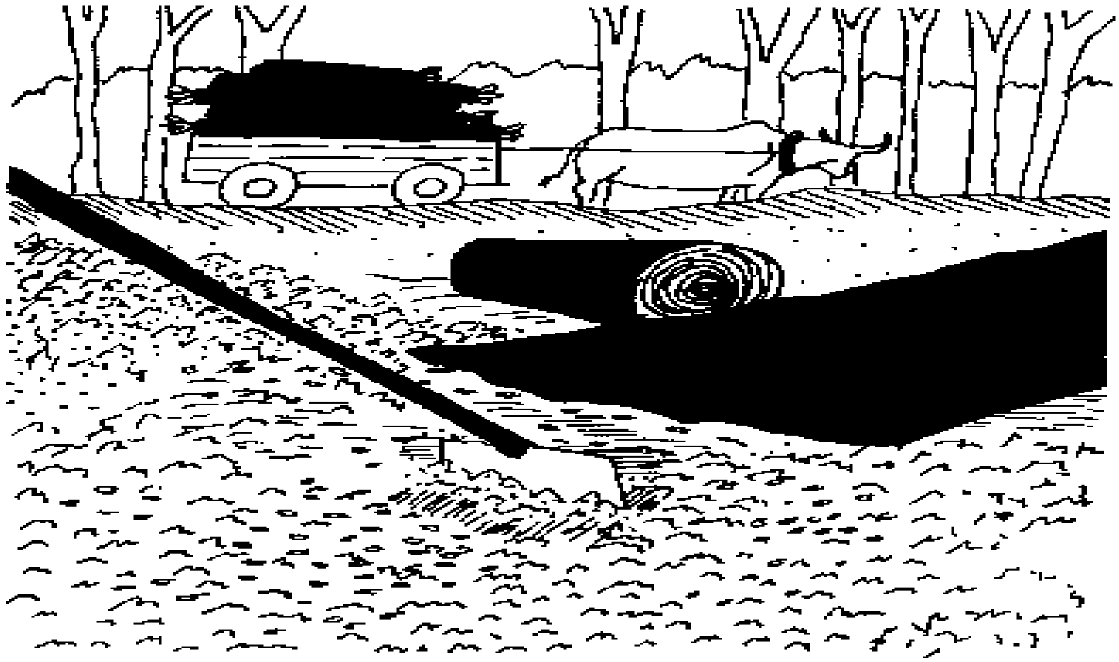


Figure 13. Drying duckweed in the sun and bagging dried meal in opaque plastic bags.

Figure 14

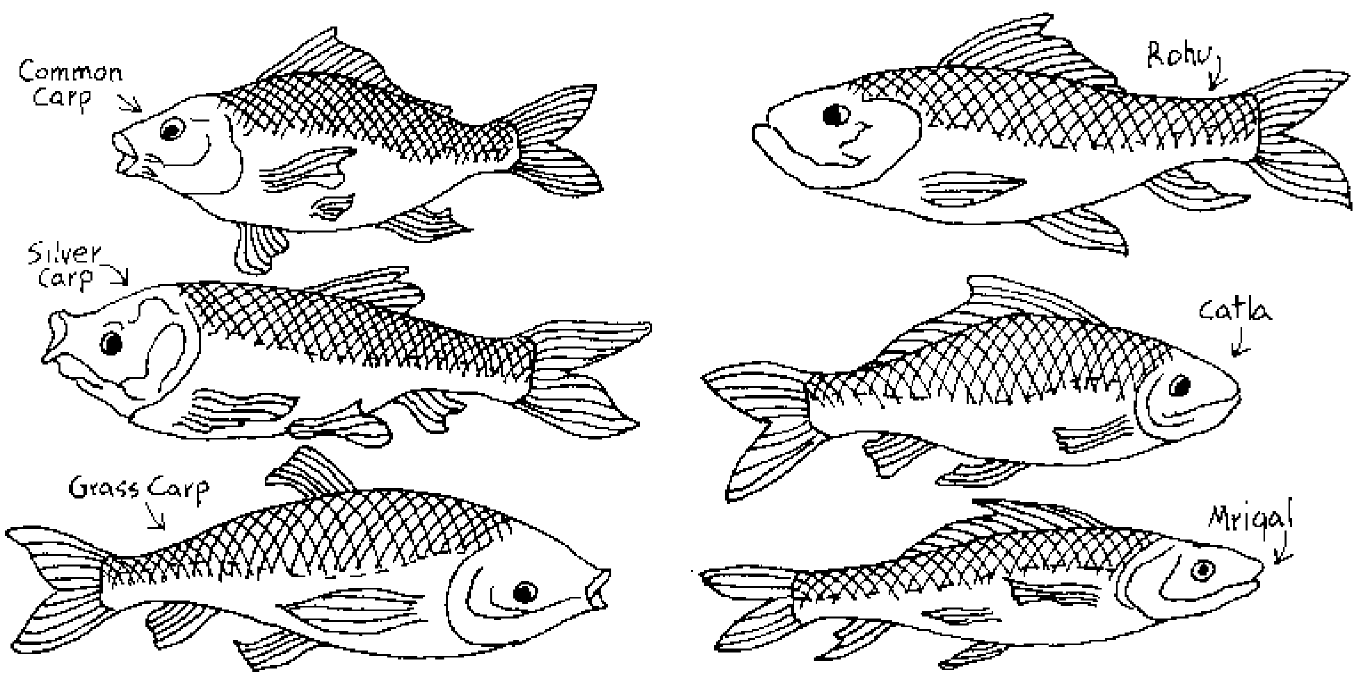


Figure 14. Chinese and Indian major carp species

Figure 15

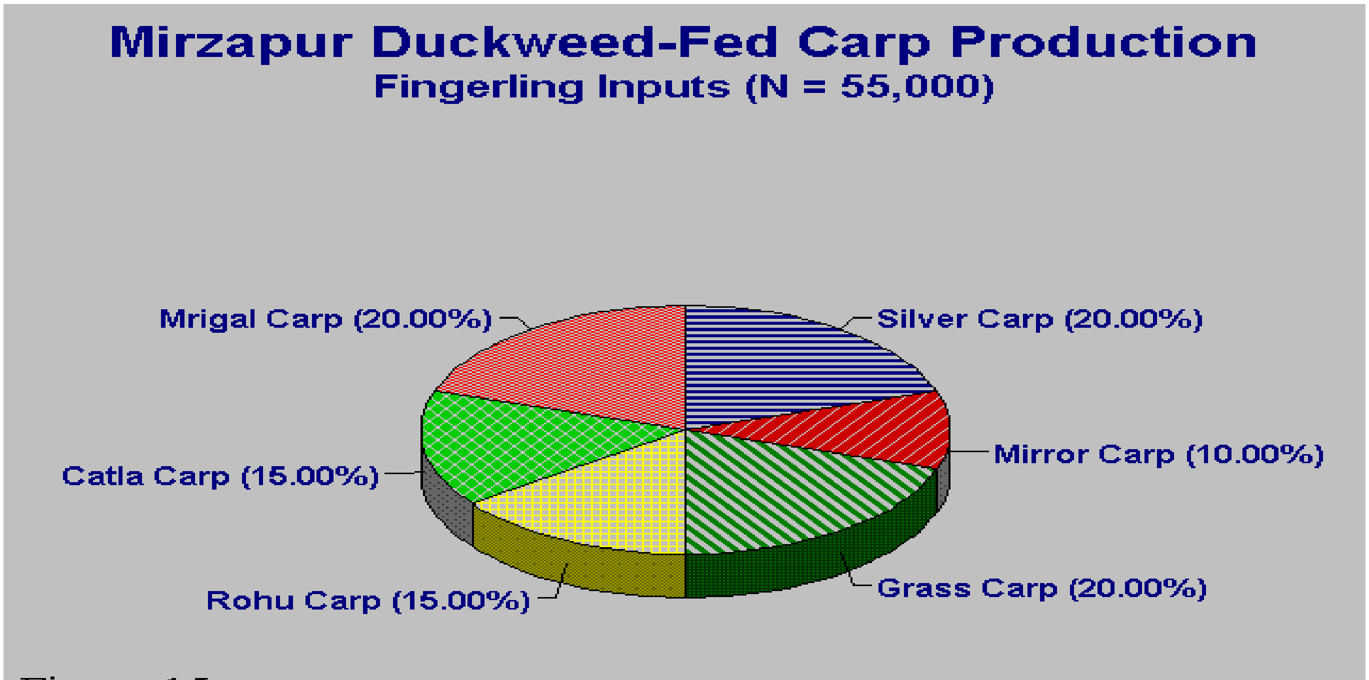
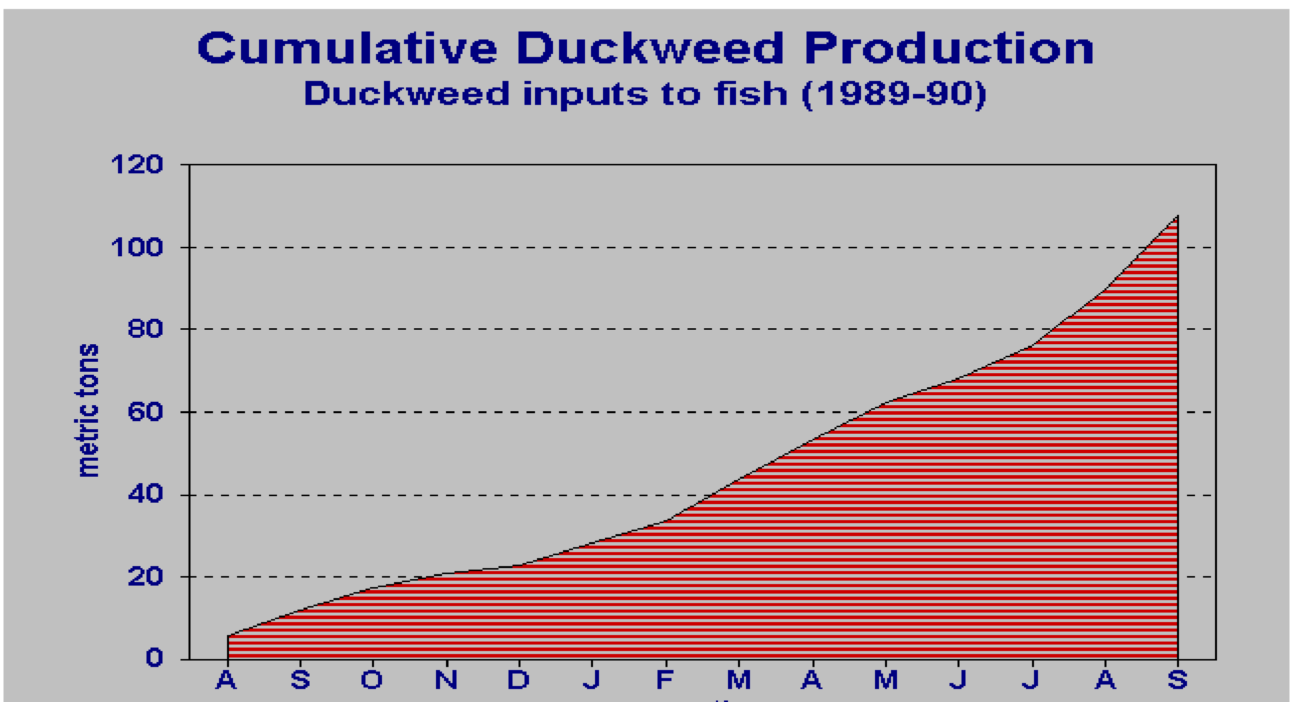


Figure 15.

Figure 16



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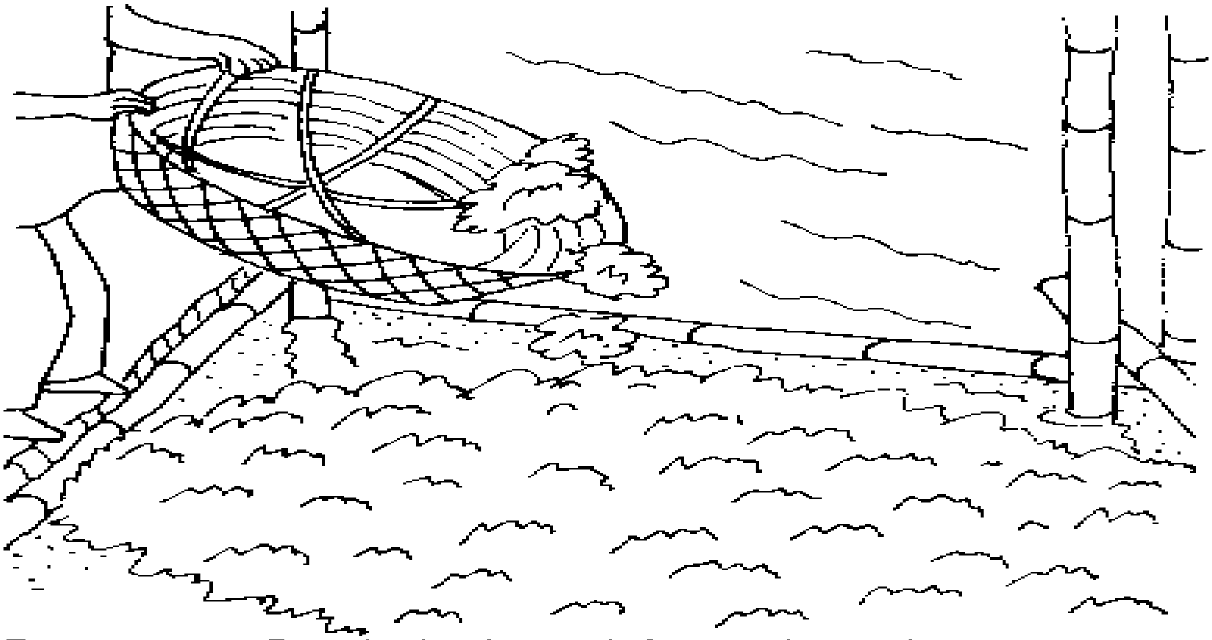

Figure 17. Fresh duckweed from the culture pond is fed directly to carp in the fish pond

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Figure 18

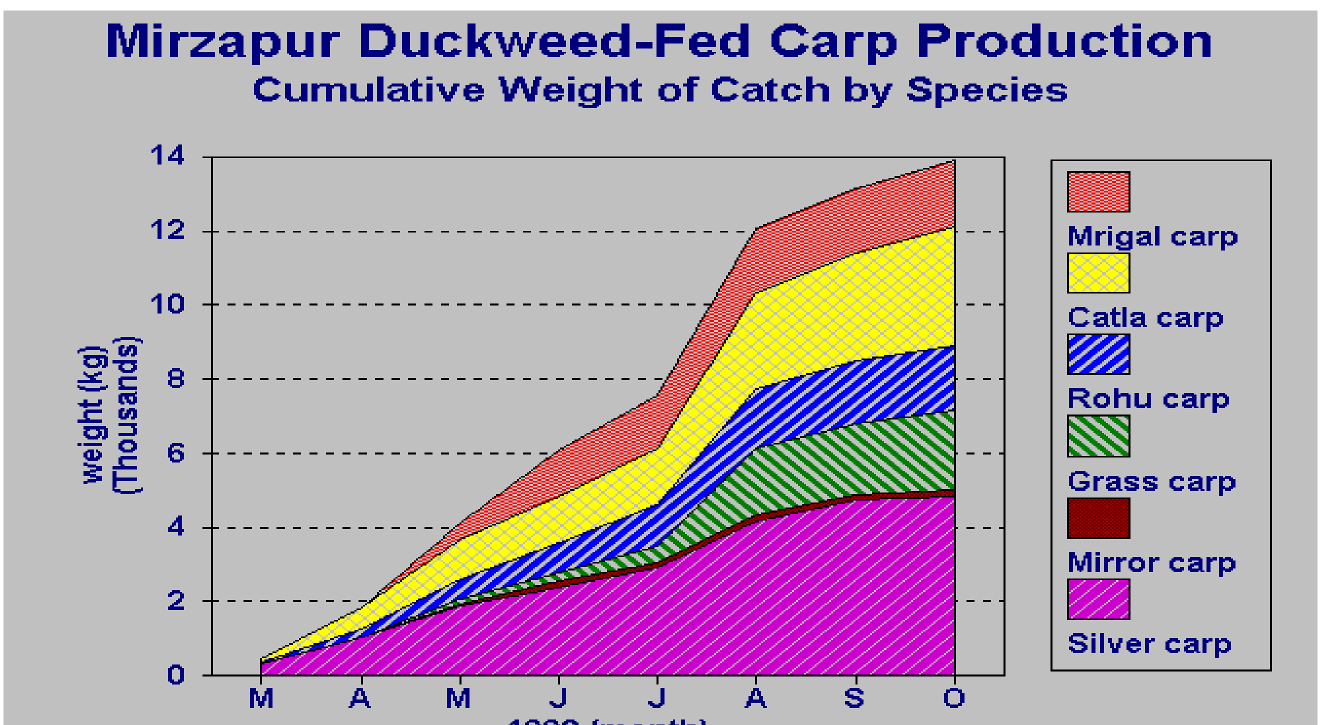

Figure 18.

Figure 19

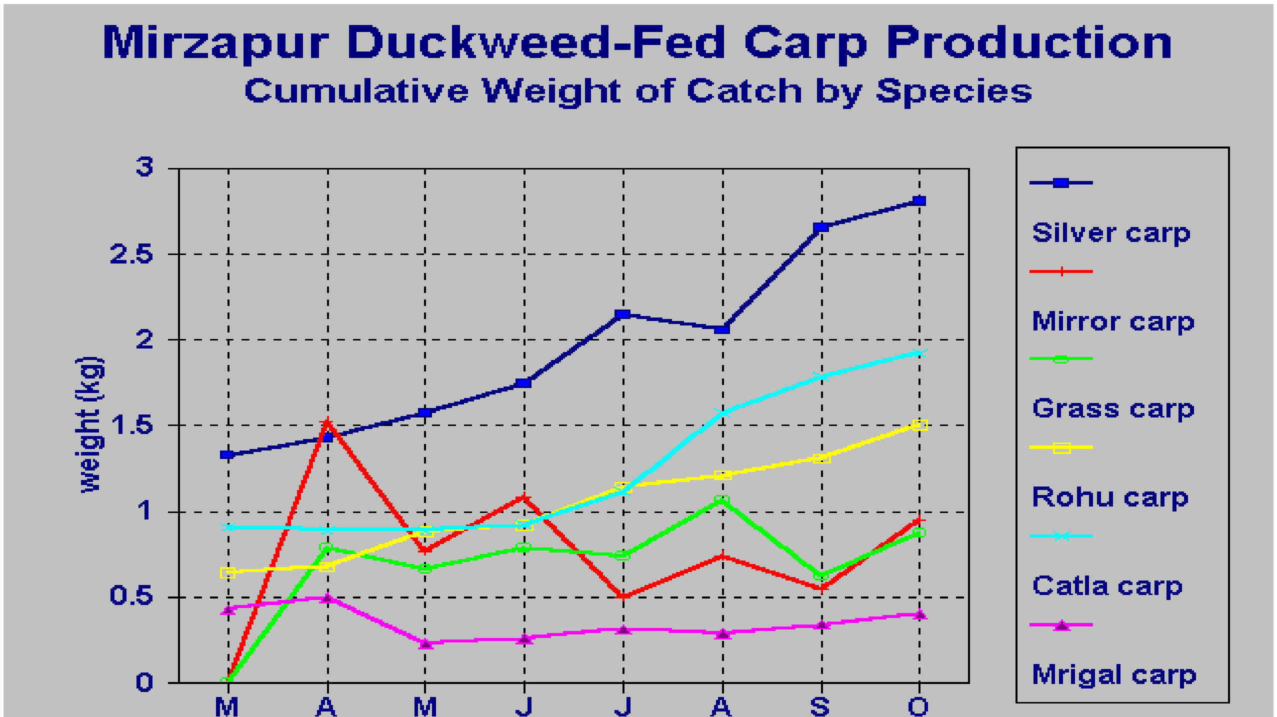

Figure 19.

Figure 20

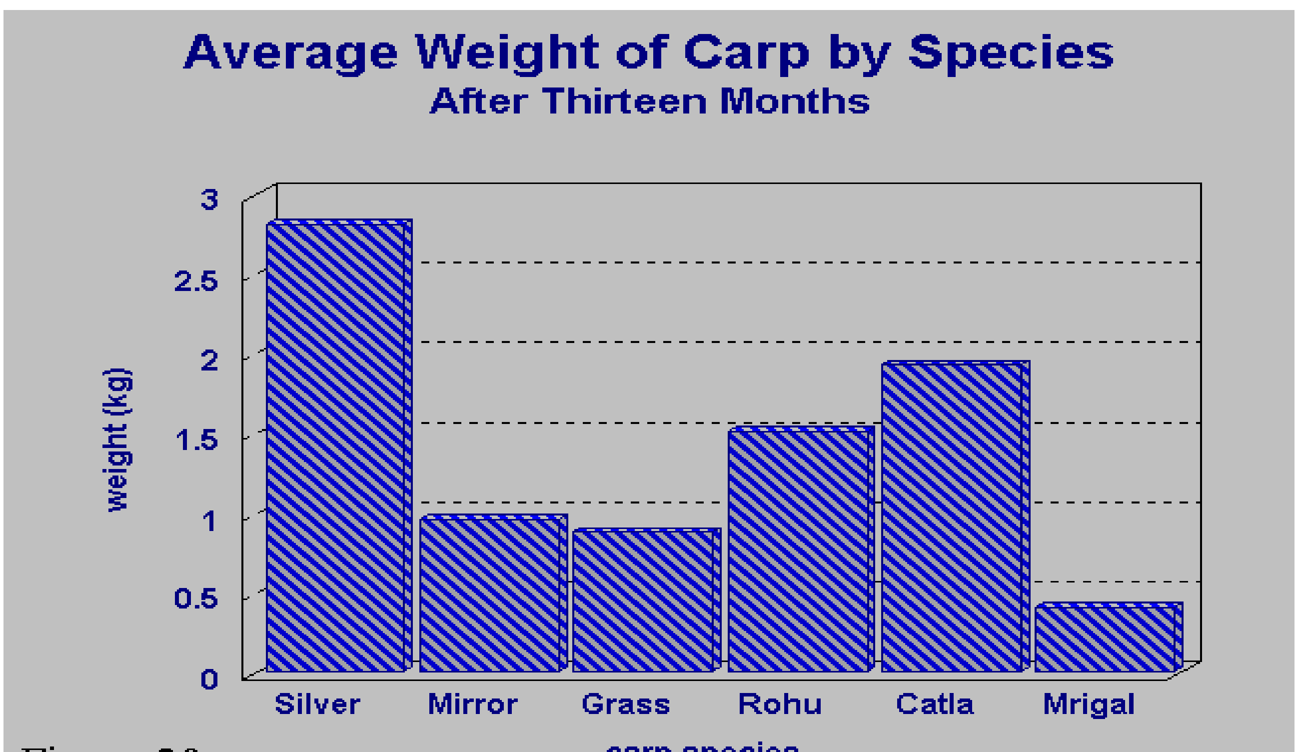

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Figure 21

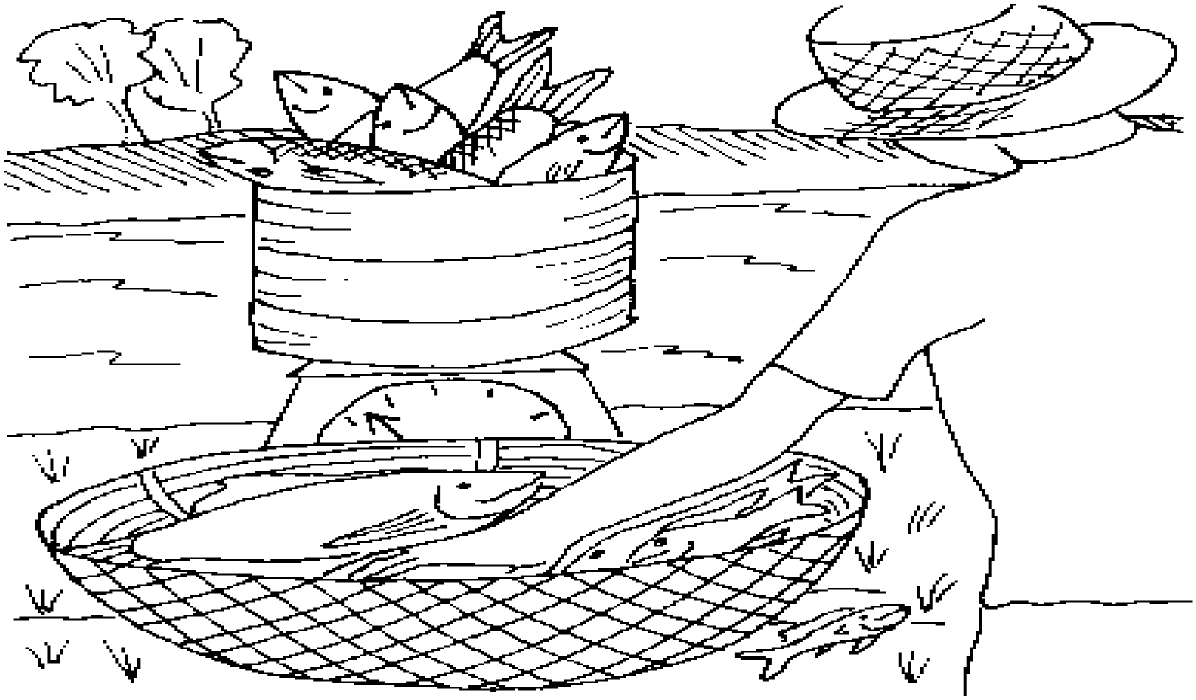

Figure 21. Market size fish are selected and weighed

Figure 22

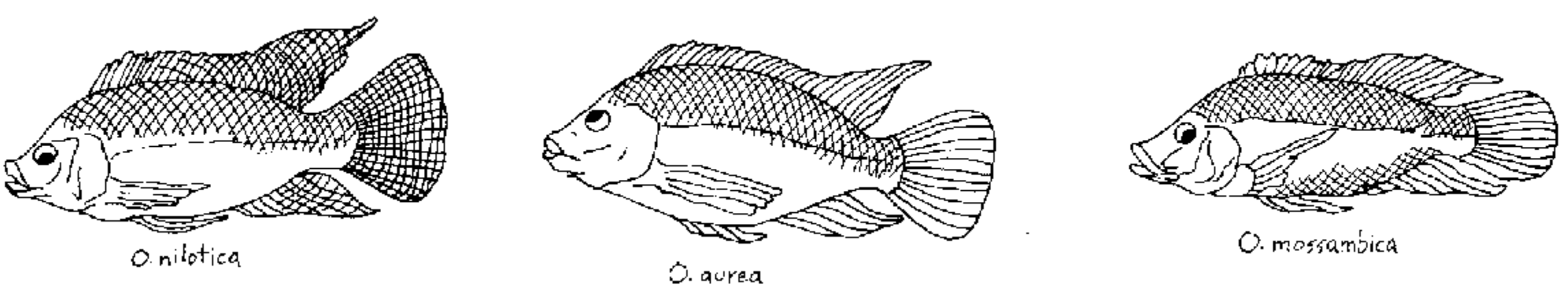

Figure 22. Major Tilapia Species

Figure 23

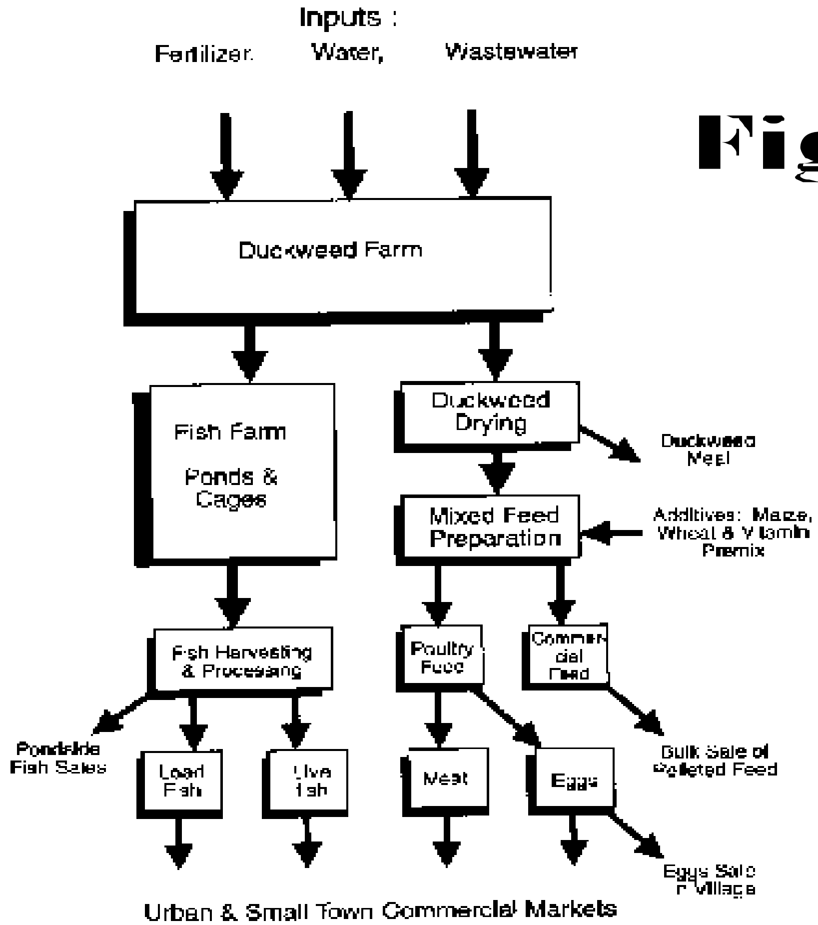

Figure 23. Product flows in integrated farming of duckweed, fish and poultry

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Figure 24

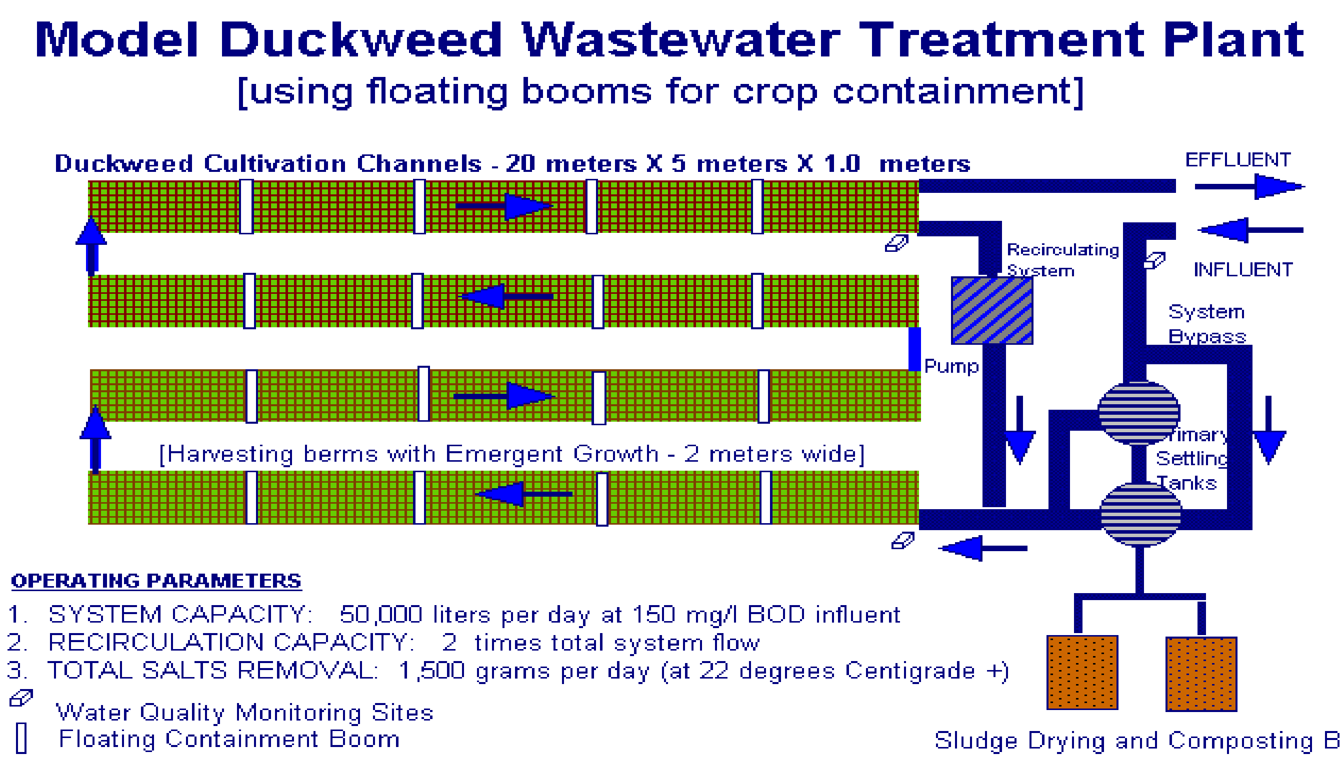


Figure 24.

The PRISM Group

Figure 25

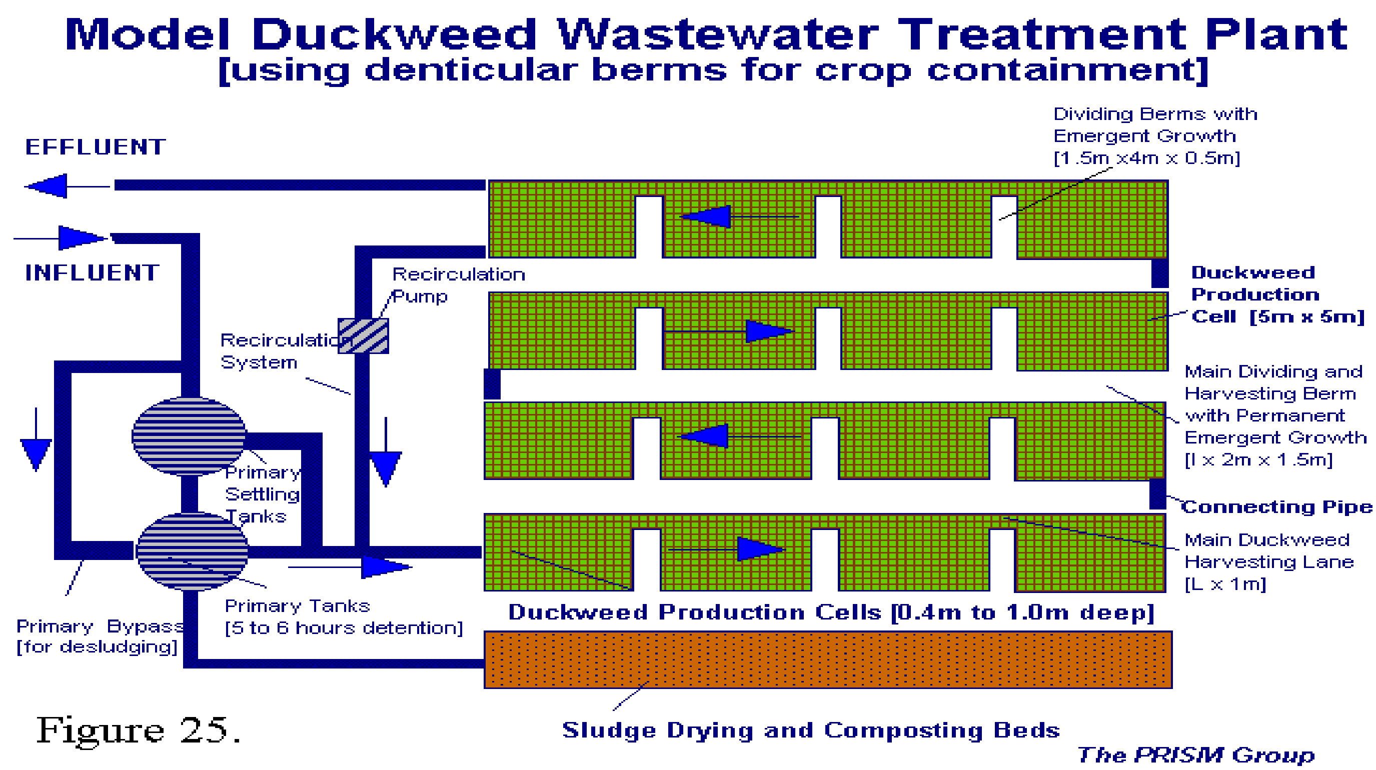
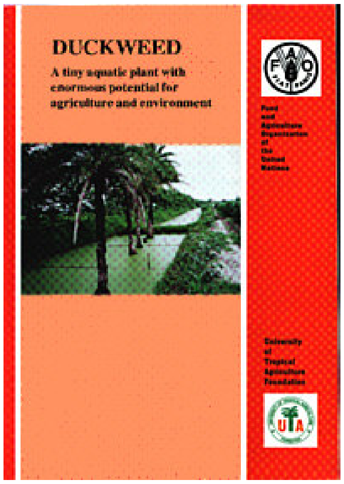


Figure 25.



DUCKWEED: A tiny aquatic plant with enormous potential for agriculture and environment

CHAPTER 1: Introduction

AQUATIC HABITATS

A considerable proportion of the world's surface is covered by saline waters, and the land areas from which the salts of the sea mostly originated are continuously leached of minerals by the run-off of rain water. Aquatic habitats abound; these may be temporary following rains or permanent largely through impediments to drainage . From the beginning of time these aquatic habitats have been harvested for biomass in many forms (food, fuel and building materials) by animals and man. From the time of the Industrial Revolution and with the onset of intensive land use enormous changes occurred. Agriculturists harvested both water and dry lands for biomass and minerals were applied to stimulate biomass yields, the aquatic habitats often became enriched (or contaminated) and water bodies were more temporary because of water use in agriculture or were lost through drainage or the establishment of major dams for irrigation, human water supplies and/or hydro-electric power generation. On the other hand other human activities, created aquatic areas for such purposes as the control of soil erosion, for irrigation, storage of water, sewage disposal and industrial waste storage or treatment and for recreational use.

Aquatic habitats have, in general, degenerated throughout the world because of pollution by both industry and other activities. Human activities have, in general, resulted in much higher flows of minerals and organic materials through aquatic systems, often leading to eutrophication and a huge drop in the biomass produced in such systems. The lack of dissolved oxygen in water bodies, through its uptake by microbes for decomposition of organic compounds, produces degrees of anaerobiosis that results in major growth of anaerobic bacteria and the evolution of methane gases.

Despite this in the areas of high rainfall, particularly in the wet-tropics, there remain major aquaculture industries, which vary from small farmers with 'manure fed' ponds producing fish through to large and extensive cultivation of fish and shellfish that are replacing the biomass harvested from the seas. The distribution of global aquaculture is shown in Figure 1. Fish production from ocean catches appear to be reduced, but production from farming practices are increasing which clearly demonstrates how important aquaculture is (and will become) in protein food production. This trend is illustrated by the trend in world prawn (shrimp) production shown in Figure 2.

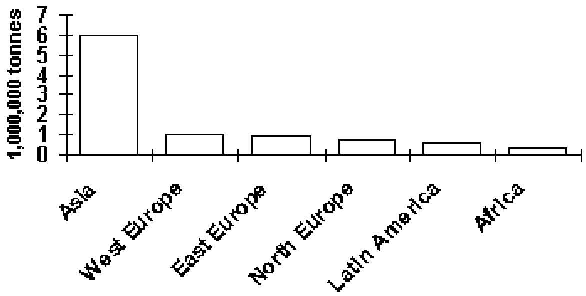


Figure 1: Distribution of global aquaculture (Source: FAO 1989)

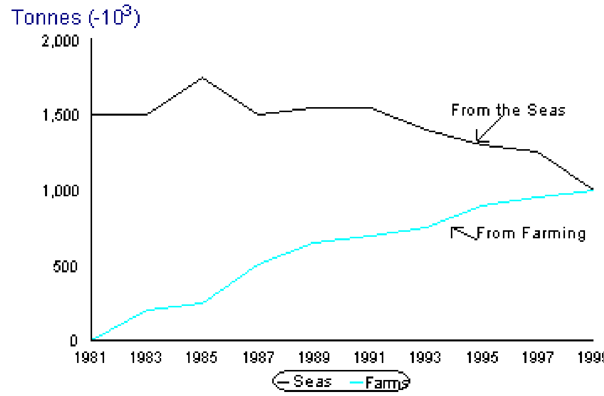


Figure 2: The changing pattern of world prawn production for human consumption (FAO 1989)

Although traditional or staple crops can be produced from water bodies and in many situations traditional people often harnessed these resources, the aquatic habitat has been considered too costly and to difficult to farm other than for extremely high value crops such as algae harvested for high value materials such as b -carotene or essential long-chain fatty acids. Intensive aquaculture (hydroponics) of crops in highly mechanised farms have been developed but require highly sophisticated management systems and are expensive.

Throughout the world, and particularly in Asia, farmers have harvested naturally produced aquatic plants for a number of purposes including animal feed, green manure and for their family feed resources. The best known of these include the free floating plants; water lettuce (Pistia), water hyacinth (Eichhcornia), duckweed (Lemna) and Azolla and some bottom growing plants.

Azolla, which is a member of the fern family grows extensively in association with nitrogen fixing bacteria, which allows it to produce on waters low in N but containing phosphorus. Azolla has been comprehensively discussed by van Hove (1989).

In recent years a commonly occurring aquatic plant, "duckweed", has become prominent, because of its ability to concentrate minerals on heavily polluted water such as that arising from sewage treatment facilities. However, it has also attracted the attention of scientists because of its apparent high potential as a feed resource for livestock (Skillicorn et al., 1993; Leng, et al., 1994). Duckweed grows on water with relatively high levels of N, P and K and concentrates the minerals and synthesises protein. These are the nutrients which are often critically deficient in traditional fodders and feeds given to ruminants and to pigs and poultry particularly where the former depend on agro-industrial byproducts and crop residues.

The growing awareness of water pollution and its threat to the ecology of a region and agriculture per se has also focussed attention on potential biological mechanisms for cleansing water of these impurities making it potable and available for reuse. In general, water availability is becoming a primary limitation to expanding human activities and also the capacity of agricultural land to feed the ever increasing population of the world.

Another pressure that has stimulated interest in aquatic plants has been the over-use of fertilisers, particularly in Europe that has led to contamination of ground water supplies that can no longer be tolerated.

ECOLOGICAL CONSIDERATIONS

In the early 1960's a number of scientists warned of the pending shortage of fossil fuels, the expanding population and the potential for mass-starvation from an inability of agriculture to produce sufficient food.

The prophesies have proved wrong in the short term, largely because of the extent of the then undiscovered fossil fuel, but also because of the impact of the development of high yielding crop varieties, particularly of cereal grain. The "Green Revolution" whilst increasing cereal crop yields faster than human population increase has had serious side effects such as increased erosion and greater water pollution in some places and a huge increase in demand for water and fertiliser. Fertiliser availability and water use are often highly dependent on fossil fuel costs. Water resources in many of the world's aquifers are being used at rates far beyond their renewal from rainfall (see World Watch 1997).

At the present time it appears that potentially the application of scientific research could maintain the momentum for increased food production to support an increasing world population, but it is rather obvious that if this is to occur it must be without increased pollution, and with limited increases in the need for water and fertiliser and therefore also fossil fuel.

GLOBAL WARMING, FOSSIL FUEL AND NUTRIENT RECYCLE NEEDS.

Global warming has now been accepted as inevitable. It is now a major political issue in most countries. Governments are now considering the need to reduce the combustion of fuels which contribute most to the build up of greenhouse gases and thus the increase in the thermal load that is presently occurring. A second problem for fossil fuel devouring industries is the potential for scarcer, and therefore, more costly oil resources in the near future. As Fleay (1996) in his book "The decline in the age of oil" has pointed out there have been no major discoveries of oil in the last ten years. This suggests that we have already discovered the major resources. Many of the oil wells are approaching or have passed the point at which half the reserves have been extracted. At this stage the cost in fuel to extract the remaining fuel increases markedly. The need to reduce fuel combustion and the potential for large increases in costs of extraction of oil from the major deposits all indicate major increases in fuel costs and the need to stimulate alternative energy strategies for industry and agriculture alike.

Fuel is a major economic component of all industries, and in particular, industrialised agriculture. Therefore food prices are highly influenced by fuel prices. The energy balance for grain production has consistently decreased with mechanisation as is illustrated by the fuel costs for grain production which is approaching 1MJ in as fossil fuel used in all activities associated with growing that crop to 1.5MJ out in the grain. A major component of the costs are in traction, fertiliser, herbicides and water use, particularly the energy costs of irrigation.

In recent times, a movement has begun to examine a more sustainable future for agriculture, particularly in the developing countries. The need in developing countries of Asia and Africa where most of the world's population lives and where population growth is the highest is to:

- decrease population growth
- maintain people in agriculture
- and produce an increasing amount of food in a sustainable way

This suggests that small farmers need to be targeted and that farming should be integrated so that fertiliser and other chemical use is minimised together with lowered gaseous pollution. At the same time a country must ensure its security of food supplies. In the 1998 financial crisis in Asia, the small farmer was seriously effected because of the relatively high cost of fuel. This is bound to have serious effects on food production in the next few years if fertiliser applications are restricted. This will show up as a decline in crop yields over the next few years.

The problem of decreasing world supplies of fuels, increased legislation to decrease use of fossil fuel to reduce pollution, and the economic disincentive to use fertilisers in developing countries indicates to this writer that there is a massive need to consider a more integrated farming systems approach, rather than the monocultures that have developed to the present time.

Integrated farming systems use require three major components to minimise fertiliser use:

- a component where nitrogen is fixed (e.g. a legume bank)
- a component to release P fixed in soils for plant use when this is limiting

- a system of scavenging any leakage of nutrients from the system.

It also requires incorporation of animals into the system to utilise the major byproducts from human food production.

Duckweed aquaculture is an activity that fits readily into many crop/animal systems managed by small farmers and can be a major mechanism for scavenging nutrient loss. It appears to have great potential in securing continuous food production, particularly by small farmers, as it can provide fertiliser, food for humans and feed for livestock and in addition decrease water pollution and increase the potential for water re-use.

The production and use of duckweed is not restricted to this area and there is immense scope to produce duckweeds on industrial waste waters, providing a feed stock particularly for the animal production industries, at the same time purifying water.

In this presentation, duckweed production and use, particularly in small farmer systems, is discussed to highlight its potential in food security, particularly in countries where water resources abound and have been misused. On the other hand, duckweed aquaculture through its water cleansing abilities can make a greater amount of potable water available to a population living under arid conditions, providing certain safeguards are applied.

CHAPTER 2: The plant and its habitat

INTRODUCTION

Duckweed is the common name given to the simplest and smallest flowering plant that grows ubiquitously on fresh or polluted water throughout the world. They have been, botanical curiosities with an inordinate amount of research aimed largely at understanding the plant or biochemical mechanisms. Duckweeds have great application in genetic or biochemical research. This has been more or less in the same way that drosophila (fruit flies) and breadmoulds have been used as inexpensive medium for genetic, morphological, physiological and biochemical research.

Duckweeds are small, fragile, free floating aquatic plants. However, at times they grow on mud or water that is only millimetres deep to water depths of 3 metres. Their vegetative reproduction can be rapid when nutrient densities are optimum. They grow slowly where nutrient deficiencies occur or major imbalances in nutrients are apparent. They are opportunistic in using flushes of nutrients and can put on growth spurts during such periods.

Duckweeds belong to four genea; Lemna, Spirodela, Wolfia and Wolffiella. About 40 species are known world wide. All of the species have flattened minute, leaflike oval to round "fronds" from about 1mm to less than 1cm across. Some species develop root-like structures in open water which either stabilise the plant or assist it to obtain nutrients where these are in dilute concentrations.

When conditions are ideal, in terms of water temperature, pH, incident light and nutrient concentrations they compete in terms of biomass production with the most vigorous photosynthetic terrestrial plants doubling their biomass in between 16 hours and 2 days, depending on conditions. An idea of their rapid growth is illustrated by the calculation that shows that if duckweed growth is unrestricted and therefore exponential that a biomass of duckweed covering 10cm2 may increase to cover 1 hectare (100 million cm2) in under 50 days or a 10 million fold increase in biomass in that time.

Obviously when biomass doubles every 1-2 days, by 60 days this could extend to a coverage of 32ha. In natural or farming conditions, however, the growth rate is altered by crowding, nutrient supply, light incidence and both air and water temperature in addition to harvesting by natural predators (fish, ducks, crustaceans and humans).

In addition to the above limiting factors there also appears to be a senescence and rejuvenation cycle which is also apparent in Azolla.

Vegetative growth in Lemna minor exhibits cycles of senescence and rejuvenation under constant nutrient availability and consistent climatic conditions (Ashbey & Wangermann, 1949). Fronds of Lemna have a definite life span, during which, a set number of daughter fronds are produced; each of these daughter fronds is of smaller mass than the one preceding it and its life span is reduced. The size reduction is due to a change in cell numbers. Late daughter fronds also produce fewer daughters than early daughters.

At the same time as a senescence cycle is occurring an apparent rejuvenation cycle, in which the short lived daughter fronds (with half the life span of the early daughters) produce first daughter fronds that are larger than themselves and their daughter fronds are also larger, and this continues until the largest size is produced and senescence starts again. This has repercussions as there will be cyclical growth pattern if the plants are sourced from a single colony and are all the same age. Under natural conditions it is possible to see a mat of duckweeds, apparently wane and explode in growth patterns.

The cyclic nature of a synchronised duckweed mat (i.e. all the same age) could be over at least 1 month as the life span of fronds from early to late daughters can be 33 or 19d respectively with a 3 fold difference in frond rate production (See Wangermann & Ashby, 1950).

The phenomena of cyclical senescence and rejuvenation may cause considerable errors of interpretation in studies that examine, for example, the response of a few plants to differing nutrient sources over short time periods.

In practice this cycle may be responsible for the need to restock many production units after a few weeks of harvesting. In Vietnam, with small growth chambers the duckweed required reseeding every 4-6 weeks (T.R. Preston personal communication) to be able to produce a constant harvestable biomass growing on diluted biogas digestor fluid. There is also the possibility in such systems of a build up in the plant of compounds that eventually become toxic or at least diminish their growth rate.

Root length appears to be a convenient relative measure of frond-age.

The senescence-rejuvenation cycle is increased by high temperatures through a decrease in individual frond life span but there is a concomitant increase in daughter frond production so that the biomass of fronds produced in a shorter life span is the same.

The rejuvenation cycle appears to be unaffected by either light density or temperature.

The cyclical changes appear to be mediated by chemicals secreted by the mother frond and growth patterns may be modified greatly by harvesting methods which mix water, wind effects and shelter as well as light intensity and temperature.

The increased death rate of duckweed mats exposed to direct sunlight has been recognised in work in Bangladesh where workers are set to cool duckweed mats by splashing them with water from below the surface and in Vietnam, Preston (personal communication) observed that the incidence of showers stimulated very rapid growth of duckweed in small ponds.

Duckweeds appear to have evolved, so as, to make good use of the periodic flushes of nutrients that arise from natural sources. However, in recent times they are more likely to be found growing in water associated with cropping and fertiliser washout, or down stream from human activities, particularly from sewage works, housed animal production systems and to some extent industrial plants.

TAXONOMY

For the many purposes related in this publication, the selection of duckweed to farm will depend on what grows on a particular water body and the farmer has little control over the species present. The various duckweeds have different characteristics. The fronds of Spirodela and Lemna are flat, oval and leaf like. Spirodela has two or more thread-like roots on each frond, Lemna has only one. Wolffiella and Wolfia are thalloid and have no roots; they are much smaller than Spirodela or Lemna. Wolfia fronds are usually sickle shaped whereas Wolffiella is boat shaped and neither has roots. Differentiation and identification is difficult and is perhaps irrelevant to the discussion. This is mainly because the species that grows on any water is the one with the characteristic requirement of that particular water and the dominant species will change with the variations in water quality, topography, management and climate, most of which are not easily or economically manipulated

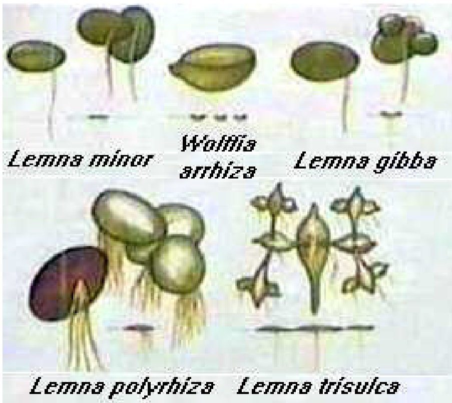


Photo 1: The various species of Lemnaeca relevant to this publication

MORPHOLOGY AND ANATOMY

The structure of the fronds of duckweed is simple. New or daughter fronds are produced alternatively and in a pattern from two pockets on each side of the mature frond in Spirodela and Lemna. In Wolffiella and Wolfia only one pocket exists. These pockets are situated in Spirodela or Lemna close to where the roots arise. Each frond, as they mature, may remain attached to the mother frond and each in turn, under goes this process of reproduction.

In all four genea each mother frond produces a considerable number of daughter fronds during its lifetime. However, after six deliveries of daughter fronds, the mother frond tends to die. Colonies produced in laboratory or naturally are always spotted with brown dead mother fronds.

The bulk of the frond is composed of chlorenchymatous cells separated by large intracellular spaces that are filled with air (or other gases) and provide buoyancy. Some cells of Lemna and Spirodela have needle like raphides which are presumably composed of calcium oxalate.

The upper epidermis in the Lemna is highly cutinized and is unwettable. Stomata are on the upper side in all four genea. Anthocyanin pigments similar to that in Azolla also form in a number species of Lemnacae. Both Spirodela and Lemna have greatly reduced vascular bundles.

Roots in both Spirodela and Lemna are adventitious. The roots are usually short but this depends on species and environmental conditions and vary from a few millimetres up to 14cm. They often contain chloroplasts which are active photosynthetically. However, there are no root-hairs.

The plant reproduces both vegetatively and sexually, flowering occurs sporadically and unpredictably. The fruit contains several ribbed seeds which are resistant to prolonged desiccation and quickly germinate in favourable conditions.

DISTRIBUTION

The Lemnacae family is world wide, but most diverse species appear in the subtropical or tropical areas. These readily grow in the summer months in temperate and cold regions; they occur in still or slowly moving water and will persist on mud. Luxurious growth often occurs in sheltered small ponds, ditches or swamps where there are rich sources of nutrients. Duckweed mats often abound in slow moving backwaters down-stream from sewage works.

In the aquatic habitat of crocodiles and alligators, duckweeds often have luxurious growth on the nutrients from the excrement of these reptiles and the local zoo can often provide a convenient source of duckweed for experimental purposes (see Photo 2).

Some species appear to tolerate saline waters but they do not concentrate sodium ions in their growth. The apparent limit for growth appears to be between 0.5 and 2.5% sodium chloride for Lemna minor

When the aquatic ecosystem dries out or declining temperatures occur, duckweeds have mechanisms to persist until conditions return that can support growth. This occurs through late summer flowering, or the production of starch filled structures or turin which are more dense than the fronds so the plants sink to the bottom of the water body and become embedded in dried mud.

Photo 2: Duckweed accumulation in the crocodile lagoon in Havana Zoo, Cuba.

The four species of Lemnacae are found in all possible combinations with each other and other floating plants. They are supported by plants that are rooted in the pond. They effect the light penetration of water resources and depending on their coverage of the area they can prevent the growth of algae or plants that grow emersed in water. They provide habitat and protection for a number of insects that associate with the plant but they appear to have few insects that feed on them. The main predators appears to be herbivorous fish, (particularly carp), snails, flatworms and ducks, other birds may also feed on duckweeds but reports are few in the literature. The musk rat appears to enjoy duckweeds and the author suggests that many other animals may occasionally take duckweeds such as pigs and ruminants.

The appearances of duckweed species not previously seen in areas of Europe have been attributed to global warming and/or a strong indication of rising water temperature throughout the world from global warming (Wolff & Landolt 1994).

HISTORY OF DUCKWEED UTILIZATION

This is a most difficult area to review since much of the information is by way of the popular press or is only mentioned in scientific papers. However, after a lecture given at the University of Agriculture and Forestry in Ho Chi Minh City in which the potential of duckweed biomass for animal production was discussed, as a novel concept, the writer was most chastened to find that duckweed was used extensively by local farmers as feed for ducks and fish and there was a flourishing market for duckweed.

The duckweed based farming system in Vietnam depended largely on manure and excrement being collected in a small pond where some eutrophication takes place; the water from this pond runs into a larger pond about 0.5m deep on which duckweed grows in a thick mat. This was harvested on a daily basis and immediately mixed with cassava waste (largely peelings) and fed to ducks which were constrained in pens on the side of the pond or lagoon (see Photo 3). The ducks were produced for the local restaurant trade.

In Taiwan, it was traditional to produce duckweeds for sale to pig and poultry producers.

There are reports that Wolfia arrhiza, which is about 1mm across has been used for many generations as a vegetable by Burmese, Laotions and Northern Thailand people. Thai's refer to this duckweed as "Khai-nam" or "eggs of the water" and it was apparently regarded as a highly nutritious food stuff. It could have been a valuable source of vitamins particular of vitamin A to these people. This would have been particularly important source during the long dry season of Northern Thailand when green vegetables may have been scarce. It is also a good source of minerals, again its phosphorous content could have been vital in areas where there are major deficiencies, such as occurs in Northern Thailand.

There are references in the literature to duckweed as both a human food resource and as a component of animal and bird diets in traditional/small farmer systems in most of South Asia.

CHAPTER 3: Nutrient requirements of duckweed

INTRODUCTION

Photo 3: Duckweed growing as part of an integrated farming system in Vietnam

Like all photosynthetic organisms, duckweeds grow with only requirements for minerals, utilising solar energy to synthesise biomass. They have, however, the capacity to utilise preformed organic materials particularly sugars and can grow without sunlight when provided with such energy substrates. In practice the ability to use sugars in the medium as energy sources is irrelevant, as in most aquatic systems they do not exist. However, they could be of some importance where industrial effluent's need to be purified and duckweed is considered for this process (e.g. waste water from the sugar industry or waste water from starch processing).

Most research on nutrient requirements have centred on the need for nitrogen, phosphorus and potassium (NPK). However, like all plants, duckweeds need an array of trace elements and have well developed mechanisms for concentrating these from dilute sources. From the experience of the Non-Government Organisation PRISM (based in Colombia, Maryland, USA, see chapter 6) in Bangladesh, it appears that providing trace minerals through the application of crude sea salt was sufficient to ensure good growth rates of duckweeds in ponded systems. However, considerable interest has been shown by scientists in the capacities of duckweed to concentrate, in particular, copper, cobalt and cadmium from water resources where these have economic significance.

Mineral nutrients appear to be absorbed through all surfaces of the duckweed frond, however, absorption of trace elements is often centred on specific sites in the frond.

The requirements to fertilise duckweeds depends on the source of the water. Rainwater collected in ponds may need a balanced NPK application which can be given as inorganic fertiliser or as rotting biomass, manure or polluted water from agriculture or industry. Effluent's from housed animals are often adequate or are too highly concentrated sources of minerals and particularly because of high ammonia concentration may need to be diluted to favour duckweed growth. Run-off water from agriculture is often high in P and N but the concentration may need to be more appropriately balanced. Sewage waste water can be high or low in N depending on pretreatments but is almost always adequate in K and P. Industrial waste water from sugar and alcohol industries for example are always low in N.

Little work has been done to find the best balance of nutrients to provide maximum growth of duckweed. The duckweed has been provided with mechanisms that allow it to preferentially uptake minerals and can grow on very dilute medium. The main variables that effect its growth under these circumstances are light incidence and water and air temperatures.

The growth rate and chemical composition of duckweed depends heavily on the concentration of minerals in water and also on their rate of replenishment, their balance, water pH, water temperature, incidence of sunlight and perhaps day length. Its production per unit of pond surface also depends on biomass present at any one time.

WATER TEMPERATURE

Duckweeds grow at water temperatures between 6 and 33° C. Growth rate increase with water temperature, but there is an upper limit of water temperature around 30° C when growth slows and at higher temperature ceases. In open lagoons in direct sunlight duckweed is stressed by high temperature created by irradication and in practice yields are increased by mixing the cooler layers of water low in the pond and splashing to reduce surface temperature of the duckweed matt.

WATER, pH

Duckweed survives at pH's between 5 and 9 but grows best over the range of 6.5-7.5. Efficient management would tend to maintain pH between 6.5 and 7. In this pH range ammonia is present largely as the ammonium ion which is the most readily absorbed N form. On the other hand a high pH results in ammonia in solution which can be toxic and can also be lost by volatilisation.

MINERAL CONCENTRATIONS

Duckweeds appear to be able to concentrate many macro and micro minerals several hundred fold from water, on the other hand high mineral levels can depress growth or eliminate duckweeds which grow best on fairly dilute mineral media. There is a mass of data on the uptake by duckweed of micro-elements which can be accumulated to toxic levels (for animal feed). However, their ability to concentrate trace elements from very dilute medium can be a major asset where duckweed is to be used as an animal feed supplement. Trace elements are often deficient in the major feed available to the livestock of small resource poor farmers. For example, in cattle fed mainly straw based diets both macro and micro mineral deficiencies are present.

Duckweeds need many nutrients and minerals to support growth. Generally slowly decaying plant materials release sufficient trace minerals to provide for growth which is often more effected by the concentrations of ammonia, phosphorous, potassium and sodium levels. There is by far the greatest literature on the requirements of duckweed for NPK and the ability of the plant to concentrate the requirements of micro nutrients from the aquatic medium is usually considered not to be a limitation. In the work in Bangladesh by PRISM, crude sea salt was considered to be sufficient to provide all trace mineral requirements when added to water at 9kg/ha water surface area when duckweed growth rates were high at around 1,000kg of fresh plant material/day.

WATER DEPTH

Depth of water required to grow duckweed under warm conditions is minimal but there is a major problem with shallow ponds in both cold and hot climates where the temperature can quickly move below or above optimum growth needs. However, to obtain a sufficiently high concentration of nutrients and to maintain low temperatures for prolonged optimal growth rate a balance must be established between volume and surface area. Depth of water is also critical for management, anything greater than about 0.5 metres poses problems for harvesting duckweeds, particularly by resource poor farmers. Whereas, where water purification is a major objective in the production of duckweed, it is impractical to construct ponds shallower than about 2m deep.

Incident sunlight and environmental temperatures are significant in determining the depth of water as undoubtedly duckweed is stressed by temperatures in excess of 30° C and below about 20° C growth rate is reduced.

In practice, depth of water is probably set by the management needs rather than the pool of available nutrients and harvesting is adjusted according to changes of growth rate, climate changes and the nutrient flows into the system.

REQUIREMENTS FOR NPK AND OTHER MINERALS

Duckweeds evolved to take advantage of the minerals released by decaying organic materials in water, and also to use flushes of minerals in water as they occurred when wet lands flooded. Duckweeds now appear to have the potential to be harnessed as a commercial crop for a number of purposes.

Water availability is likely to limit terrestrial crop production particularly of cereals in the coming years (see World Watch 1997). Water purification and re-use particularly that water arising from sewage works, industrial processing and run-off from irrigation appears to be mandatory in the future, both to reduce pollution of existing water bodies and to provide reusable water for many purposes including that required by humans in some places as drinking water.

Nitrogen requirements

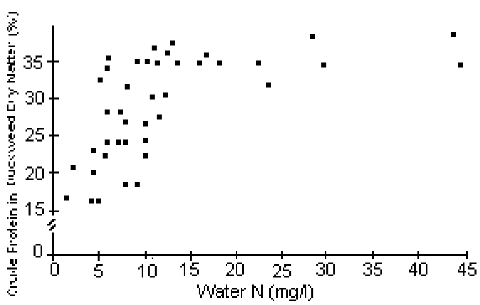
Duckweeds appear to be able to use a number of nitrogenous compounds either on their own or through the activities of associated plant and animal species. The ammonium ion (NH_4^+) appears to be the most useful N source and depending on temperatures duckweeds continue to grow down to extremely low levels of N in the water. However, the level of ammonia N in the water effects the accretion of crude protein in the plant (see Table 1).

The value of duckweed as a feed resource for domestic animals increases with increasing crude protein content. In studies at the University of New England, Armidale, Australia, the crude protein content of duckweed growing on diluted effluent from housed pigs increased with increased water levels of N from about 15% crude protein with trace levels of N (1-4mg N/l) to 37% at between 10-15mg N/l. Above 60mg N/l a toxic effect was noticed perhaps due to high levels of free ammonia in the water. Whilst few experiments have been undertaken on the optimum level of ammonia required, these results give a guide-line for the levels of N to be established and maintained in duckweed aquaculture to obtain a consistently high crude protein level in the dry matter.

Table 1: The composition of duckweed harvested from a natural water source or grown on waters with minerals enriched (Leng et al. 1994)

	Crude Protein	Fat	Fibre	Ash
Source	(%DM)	(%DM)	(%DM)	(% DM)
Natural lagoon	25-35	4.4	8-10	15
Enriched culture	45	4.0	9	14

Figure 3: The influence of the concentration of N in culture water on crude protein in duckweed (Spirodela spp) grown on diluted effluent from a piggery. The P levels in water varied from 1.2-6.1 mg P/litre (Leng et al., 1994).

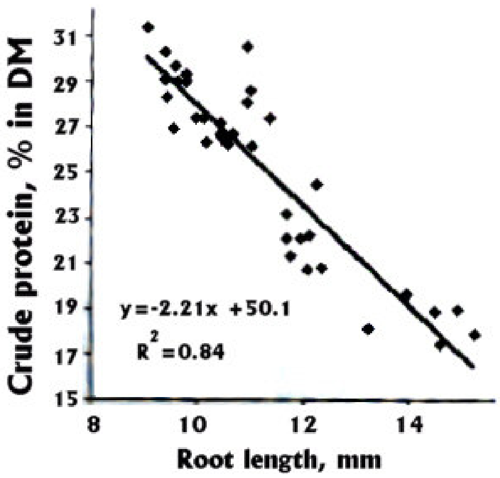


In most practical situations the approach to growing duckweed is to find the dilution of water where N is not limiting growth and supports high levels of crude protein in the plant. This is usually done by an arbitrary test. Serial dilutions of the water source with relatively pure water (rain water) is carried out and duckweed seeded into each dilution and weight change recorded after, say, 4 weeks. In this way the appropriate N concentration is established.

A useful indicator of whether conditions in the pond are appropriate for growth of duckweed (Lemna spp) of high protein content in the length of the roots. Many experimental observations (Rodriguez and Preston 1996a; Nguyen Duc Anh *et al* 1997; Le Ha Chau 1998) have shown that over short growth periods there is a close negative relationship between root lenght and protein content of the duckweed and with the N content of the water. Data taken from the experiment of le Ha Chau (1998) are illustrated in Figure 4. In most small-scale farmsituations it is not feasible to determine the protein content of the duckweed that is being used; nor can the nutrient content (especially nitrogen) of the water be estimated easily. To determine the root length of duckweed is a simple operation and and requires neither equipment nor chemicals. By monitoring this characteristic, the user can have an indication of the nutritive corrective measures when the lenght of the roots exceeds about 10mm.

Figure 4: Relationship between root length and protein content in duckweed (Lemna minor) (Le Ha Chau 1998)

In duckweed aquaculture a source of N essential and in many start-up systems, based on water effluent from sewage or housed animals, the project has been considered by pre-treatments that denitrify the water and reduce ammonia concentrations. Most forms of aeration in sewage works are highly efficient in de-nitrification of waste waters, but this process compounds pollution peoblems. for instance where the effluent is high in P this promotes the growth of algae that fix N. In Australia the contamination of river systems with phosphorus often led to massive blooms of blue-green algae that rae toxic to humans and animals.



Although there is an association of N fixing cyanobacteria with duckweeds, these are certainly not important from a standpoint of farming duckweeds. Duong and Tiedje (1985) were able to demonstrate that duckweeds from many sources had heterocystous cyanobacteria firmly attached to the lower epidermis of older leaves, inside the reproductive pockets and occasionally attached to the roots. They calculated that N fixation via these colonies could amount to 3.7-7.5kg N per hectare of water surface in typical Lemna blooms, but the association of cyanobacteria with Lemna trisulca was 10 times more effective.

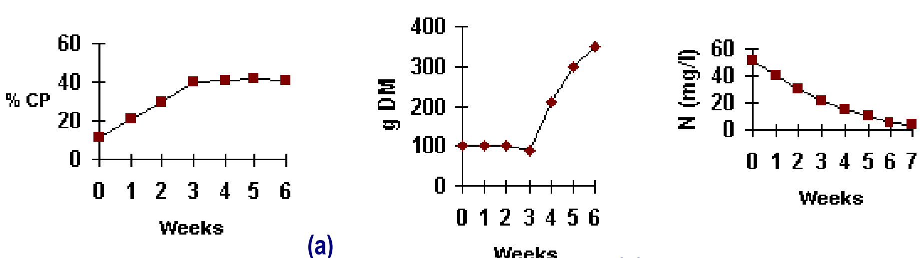
Probably, under most practical situations ammonia is the primary limiting nutrient for duckweed growth and the establishment of the optimum level for maximum growth of duckweeds needs research, particularly in the variety of systems the plant may be expected to grow. The effects of time and lowering of N content of sewage water on yield and crude protein content of duckweed is shown in Figure 5 and Figure 6.

From recent research it appears that duckweed require about 20-60mg N/l to grow actively and from two studies [(those of Sutton & Ornes, (1975) compared with those of Leng et al., (1994)] it is apparent that there is a complex relationship between, the initial composition of the duckweed used in research and the level of nutrients required.

Stambolie and Leng (1993) showed with duckweeds harvested from a backwater of a river and with an initial low crude protein content, it was only when the duckweed protein increased to the highest level that rapid growth of biomass commenced (i.e. at 3 weeks after introduction to the water) (Figure 6) even though by that time the N content of the water had declined to levels that were below the optimum that appears to be necessary for maximum protein levels (Figure 3).

In the work of Sutton and Ornes (1975), however, duckweed of a higher protein content was initially used and growth rate again peaked at about the third week (Fig. 6) but by this time the crude protein content had declined to below 15%. This apparent opposite result can be rationalised if there is a stress factor involved which requires 3 weeks to overcome, and under these circumstances its growth may be considered to be optimised at about 20mg ammonia N/l but to obtain maximum crude protein content it requires ammonia levels to be about 60 mg N/l (see Figure 5). A further implication is that where a high protein content is present in duckweed at the commencement of a growth study, the duckweed can grow through mainly synthesis of only carbohydrate. However, the variable results using duckweeds harvested from the wild and the slow "adaptation" to new conditions is obviously a confusing factor in interpreting any data of the requirements for duckweed for nutrients in such short term studies.

Figure 5: The effect of N level in culture water on growth of duckweed and its crude protein content.The experiments were conducted on duckweed collected from a billabong down stream from a sewage works. The sewage water used in the incubation was taken from that flowing into the sewage works prior to denitrification processing. The pond were 2.5m. (Stambolie & Leng, 1994)



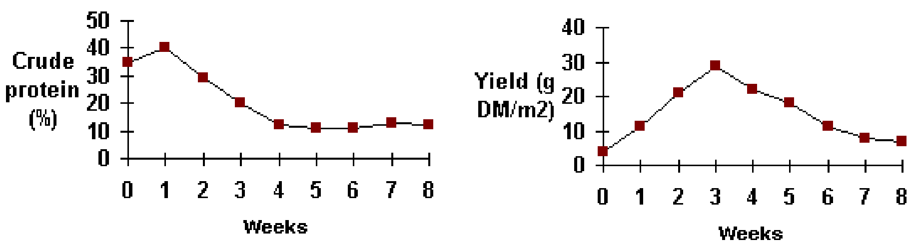
(a) Crude Protein in duckweed

(b) Changing biomass on water

c)Level of N in water

The most important issue is that duckweed increases its protein content according to the ammonia level in an otherwise adequate medium up to levels of 60mg N/l (see Figures 3, 4, & 5). For food or feed purposes there is a vast difference in the value of duckweed biomass depending on its protein content (see later). Rapid growth of duckweed is also associated with high protein accretion and low fibre content and fibre content increases where root growth occurs.

Figure 6: Yield and crude protein content of duckweed biomass growing on sewage waste water (Sutton & Ornes 1975)



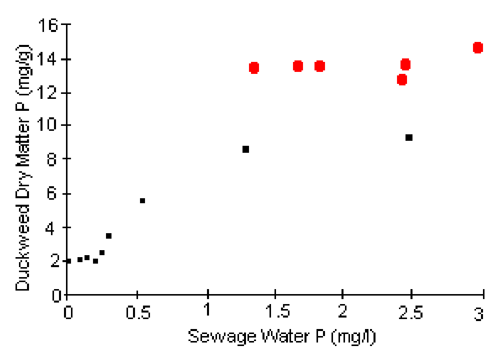
Phosphorus requirements

Duckweeds appear to concentrate P up to about 1.5% of their dry weight and as such are able to grow on high P waters provided the N concentrations are maintained. The plant also appears to be able to draw on the pool of P in its biomass for its biochemical activities and once P had been accumulated it will continue to grow on waters devoid of P. On the other hand the P in duckweed appears to be highly soluble and is released rapidly to the medium on death of the plant (Stambolie & Leng 1994).

The relationship between P content of sewage water and P content of duckweeds growing on such water are shown in Figure 6. Leng et al (1994) found a higher concentration of P in duckweed at high water P levels than that found by Sutton and Ornes (1975). The time course of uptake of P by duckweed in static sewage water is shown in Figure 6. The differences in accumulation levels in the two studies cited possibly resides in the rates of growth when the samples were taken. The capacity of duckweed to concentrate P is clear and maximum P levels in tissues (10-14mg P/kg dry weight) are achieved with water P levels as low as 1.0 mg P/litre.

The important issue here is that duckweeds concentrate P when water levels are enriched with P and it appears to be readily available once the plant is disrupted or dies. The P level in duckweed is sufficiently high to be a valuable source of this nutrient for both plants and animals.

Figure 7: The relationship between the quantity of P in duckweed and the concentration of P in water. Filled squares are results from Sutton and Ornes (1975); the filled circles (upper values) are results from research in Australia (Stambolie & Leng 1994).



Potassium requirements

Vigorously growing duckweed is a highly efficient K sink, but only low concentration of K in water are needed to support good growth when other mineral requirements are satisfied. Most decaying plant materials would easily produce the K requirements of duckweed.

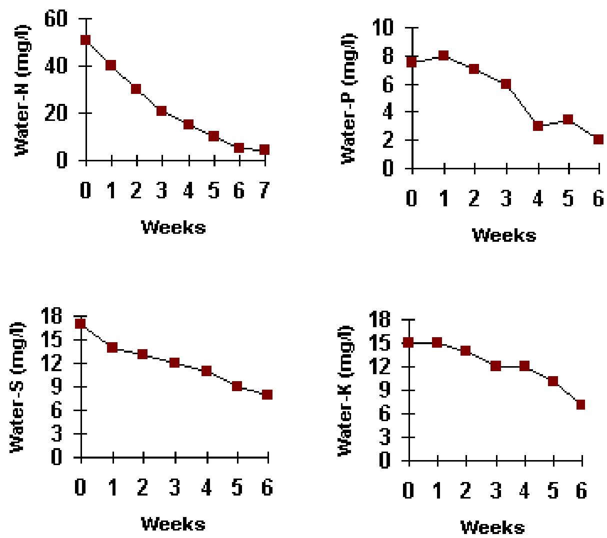
Sulphur requirements

Little work has been done to examine the S requirements of duckweeds. The mechanisms for sulphate uptake have been studied since uptake of sulphate is the first step in the biosynthesis of S-amino acids. Such biosynthesis needs the integration of pathways providing carbon building blocks and reduced sulphur (Datko & Mudd, 1984). It is possible that S levels are at times limiting to growth or protein accretion because of the high level of S-amino acids in the plant when growth rate is high and ammonia in the medium is non-limiting. Salts of sulphate appears to meet the requirements. As S is so readily leached from soils it is an unlikely candidate for deficiencies in systems that may be established to farm duckweed except where huge dilutions of the water are needed to obtain a suitable N level.

The uptake of NPSK by duckweed from sewage water is shown in Figure 7 and the experimental design for such studies are shown in Photo 4.

Sodium requirements

Sea salt (9kg/ha/d) has been applied as part of a fertiliser program in pilot studies of duckweed farming in Bangladesh (see the discussion of PRISM's work in Chapter 6). This work suggested a good ability of duckweed to accumulate sodium as there was no apparent problems with salination. It appeared possible that duckweed removed up to 9kg salt/ha/d when grown under fairly optimal conditions, suggesting a potential for duckweed to rehabilitate saline land and water.



In studies undertaken at the University of New England it soon became apparent that the requirement for salt and the capacity of the plant to concentrate sodium was not significant in relation to salt levels that accumulated in lagoons fed by open cut coal mines. However, the exercise pointed a way for the potential use of such waters for duckweed production as duckweeds tolerated the salt levels and grew substantially when additional nutrients were provided. Using small galvanised iron tanks (see Photo 4) the effect of growing duckweed on saline mine waters with or without extra added nutrients was studied. Growth rate and protein content of duckweed is shown in Figure 8 together with the effects on mineral levels in the water. Duckweed grew on the water with or without added fertilisers but the uptake of sodium was low. The quality of the duckweed (indicated by its crude protein content) was maintained for some time by fertiliser application. The phosphorous requirement for growth was apparently low.

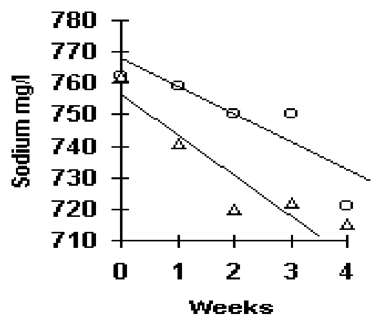
This data is introduced here to show that even saline waters can be used to grow duckweed, although research is needed to investigate the needs for additional nutrients on saline waters.

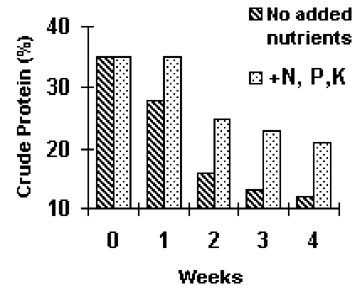
Photo 4 : Small scale containers used for duckweed growth studies. Sewage water, collected at a site where it is flowing into the works, was transported, diluted and used for the growth trials. Duckweed was seeded onto the "ponds" so that half the surface area was covered and harvests were made when the "ponds" were 100% covered. Duckweed was harvested by placing a stick across the diameter of the pond and taking half of it.

Figure 8a. The effects of growing duckweed on saline mine waters with (D) or without (o) added NPK fertiliser to optimum levels on crude protein and salt content. (Sell et al., 1993; Sell, 1993).

Figure 8b. The effects of growing duckweed on saline mine waters with (D)or without (o) added NPK fertiliser to optimum levels on dry matter harvest and P content. (Sell, et al 1993, Sell, 1993).

8(b) Sodium content **8(a) Crude protein of duckweed**

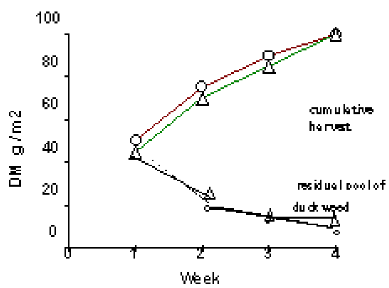




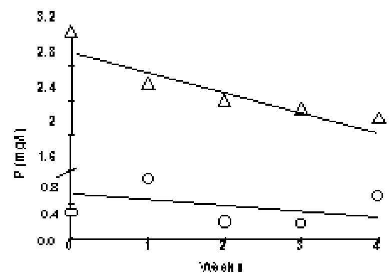
8(c) Duck weed dry matter harvested: cumulative and residual pool

8 (d) Phosphorus content of mine waste water growing duckweed

8 (c) Dry matter



8 (d) Phosphorus content



Conclusions on mineral requirements

The well developed system of concentrating minerals in duckweed allows them to grow under a wide range of conditions. The concentrating ability of duckweed for trace elements has been estimated to be many hundreds of thousands times. A simple comparison indicates some of the potential for duckweed to accumulate nutrients by comparing water levels and tissue dry matter levels of a number of minerals.

Table 2: Some mineral compositions of duckweed and their potential to remove minerals from water bodies (calculated from the literature).

	Concentration in		Potential removal
	Culture medium	Duckweed tissue	at 10ton DM/ha
Element	(mg/l)	(mg/kg DM)	(kg/ha/y)
N	0.75	60,000	600
P	0.33-3.0	5,000-14,000	56-140

K	100	40,000	400
Ca	360	10,000	100
Mg	72	6,000	60
Na	250	3,250	32
Fe	100	2,400	24

Along with this advantage of mineral removal is obviously the potential detrimental effects of accumulation of heavy metals.

Heavy metal accumulation by duckweeds

All members of the duckweed family concentrate heavy metals in particular cadmium, chromium and lead which may at times reach levels in the plant which are detrimental to both the health and growth of the plant in addition to creating problems where the plant is used in any part of a food chain eventually leading to human consumption.

The accumulation of heavy metals by duckweed is not normally a problem for those wishing to use duckweeds from natural water resources or effluent from human or intensive animal housing as these metals are normally at extremely low concentrations.

Duckweeds, however, are contaminated by such heavy metals from industries such as tanning (chromium) leachates from mining (e.g. cadmium) and great care is needed where water is contaminated to be sure that heavy metals do not get into the human food chain.

On the other hand, duckweeds may find use in stripping heavy metals from industrial water. Also their content of heavy metals can be used to indicate potential pollution levels of waters.

Cadmium appears to be absorbed by both living and dead duckweed plants and the cadmium is actively taken up by the plant (Noraho & Gour 1996). Cadmium at high concentrations, that is the concentration that prevents vegetative reproduction (EC-50) was found to be 800ppb but duckweeds grown in medium of 2.2ppm still accumulated most of the cadmium over 7d and when fed to crayfish increased cadmium in the hepatopncreata 26 fold and in muscles almost 7 fold (Devi et al., 1996). It is therefore, extremely important to be sure of low cadmium levels in water prior to any large scale use of duckweeds as feed for domestic animals or humans.

Many reports are available on the uptake of metal ions by duckweeds and the numerous interactions that occur. Duckweeds will uptake and concentrate Cd, N, Cr, Zn, Sr, Co, Fe, Mn, Cu, Pb, Al and even Au. To attempt to define the rates of accumulation is not important here, except to point out that as the levels of these minerals rise to higher than normal in general they may directly inhibit growth of the plant and any animal that consume significant quantities. At low level accumulation the plants become a very useful source of trace minerals particularly for livestock and fish.

Problems of heavy metal contamination obviously arise where duckweeds grow on industrial and mining waste where the contaminating elements are known and therefore the problem should be apparent from the beginning of any study.

In conclusion, it is only where heavy metals are washed out in effluents from industry and mining that there is potential for duckweeds to become toxic to livestock, and in these situations duckweeds harvested from such sources should be disposed of differently. A most useful disposal method being as a mulch for non-food crops such as trees.

MEETING MINERAL REQUIREMENTS

Fertilisers

A commercial balanced NPSK with sea salt to provide trace minerals can undoubtedly be used with relative unpolluted waters to meet the growth requirements of duckweeds. In the Mirazapur project, (see chapter 6) muriate of potash (KCl), urea and superphosphate (supplying P+ S) were successfully used to produce duckweeds on inundated lands that also collected the effluent waters from the local hospital. Fertilisers were applied on a daily basis, which together with the need for regular harvesting had a high labour cost. Sea salt was added as a source of trace minerals.

Manure

Slow decomposition of manure and other organic materials are good ways to continuously supply a water body with nutrients required for duckweeds to grow. The skill here resides in somehow controlling the nutrient inflow into the growth ponds. In many instances this can be established by trial and error. This has been apparently highly successfully in Vietnam where, commercial producers of duckweed used ruminant and pig excrement. This was collected in a small settling pond, the water from which then passes through a series of duckweed ponds before either entering the river or being used for irrigation. These systems appear to work because of long established experience with growing duckweed. The series of ponds all apparently produced a good harvest of duckweed.

A further extension of this method was seen in Bangladesh. The system was based on a simple toilet block, which may be just a hole in a concrete slab from which human excrement could be directed by gravity through a plastic pipe into a basket (usually split bamboo) situated at the centre of the pond and from which nutrients slowly diffused into the duckweed pond (see Photo 6).

Manure and biogas

The effluents from biogas digestors, suitably diluted are very effective media for growing duckweed. These can be extremely simple systems, easily incorporated into a small farming areas based on home-biodigestors, constructed from plastic (see Photo 6) through to industrial size biodigestors made of metal. In all cases the excrement plus washings from animals held under penned conditions are collected, held in some form of settling pond to remove solids and then into an enclosed container which allows anaerobic microbes to grow and convert the residual carbohydrates to carbon dioxide and methane. The gaseous effluent containing methane and carbon dioxide is collected and combusted for various purposes including household cooking. The water leaving the biodigestor retains the minerals and with suitable dilution is a good media for the duckweed farm.

Photo 5: A young boy harvests duckweed as a protein source for ducks in Vietna

Figure 9: Schematic representation of present duckweed framing in Vietnam.

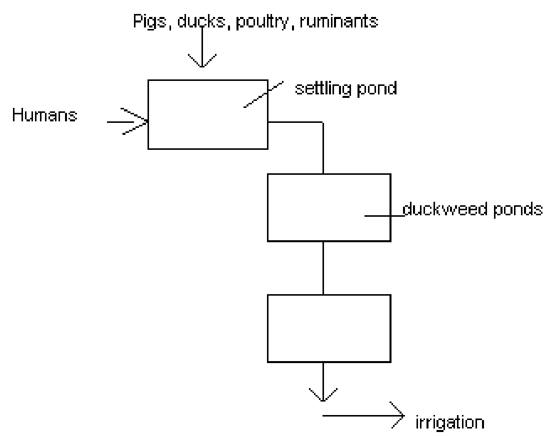


Photo 6. Duckweed mats fed from faecal materials through a small basket which collects the solids in the middle of the pond

Biodigestor effluent from animal production is usually pH neutral and has a relatively high ammonia content. The mineral component of the diet effects the levels of nutrients in the water and therefore the need to dilute the effluent depends on the animal's diet. Ammonia treated straw results in an effluent from cows fed this that is high in ammonia. A simple system is shown in Figure 10.

The system advocated by Dr. Preston, (Photo 7) is relatively simply to apply on small farms. A cow and calf, mainly fed crop residues provide both urine and faeces to a biodigestor suitably diluted with wash water. The biodigestor in this case is a simple polyethylene tube placed in a ground pit. The washings from the stall enter the digestor and have a half time of 10-15 days during which time most of the organic matter is converted to carbon dioxide and methane. The effluent is diluted and run into narrow plastic lined channels or concrete cannels in which the duckweeds are seeded and grow for several weeks, harvesting the duckweed occurs every few days. The duckweed is then fed either fresh as a supplement to pigs and poultry or is sun dried for the same use.

Figure 10: Diagrammatic representation of flow of nutrients through simple biogas digestor to feed duckweed.

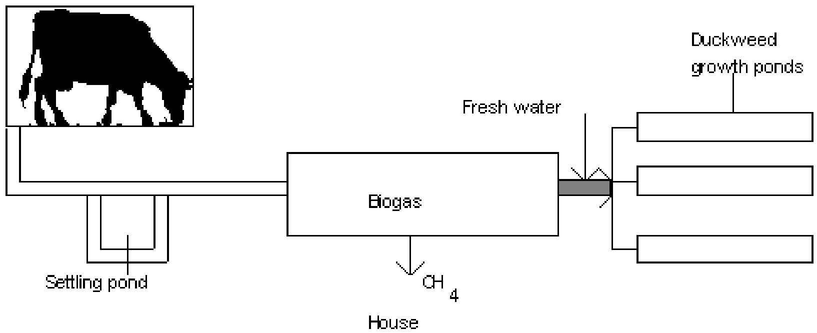


Photo 7: Duckweed growing on small plastic lined containers fed by biogas digestor fluid

Another system that has been proposed uses the effluent (washings) from large numbers of housed animals under intensive management or from abattoirs. The effluent is channelled through a lagoon covered with a 5-10cm thick plastic film and methane is collected from a convenient site beneath the plastic. The effluent being run into ponds, diluted and duckweed produced on the effluent (Figure 11)

Miscellaneous systems

Wherever there is an effluent of polluted water associated with industry or agriculture there is potential to purify the effluent waters with duckweeds. Each process, however, requires particular attention and it is beyond the scope of this presentation to make recommendation here for such systems. Some examples of where duckweed cleansing systems might have application are listed Table 3.

Figure 11: Schematic Diagram showing abattoir or intensive animal production waste processing and biogas flow

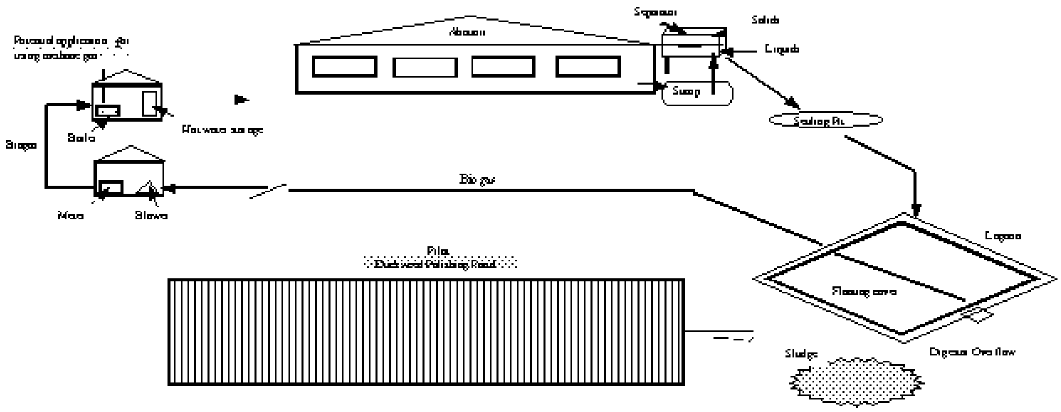


Table 3: Some examples of where duckweed might be used to cleanse wastewater of mineral pollution and produce a feedstock of duckweed biomass

1. Effluents from:

- Dairies
- Piggeries
- Cattle and sheep feedlots
- Urban sewage
- Industrial waste from:
    - Brewing &alcohol production (solubles)
    - Milk processing
    - Sugar factories
    - Starch factories
    - Wool scouring
    - Abattoirs & tanneries
    - Food processing

1. Run-off from:

- Agricultural practices
    - Cotton growing
    - Sugar industry
    - Beef and sheep grazing industry
    - Horticulture and nurseries
    - Mining
        - Sodium run-off water
        - Heavy metals in other mining activities
    - Parks and sporting facilities

Sewage

Possibly the best case can be put for the use of duckweeds to remove P from human sewage which is mostly collected strategically at a point site in a township and although treated to varying degrees is often finally exported via rivers to the sea. There are now a number of commercially viable duckweed based sewage systems that have been developed.

These systems are expensive because of the obvious need for high technology to ensure success in treatment. It appears, however, that both

chemical and microbiological treatment plants are much more costly. On the other hand the use of aquaculture does not necessarily replace such systems and they can often be incorporated into or added on to a number of sewage purification plants. However, in small communities in the tropics the cultivation of duckweed on lagoons may be the only treatment necessary for simple sewage treatment.

RECORDED YIELDS OF DUCKWEEDS

The literature contains a great deal of information on the potential growth rates of duckweeds. In many early studies the growth rates were measured under controlled conditions for short periods of time. In the absence of large scale field data obtained over 12 month periods these data have been used to estimate potential production rates. The data needs to be treated with reservations as the data in Figures 4 and 5 point to serious problems in doing growth trials with duckweed under laboratory conditions.

The results in Table 4 are from research with near optimum conditions for duckweed growth. Landolt and Kandeler (1987) concluded that under such conditions a 73ton of dry matter are possibly produced per hectare per year or 20g DM/m2/d. Results up to 180ton DM/ha/y have been recorded. Under less than optimum conditions it is more realistic to target between 5 and 20ton DM/ha/y (Table 5).

In practice the yields of duckweed often depend on the skill of the farmer in solving the problem of how to balance the mineral requirements of duckweeds and to identify with time the need for continuing and varying mineral supplementation. Waters that are high in P and K and trace element need minimal but repeated inputs of an ammonia source, keeping ammonia at around the 60mg N/l when growth and protein accretion is greatest.

Table 4: Field results of duckweed growth in near-optimal conditions

Location	DM Yield	Source
	(t/ha/yr)	
Louisiana USA	44-55	Mesteyer et al (1984)
Louisiana USA	27-38	Mesteyer et al (1984)
Louisiana USA	182.5	National Academy of Science (1976)
Southern States USA	54	Said in Mbagwu and Adeniji (1988)
Southern States USA	20	National Academy of Science (1976)
Israel	36-51	Oran et al (1987)
Israel	39	Heppher in Landolt et al (1987)

Table 5: Field results of duckweed growth in sub-optimal conditions.

Location	DM Yield	Source
	(t/ha/yr)	
Thailand	10	Hassan and Edwards (1992)
Thailand	11	Hassan and Edwards (1992)
Thailand	10	Bhanthumnavin in Landolt et al (1987)
Israel	10-17	Porath et al(1979)
Russia	7-8	Rejmankova in Landolt et al (1987)
Uzbekistan	7-15	Taubaev et al in Landolt et al (1987)
Germany	22	National Academy of Sciences (1976)
Germany	16	Schultz in Landolt et al (1987)
India	22	Rao et al in Landolt et al (1987)
Egypt	10	El Din in Landolt et al (1987)
Louisiana USA	9	Culley and Epps (1973)
Louisiana USA	20	Russoff et al (1980)
Florida USA	5-13	Reddy and DeBusk (1985)
Florida USA	17-21	Reddy and DeBusk (1985)
Florida USA	13	DeBusk et al in Landolt et al (1987)
Florida USA	19	Stanley et al in Landolt et al (1987)
Florida USA	23	Culley et al in Landolt et al (1987)
Florida USA	14-27	Meyers in Landolt et al (1987)
Florida USA	2-14	Sutton and Ornes (1977)

Yield of duckweed will depend on how the farmer monitors the duckweed system and whether a high protein meal is the objective. Industrial waters can only be discharged when the P levels have been depleted by consistent cropping and fertilisation with urea as ammonia levels decrease and become limiting to growth. How often to feed urea into the system and how long can duckweed growth be maintained can only be understood from research in the locality.

Where the production of clean water is a major objective then it becomes necessary often to balance other nutrients as well as ammonia in order to end-up with water that has had its total mineral composition decreased to levels that will allow its re-use.

In Table 6 the residual P in wash water from piggeries shows that with skill, a number of fertilisations with urea followed by harvesting of duckweed could result in very low P levels occurring. Recharging ammonia levels could be expected to stimulate growth so that P levels can drop below 1mg P/litre.

Density of duckweed and yield

The growth rate of duckweed under ideal light, temperature and pH would be exponential if there were no limitation in terms of mineral (including ammonia) deficiencies or excesses. However, in practice many issues reduce the biomass yield. One of the most important is obviously plant density. The rate of harvesting duckweed is important since there is a minimum biomass at which yields will decrease and an upper biomass where yield will be limited by crowding, all other variables being equal. In a study where most of the conditions for growth were unlimited the effect of harvesting indicated that, above about 1.2kg/m2 duckweed (fresh) growth decreased and below 0.6 kg/m2

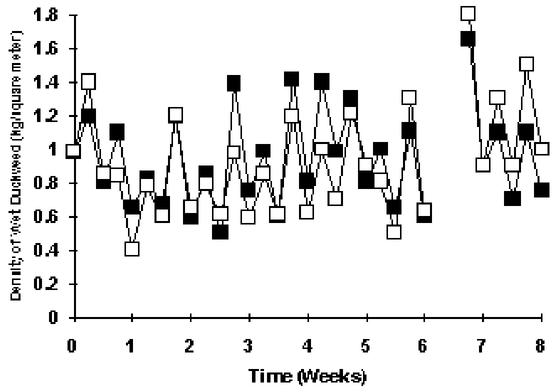
Table 6: Removal of nutrients by Lemna from a flow through pond fed by aerated piggery waste water (Instituto de Investigaciones Porcinas, Havana, Cuba (unpublished observations)

	Concentration (mg/l)	
	Inflow water	Outflow water
COD	461	323
BOD	51	30
Total N	42	21
NH3	17	2.2
Total P	6.4	3.3

duckweed (fresh) biomass limited growth potential. It appeared that if 1.0kg fresh duckweed/m2 could be maintained by frequent harvesting then an extrapolated yield of 32 tonnes DM/ha/yr could be produced under other non-limiting conditions. The data is shown in Figure 12.

Figure 12: The range of densities of duckweed biomass on the water surface after harvesting at which duckweed grows optimally (Stambolie and Leng, 1994). In this case the average yield was 32 tonnes DM/ha/year. The upper density (filled squares) appears to be that at which crowding limits growth and the lower density (unfilled squares) is the density at which growth is insufficient to prevent algal blooms (Stambolie 1994

reported by Leng et al 1994)



CHAPTER 4: Integrated farming systems

WHY DO DEVELOPING COUNTRIES NEED TO EXAMINE THE POTENTIAL FOR INTEGRATED FARMING SYSTEMS?

Integrated farming systems, so long as they improve soil fertility (or at least maintain the same soil fertility) in the long term have major advantages which can improve both the overall production of land without losing sustainability.

The World Commission on Environment and Development defines sustainability as:

> "ensuring that development meets the needs of the present without compromising the ability of future generations to meet their own needs".

However, development opportunities and aspirations change with changing economic considerations. Major increases in the cost of food production is likely to arise where cost of fuel (fossil) increases relative to income. Fuel prices must surely increase in the future in response to:

- increasing depletion of world reserves (Fleay, 1996)
- as a result of economic decisions taken at government level to reduce their countries fuel use and reduce global warming.
- because of economic downturn which puts enormous pressure on gasoline prices.

The cost of food production in a country is highly dependant on fuel prices, and food prices in the 1998 Asian financial crisis rose and must continue to rise.

The two important agricultural cost factors that will be effected most are, mechanisation, where fuel is directly consumed in crop farming, and fertiliser availability and application since the cost of NPK is highly related to gasoline prices. The fuel crisis in Cuba brought about by removal of economic support from Russia and the embargo by the United States has seen a return to animal traction in the past 6 years and a massive decline in crop yields through decreased use of inorganic fertilisers.

Farms export considerable mineral nutrients in products and also effluent from many sources. In the future and for continuing sustainable food production, these minerals must be replaced. In industrialised farming systems this is done largely by inorganic fertilisers produced and delivered at an increasing cost of fossil fuel combustion.

High level use of NPK have resulted in the sustained yields of feed crops in industrialised countries and in the last 20 years greatly improved yields in developing countries where these inputs have been used together with improved crop varieties.

The other major issues in terms of crop production has been the increased use of water resources, some of which are irreplaceable. Levels of fertiliser and water application are almost always in excess of plant needs and water run-off contaminated with minerals has created great problems with salination and eutrophication in river and pond systems throughout the world, changing the aquatic ecology of whole regions in places.

Integrated systems are aimed at minimising (or preventing) loss of nutrients from a farming system and in many situations conserving water for reuse (Preston & Murgueitio, 1992).

Integrated farming systems to be employed by small farmers in developing countries, require considerable skills in operation in order for them to be economic and/or sustainable. Integration may be developed on a single land holding or may be more easily applied where a number of farms combine their requirements to develop an integrated system where the minerals leached from the land by farming are returned to the land via good conservation practices involving a number of farms. In Australia the Land-Care Movement involves usually a number of land-holders to combine their efforts to conserve a whole catchment area. Similarly in India a catchment area approach to sustainability has been implemented through ICRASAT.

Integrated and sustainable systems must be developed in order to prevent land degradation, minimise external (costly) inputs, conserve resources otherwise lost through effluents and potentially increase the income and standard of living of the farmer and at the same time maintain the fertility of the land. Integrated farming systems, that are also sustainable require that:

- depreciation of minerals within the system are minimised and/or eliminated (this I term nutrient recapture).
- replacement of minerals, exported in products, by sources generated on the farm or from byproducts of agro industries (e.g. minerals in water from industries such as sugar production, fertiliser production or from commercial biogas digestors).

RECYCLING OF NUTRIENTS

Integrated systems were traditional in most developing countries prior to the "green revolution" and many ancient societies recognised and put into practice sustainable cropping systems often through application of taboos against practices that caused degeneration of food supplies. In more recent times (say the 1920's) this took the form of integration of crop and animal production. The animals being an intermediate in conversion of crop residues and other wastes to dung which was then returned to the land. In some countries composting and biogas digestors were instrumental in recycling nutrients within the farm(s). The net result was that the minerals in biomass produced on the farm were recycled by re-incorporating the nutrients back to the land via human or animal excrement. Often the animal was a draught animal which is now being replaced by tractors. However, even in these systems effluent loss was considerable in water run off and in product where crops and animal products were sold from the farm.

FIXATION OF N AND MOBILISATION OF P FROM PLANT GROWTH

Within the integrated farming systems, strategies to encourage N fixation and for increasing P availability are primary targets.

N accumulation in land or maintenance of levels through N fixing plants (e.g. legumes) or the extraction from effluent waters by aquatic plants are strategies that were used by small farmers only a few decades ago. Similarly P fertilisers have often been developed from aquatic plants. For example, in Kashmir, aquatic bottom growing plants are harvested from the lakes for use as fertilisers, and seaweeds have been used where ever they are washed ashore for application to soils.

Ruminants in general, if they graze non cultivatable land harvest considerable N and P and this then can find its way into crops via manure and therefore potentially avoid downstream problems.

The major constraint to the establishment of integrated farming systems is the level of management that must be exerted by small farmer. This can often be beyond his presently developed skills. An exception to this statement however, was seen in Vietnam and Bangladesh where the collection of all animal and human wastes into ponds and the subsequent growth of duckweeds has proven to be relatively free of problems and is very skilfully managed by a number of cooperating farmers. However, if these tropical systems had to be managed for production of quality water as well as feed for ducks or fish a greater degree of control of the duckweed growth would need to be exerted.

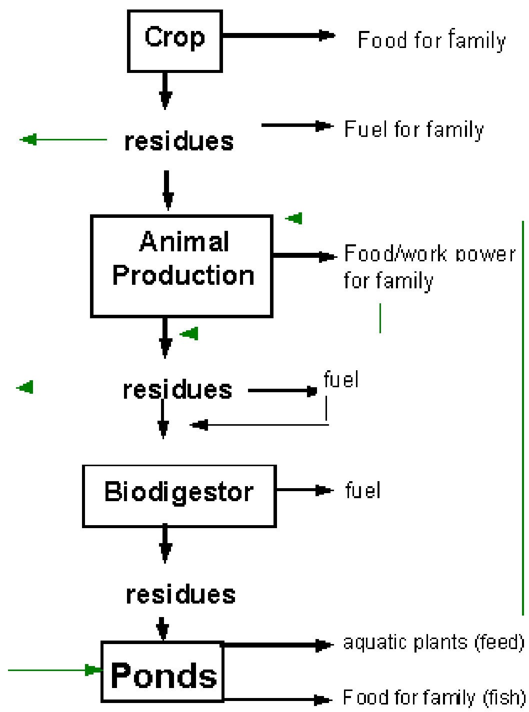
INTEGRATED FARMING (THEORETICAL CONSIDERATIONS)

One of the major reasons for the development of livestock production in cropping systems in developing countries was to utilise crop residues efficiently, thus, eliminating waste and optimising the use of the total biomass produced within the small farm system. The small farmer has often a requirement for draught power with animal products (milk and meat) as secondary considerations.

Integrated crop and livestock production systems can be highly efficient; potentially crop residues are used as livestock feed; the waste products (e.g. faeces and urine) are fed into a biogas digestor and the effluent used to fertilise ponds for aquatic plant/algae production, with fish farming as the terminal activity. These systems are worthwhile pursuing as a means of providing nutrients/fuel for the family, minimising fuel combustion and reducing environmental pollution (Preston, 1990).

The array of integrated strategies that could be developed is large. They all have as a central core a basic flow of nutrients through a number of systems. At each of these steps research can be brought to bear to optimise the partitioning of the available biomass into food, fuel and residues (see Figure 13). The environmental attributes of such systems are the methane emissions into the atmosphere and fuel (fossil fuel and fire wood) use are minimised. In addition the efficient and also

Figure 13: Flow diagram showing the potential recycling of feed and faeces biomass from crop residues in an integrated farm.

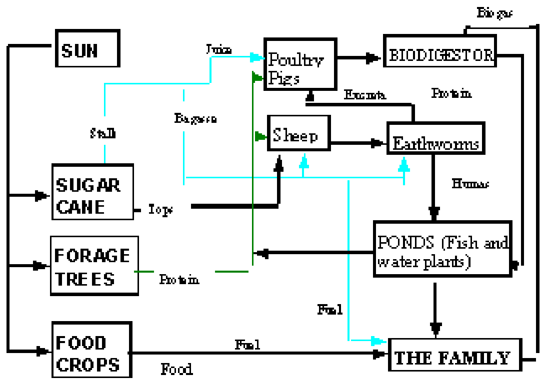


total harnessing of the energy from high producing crops reduce the land areas required per unit of product (see Preston, 1990).

A complete discussion of these systems is beyond the scope of this document but two examples are:-

- The use of aquatic plants/algaes grown on biodigestor effluent for protein production for pigs, poultry, ruminants, rabbits and horses particularly in the humid tropics and
- The farming of duckweeds on biogas digestor effluents to feed fish.

Figure 14: An example of an integrated farming system based on sugar cane and forage trees fractionated to provide feed for pigs and poultry (the juice and tree leaves), sheep (the cane tops and tree leaves), fuel for the family (bagasse and firewood) and litter for sheep and earthworms (bagasse), with recycling of excreta through biodigestors to provide fuel (biogas) and fertiliser (the effluent) for water plants in ponds and for the crops (Preston, 1990)



INTEGRATED SYSTEMS INVOLVING DUCKWEED PONDS

The publication of a booklet by Skillicorn et al. (1993) on duckweed aquaculture based on the experiences of a project in Bangladesh operated by PRISM stimulated considerable interest the use of duckweed.. In Cuba, major research has been developed as a result of the lead-work of the PRISM group. It is of significance that both these countries have relatively high priced fuel and in Bangladesh draught animal power is still the main farm power, whereas in Cuba, the farmers have reverted to draught animal power mainly because of the increased price of gasoline. Neither country, however, has been able to efficiently establish integrated farms. In both countries the objective behind the research on duckweed has been to provide food for carp and/or tilapia production with some spin off for pig/poultry production.

A system, that appears ready to be put straight into farm practice arises from the work of Dr. Preston and his colleagues in Vietnam. It incorporates a duckweed production system into a rice farm or market garden. It depends on a typical 1 to 0.5ha farm with one milking animal, a calf and a bullock for work and with additional small ruminants (goats or sheep) or rabbits and where possible a pig.

The pig is a crucial animal in much of the cropping system of small farmers in Vietnam particularly to maintain rice yields. They are produced on the byproducts of the household and from small inputs of other feeds. The faeces of these animals has been the mechanism by which soil fertility has been maintained over the centuries in much of the Mekong Delta. However, the systems are decreasing because of the importation of high technology pig production based on European technology and this could be highly detrimental to small farm rice production in the future.

GROWING DUCKWEED IN AN INTEGRATED SYSTEM

The nutrient requirements for high rates of duckweed growth has been discussed. In practice, however, standards and requirements only provide a basis for the "adviser" to give recommendation to the farmer. Most scientists are distracted by the establishment of "nutrient requirements". The application of precise levels of nutrients into any system is problematic particularly where these are to be met from the farm resources. However, nutrient requirements estimated in research laboratories may possibly emphasise a critical limitation in duckweed production through mineral analysis of the water.

Essentially, duckweeds must grow on the effluent from plant and animal production. Often the effluent from plant production (drainage) is too low in nutrients for high growth rates of duckweed. An exception to this occurs in some areas where high levels of fertiliser are applied to crops under irrigation. In Pakistan close to Faisalabad duckweed growth in drainage ditches can sometimes be so great as to create major problems in water pump blockage. Similarly the run-off from cotton production often provides a good medium for duckweed growth. On the other hand effluent from intensive animal production almost always is a too concentrated source of minerals particularly ammonia and needs dilution with other waste water sources.

Scientists can measure ammonia-N and phosphorous in effluent waters and then make recommendations for the appropriate dilution to provide pond water for duckweed farming. On the other hand chemical analysis of water is not feasible or affordable for large numbers of resource poor farmers that may be involved. However, some practical recommendations based on simple research at the farm level can be given to assist farmers to establish a duckweed farm.

OTHER BENEFITS FROM INTEGRATING DUCKWEED INTO CROP FARMING

Aquaculture of duckweed has been largely promoted as an opportunity crop for use as animal or fish feed. This is particularly appropriate where ponds have become unusable for other purposes because of pollution. This emanates largely from fertiliser run off or from wash out of animal/human manure. Such ponds are abundant in countries such as Bangladesh, where there are an estimated 1.3 million ponds (average size 0.11ha) covering 147,000ha. Only 46% of the ponds contain fish. The ponds have multiple use, bathing (washing) irrigation and livestock watering which interferes with fish culture but which could make them useful for duckweed production. A recent World Bank review suggested that about 40,000 ha of ponds could be brought into duckweed production and that if yields varied from, 4-20ton DM/ha/y then 160,000 to 800,000ton of duckweed could be available to poultry farmers. The potential value of this can be seen from the fact that the higher quantity of duckweed represents twice the availability of 'home grown' feed concentrates in Bangladesh.

The major problems of developing such a system of concentrate production are associated with multiple ownership of ponds, lack of credit and the unavailability of extension services. A major constraint is the lack of a marketing mechanisms including quality control, that can effectively allow a duckweed meal to compete with imported protein meals particularly those from Europe and derived from animal offal.

OTHER CONSIDERATIONS

A major benefit of using duckweeds is emerging. There is accumulating evidence that duckweeds release compounds that have insecticidal properties particular to the larval stages of mosquitoes. Thus the development of duckweed aquaculture in the wet tropics may have implications for mosquito control in rural areas where malaria is again becoming a serious problem.

Eid et al. (1992a) published evidence that an extract of Lemna minor had insecticidal action against the mosquito Culex pipens pipens. The same extract contained synomones which also repelled oviposition by the female mosquito. Where sublethal doses of synomones were added to water it was found that all larval stages of the mosquitoes were malformed. Duckweed synomones added to water also repelled the ovipositing of Piophila casei, and effected larval development and reduced survival. Similarly Spodephera littarolis larvae were malformed when synomones from Lemna minor were added to their culture medium.

If the insecticidal properties of Lemna minor and other duckweeds are sufficient to truly control mosquito populations it will have an immense effect on health of people in areas where mosquito borne diseases are endemic and resistance of the parasitic stage to drugs has increased. It is also a further inducement to cultivate duckweeds widely for water treatment (purification) and animal feed. A further potential is the commercial cultivation of duckweed as a source of insecticides in water where it is difficult to spray for control of mosquito larvae or where the use of other control measure are impractical.

Other research workers have also associated duckweed presence with reduced (or elimination) of mosquito development. For example Marten et al. (1996) showed that Anopheles albimanus populations were negatively correlated with the amount of cover of the water by Lemna. The relative cover of water surface with duckweed was also negatively correlated with populations of fish and other insects indicating how intricate the associations are in natural ecosystems.

Eid et al. (1992b) have made the observation that the mosquito Culex pipens pipiens never colonised sewage water covered with duckweed and Bellini et al. (1994) observed that Lemna covering the surface of rice paddy-fields strongly effected mosquito populations. However, again other organisms might also have been involved in the control of mosquitos.

Lemna trisulca appears to produce allelo chemicals that are active against algae (Crombie & Heavers 1994) and Mesmar and Abussaud (1991) suggested that extracts of Lemna minor were active in inhibiting the growth of Staphylococcus aureus.

The role of duckweeds in preventing algal growth can be by shading, by perhaps the production of algacides if this can be satisfactorily proven and in addition because they lower the nutrient supply, particularly P concentrations either in effluent waters from sewage plants or in water bodies.

Cholera has long been associated with seasonal coastal algal blooms off Bangladesh. Fluorescent antibody techniques have shown that a viable, non cultivatable form of Vibro cholerae in a wide range of marine life, including algae. In unfavourable conditions V. cholerae assumes spore-like forms which as conditions improve reverts to a readily transmittible and infectious state. Algal blooms which are associated with eutrophication have been related to the spread and persistence of cholera. Prevention of algal blooms may therefore be of considerable benefit (see Epstein, 1993).

CONCLUSIONS ON THE POTENTIAL OF DUCK WEED TO PRODUCE CHEMICALS OF IMPORTANCE TO HUMAN HEALTH

Although the literature is sparse and not totally convincing on the potential of duckweed to control of mosquito populations, the author has heard farmers in many countries express opinions that growing duckweed on ponds control mosquito populations. Farmers in a group of villages in Vietnam that traditionally produced duckweeds were adamant that mosquitoes were not a problem so long as their lagoons were covered with duckweed.

Research into the insecticidal properties of duckweed is worthy of follow-up. If the production of natural insecticides can be promoted at the same time as improving health conditions, purifying water and providing a natural food resource for animal production it may have far-reaching implications. A new naturally occurring insecticide produced from duckweeds may be as revolutionary as the discovery of pyrethrins and perhaps this potential alone may give the necessary government resolve to support integrated farming with a duckweed crop as a major component of such farms in countries where this is appropriate.

FARMING SYSTEMS FOR DUCKWEEDS

Why duckweed?

A number of aquatic plants including duckweeds have great potential for development for various purposes.

Essentially aquatic plants may or will be grown in developing countries where:

- there is an unused area of standing water available that is either free or is relatively inexpensive to purchase, rent or lease.
- fresh water fish/crustacean production is impractical, not practiced or there are other constraints to their production, such as pollution.
- there is a need to clean water of chemicals before reuse or release into the aquatic ecosystem of rivers/deltas or seas.
- there is a market for the product or the product can be integrated into a system of production enhancing the economic viability of the farm either being used as mulch, fertiliser, feed/food and perhaps even fuel.
- there is a levy on industries in disposing of water contaminated with chemicals.
- legislation is enacted in order to clean up vast areas of ponds or wet lands that have become unusable for, in particular, fish production.
- duckweed mats on standing water reduce the health hazards from clean or polluted water bodies

Candidates for use in any of these applications include duckweeds, Azolla, Pistia, Ecihhornia and a few lessor known aquatic plants.

There are major advantages for floating aquatic plants as the water depth is not critical and harvesting does not necessarily disturb the underlying ecosystem in the mud. Ease of harvest is important and Azolla and duckweed are readily harvested, but have the disadvantage of having to be protected from wind and water currents to encourage total coverage of lagoons and hence maximum yields. There is some evidence for a symbiotic association of Lemna and N fixing bacteria, but on low N waters Lemna growth is slow and the product is low in protein, on high phosphorus water low in N, Azolla with its association with N fixing bacteria is more appropriately grown. However, Azolla has some greater problems associated with its continuous growth as compared to Lemna particularly from insect damage. Addition of N fertiliser in aquatic media mostly removes the major advantage of Azolla, that is, its ability to grow on low N water.

RUSTIC METHOD FOR ESTABLISHING DUCKWEED

A simple approach to establishing a duckweed pond system is often the only way to start.

If water emanating from an animal production unit is taken as an example of how to approach its use for duckweed production. First the water has to be collected in some suitable settling pond. To obtain information on the water's potential to grow duckweed, the water is serially diluted in small containers with water relatively free of minerals. Duckweed is seeded into each water container and its relative growth monitored by eye. It quickly becomes apparent what is the appropriate dilution and this can be further refined by successive harvesting from the containers to determine the dilution at which duckweed grows at the greatest rate. This system can be recommended where the objective is to produce duckweed and there is no constraint to disposing of the effluent or it is not required to recycle the water.

In general, it appears that in most systems, N quickly becomes the limiting nutrient as duckweed mats grow. The second potentially limiting nutrient is P. Thus there is sometimes great benefits in providing extra N (as urea) at the end of the growth period following harvest of half the duckweed mat. This allows further growth of duckweed and further reduction of P content in the effluent water. Water can be cleaned effectively by growing and harvesting duckweed only when this is a well designed succession of fertiliser applications that rebalance NPK for growth after each harvest. Eventually the minerals may be reduced to acceptable levels.

CHAPTER 5: Duckweed as a source of nutrients for domestic animals

PRELIMINARY

Although farmers, particularly in South East Asia and probably elsewhere had developed the use of duckweeds as a source of nutrients for livestock, the actual controlled experimentation that has been typically used to develop such commercial crops as soyabeans or maize for livestock feed has not been undertaken. There are, however, a number of reports in the literature on the use of duckweeds as feed supplements for fish and livestock. These report research with domestic animals in which normal feed protein sources have been replaced by duckweed meal on an isonitrogenous bases in complete diets based on compounded concentrate diets.

Duckweeds are highly variable in their composition. They grow slowly on low nutrient waters and are high in fibre, ash and carbohydrates but contain low crude protein. In contrast when grown on waters high in ammonia and minerals they grow rapidly and have a high protein content associated with a high ash and are often lower in fibre. Because duckweeds respond quickly to the availability of nutrients they often have highly variable levels of some nutrients which makes it difficult to prescribe the amounts needed for livestock and fish over a period of, say, one year. Careful interpretation of some studies reported is required when the quality of duckweed given in diets to livestock is not consistent throughout the study. In terms of domestic animal/fish nutrition, duckweeds may be used in many ways. These include:

- As a total feed
- As a supplemental source of:

- protein
- phosphorous and other major minerals
- trace minerals
- colouring pigment for egg yolk/flesh of chickens
- vitamin A and the B group
- fibre in low fibre diets for pigs and poultry

Duckweeds have been largely researched as a total feed for fish, including carp and tilapia production, as a protein supplement for pigs and poultry (including ducks) and as fermentable N and mineral supplement for ruminants.

The research on duckweeds as a feed are summarised below. The uncertainty of the conclusions and the difficulty in making clear recommendations largely pertains to the fact the quality of the duckweed used by various researchers (i.e. its nutrient densities) were variable. However, as a resource that can be harvested for labour costs alone in natural conditions, it obviously represents a valuable asset to the resource poor farmer. In many countries it could have a low cost where it is grown on sewage and it has to be disposed of from the works at a subsidised price.

It appears to be a resource that is most conveniently used by the small holder farmer, particularly in an integrated farming system. Unfortunately much of the research has attempted to demonstrate the value of duckweed as a protein source in diets that are most commonly used in industrial production systems. This is particularly true of the research with poultry and yet its major application probably lies in the more difficult situation of increasing animal production on small farms.

CHEMICAL COMPOSITION OF DUCKWEED

Protein and amino acid composition

The crude protein content of duckweeds depend mostly on the N content of the water upon which they grow. Some publications have indicated that there are some variations in amino acid content of duckweed proteins. High levels of lysine have been reported in studies coming from the duckweed research programmes in Bangladesh. However, it appears that the protein component of most aquatic plants including duckweeds have similar amino composition to terrestrial plant proteins in general (Table 7). In this respect the amino acid composition is influenced by the major enzyme protein in plant that is ribose bisphosphate carboxylase. Protein extracted from Lemna minor when fed to rats compared equally with the nutritive value of a wheat flour diet. This indicates that Lemna meal has a relatively high biological value for rat growth (Dewanji & Matai, 1996). Duckweeds therefore are good

Table 7: Amino acid composition in aquatic plants (g/100g protein) grown on wash water from a pig farm in Cuba (unpublished Instituto de Investigaciones Porcinas, Havana) The wash water was collected and aerated to reduce total N (Figueroa, V. personal communication)

	Azolla	Lemna	Water Hyacinth	Soybean
Crude protein	31.0	28.0	19.0	44.0
Lysine	3.4	3.7	3.1	6.6
Histidine	1.7	1.7	1.4	2.5

Arginine	4.6	5.1	3.7	7.3
Aspartate	-	-	-	-
Threonine	3.5	4.2	3.3	3.9
Serine	-	-	-	-
Valine	5.1	5.8	4.5	4.6
Methionine	1.4	1.5	1.2	1.2
Isoleucine	3.8	4.3	3.1	4.5
Leucine	7.1	7.8	5.6	7.7
Tryptophane	3.5	4.2	3.3	3.6

Note: that Lemna protein has a lower lysine content considerably below that of soybean protein, which is contrary to the data produced by Skillicorn et al. (1993). It is possible but highly unlikely that the essential amino acid content in Lemna is dependent on the protein content. It is important to emphasise that it is not true that there is a better content of lysine in Lemna as compared to soyabean although extracted protein from Lemna minor has sufficient lysine to meet the FAO/WHO Reference Standards and NRC requirements for chicks (Dewanji, 1993) laying hens or pigs (Hanczakowski et al., 1995) sources of essential amino acids but are not enriched in any particular amino acid in comparison with the usual protein sources used in animal production.

DUCKWEED FOR SUPPLEMENTAL NUTRIENTS IN AVIAN DIETS

Poultry - egg production

The value of duckweed as a protein supplement to poultry was recognised some time ago (Lautner & Muller, 1954; Muzaffarov, 1968; Abdulayef, 1969).

Truax et al. (1972) showed that dried duckweed was superior in protein quality for poultry as compared to alfalfa meal and could fully substitute for alfalfa meal at 5% of the total diet.

Interpretation and extrapolation from much of the earlier studies are confusing because the duckweed was harvested from natural sources and often the material could have been "old" and low in protein but high in fibre. This situation led Haustein et al. (1990) to reassess the value of duckweed as a protein supplement for pigs and poultry. They established studies to examine the potential to substitute not only alfalfa meal, but also fish meal and/or soyabean meal with Lemna meal in a compounded feed.

The diets used by these researchers at the University of La Molina, Lima, Peru were based on those used in the intensive egg production industry (Table 8). Duckweed was harvested from a tertiary sewage effluent and lagoon run-off and in general had a medium level of protein (33%CP). Both Wolfia and Lemna species were harvested and their estimated metabolisable energy level was 1,200kcal/kg (in young broilers) and 2,000kcal/kg (in mature cockerels) indicating a poor overall digestibility of duckweed for monogastric animals (see also Hanczakowski et al. 1995). It might be inferred here that there was considerable intestinally indigestible carbohydrate (fibre?) present.

Table 8: Composition of diets fed to Topaz layers (Haustein et al. 1990)

Ingredient (%)	Diet				
	Control	Lemna (15%)	Wolfia (15%)	Lemna (25%)	Lemna (40%)
Ground corn	52	51	51	48	50
Wheat Middlings	19	16	16	*	*
Fish Meal (65% CP)	7.5	7.5	7.5	2	-
Soyabean Meal (46% CP)	11.0	-	-	-	-
Duckweed	-	15	15	25	40
Fishoil	2.5	2.7	2.5		2.5
Minerals and Vitamins	+	+	+		+
Calculated ME (kcal/g)	2,800	2,800	2,800	2,840	2,800
Crude Protein (%)	17	17	17.5		17.0

** Approximate as the level of wheat middlings was not stated by the authors and small amounts of other carbohydrates were included in the diet to balance the energy.*

The diets used are important, because these studies only compared duckweed protein with other sources of protein in an otherwise commercial diet used for intensive production Table 8. The results of replacing soyabean with a meal made from Lemna or Wolfia clearly indicated that the latter two are at least as good as soyabean as a source of essential amino acids as there is virtually no differences between egg production of birds on all diets (Table 9).

Table 9: Performance of Topaz layers fed three isonotrogenous diets based on protein either from soyabean or duckweed after 2 weeks (Wolfia diet) or 10 weeks (Control and Lemna diets (Haustein et al. 1990)

	Diet		
	Control	Lemna	Wolfia
		(15%)	(15%)
Egg Production * (%)	89	90	90

Eggs per week	6.2	6.3	6.3
Feed conversion efficiency (g/g)**	2.3	2.4	2.4

** As a percentage of the egg production when all birds were fed the control diet in the pre-experimental 2 week period*

*** total egg produced (g) divided by total feed consumed.*

Table 10: Performance of poultry kept for egg production when dried Lemna powder replaced soyabean and some of the fishmeal in the diet shown in Table 8. The experiment lasted 18 weeks.

	Diet		
	Control	Lemna	Lemna
		(25%)	40%) **
Egg Production (eggs/week)	5.9	5.9	5.5
Feed consumed (g/d)	131	131	125
Feed conversion efficiency (g/g)*	2.4	2.5	2.5
Liveweight change (g/18 weeks)	46	114	-118

** represents total egg weight produced divided by total feed consumed*

***Lemna completely replaced both fish meal and soyabean meal in the diet.*

Even when Lemna powder was increased to 40% of the diet, egg laying was sustained for 18 weeks but the birds were losing weight and therefore it could be anticipated that eventually egg production would have decreased (Table 10).

These studies clearly demonstrated the value of a duckweed powder, that was of only medium quality, as a source of essential amino acids for egg production. The excellent outcome from these experiments also led to a number of other issues being researched and the following observations were made:

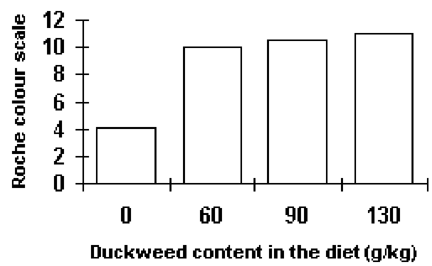
- There was no contamination with faecal organisms of the meat from birds consuming duckweed produced on sewage water.
- The quality of the eggs was probably not changed, however, the authors do suggest an improved taste and preferred higher pigmentation colour of the egg
- There was no problems of heavy metal concentrations in the duckweed from sewage farms.
- Bulky, wet faeces were produced by the birds given 40% Lemna in the diet. This has implication for the large commercial producer but is irrelevant to the small farmer and may even be an advantage.

This demonstrated quite effectively that in areas where protein resources are scarce, duckweed represents potentially a high quality protein source that can be safely exploited for poultry production.

Recent research in Australia investigated egg production and egg characteristics in two strains of layers Tegel Hi-Sex and Tegal Super Brown birds (Nolan et al., 1997). The birds were changed from conventional layer diet to diets in which duckweed (Spirodela) represented 10, 30, 50, 80, 120 and 200g/kg of feed replacing both grain and soyabean to retain a diet with 160g crude protein, 40g Ca, 10g P and 11.3 MJ of metabolisable energy per kg feed. Egg mass production was slightly reduced in the Hi-Sex hens given diets containing higher duckweed content (a 59.7g egg/d was reduced in size by 0.046g per g duckweed included in the diet), but it was more markedly reduced in Super Brown hens (44g egg/d was reduced by 0.088g per g duckweed in diet). Duckweed in a diet increased the pigmentation colour substantially see Figure 15. The more recent results confirm the value of duckweed as a protein source and a source of minerals and pigment for poultry.

The researchers in these particular studies were motivated by the potential for large scale production of duckweeds on for instance sewage lagoons. Large scale production which involves mechanical modification of sewage systems, implementation of mechanised harvesting, drying and processing is an unknown cost and does not have much application to small resource poor farmers who produce eggs and meat from birds often scavenging for a proportion of their feed.

Figure 15: Variation in yolk colour of eggs from hens fed four conventional diets without artificial pigments with duckweed replacing soyabean meal.



Poultry - meat production

Recent studies have demonstrated that on conventional diets for young broiler chickens, replacing a protein source with Lemna meal retarded growth as levels increased (Haustein et al., 1992b, 1994) whereas layers produced efficiently (Haustein et al., 1990) and older broiler birds had excellent growth characteristics when fed relatively high levels of Lemna meal. This is of significance to the factory production systems for poultry where margins per bird are often small and small decreases in profitability per bird are important. The reduction in growth of young birds has little significance where Lemna meal would be used in a small farmer systems, particularly where birds balance their own diet by scavenging from cropping areas.

A major question arising from this work is what would have been the value of the duckweed as a protein supplement had the duckweed been fertilised with a little extra nitrogen (urea) so that protein level had approached the upper limit (about 40% CP)?

Conclusions on the use of duckweed for poultry

Emphasis now needs to go to the other end of the spectrum of production systems for poultry. Major research efforts are needed to find ways by which duckweed can increase egg and meat production from non-conventional diets as used by small farmers at the village level. It appears that dried duckweed could be used very effectively with scavenging poultry, particularly where grain is fed as a separate meal.

Poultry have a well developed ability to select a balanced diet from individual resources made available to them, or by scavenging. The use of both energy supplements (e.g. spoilt grains) and duckweed made available as separate components on poultry production needs considerable research (see Mastika & Cumming 1985). In such practices there is also the additional need for a distinct source of calcium that can be ingested as the bird needs it. This is particularly so in laying birds as the intake and absorption of calcium must occur at the same time as the shell is being synthesised.

Research in Vietnam is attempting to define where duckweed can be fitted into small farmer operations. The major costs of drying and transporting for the feed industry is a real drawback, but it can cost little on the small farm where sun-drying on black plastic sheets is feasible.

If duckweed can be harvested at frequent intervals and fed fresh or partially dried this would be a major advantage at the village level However, the small farmer who is more and more advised to use supplements often feed brans or pollards. These have considerable fibre and therefore the duckweed used should not increase the fibre load. There would be great benefit therefore in growing duckweed as a crop, managed so as to minimise fibre and ensure it blends with primitive diets and equally with the more nutrient rich compounded feeds.

Duck production

Duckweed is perhaps named because ducks were observed to use it in the wild. The more omnivorous duck appears to utilise it highly effectively under field conditions. On sewage farms in the New England territory of Australia wild ducks so vigorously consumed duckweeds that they initially prevented the high growth rates needed to lower water nutrients to desired levels. In Vietnam duckweed produced on nutrients from animal and human waste is given fresh with cassava waste (Photos 8-12) to ducks. Duckweed provides both energy and protein and also a complement of essential minerals needed to grow ducks to a body composition and a weight for age that was needed by the excellent restaurant trade.

Photo 8: Duckweed harvest is a daily routine for the small boys in a village in Vietnam growing duckweed.

Photo 9: Cassava waste and duckweed being mixed for duck feed

Photo 10:Ducks being fed the harvested duckweed mixed with cassava meal

Photo 11: Ducks grown on duckweed and cassava head for the excellent restaurant trade in Ho Chi Minh City, Vietnam

Photo 12: Ducks fed sugar cane juice and duckweed at The University of Agriculture and Forestry, Ho Chi Minh City, Vietnam.

Duckweed (Lemna trisulca) has been shown to be able to replace 50% of the fish meal in a conventional diet for ducklings (Hamid et al., 1993) but its use as a major feed has not been considered.

In Vietnam there are 30 million ducks raised annually These ducks traditionally scavenge their food supplies from the rice fields. They obtain a considerable amount of spilt grain, especially just after harvest and also consume insects, crustaceans and slugs and snails. Similar systems are well developed in Indonesia where ducks are induced to "graze" various land areas being led in groups after being fixated at birth to some common object.

Ducks are preferred over poultry in these countries because they are highly resistant to poultry diseases. Changing conditions, particularly introduction of short rotation rice varieties and government regulation is resulting in more and more confinement of ducks which are fed on any locally available feed stuffs. Typically such ducks, whilst allowed limited scavenging are fed broken rice of low market value and soyabean meal or roasted soyabean.

Duckweed is proving a valuable replacement for soyabeans in these "more intensive" production practices. The intake by ducks of broken rice and either a combination of roasted soyabean or fresh duckweed has been compared. The intake and dietary ingredients used in these experiments are shown in Table 11.

Table 11: Mean intake of fresh foods by ducks (Men et al., 1995).

	Treatments				
Intake (g/d)	0	30	45	60	100
Broken rice	82	78	83	82	92
Roasted soyabean	27	19	15	12	0
Duckweed (Fresh)	0	496	499	505	566
Mineral Premix	0.25	-	-	-	-
Total DM intake (g/d)	95	108	108	105	107
Total CP intake (g/d)	17	23	22	21	18
LWt gain (g/d)	26	29	28	27	28
FCR (g.DM/g gain)	3.7	4.2	4.2	4.1	4.2

It is clear that for fattening ducks, in these "intensive" farm practices duckweed fed fresh, can totally replace soyabean as a protein source without effecting production other than for a small decrease in feed conversion efficiency.

The truly important issue here is that the research confirms the potential of duckweed as a high quality mineral source with protein equivalent to soyabean protein but which is readily produced locally on farm.

Expensive mineral premixes were unnecessary when duckweed was added to a diet indicating a major practical and economic role of duckweed to provide the array of minerals for this level of production. An analysis of duckweed used in all experiments (i.e. in lab and on farm) indicates the ability to supply major mineral elements and trace minerals. They have a well balanced source of calcium and phosphorous. The array of analysed nutrients are shown in Table 12.

In an attempt to find alternative energy sources low in fibre for production, Becerra (1995) studied the use of duckweed as a protein/mineral supplement to ducks given sugar cane juice. Supplements were either boiled soyabeans or freely available fresh Lemna. These studies, however, clearly showed a negative effect on production as Lemna increasingly replaced soyabeans in the diet. The

Table 12: Values for the composition of duckweed, broken rice and soyabeans used in the studies of Men et al (1995,1996)

	Duckweed	Broken rice	Roasted Soyabeans
Dry Matter (%)	4.7	86.8	87.0
Composition (% DM)			
Crude Protein	38.6	9.5	44.0
Ether extract	9.8	1.4	21.1
NFE	8.6	8.0	16.1
Fibre	18.7	2.0	9.8
Ash	19.0	1.1	5.6
Ca(%)	0.7	0	0.2
P (%)	0.6	0.2	0.9
K (%)	4.3	-	-
Na (%)	0.1	-	-
Fe (%)	0.3	-	-
Mn (mg/kg)	1723	-	-
Zn (mg/kg)	75	-	-
Cu (mg/kg)	20	-	-
Carotene (mg/kg)	1025	-	-

experiment was perhaps a little over optimistic considering the large intake of water needed to obtain energy (as sugar) from the juice (in actual fact it was sugar in solution mimicking sugar cane juice) and the large intake of water from Lemna may have been a primary limitation. The Lemna in this study contained only 26% CP and would have had 5-10% dry matter.

Table 13: Effects of replacing boiled soyabeans with Lemna in a diet of reconstituted sugar cane juice on intake and production of ducks (initial weight was 920g) (Becerra et al., 1995)

	0	15	25	35	45

Liveweight gain (g/d)	29.5	25.5	24.4	21.6	20.8
Feed intake (g DM/d)	147	154	149	145	138
CP (g/d)	25.7	27.3	24.8	22.2	19.8
Calculated H2O from feed (g/d)	390	790	790	792	780

The amount of water ingested by these small ducks (average liveweight 2kg) appeared to plateau at about 800g H2O per day suggesting that the high water content limited the intake of Lemna and sugar. This emphasises again the necessity to use wherever possible the highest quality of duckweed that can be produced (i.e. high in protein) and at least partially dry prior to feeding.

Sugar cane juice, if it can be used in animal production has enormous implication because of the potentially high yields of carbohydrate that can be achieved per unit of land area from this crop (Preston, 1995) and the fact that grain has to be imported for poultry production in many developing countries in the tropics. Further work in this area should be encouraged to find ways of combining energy from sugar cane with duckweed to produce a feed efficiently used by ducks.

PIG PRODUCTION

Undoubtedly farmers have used aquatic plants to feed pigs in many countries but only a small amount of controlled research has been reported. Haustein et al. (1992a) fed pigs on a conventional grain based diet and replaced part of the protein requirements with a low quality duckweed (23% CP with 7.5% fibre) harvested from a natural lake. In this instance the pigs were relatively young and as the Lemna meal increased in the diet, liveweight gain was significantly reduced. The results of this study are shown in Table 14.

Table 14: The effect of replacing "conventional" protein sources in a concentrate based diet for pigs with Lemna meal (23% CP)

	Level of Lemna in diet (%)		
	0	5	10
Initial weight (kg)	6.9	6.8	6.8
Final weight (kg)	23.8	19.5	17.2
Live weight gain (g/d)	423	320	260

A number of issues may be raised with this study. The liveweight gains of these pigs was low on the control diet and the Lemna meal may have been relatively old since it was low in protein. Other problems may also have occurred, for instance, a high level of oxalate in the duckweed or the accumulation of some toxin or heavy metal is always a possibility and the disappointing result reported here should not detract from further studies.

Pigs are omnivorous and the systems under which they are produced vary from scavenging their food, through to intensive production on high cereal based diets. The results with poultry that were fed duckweed were indicative of a negative influence of low protein Lemna (fed fresh) on production, whereas high protein (33% CP) duckweed supported similar growth rates to soyabean meal. It appears in this case that a Lemna meal, higher in protein may have been much more beneficial than the one used in the reported studies.

In unpublished work from Instituto de Investigaciones Porcinas (Havana, Cuba) the partial replacement of soyabean meal with Lemna-meal produced on the effluent from pig houses demonstrated that Lemna meal appeared to provide a high quality protein to support growth on molasses (molasses here is produced from sugar cane juice after only two extractions of sugar so it is higher in energy than most molasses). The results are shown in Table 15. (Figueroa, V. unpublished).

Table 15: Effects of replacing soyabean meal (SBM) with Lemna on the growth of pigs over 3 months on a basal diet of molasses.

	Diet	Supplement	Liveweight gain (g/d)
Treatment 1	Molasses B	30% SBM	635
Treatment 2	Molasses B	24% SBM + 10% Lemna*	630
Treatment 3	Molasses B	24% SBM	564

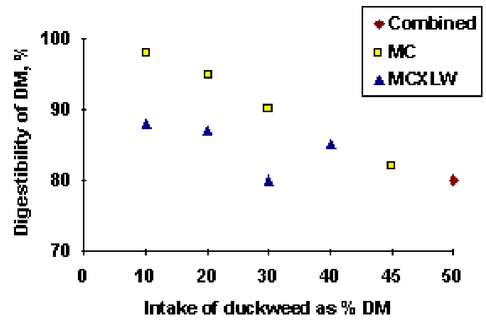
* *Lemna replaced 10% of the protein from soybean*

More recently Rodriguez and Preston (1996b) have fed three groups of genetically different mature pigs, unconventional diets containing duckweed. The experimental groups were local Monc Cai (MC) pigs, Large Whites (LW) or Mong Cai crossed with Large Whites (MCxLW). These were given sugar cane juice as the major energy source together with duckweed as a protein/mineral supplement. The pigs that had been highly selected for their abilities to utilise high grain/high quality protein diets (the 'so called' high-genetic potential Large White) appeared to be unable to utilise the duckweed, whereas the native pigs and their crosses utilised duckweed efficiently, consuming significant quantities in addition to the free choice sugar cane juice mixture.

No growth data is yet published from these studies but as the intake of drymatter from duckweed was increased in the total dry matter consumed (from sugar cane juice and duckweed) there was a linear increase in N retained. As the proportion of the N intake from duckweed increased, 50% of the N in duckweed consumed was stored in tissues when duckweed was about 50% of the total feed dry matter intake. Dry matter digestibility decreased as the proportion of duckweed in the diet dry matter increased (Figure 16). Rodriguez and Preston (1996b) suggest that the protein of duckweeds are readily utilised and have a higher biological value than meals such as those prepared from cassava leaves which are often fed to pigs in these countries.

The results of this preliminary experiment clearly indicate an interaction of genotype and non-conventional feeds. Protein from duckweed can be well used by mature, native pigs and presumably therefore it is a well balanced source of essential amino acids and minerals.

Figure 16: Relationship between percent of diet DM consumed as duckweed and apparent DM digestibility of Mong Cai (MC) or Mong Cai/Large White crossed (MCxLW) pigs.



The data discussed above for pigs and poultry also indicates that there may be some large differences in the composition or availability of nutrients from low protein duckweeds (i.e. slow growing) in particular there are indications that the protein is lowered in value (availability or essential amino acids or composition) as the protein content of duckweeds are reduced as they age on low-nutrient water.

RUMINANTS

Unlike monogastric nutrition where feed analysis are indicative of nutrient availability to the animal, ruminants through their fermentative digestive system modify virtually all the protein and carbohydrate in the feed they consume. The nutrients become available as volatile fatty acids (which are the major energy source), and amino acids (produced by enzymatic digestion of microbial cells that have grown and been washed from the rumen in liquor). Forage proteins are in general, degraded to ammonia in the rumen and the animal depends on microbial protein for its essential amino acid supply. The efficiency of production is primarily dependent on the establishment of an efficient microbial ecosystem in the rumen. The potential use of duckweed in ruminants diets is two fold:

- as a mineral source to correct deficiencies of minerals in the diet for both rumen microbes and the animal
- an ammonia source for the rumen microbes.

These two roles are largely confined to the rumen since an efficient microbial digestive system is dependent on a full complement of essential minerals and a high level of ammonia in the fluid. Deficiency of minerals and/or ammonia (which may be produced from supplemental non-protein-nitrogen sources or by the degradation of dietary protein) results in a lowered microbial growth in the rumen with inefficient growth of the microbial milieu. The consequences of low microbial growth is a reduced protein relative to energy in the nutrients absorbed (see Preston & Leng 1986 for review) and often lowered digestibility of forage and reduced feed intake.

Ruminants under feeding systems found in most areas of the world are often deficient in an array of nutrients required by the microbial fermentative digestive system. This is the case, particularly when consuming mature dry forages or crop residues (straws/stubbles) and at times agro-industrial byproducts (e.g. sugar cane tops, molasses and fruit residues). Duckweed with its high mineral and protein content can provide an array of nutrients for the rumen microbes to function efficiently on such diets. These food resources are the basis of diets for ruminants in large areas of the world, particularly in countries that are considered to be developing. In this way a quantity of duckweed could replace the use of multi-nutritional supplements based on such things as molasses urea block licks (see Leng 1984).

Duckweed also has some potential as a dietary protein source that may be modified or may actually provide bypass protein that is required by productive animals to meet their extra requirements for essential amino acids (see Preston & Leng, 1986).

There are some preliminary research results where duckweed has been fed as a supplement to ruminants, but clearly there is a need for major research effort in this area to develop a clear definition of the strategic importance of duckweed as a N source, as a bypass protein source, as a source of essential minerals including S, P, Na, K, Mg and trace minerals.

A duckweed, corn silage diet (1:2) produced higher growth rates in Holstein heifers than a diet based on corn silage, concentrate and grass (Rusoff et al., 1978, 1980). These studies and preliminary studies at the University of New England indicate the high potential of duckweed as a supplement.

More recently Huque et al. (1996) have commenced work to examine duckweed as a source of N and minerals for ruminant animals in Bangladesh. In a study of the kinetics of the utilisation of duckweed dry matter and protein they used nylon bag incubation techniques to study the breakdown of duckweeds in the rumen of cattle. The duckweeds used in these studies were around 30% crude protein. Overall the studies illustrated that, in cattle fed forage and concentrate, the potential degradation of duckweed dry matter in the rumen was 85% (Spirodela), 72% (Lemna) and 93% (Wolfia). The protein of duckweed were highly soluble in the rumen at 24% (Spirodela), 42% (Lemna) and 18% (Wolfia) and overall 80, 87 and 94% respectively of the protein was apparently degraded in the rumen. At high feed intakes there was apparently some potential for a small amount of the protein from duckweeds to escape degradation in the rumen and provide essential amino acids directly to the animal.

It seems probable that dried duckweed will provide a readily fermentable protein source together with a rich mineral level needed for creating an efficient rumen for animals fed low protein forages such as straw. The extent that duckweed can correct mineral deficiencies in diets for ruminants will depend on the composition of the duckweed which in turn depends on the level of minerals in the water body growing the duckweed.

The major role of duckweed in ruminant diets is likely to be as a major source of minerals and ammonia-N for the rumen and future research should examine its strategic use to stimulate ruminant production on high mature forage diets.

In developing countries, ruminants often subsist on byproducts of agro-industries and crop residues that are often (mostly) low in minerals and a source of ammonia in the rumen. In many situations duckweeds would be a valuable resource to ensure that ruminants utilise these feeds effectively by providing a soluble N source (e.g. ammonia) needed by the cellulolytic organisms for protein synthesis and also a source of particularly P and S which are essential for microbial growth and therefore the animal (Preston & Leng, 1986).

From the research of Huque et al. (1996) it appears that duckweed would require treatment to protect its protein to produce a meal that will deliver protein to the intestines and produce a high protein to energy ratio in the nutrients absorbed that will further advance ruminant productivity from crop residues. The potential responses of cattle to both fermentable N (i.e. N sources that give rise of ammonia in the rumen such as urea or leaf proteins) and to bypass protein have been discussed in many publications. Duckweed might be able in the future through research to replace multi-nutrient blocks used in these feeding trials (Sansoucy, 1995)

Treatment method for duckweed, which provide say half the protein as protected and half soluble to give bypass protein to the animal and ammonia for the rumen microbial digestive system together with the minerals in duckweed could remarkably enhance meat and milk production by ruminants given crop residues that contain major nutrient deficiencies.

Smith and Leng (1993) incubated duckweed meal in rumen fluid from sheep where it was rapidly fermented with the production of ammonia. Unfortunately treatment by heat, formaldehyde or xylose - three methods that have been successful in turning soyabean meal into bypass protein had no effect on the rate of release of ammonia. However, these chemicals were only sprayed on the meal and it is probable that some heat is necessary to effect protection of the protein. Duckweed protein, like terrestrial plant leaf protein is not easily protected from rumen degradation by any presently known methodology.

It is possible that when the protein is at high concentrations in duckweed that some of it is as peptide, amino acid or non protein-nitrogen. On the other hand it could be that leaf proteins have failed to come into contact with the dilute solutions of protecting agents that are used to protect the finely prepared extracted seed meals such as soyabean (formaldehyde or xylose) and future research should examine the application of heat after spraying to complete the reactions.

FISH

Most intensive fish farms culture fish that have very high value on national or world markets. In these intensive systems the fish require feed with extremely high protein levels and a well balanced array of essential amino acids. This is quite often provided by high cost fish meals. These farming systems have achieved a high level of production but with high cost inputs (including feed, fresh water, and the prevention of pollution) which makes them expensive. In the context of this book, duckweeds are not easily accommodated into such high technology systems, even though with great care a dry meal with excess of 45% crude protein may be produced and it may be possible to blend this with fish meal as a major protein source for intensive fish farming.

Herbivorous fish are cultured in many parts of the world. They include many varieties of carp and tilapia which provide a protein source of high biological value for humans. These fish are often regarded as inferior in taste but they are of great benefit in the diets of poor people who are often financially confined to largely vegetarian diets. These diets may at times be deficient in essential amino acids, depending on the source and variety of vegetables available. In the same way as milk is a source of potentially deficient essential amino acids in resource poor people, particularly those who are vegetarians, fish can play the same role.

Fresh duckweed (and also the dried meal) is suited to intensive production of herbivorous fish (Gaiger et al., 1984) and duckweed is converted efficiently to liveweight gain by carp and tilapia (Hepher & Pruginin, 1979; Robinette et al., 1980; van Dyke & Sutton, 1977, Hassan & Edwards 1992, Skillicorn et al., 1993).

A major investment in duckweed aquaculture research in Bangladesh (see later) has potentially important repercussions particularly for the host countries where the research has been carried out. This research has been the single most important research in this area and has focussed world attention on duckweed both as a feed for freshwater fish and as a water cleanser (Skillicorn et al., 1993) and the book by these authors is mandatory reading for anyone becoming interested in this area.

The PRISM group initiated the pilot project in Bangladesh to develop farming systems for duckweed and to test its values as a fish feed in polycarp production.

The outcomes of this project points the way for the efficient use of duckweed in many situations. It has important lessons for the development of small farmer systems where integration of crop and animal production benefits from the use of duckweed's ability to scavenge and retain major mineral nutrients within the system.

Carp production

Introduction

Carp species are by far the most commonly cultivated freshwater fish in Asia. They grow under diverse conditions, tolerating reduced water quality in even stagnant water ways. Their greatest attribute is the ease with which they can be managed in ponds and the huge production potential under good environmental and nutritional conditions.

Different carp species tend to occupy different ecological niches and therefore a number of species that are highly selective in their dietary preferences can be places in the same pond and will occupy different feeding zones. The development of polycarp culture depends on maximally using the feed biomass in a pond system by having top feeders, middle feeders and bottom feeding fish. These include an herbivorous species capable of feeding on surface plants or plants accessible on the sides of the pond or fed to them freshly harvested from another site as would be the case with duckweed; Two middle feeders which feed on either zooplankton and/or phytoplankton that grow on the detritus produced by the top feeders and a bottom feeding species which use the faecal materials produced by the middle and upper feeding fish.

Carp polyculture depends on most of the fish being produced on the zooplankton and phytoplankton (up to 85%). Providing extra feed for the surface feeders may increase carp production and it was a major reason for establishing the PRISM projects at Mirazapur as the surface feeders were restricted to very low stocking rates because of the small availability of plant biomass from the pond edges.

The polycarp systems depend on balancing biochemical oxygen demand (BOD) and maintaining oxygen levels in the water. Aeration and fertiliser use rates are critical in this way. BOD is created by:

- high densities of phytoplankton that respire at night
- the high oxygen demand from the heavy stocking rate of fish
- microbial aerobic degradation of organic matter.

In a traditional manure fed water body for polyculture of carp the main consideration is at what rate should the manures be fed to the water body? Stocking rate then is determined by the resultant demand for oxygen.

The special aspect of carp production from duckweed is that it can be set up using a single species of surface feeding carp or it can be used in polyculture to increase the total stocking rates. By providing fresh duckweed daily which does not decompose and can be fed ad lib, the top feeding carp densities might be increased together with an increase in bottom feeders increasing stocking density overall.

As the biochemical oxygen demand is turned down by reduced aerobic degradation of plant materials (that is replacing dead plant materials with live duckweed), the fish levels can increase to an extent that their respiration approaches the oxygen needs for the degradation of the organic matter entering the pond. The incremental production of the top feeders (Grass, Catla and Mirror carps) and bottom feeders (Mrigal carp) represents the potential extra production from a duckweed system (Skillicorn et al., 1993).

Duckweed-fed carp polyculture

The reader should refer to Skillicorn et al. (1993) for the most authoritative discussion of this subject.

In this document I will take the main issues from these authors. The major arguable criticism of Skillicorn et al. work put forward here is that it is too sophisticated for simple application by a small farmer. Resource-poor farmers need considerable economic support to set up fish farming. It becomes more complex where there is an attempt to integrate the farm in order for it to be sustainable. Under these conditions the use of artificial fertiliser as used in the Mirazapur project limits the application by small farmers. Fertilisers are often too expensive to use even for rice crop production, for example, much of the rice grown on small farms in Vietnam depend on recycling of nutrients via pig manure and fertilisers are either not used or are used sparingly. At the present time the financial crisis in Asia is likely to make fertilisers more expensive and it can be anticipated that there will be decreasing grain production in Asia over the next few years. Despite these reservations about their approach Skillicorn et al. (1993) have provided immensely valuable data which is essential for future small-farm systems to develop. It will be particularly important for the establishment of manure fed duckweed aquaculture and systems based on manure/biogas.

The Mirazapur carp stocking strategy and carp growth rates

Grass carp (Ctenopharyngodon idella) are the major users of duckweed but Catla (Catla catla) and Common carp (Cyprinus carpio) compete aggressively for duckweed. About 50% of the potentially digested nutrients in duckweed are used by the fish and so the faeces from duckweed fed carp are of relatively high in organic materials useable directly or indirectly through microbial action by the bottom feeders and these can be increased to 30% of the total population (see Skillicorn et al. 1993).

In general over 1989-90 the distribution of carp in the Mirazapur venture was:

- 45% top feeders (15% Catla, 20% Grass Carp, 10% Mirror Carp)
- 35% middle feeders (Rohu 15%, Silver Carp 20%)
- 20% bottom feeders (20% Mrigal Carp)

The initial population was about 23,000 carp fingerlings per hectare. Yields have been difficult to estimate but around 10tons per hectare were claimed to be produced. The weight of fish captured by month is shown in Figure 17 and of fish weights in Figure 18. The feed conversion efficiency was estimated to be between 10-12kg fresh duckweed to 1kg of gain. This suggests that considerable other sources of food were available to the fish. A major cost is the fertiliser application to the duckweed ponds which was put into the water on a daily routine.

The growth rates of fish were largely in middle feeders with Silver and Rohu Carp showing fastest growth rates. Grass carp grew disappointingly slowly. The weight of fish after 13 months feeding of duckweed to the polyculture is shown in Figure 18.

Figure 17: Average weight of fish catch by month in Mirazapur duckweed-fed carp production trials

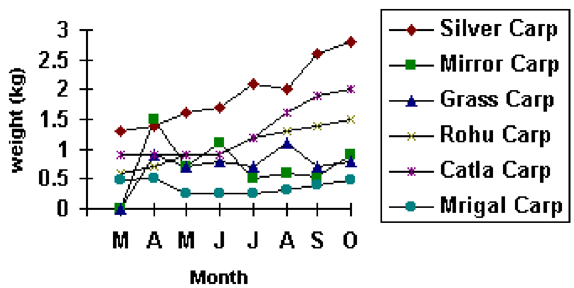
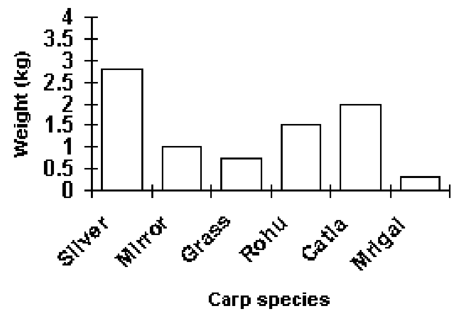


Table 16: Weight of different carp species in polyculture fed with duckweed

Species Carp	Weight (kg) at			Calculated
	8 months	13 months	Growth rate (g/d)	
Catla	0.9	1.9	1.0	
Grass Carp	0.7	0.8	0	
Mirror Carp	1.5	0.9	-0.6	
Rohu	0.6	1.5	+0.9	
Silver Carp	1.4	2.7	1.3	
Mrigal	0.5	0.4	-0.1	

Figure 18: Average weight of fish catch after 13 months in Mirazapur



If the fingerlings weighed only a few grams when placed in the unit, and this is considered negligible to the final weight, then the average growth rate of the carp in polyculture is shown in Figures 17, 18 and Table 16.

Feeding duckweed

In the Mirazapur venture, fresh duckweed is the only food provided to the fish in the water body by the farmer. The rate of feeding is as high as is needed to produce a slight excess after feeding activity and at 30,000 fish per hectare there were no problems of low oxygen levels in the water. The duckweed is fed either at enclosed (surface) feeding stations or simply tipped into the pond.

The data on fish growth as reported by Skillicorn et al. (1993) is unfortunately compromised by the "normal" problems encountered by research workers that to set up demonstrations under practical conditions and then attempt to analyse collected data from rather uncontrolled "research". There were serious logistic problems, at least initially, particularly in providing the feed consistently. The recommended harvesting techniques were based on frequent harvesting with removal of the largest and smallest fish at each harvest. The large ones were presumed to be reaching the weight at which their growth rate slows whereas the small ones were deemed to be "poor doers".

Obviously from their studies Silver carp, Catla and Rohu grew significantly more rapidly than the others, but feed availability problems make the growth rates in Figures 17 and 18 merely guides, as the authors claim that whereas in the first 13 months grass carp grew to less than 1kg, in other studies when they were fed ad libitum duckweed they grew to 4kg in six months (say 20g/day) suggesting that the production of grass carp may be more appropriately promoted as a monoculture.

Some ideas on duckweed use for carp production at small farm level

Carp polyculture in manure fertilised lagoons is an efficient and established method of producing carp. However, it is somewhat specialised and not managed easily by small farmers with limited resources, including availability of land, water and a continuous source of nutrient enriched water. A further constraint is also the capital outlay for the relatively deep lagoons that are required.

Duckweed production can be intermittent, it can be produced in relatively shallow ponds, simply lined with plastic or other inexpensive materials. Duckweed can be fed fresh or after drying and storage or both dried and fresh together. Simple systems that can be fitted into the daily routine of a family farm and according to the availability of water need to be researched. Undoubtedly there are many ways to approach a monoculture strategy for carp. The variations in practice are multiple. One potential system is described below as an indication of the approach that could be taken to such a development.

If grass carp are capable of the high growth rates indicated by the PRISM work it suggests that it could be advantageous to move away from polyculture to the culture of single species perhaps produced in a succession from a pond; Grass carp would be fed duckweed then following their removal from the pond, Rohu and Silver carp would be introduced to utilise the phytoplankton/zooplankton that build up and then the pond could return to duckweed to extract the nutrients in the water liberated from the detritus. The detritus feeders not being very productive would not be included in such an enterprise.

Thus, a potential strategy would be to periodically reverse the roles of the duckweed pond and the fish pond. This would be especially effective where effluent low in organic matter is used as the medium for duckweed culture, particularly the liquid from a biodigestor and where water is scarce and therefore must be used efficiently. The system that could be exploited is shown below (Figure 19).

Trial and error would be needed to work out a routine but a safe bet might be to use 0.2ha of duckweed to produce the necessary food for 0.2ha of fish ponds. At any one time therefore a pond could be producing duckweed or Grass carp or Silver carp. Three ponds could be used. One of these would receive the effluent from a biogas digestor and the other two would be producing fish, one pond fed with duckweed and the other used for phyloplankton/zooplankton feeders. These could be used with a rotation of the duckweed between ponds so that each pond produces fish and then duckweed reuses the minerals released by the faeces of the fish. The fish are then maintained until the oxygen concentration in the water declines to levels where Grass carp cease to produce. Then plankton consuming carp could be introduced. Duckweed is grown to lower the mineral content of the pond water after which the duckweed pond then reverts to a fish pond for Grass carp. Such a system would allow the use of static or slow moving water with a relatively slow rate of turnover. Rotation among ponds might be:

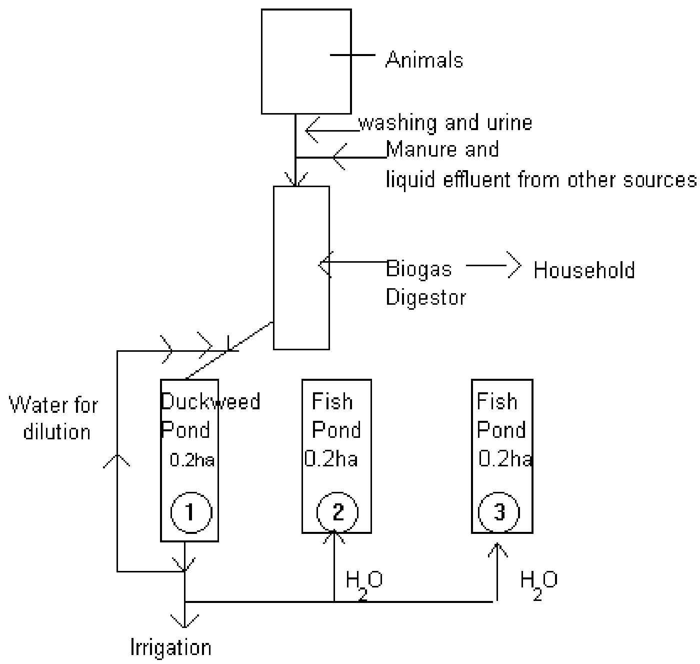
1. duckweed production
2. fish pond (Grass carp)
3. fish pond (Silver carp)
4. duckweed production.

The only major water loss from the system being by evaporation if seepage and use of water from other purposes is minimised. The three pond system over 18 months is indicated in the table below:

Table 17: Potential monoculture of carp using duckweeds in an integrated system

	Management	
Pond 1	Pond 2	Pond 3
Duckweed	Grass carp	Silver carp
Grass carp	Silver carp	Duckweed
Silver carp	Duckweed	Grass carp

Figure 19: A schematic outline of a potential system for production of mono cultures of carp in a three pond system. Duckweed in pond 1 feeds the top feeding carp in pond 2 and plankton feeding carp are placed in pond 3 after the Grass carp have been harvested. The ponds can then be rotated in their use.



The success of such a project would depend on:

- Relatively clean water emerging from the duckweed pond
- Being able to harvest grass carp before the BOD falls too low.
- The continuous growth of plankton on the nutrients in the faeces from the previous crop of Grass carp but before oxygen levels in water become limiting. Stocking rates would need to be adjusted to allocate sufficient feed for the Silver carp to reach market weight.
- Low organic matter in the inlet to the duckweed pond.

Where water is scarce, either year round or seasonally, this system could have a great advantages. The numbers of animals (large or small ruminants) needed to effectively feed the static ponds would need some considerable research but initially the finding of NPK fertiliser needs in the Mirazapur venture would give some guidelines.

In the studies in Bangladesh or a lagoon producing 100kg fresh duckweed per ha per day about 10kg of urea, 4kg of trisodium phosphate, 4kg of muriate of potash and 9kg of sea salt were needed per hectare of the surface area. Of these nutrients probably urea or ammonia is the nutrient that needs to be most carefully controlled as it can quickly limit duckweed production above 60mg N/l and below about 10mg N/l.

If a cow is consuming ammoniated rice straw supplemented with minerals and some protein meal, the faeces and urine probably contains only slightly less than the concentrations of N present in the ration. A cow would consume 2.5% of its body weight as dry matter of ammoniated straw. Thus a 400kg cow would consume 10kg of feed dry matter and produce 5kg of faeces dry matter plus urine containing most of the N fed as ammonia in the straw.

If 4% urea had been used to treat the straw then in 10kg of straw there would be the equivalent 400g of urea in the wash water from the cows stall. Washwater from the animals stall may be 80 litres/day so we have about 50mgN/l. This is fairly close to the level recorded in laboratory work for the optimal growth of duckweed. With a number of cows producing faecal and urinary N at this rate it would mean that 5 cows would produce 2kg urea and therefore 50 cows could fertilise 1ha or 5 cows to 0.1 ha. of duckweed lagoon.

Production of tilapia

Undoubtedly tilapia can use duckweeds efficiently when fed at an appropriate rate. In recent studies in Thailand, Hassan and Edwards (1992) have grown tilapia in static water in concrete tanks and fed them two species of duckweed

Lemna perpusilla and Spirodela polyrhiza at various levels of duckweed dry matter per kg wet weight of fish per day.

The duckweeds were relatively low in protein (approx. 24% CP). The Spirodela was poorly consumed whereas Lemna was rapidly ingested by fish. The growth rate and feed conversion rates for Lemna-fed tilapia are shown in Table 18.

Table 18: The effects of feeding tilapia increasing levels of Lemna. Tilapia were held in static water in concrete tanks (Hassan & Edwards, 1992). The fish initially weighed approximately 41g

Feeding rate	Survival	Mean live	Conversion of Lemna
of Lemna	rate of fish	weight gain	DM to fish live weight
(g DM/kg fish)	(%)	(g/d)	(g/g)
10	97	0.2	1.9
20	100	0.4	1.9
30	100	1.0	1.6
40	60	1.0	2.3
50	27	0.7	3.3
60	17	0.8	3.3

The tilapia in this case were fed duckweed in static water in small concrete tanks and the high death rates above a feeding of 30g dry lemna per kg fish was presumably due to the eventual eutrophication of the water. Over consumption of duckweed, however, cannot be ruled out as a cause of the high death rate.

Where duckweed is fed to tilapia in open waters or lagoons it is fed fresh and does not appear to effect the biochemical oxygen demand directly as the rate of feeding is controlled by the farmer so as to maintain only small amounts of excess duckweed on a daily basis (personal observations).

The work of Hassan and Edwards (1992) indicates the voluntary consumption rates of duckweed and its potential role as a feed that can be added to relatively unpolluted lagoon waters.

The growing importance of farmed tilapia suggests that a greater research effort is needed to develop inexpensive system where tilapia densities can be increased by addition of extra feed without reduction in size of fish. Tilapia could replace the top feeding carp in the systems proposed for research in Figure 19, retaining the rotation of phytoplankton consuming carp and the production of duckweed.

Indirect use of duckweed to produce feed for fish

Ogburn and Ogburn (1994) developed an oxidation treatment of sugar-mill waste water using duckweed that appeared to be highly successful. The work was carried out in Negros Oriental, in The Philippines. The mean ammonia concentration in the influent relative to effluent water from the treatment plant over a six month period was reduced before release to the ocean from 0.87 to 0.31mg ammonia/l, orthophosphate from 0.93 to 0.5 mg P205/l and biochemical oxygen demand from 611 to 143 mg BOD/l.

The treatment water over the three years since the inception of the treatment plant apparently prevented the mass death rates of fish that occurred annually in the bay that received the water. Duckweed production represented 8.8g/m2/day. Whilst milk-fish did not consume duckweed, the duckweed was used to generate acceptable food. Duckweed was harvested and applied to the base of the pond prior to introduction of water. The dead duckweed fertilised the production of lablab which the fish consumed. Lablab is Filipino for the biological complex of blue green algae, diatoms, bacteria and animals that form on the bottom or float to the surface of ponds. Fertilising fish ponds in this way, as compared to inorganic fertiliser or cow manure enhanced fish production as shown in Table 19 (Ogburn & Ogburn 1994).

Table 19: The effects of different fertiliser application on the production of fish (Chanos chanos).

Lagoon system for	Milk fish harvested
providing feed	(kg/ha/90d)
1. Inorganically fertilised	320
2. fed with cow manure	545
3. fed duckweed	820

DUCKWEED AS A SOURCE OF NUTRIENTS FOR HUMANS

Duckweed has been used as a food by poor people in the past. The major benefit from such an addition to a diet is likely to have been as a supplement rich in phosphorous and/or vitamin A. However, undoubtedly there is a role for Lemna as a source of essential amino acids. Duckweed makes a fine addition to a salad and is quite tasty.

Where vegetable proteins are scarce in some regions of the world and particularly during a prolonged dry season or in normally arid areas, there is considerable scope to improve the nutritional status of the mal-nourished child through the use of duckweed directly or after extraction of a protein from the plant. Many aquatic plants may be used for such purposes with some additional purification to remove any toxic materials and also reduce the level of polyphenols. Dewanji (1993) demonstrated this effectively with several aquatic weeds in India. The aquatic weeds were subjected to pulping and filtration to extract mainly protein which was precipitated by steam injection. The chemical composition of such protein extract is shown in Table 20 and the amino acid composition in Table 21.

Table 20: Composition of protein extracts from three common aquatic weeds (modified from Dewanji & Matai, 1991)

	Azolla	Lemna	Pistia
N (%)	6.3	6.1	8.2

Crude Fat (%)	9.9	11.4	14.4
Crude Fibre (%)	2.8	2.7	1.5
Ash (%)	4.1	6.0.	5.8
b -carotene (m g/g)	632	627	654
Polyphenols (%)	1.7	2.1	1.3
Invitro digestibility(%)	78	78	81

As a source of essential amino acids then the protein of water plants have comparable amino acid compositions to that of most leaf proteins. The protein extract would provide quite considerable benefits to communities constrained to vegetarian diets through their economic situation. This would particularly apply to those without a source of milk and where there is a long period of dependency on dried foodstuffs deficient in vitamin A or in phosphorous as occurs in many of the arid regions of the world. On the other hand with the increasing demand for vegetable proteins in the industrialised world duckweeds could make a fine addition to most mixed salads and could be regarded as a commercial crop, provided quality water was used to grow the plants.

Safety considerations when duckweed enters the human food chain

Whilst there appears to be considerable scope to use duckweeds as components of diets for animals and to a small extent humans, it is necessary to be cautious in recommending wide scale application. The nature of duckweed as a scavenger of minerals from water bodies poses

Table 21: Some amino acids in a leaf protein extracted from three aquatic weeds compared with leaf protein form alfalfa (see Dewanji 1993 for details)

Amino acid	Azolla	Lemna	Pistia	Alfalfa
lysine	6.1	5.9	7.0	6.7
histidine	2.3	2.7	2.9	2.5
argenine	6.2	6.0	6.3	6.5
aspartate	1.3	10.6	9.6	10.2
threonine	5.0	5.1	4.8	5.2
serine	5.3	5.4	4.8	4.3
glutamic acid	13.8	13.6	13.4	11.1
proline	4.7	4.5	5.0	4.8
glycine	5.8	5.6	5.7	5.3
alanine	7.0	7.1	6.3	6.0
valine	6.8	6.4	6.7	6.8

methionine	1.2	1.4	1.1	2.3
isoleucine	6.0	5.7	5.9	5.3
leucine	9.4	9.6	9.6	8.9
tyrosine	4.2	4.2	4.6	4.4
phenylalanine	5.9	6.0	6.0	5.7

potential danger where heavy metal contamination of water occur. This is of increased concern where radionuclides from nuclear reactors have leaked into the environment and these may also be concentrated in duckweeds. Heavy metals can enter the food chain at a number of points and it needs to be stressed strongly that monitoring of heavy metals in any large scale development of duckweed for any food/feed purposes.

CHAPTER 6: Production of duckweed and its potential for waste management

INTRODUCTION

A major problem of the 21st Century will be the control of environmental pollution. The major forms are pollution through emissions of gases into the atmosphere which is now an international issue with recognition of the potential (perhaps now unavoidable) global warming. There are both benefits and disadvantages to regions from global warming, but it now appears the disadvantages will certainly vastly outweigh any benefits, with tragic effects if global weather patterns are changed and sea levels rise inundating vast areas of agricultural (the deltas) and other land.

Whilst gaseous pollution is now an international issue the pollution of water (and indirectly land) remain national problems. Some governments view water pollution as a very serious problem, and legislate to prevent it occurring whereas, it is hardly considered by others.

Water pollution may be with industrial wastes which are outside the scope of this book or it maybe caused by residues of plant nutrients, naturally occurring or through fertiliser application. These run-off nutrients can potentially be harvested and provide valuable food and fertiliser sources through the development of aquatic plant crops.

Salination and acidification of previously undisturbed soils because of cultivations is also occurring and are global problems which will also need attention in the future.

Human settlements, provide great problems in the disposal of household wastes. In most industrialised countries the intensification of animal production has been promulgated in order to produce a consistent quality of animal products. This has also created major waste disposal problems. A major issue facing both human settlements and intensive animal housing systems is the concentration of nutrients locally and the difficulty and costs of disposal of these nutrients.

In the United States for instance there were in 1992 about 5,500 waste water treatment lagoons. Sewage systems world wide were developed mainly for the removal of organic materials and lowering of N levels but often major minerals (P,K etc) remain in the water when it is discharged from the works.

Intensive animal industries have now multiplied world wide, largely stimulated by world surpluses of inexpensive cereal grains and the increasing demand for animal protein as the standard of living of people improves.

The Environmental Protection Agency of the United States estimates that from all animals other than humans, 13,250 million tonnes of waste are produced per year (Hogan, 1993). A considerable proportion of which is concentrated in small areas. A figure for human waste may be around 5,700 million tonnes. The loss of P in sewage water discharged into oceans where it is non-recoverable is particularly concerning as P is rapidly becoming the most deficient nutrient for plant growth world wide. Disposal, and/or redistribution of nutrients and prevention of water contamination from the excrements of humans and animals will surely be one of the great problems of the 21st Century. Feedlots may concentrate 100,000 cattle or more at one site, poultry likewise may concentrate up to the same numbers with pigs and other animals usually in smaller concentrations. On the other hand humans are concentrated in cities with more than 10 million inhabitants.

The accumulation of animal wastes at one site, whilst having a number of overriding negative aspects, should potentially aid the economic extraction of the available minerals with the harvest of the "energy" through the controlled production and collection of methane in a biogestor. Growth of aquatic plants combined with other treatments may well serve the triple functions of extracting nutrients from waste water effluents for use as fertilisers or feed and at the same time allowing re-use of the water.

DUCKWEED TREATMENT AND SEWAGE WORKS

Some use has already been made of Lemna to treat sewage lagoons in USA, Europe and Australia. Intensive animal production industries have, however, taken little notice of such developments, perhaps because they have not been forced to pay the cost of an appropriate dispersal of nutrients they concentrate in one place. The problems in disposing of the nutrients are vast and mostly economic.

Skillicorn et al. (1993) devote a chapter in their book to duckweed based wastewater treatment systems. Urban wastewater treatment systems occur throughout the tropical developing countries but service only a small percentage of the total population. Skillicorn et al. (1993) argue that duckweed-based wastewater treatment systems provide genuine solutions to the problems of urban and rural human waste management with simple infrastructure at low cost. Their arguments should be read by anyone interested in this particular aspect of the use of duckweeds.

Social structures in densely populated developing countries and the problems and costs of installation and management of sewage works are problematic, particularly in a country where these costs of installation must be met by poor people with an income of only between $100-$500 US per annum. It is difficult, under these conditions to visualise large scale sewage works being implemented in rural areas or shanty towns except where people can pay for the service. In many countries nightsoil is regarded as a valuable asset particularly for recycling of nutrients back to the farm and sewage farm in rural areas may not be regarded as an asset, particularly if it had to be funded from local resources.

The use of duckweed as envisaged by Skillicorn et al. (1993) appears to have only limited application in the rural areas of developing countries because it largely exports the nutrients to a central site where sewage works are installed and the cost of transporting nutrients back to the farm where they can be an asset would be extremely high.

However, the valuable contribution of the work of Skillicorn et al. should not be neglected as there is some scope to develop such systems in crowded cities and urbanised areas populated by the relatively rich and where sewage disposal is often via open drains to the river, lake or sea. The resultant duckweed availability may assist urban-animal production or it is likely to be used as fertiliser on vegetable gardens. Many cities in developing countries have huge animal populations; intensive poultry production is often close to sea ports that import grains and in India milch animals abound in cities such as Bombay.

Duckweed waste water treatment systems are based on stand alone lagoons, and a single or a series of lagoons may be used depending on the size of the treatment plant. The settling tanks need to be dug out once in a while and two tanks are often needed so that whilst one is cleaned the other is in use. Following the sedimentation tank are a series of duckweed ponds and depending on the ultimate water use a 'polishing pond'. In the latter pond sunlight largely removes any pathogens that remain in the water. Generally these systems require about a 30 day turnover rate of water to be sure of minimum mineral contamination and low bacterial counts in water leaving the works. The potential efficiency of a duckweed treatment plant can be gauged by the fact that in the Mirazapur pilot scale plant the effluent water from such an operation was lower in ammonia, phosphorous and had a lower biochemical oxygen demand and turbidity than required by US Standards for the Washington DC area.

In most modern sewage works the ammonia levels have been reduced by a combination of microbial treatment methods. Usually for these systems to effectively grow duckweed either the denitrification step in the treatment works needs to be bypassed or urea must be applied to provide ammonia so that duckweed growth is vigorous enough to remove the residual phosphorus and other minerals. Even where no denitrification is brought about, fertilisation with urea in some of the 'downstream' ponds may be necessary to capture as much P as possible.

There are probably as many as 100 duckweed sewage treatment plants throughout the world, some of enormous complexity. Management has to be well informed and skillful for optimum performance. When this level of sophistication is achieved then management can be aided by dynamic modelling, which is able to simulate the behaviour of waste water treatment plants based on using Lemna gibba. A model developed by Vatta et al. (1995) clearly accounts for the main biochemical and chemical changes owing to such variables as water temperature, light incidence, nutrient levels and harvesting and replenishment rates etc. This opens up the way for more informed application of duckweed in the management of wastewaters.

The sophisticated lagoon systems, together with the need to provide floating chambers or grids, mechanised harvesting and good management do not preclude their use in developing countries but emphasise their unlikely rapid acceptance and development. However, with more simplified systems there are clear opportunities to develop small units easy to manage, that may be regarded as assets to the household.

In this context the potential of duckweed is to:

- provide an inexpensive home grown feed for livestock
- allow water recycling either year round or through the dry season.

WATER RECYCLING AND HEALTH STANDARDS

Most people in developed countries have access to relatively pure water free of pathogens and low in mineral components,. However, in the OECD countries more than half the population drink water that has passed through waste water treatment works.

In many developing countries, safe water is a luxury, enjoyed by a small proportion of the population. Particularly in arid areas water is a precious resource. It was estimated in 1988 that the health of between 9-22 million children of less than five years old are compromised each year in developing countries because of lack of water, inadequate sanitary facilities and water born diseases and around fifty per cent of people in third world countries have inadequate supplies (Maywald et al. (1988).

The recycling of water through waste water treatment works or purification of water for human use from presently unused surface water, whilst aesthetically not very acceptable, may be an only recourse in many developing countries. However, care must be taken to effectively treat such water to ensure that health standards are achieved and duckweed growth is only one potential step in such treatment processes.

CHAPTER 7: Overview

The future for duckweed farming may reside in establishment of duckweed cooperatives alone the line of the milk cooperatives in India. It may surprise the reader that there are many things in common between milk and duckweed production including:

- there is a need to harvest daily or very regularly.
- it begins to decompose quickly on harvest and needs processing if it is to be stored, prior to collection and transport to a market.

- it is produced at widely dispersed sites
- when produced on a small scale it needs organised collection, processing and marketing if it is to become an economic crop in the true sense.
- they both supply considerable high quality protein and minerals needed by animals.

In Bangladesh the Grameen bank has sponsored a highly successful small-scale loan system which encourages the development of small scale farming practices. This particularly applies to the raising of poultry. Much of this program is precarious because it is supported largely by imported protein meals (offal, meat, soyabean etc) from Europe and inexpensive grain often from India. Bangladesh could be genuinely termed the home of duckweed.

Taking Bangladesh as an example, the organised production of duckweed could provide in sufficient quantities to replace at a minimum 50% of the protein meals required by the small poultry producer if a simple and economic system of collection/sun drying and marketing could be put in place.

There are thousands of hectares of derelict ponds polluted to eutrophication levels in Bangladesh alone, that could potentially be cleansed of much of their pollutants and resurrected for duckweed aqua-culture and fish farming at the family farm level. In these systems the objective would be largely to provide protein of high biological value for the family of small farmers, who often have no animal protein in their diets.

To resurrect derelict ponds, the approach might be to first establish duckweed aqua-culture as a source of nutrients for terrestrial crop production (e.g. mulches and organic fertiliser) and as the ponds oxygen levels rise with harvesting of the crop to introduce fish farming either in part of the pond or in adjacent (clean water) ponds.

A further interesting approach would be to create a market for duckweed locally, as is the case presently in Vietnam, in order to encourage duckweed aquaculture as a cash crop. Undoubtedly a cash flow from such a market would then stimulate village people to clean-up the huge number of polluted ponds. In this case duckweed collection centres may be established to either sell duckweed directly or after drying for pig, duck, poultry or even ruminant production through local outlets or to blend duckweeds for use in compounded feed. The latter in Bangladesh is largely imported at great cost.

Creation of markets is essential if duckweed is to realise its potential in all the countries in the subtropics and tropics that have large areas of ponds or swamps that are presently eutrophic because of man's activities.

Many countries in the wet tropics could maximally use duckweeds where guaranteed acceptance of the product with payment on quality terms is introduced. Processing and product development could quickly develop with great potential for chemical extraction of the protein (and perhaps other chemicals including insecticides), production of feed and food production could encourage the very poor to participate. The bottom line would be healthier conditions for particularly the poor in a less polluted society.

Duckweed will remain an underutilised resource unless governments accepts that polluted water cannot be released into water bodies without removal of minerals and that there is some form of organised trade in duckweed introduced to ensure small farmers receive an adequate compensation for it's production. There is a vast need for research support for this little plant with such a great potential.

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Duckweed Aquaculture

Potentials, Possibilities and Limitations for Combined Wastewater Treatment and Animal Feed Production in Developing Countries

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Sascha Iqbal

Table of Contents

Acronyms, Currency Conversions, Glossary, and Abbreviations

Acronyms

AIT	Asian Institute of Technology, Bangkok, Thailand
FAO	UN Food and Agriculture Organisation
EAWAG	Swiss Federal Institute for Environmental Science & Technology, Duebendorf, Switzerland
DWRP	Duckweed Research Project (discontinued), Dhaka, Bangladesh
ODA	Overseas Development Administration
PRISM	Projects in Agriculture, Rural Industry, Science and Medicine, an NGO in Bangladesh
U. S. EPA	U. S. Environmental Protection Agency
SANDEC	Dept. of Water & Sanitation in Developing Countries at EAWAG

Currency Conversions

Bangladeshi Taka: 1 BdT = 0.026 ... 0.021 US$ (1993...1999)
Taiwan Dollar: 1 TwD = 0.025 US$ (1985)

Glossary

Aquaculture	Artificial and commercial cultivation of aquatic products.
Batch	Pond or stagnant water body loaded with excreta or wastewater at regular or irregular intervals for biological treatment. The treated water may be discharged from the pond and replaced by a next load of wastewater.
Frond	Name of the flat oval-shaped body of duckweed plants.
Lemnaceae	Botanical family of duckweeds.
Nutrients	Chemical elements necessary for biological growth, notably N and P, found in agriculture as fertilisers, but causing pollution when discharged arbitrarily into water bodies.
Pathogens	Organisms causing disease in man.
Plug-flow	Channel-like, often serpentine shaped pond system where wastewater flows slowly but continuously from its inlet to its outlet, while being biologically treated.

Abbreviations

Al	Aluminium
BOD	Biochemical oxygen demand
Ca	Calcium
CaO	Lime
CH_4	Methane gas
Cl	Chloride
CO_2	Carbon dioxide gas
COD	Chemical oxygen demand
dry wt	Dry weight
FCR	Feed conversion ratio
Fe	Iron
HCO_3^-	Bicarbonate
HRT	Hydraulic retention time
K	Potassium
K_2O	Potassium oxide
M.Sc.	Master of Science
Mg	Magnesium
N	Nitrogen
N_2	Nitrogen gas
Na	Sodium
NGO	Non-governmental organisation
NH_3 (-N)	Ammonia (-nitrogen)
NH_4^+ (-N)	Ammonium (-nitrogen)
NO_3^-	Nitrate
Ntot	Total nitrogen
o-PO_4^{3-}	*Ortho*-phosphate
P	Phosphorous
P_2O_5	Phosphorous pentoxide (Phosphoric anhydride)
S	Sulphur
t/ha·y	Annual production in tons per hectare
TKN	Total Kjeldahl nitrogen
TP, Ptot	Total phosphorous
TSS	Total suspended solids
UASB	Up-flow anaerobic sludge blanket
wet wt	Wet weight

List of Tables, Figures and Photographs

Tables

Figures

Photographs

Foreword

What is this literature review about and what is its background?

This literature review provides a first overview of the possibilities, potentials and limits of duckweed aquaculture and its combined use in wastewater treatment and animal feed production in low and middle-income countries. It is somewhat limited as critical literature on duckweed field use is scarce and difficult to obtain (e.g. unpublished internal documents). According to NGOs and commercial suppliers, the duckweed projects seem very positive and promising, and the practical problems encountered with their application rarely mentioned.

Which were the major information sources for this review?

Nevertheless, extensive scientific literature is available on the taxonomy, physiology and ecology of duckweed. The comprehensive monographic study by Landolt (1986) and Landolt and Kandeler (1987) lists over 3400 references. This can be attributed to the fact that duckweed is regarded by botanists and plant physiologists the same way as *E. coli* is viewed by microbiologists and biochemists, namely a model organism for physiological, biochemical and metabolic studies, easy to handle and cultivate under laboratory conditions. This monographic study is of key importance for further research on the use of duckweed. Other references of major importance are the literature review by Gijzen and Khondker (1997) and the DWRP reports (DWRP 1996, 1997a and 1997b) which give a comprehensive overview of the "state of the art" of duckweed-based treatment/production systems and duckweed related research. These references were a major source of information for the present document.

The current review focuses on the *combined* use of duckweed in wastewater treatment and animal feed production in economically less developed countries. Despite the fact that most of the available literature originates from industrialised countries and often describes either the wastewater treatment or the feed production aspect of duckweed, but its dual use is rarely discussed.

Summary

Why have duckweed treatment/ farming systems, so far, not achieved a major breakthrough?

For more than twenty five years, duckweed aquaculture has been regarded as a potential technology to combine both wastewater treatment and feed production in developing and industrialised countries. However, real-scale application of the technology dates back to about ten years. So far, it has not achieved a major breakthrough. System management never appeared sophisticated enough to reveal decisive advantages of duckweed aquaculture over existing technologies. Nevertheless, the experience gained so far reveals interesting data with regard to BOD and nutrient removal, including nutritional value for raising animals.

What are the potentials of duckweed-based wastewater treatment?

The rapidly growing and small floating aquatic plants of the botanical family of *Lemnaceae* are capable of accumulating nutrients and minerals from wastewater. The latter are finally removed from the system as the plants are harvested from the pond surface. Because of their comparatively high productivity and nutritional value, particularly their high content of valuable protein, they provide an excellent feed supplement for animals such as fish or poultry. Duckweed holds the potential to create a financial incentive for controlled faeces and wastewater collection in both rural and urban areas and, therefore, improve sanitary conditions. When duckweed biomass is used for animal production, the generation of income and nutritional improvement appear as possible side-benefits from the wastewater treatment process. Thus, the full potential of duckweed aquaculture lies in its combined use in the fields of sanitation, food production and income generation.

Yet, this combined potential is far from being fully realised in economically less developed countries, and only partially exploited in industrialised nations.

What is the current use of duckweed in the USA?

In the USA, use of duckweed-covered lagoons for tertiary treatment is classified by the U.S. EPA as an innovative/alternative technology. Duckweed is used as a wastewater purifier mainly for treatment of secondary effluents from aerated and non-aerated lagoons. The systems are operated at minimal duckweed production and the biomass is generally composted or landfilled. The harvested duckweed has so far rather been regarded as an undesirable by-product of the treatment process and rarely used as a feed supplement, however, feeding applications are currently being developed.

What is the aim of duckweed application in developing countries?

In economically less developed countries, duckweed systems aim at combined secondary and tertiary wastewater treatment with valorisation of the biomass. Full-scale applications are, for example, known from Taiwan, Bangladesh and India, where duckweed, grown on urban and rural wastewater, is used as a feed supplement for raising fish, chickens and ducks.

What kind of waste can be treated by duckweed?

Duckweed has been used for treatment of raw and diluted sewage, septage, animal manure from cattle and pigs, and stabilisation pond effluents. Potentially, the plants can be used to treat various liquid waste streams, including industrial wastewaters from food processing or fertiliser industries, provided their nutrient content is high enough to sustain duckweed production. Since *Lemnaceae* show a very high capacity of accumulating heavy metals and organic xenobiotics in their tissues, it makes them potentially suitable for removal of these compounds from industrial wastewaters.

How do industrial wastewaters limit duckweed cultivation?

Industrial wastewaters containing high concentrations of BOD, oil and grease seem to limit duckweed growth. Use of biomass as feedstuff is restricted to duckweed grown on wastewaters containing extremely low levels of heavy metals and organic toxins. Due to the high bioaccumulation of such compounds in duckweed potential health hazards may not be excluded.

Besides public health risks resulting from a possible accumulation of toxins in the food chain, the technology faces several other limitations:

Which external climatic and environmental factors limit duckweed application?

The biological characteristics of the plants limit their efficient application to subtropical and tropical zones. Moreover, duckweed cultivation is not feasible in very windy regions and in rapidly flowing water streams. As an aquaculture farming method, the technology requires a year-round supply of (waste)water containing a high load of nutrients. Therefore, the technology is less suited for arid regions with scarce water resources.

What are the land and soil quality requirements of duckweed-based wastewater treatment and piscicultural systems?

Duckweed treatment and farming systems have relatively high land requirements. 2 to 3 m^2 per inhabitant are necessary for duckweed-based wastewater treatment systems. Duckweed-based pisciculture requires a duckweed/fish pond area ratio of at least 1:1 to provide enough duckweed to sustain fish production. A flat to slightly sloped topography is preferable. Soils with a poor water retention capacity or extreme pH values are less suitable for duckweed and fish production.

What technical aspects have to be taken into consideration when designing a duckweed-based wastewater treatment lagoon?

Adequate primary treatment of raw wastewater is indispensable prior to duckweed treatment. Anaerobic pretreatment in earthen sedimentation ponds with a clay lining or closed settlement tanks are a good option for primary treatment. Duckweed treatment systems can either be designed and operated as plug-flow or batch systems. Continuous flow through lagoons are suggested for medium-scale applications at community or (peri-) urban level. Ponds operated as batch reactors are commonly encountered at village-level. Optimum water depths are reported between 0.4 and 1 m. Plug-flow design should allow a HRT of at least 20 days with a length to width ratio of 1:10 or more. In general, a narrow pond design is more suitable as it allows operational work to be carried out from the pond perimeter and avoids direct contact of workers with the wastewater. A floating bamboo or plastic containment grid system is required to prevent the plants from drifting to the shore by the action of wind and water current. Vegetables and fruit planted on the pond embankments can serve as a protection for duckweed from wind and direct sunlight. Besides, the co-crops may generate additional net income.

What are the labour requirements for operation and maintenance of a duckweed treatment system?

Operation and maintenance of a duckweed treatment farm require a high input of skilled labour. Almost daily attention is necessary to maintain optimum growth conditions and treatment efficiencies. Duckweed biomass has to be harvested at regular intervals to remove nutrients or toxins from the system. The harvested amount should ensure a more or less dense duckweed cover on the water surface to prevent algae growth and development of odours and mosquito breeding.

How significant is the removal of BOD, TSS, nutrients, mosquitoes, odours, heavy metals, and organic toxins in duckweed-covered lagoons?

The removal of organic matter, nutrients, mosquitoes, and odours in duckweed-covered lagoons, and the relative contribution of a duckweed mat to it, are far from being well understood, especially with regard to BOD removal. However, a positive effect of duckweed on the efficient removal of TSS, heavy metals and organic compounds has been clearly demonstrated. Since nutrient removal by duckweed is reported to vary around 50±20 %, the total nitrogen and phosphorous input recovered in the harvested biomass amounts to 50±20 %.

Removal efficiencies of over 90 % for BOD, over 74 % for nutrients and 99.78 % for faecal coliforms were reported from a duckweed-covered sewage lagoon in Bangladesh. The studied system, however, treated sewage of relatively low strength as regards BOD and experienced substantial nutrient losses due to seepage.

What are the main advantages and disadvantages of duckweed treatment systems in comparison with waste stabilisation ponds and water hyacinth systems?

Duckweed treatment systems have a competitive economic advantage over waste stabilisation ponds and water hyacinth systems due to the generation of a valuable, protein rich biomass. The latter two systems, however, seem to be more robust with regard to high BOD loads.

How important are the public health risks related to the transfer of pathogens in excreta/ wastewater-duckweed-fish systems?

The risk of pathogen transfer in duckweed systems has hardly been assessed. The few studies conducted so far have not revealed serious public health risks. Though duckweed shows a tendency to accumulate bacteria from wastewater on its surface, fish fed on excreta-grown duckweed was judged safe for human consumption following gutting, washing with safe water and thorough cooking. Moreover, duckweed-fish cultivation in two-pond systems separates fish production from direct contact with the wastewater.

Why is duckweed a valuable feed supplement for fish and poultry?

Average annual duckweed productivity in tropical and subtropical regions is estimated at 10 to 30 t (dry wt)/ha with an annual per ha protein production of about ten times that of soybean. Due to its contents of high quality protein, minerals, vitamins and pigments, duckweed proved to be a valuable fresh and dried feed supplement for raising fish and poultry. Whether duckweed feed has a positive effect on the growth of pigs and ruminants is currently uncertain.

What factors are likely to influence the sociocultural acceptance of duckweed treatment and farming systems?

Indirect reuse of excreta via duckweed has a potentially greater chance to meet with social acceptance, especially in countries where direct excreta reuse is put under a cultural or religious taboo. In regions where duckweed is introduced as a novel crop, the technology is likely to meet with initial rejection due to its intensive and aquacultural nature. The possible benefits of a duckweed treatment system, such as income generation, reduced odours and mosquito breeding, as well as clean water, may favour its social acceptance.

Under what conditions is wastewater-based duckweed-fish production economically profitable?

Experiences at a demo farm and to some extend also at village level in Bangladesh proved that, on the basis of operating costs and positive gross margins, integrated sewage/excreta-duckweed-fish farming is economically feasible. The operating profit at demo farm level was achieved by relatively high financial and skilled labour inputs, by a sufficient and year-round supply of nutrients and water, and by sophisticated management. Nevertheless, the positive operating profits achieved during four consecutive years (1994-1997) are remarkable, especially since wastewater treatment plants worldwide are generally never operated at a profit. However, high interest and repayment charges due to large capital investments, and high expenses for supplementary feed other than duckweed, were the reported factors responsible for net financial loss of farming groups practising excreta-based duckweed-fish production at village level.

Which research fields related to duckweed treatment/farming systems should receive further attention?

As regards duckweed-based treatment and farming systems in developing countries, the following major research fields were identified:

- Public health and environmental effects of duckweed treatment/farming systems
- Design and operation of duckweed-based pond systems for combined wastewater treatment and biomass production
- Economic assessment of wastewater-based duckweed farming models
- Sociocultural and institutional aspects of wastewater-based duckweed farming
- Duckweed production and feeding applications

Chapter One

Climate and Site Selection

Lemnaceae show a worldwide geographic and climatic distribution ranging from cold temperate to tropical regions with the exception of waterless deserts and permanently frozen polar regions. In arid and extremely wet areas (Malaysia, Iceland and others), natural occurrence of duckweed is also rare (Landolt 1986). Most species, however, are found in moderate climates of subtropical and tropical zones. The small floating vascular plants grow on still, nutrient-rich fresh and brackish waters. The family of *Lemnaceae* consists of the 4 genera: *Spirodela, Lemna, Wolffia,* and *Wolffiella*, with a total of about 37 species worldwide.

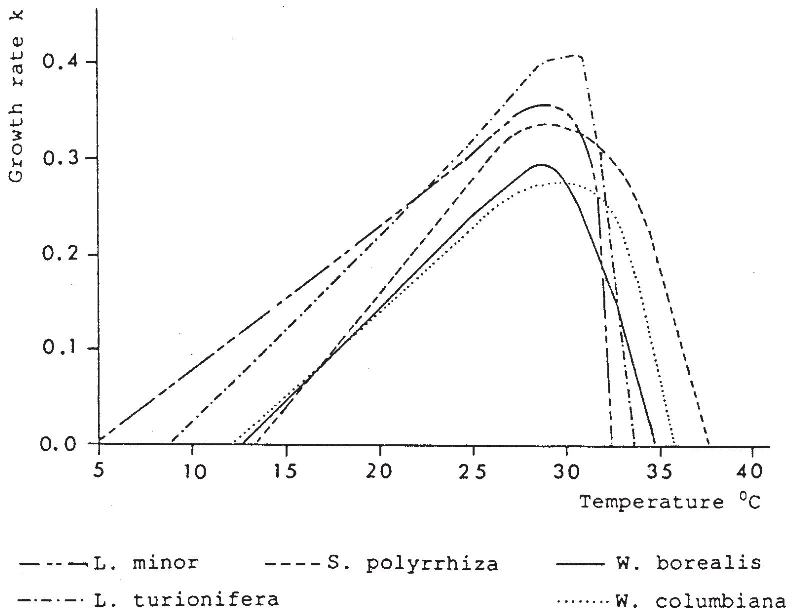
Efficient use of duckweed is restricted to semitropical and tropical zones.

Temperature Requirements

The minimum water temperature allowing their use in wastewater treatment is reported to be 7 °C (Reed et al. 1988, USEPA 1988, WPCF 1990). Depending on the species, optimum growth rates between 25 °C and 31 °C (Fig. 1), however, limit an efficient application for wastewater treatment in warmer climates. Experience in Bangladesh revealed a significant decrease in productivity, and, therefore, treatment efficiency of *Spirodela* and *Lemna* below 17 °C, and severe heat stress at temperatures above 35 °C (PRISM 1990).

Minimum water temperature for duckweed growth lies at 7 °C, optimum temperatures range between 25 °C and 31 °C. The plants experience severe heat stress at temperatures above 31 °C to 35 °C.

Figure 1. *Growth rate of different Lemnaceae species in relation to temperature (after Docauer 1983, in Landolt 1986).*



In regions where temperatures drop below 0 °C during part of the year, the plants sink to the bottom of the water body and remain inactive in a form called turion until warmer conditions

Duckweed survives periods of frost in an inactive form called turion at the pond bottom.

return. In such climates, only seasonal use of duckweed for nutrient removal is possible.

Surprisingly, a company called Lemna Corporation is using duckweed for tertiary post-treatment of wastewater in desert climates and regions with very cold winters (-20 °C to -30 °C). The high temperatures are buffered by increasing pond depths of up to 5 m. Under freezing conditions, their treatment relies on the addition of aeration to keep the ponds partially free from ice. The microbial degradation process slows down but is not completely stopped in contrast to the nutrient uptake by duckweed which is inactivated and, hence, does not contribute to the treatment efficiency in winter (Lemna Corp. 1994).

Influence of Wind

Duckweed cultivation is unsuitable in very windy regions.

Duckweed is very sensitive to wind and, therefore, not suitable for wastewater treatment in very windy regions. Duckweed is blown in drifts to the shore of the ponds, where it piles up and subsequently dies. If plants are not redistributed, which requires manual labour, it will lead to decreased treatment efficiency due to incomplete coverage of the pond surface. A complete duckweed cover has to be maintained to suppress algal growth, nutrient competition and development of odour and mosquito breeding.

Influence of Water Current

Fast water currents limit duckweed cultivation.

Lemnaceae are very sensitive to water current. The natural habitat of the free floating plants are stagnant or almost quiescent water bodies. *Lemnaceae* can withstand higher water currents when the plants are protected by larger ones like *Eichhornia* or *Phragmites*. In water bodies without rooted plants, *Lemnaceae* can withstand a water movement of 0.1 m/s velocity (Duffield and Edwards 1981). A sufficiently low flow velocity has, therefore, to be considered in duckweed treatment systems designed as plug-flow.

Effects of Dryness and Rain

Duckweed cultivation requires a year-round and high supply of water.

Climates with pronounced rainy and dry seasons limit an application of duckweed. A major constraint of duckweed use in some economically less developed countries is the drying up of ponds during dry seasons, especially if wastewater flows are too low to compensate for losses through evapotranspiration and pond leakage. If additional water supply is not available or too costly, duckweed productivity and treatment efficiency can drop drastically during dry seasons. Although community facilities may succeed in maintaining duckweed production through higher wastewater flows and the supply of additional water, the treatment systems may lack effluents during dry seasons, thus preventing reuse of the treated water for irrigation, pisciculture or other purposes.

Duckweed cultivation is intensive in terms of water. Ideally, water resources like wastewater, surface and groundwater should be available throughout the year to maintain a minimum water level of 20 cm during dry periods, and also to buffer heat, nutrient and pH extremes by dilution (Skillicorn *et al.* 1993). Nevertheless, duckweed wastewater treatment may be potentially suitable for dry areas with limited water resources, as a complete cover of duckweed was reported to reduce evapotranspiration by about one-third compared to open water (Oron *et al.* 1984).

Floods can simply wash duckweed and pond infrastructure away or can dilute the wastewater to be treated to such an extent that nutrient concentrations become too low for duckweed growth. Flood protected land should, if possible, be selected in flood prone areas, as constructive flood protection measures are often too expensive for low-income countries.

The effect of rainfall on duckweed growth is unclear. Various positive effects have been reported and include improved nutrient uptake by cleansing absorption surfaces, exertion of physical force for quick separation of daughter from mother fronds, and addition of sulphur, phosphate, nitrate, and bicarbonate. Possible negative effects include prolonged rainfall which drastically cuts off light, dilution of nutrients and partial submerging of the photosynthetic parts of the plants (Gijzen and Khondker 1997).

Rainfall has both positive and negative effects on duckweed growth.

The main constraints in coupled duckweed-fish production reported by rural farming groups in Bangladesh include a lack of duckweed and water during dry seasons, as well as floods (DWRP 1996).

Land Requirement

Land requirement for duckweed wastewater treatment is estimated at 2 to 3 m^2 per inhabitant, not including the possibly required area for primary wastewater treatment. The availability of suitable land for duckweed application becomes a key element, especially in areas where land is scarce due to population pressure and urban development. Nevertheless, urban and peri-urban duckweed systems are known or planned.

Duckweed wastewater treatment systems require relatively large areas of land for pond construction.

Unproductive marginal land along roads and paths or derelict ponds may be a suitable choice to cultivate duckweed, as rental or purchase prices for such land are usually lower than for arable soil.

Additional land for fish ponds is necessary in the case of integrated duckweed-fish production in two-pond systems. The required duckweed/fish pond area ratios of 1:1 to 2:1 are reported to provide enough duckweed for fish production. The optimal duckweed/fish pond area ratio will probably vary according to the site, duckweed productivity, available space, and other low-cost fish feeds (DWRP 1997a).

Land requirement for combined duckweed and fish production in separate ponds is at least twice as high as for duckweed production alone.

Cultivation of duckweed and fish in the same pond could decrease land demand, however, experience with one-pond duckweed/fish systems has not been reported so far.
According to Edwards *et al.* (1990), the area required for indirect duckweed/tilapia production in separate ponds, using septage as a fertiliser for duckweed production, was about three times greater than that required for cultivation of tilapia in ponds directly fertilised with septage. However, the yield of tilapia fed on septage-grown duckweed (6.7 t/ha·y) was almost double than that of tilapia grown in ponds directly fertilised with septage.

Ideal Site Topography

A flat to slightly sloping and even topography is necessary for construction of duckweed treatment lagoons, channels and ponds. Steeper or uneven sites require higher amounts of earthwork, thereby significantly increasing the costs of the system (Metcalf and Eddy 1991).

Soil Characteristics

Soils with a good water retention capacity are most suitable for duckweed aquacultural systems.

Sites with slowly permeable (hydraulic conductivity <5 mm/h) surface soils or subsurface layers are most suitable for duckweed systems, as percolation loss through the soil profile is minimised. The pond bottom is expected to seal with time due to deposition of colloidal and suspended solids and growth of bacterial slimes. Sites with rapidly permeable soils may be used after sealing with clay or artificial materials (Metcalf and Eddy 1991).

Depth to the groundwater table and distance to surfacewater streams may be other limiting factors. Nearby groundwater tables and surfacewater streams lying at a lower level than the pond system may enhance percolation, especially during dry seasons. Dense bottom and side sealings are essential to prevent loss of nutrients and deterioration of groundwater and surrounding surfacewater quality.

Duckweed treatment systems built on sandy soils may suffer from significant nutrient loss due to percolation. This in turn leads to a deterioration of the surrounding ground and surfacewater quality and to lower duckweed yields.

In practice, complete sealing is often difficult to achieve. Nutrient mass balance of a full-scale duckweed treatment system in Bangladesh revealed that about 30 % of the nutrients were lost during the dry season through the side embankment. The sandy characteristics of the soil (hydraulic conductivity was found to be over 50 mm/h) and a nearby flowing river lying lower than the system were responsible for the leakage, even though the bottom was sealed with a 30 cm clay layer (Rahman 1994, Alaerts *et al.* 1996).

If affordable, concrete pond lining is recommended for systems treating industrial wastewater.

Concrete lining can be used to completely exclude seepage. The costs of this lining are dependent on the size of the system. For large-scale systems, concrete lining will significantly increase fixed costs. Concrete lining is recommended where wastewater contains toxic compounds which could potentially deteriorate the quality of surrounding water.

A clay lining of 30 cm is a feasible option. Although the costs for this lining are low and the material quite reliable, total seepage prevention cannot be ensured (PRISM unpublished).

Clay lining is a feasible low-cost option to significantly reduce seepage.

A second critical soil parameter is pH. The optimum pH for duckweed growth ranges between 4.5 and 7.5 (Landolt 1986). Other authors report a more narrow pH optimum ranging from 6.5 to 7.5 (Skillicorn *et al.* 1993). Therefore, highly acid and alkaline soils are unsuitable for duckweed cultivation. Alkaline conditions favour, in particular, the transformation of ammonium to ammonia which is harmful to duckweed.

Alkaline soils are unsuitable for duckweed aquaculture. Acid soils can be somewhat buffered by the use of lime.

A study conducted in the Pathumthani Province in Thailand using family pour-flush latrine effluent for duckweed cultivation revealed that acid sulphate soils with pH values around 4 could be raised to values around 7 by adding quicklime (CaO) to the pond's bottom and slopes.

Chapter Two

Duckweed for Domestic, Agricultural and Industrial Wastewater Treatment

Duckweed wastewater treatment is potentially suitable for small-scale application at rural level and for medium-sized facilities at community, (peri-)urban and industrial level.

Duckweed wastewater treatment systems have been studied for dairy waste lagoons (Culley *et al.* 1981, Whitehead *et al.* 1987), raw and diluted domestic sewage (Skillicorn *et al.* 1993, Oron 1994, Mandi 1994, Hammouda *et al.* 1995, Alaerts *et al.* 1996), secondary effluents (Harvey and Fox 1973, Sutton and Ornes 1975), waste stabilisation ponds (Wolverton 1979), septage-loaded ponds (Edwards *et al.* 1992), and fish culture systems (Porath and Pollock 1982, Rakocy and Allison 1984). Several full-scale systems are in operation in Taiwan, China, India, Bangladesh, Belgium, and the USA (Edwards 1987, Zirschky and Reed 1988, Alaerts *et al.* 1996, Koerner *et al.* 1998).

Duckweed systems have been applied for treatment of various domestic and agricultural wastewaters.

The duckweed treatment plants installed so far almost exclusively treat domestic or agricultural wastewaters. Hardly any literature is available on the treatment of specific industrial wastewaters (Gijzen and Khondker 1997). Potentially, duckweed may also be applied for the treatment of industrial wastewaters, provided their nutrient content is high enough (see also Chapter Four, pp. 45). Effluents with both a high BOD and nutrient load may require adequate primary treatment to reduce the organic load. The upper BOD limit of tolerance for duckweed growth is unknown. In Niklas (1995), *Lemna gibba* was reported to grow on waters with a COD of over 500 mg/l. However, Skillicorn *et al.* (1993) reported that a simple rule of thumb for dilution of primary effluent is to ensure that BOD_5 at the head of a duckweed

With a sufficiently high level of nutrients, duckweed systems are potentially suitable for treatment of industrial wastewaters.

plug-flow treatment system is maintained below 80 mg/l. Industrial wastewaters with a high BOD load and low nutrient content are less suitable to favour duckweed growth.
Mdamo (1995) reported that duckweed growth on paper mill effluents was only observed when BOD was relatively low (150 mg/l) and nutrients were added externally. High BOD removal of over 98 % was observed when 2 mg per m^2 of both N and P were added daily. Without the addition of nutrients, almost no duckweed growth was observed on the paper mill wastewater. Neither did wastewater with a very high BOD level (2900 mg/l) promote duckweed growth.

High concentrations of BOD, oil, grease, and detergents may hamper duckweed growth.

Apart from high BOD concentrations, fatty acids, oil and grease were reported to have a negative effect on duckweed growth. This is probably due to adsorption to the plants' submerged surfaces and subsequent inhibition of nutrient uptake. Duckweed is reported to tolerate rather high concentrations of detergents (Gijzen and Khondker 1997). Skillicorn *et al.* (1993), however, suggest that high concentrations of detergents may destroy the duckweed's protective waxy coating, thereby rendering the plant more vulnerable to diseases.

Duckweed may be used for extraction of heavy metals and organic compounds from industrial wastewaters. However, the harvested biomass should definitely not be introduced into the food chain, but rather burnt and/or disposed of in sealed landfills.

The efficient absorption of heavy metals and other (organic) toxic compounds could be used for extraction of such toxins from industrial wastewaters. It is, however, important that the biomass is harvested at regular intervals, otherwise, the toxins will settle on the sediments with the decaying plants. The harvested plants should be burnt and/or disposed of in sealed landfills.

Duckweed for food production should only be grown on wastewaters with extremely low toxin concentrations. Even low concentrations in the raw wastewater may become hazardous due to the manifold bioaccumulation in duckweed and, possibly, in the food chain.

Separate collection of toxin containing domestic and industrial wastewaters is recommended. In practice, separation of critical industrial wastewaters is very difficult as the countries concerned dispose of only elementary or no wastewater collection systems. A few point sources of industrial wastewater pollution, such as for example from leather tanneries, may render, due to mixing, most of the domestic wastewater unsuitable for food production not only in cities but also in villages.

Design Considerations

Type and quantity of wastewater to be treated are decisive factors in the design of duckweed treatment systems and for infrastructural requirements necessary to ensure daily nutrient inputs and use of biomass (Tab. 1).

Table 1. *Different duckweed treatment systems depending on type and amount of wastewater.*

Type of wastewater		*Domestic*	*Non-domestic*
Origin of wastewater	*Village*	*Community/(peri-)urban*	*Industries*
Hydraulic load (m^3/d) Population	<5 50-150	>100-1500 1000-15,000	<1500
Infrastructure required to ensure daily flow of nutrients	Pour-flush-type latrines	• Sewage system (separation of waste-water containing toxins) • Access for septage trucks	• Sewage system
Primary treatment	• Water-sealed pits • Submerged bamboo baskets	• Open or closed settling tanks • Sedimentation ponds • Waste stabilisation ponds	• Open or closed settling tanks • Sedimentation ponds • Waste stabilisation ponds • Biogas digesters (high BOD waste)
Secondary and tertiary treatment	Duckweed ponds (batch)	Duckweed ponds (plug-flow)	Duckweed ponds (plug-flow)
Use of biomass	Desired	Possible	Restricted

Metcalf and Eddy (1991) suggest that duckweed systems, exploiting mainly the wastewater treatment aspect of duckweed, can be designed as conventional stabilisation ponds with the addition of a floating grid system to control the effects of wind. However, reliable design and operation guidelines aiming at the dual use of duckweed in wastewater treatment and optimum biomass production are lacking. They can be operated as batch or plug-flow (continuous flow) systems. Easy access to the pond surface for operation and maintenance should be ensured in site selection and design of a duckweed treatment pond system. Therefore, a narrow, channel-like pond design is more convenient than wider ponds.

Duckweed treatment systems can be designed and operated as batch or plug-flow systems. A narrow pond design should allow operation and maintenance work from the pond embankment in order to avoid direct contact of workers with wastewater.

Primary Treatment of Raw Wastewater

Primary treatment of raw wastewater is essential for initial separation of some of the settleable fraction of pathogens, settleable solids and floating material. In the case of plug-flow systems, efficient sedimentation is important to prevent degradation of initial treatment runways. Adequate pretreatment is also important to release organically bound nitrogen and phosphorous through microbial hydrolysis, as the availability of NH_4^+ and o-PO_4^{3-} was suggested to be the limiting step for fast duckweed growth (Alaerts *et al.* 1996). Anaerobic pretreatment promotes the release of organically bound NH_4^+ and o-PO_4^{3-}, the favoured forms of nutrients for duckweed growth.

Primary treatment of raw wastewater is essential for overall treatment performance and supply of nutrients for duckweed growth.

Compared to open systems, closed primary treatment systems enhance TSS removal due to the absence of light and subsequent inhibition of algal growth. Another advantage of a closed system is the possibility to collect and use the biogas generated. However, pretreatment using closed settling tanks, biogas digesters or anaerobic up-flow sludge blankets (UASB) are techni-

Closed primary treatment systems are technically more difficult and costly to install and operate than open systems. However, they are more efficient and allow the use of biogas.

cally more difficult and costly to install and operate. Despite their high efficiency, they are more suitable for treatment of highly concentrated industrial and municipal wastewaters.

Biogas digesters followed by duckweed treatment systems are a potential method for substantial carbon, nitrogen and phosphorous recovery and reuse from wastewaters containing high BOD and nutrient loads.

The use of biogas digester effluents for duckweed cultivation seems promising. In a duckweed wastewater treatment system, the organic carbon fraction is not assimilated and converted into valuable biomass by the plants themselves, but degraded by aerobic, anoxic and anaerobic microbial processes on the plants' surfaces, in the water column and sediment. The carbon is finally released from the system as CO_2 and CH_4 green house gases and microbial sludge.

Anaerobic pretreatment in a biogas digester (partially) allows recovery of the carbon fraction via the biogas, whereas nutrients like nitrogen and phosphorous in the remaining effluent can be (partially) recovered by duckweed. In this way, optimal reuse of energy and nutrients can be obtained. Moreover, anaerobic pretreatment seems to favour nutrient availability of nitrogen and phosphorous due to hydrolysis of complex organic N and P compounds.

Biogas digesters followed by duckweed effluent treatment may be a suitable system combination for treatment of waste(water) with a high BOD load, such as from sugar, rubber and food processing industries or from rice mills.

Earthen anaerobic sedimentation ponds are a simple and low-cost option for primary treatment in low-income countries.

Use of conventional earthen anaerobic sedimentation ponds is an efficient, low-cost and easy manageable alternative for primary treatment, especially in low-income countries. The most widespread design criteria include a depth of 2-3 m, a HRT of 1-6 days, construction of berms or baffles to prevent short-circuiting and clay lining. However, compared with closed set-

Photograph 1: *Duckweed cultivation pond at village level in Bangladesh during the dry season. Nutrients are supplied by low-cost pour-flush latrines masked by vegetation on the right pond embankment. Excreta of latrine users is collected via a pipe and digested in the shown bamboo baskets from where the nutrients are released by diffusion.*

tling tanks, biogas digesters and UASBs, conventional ponds offer the following disadvantages: higher land requirements, unused biogas, bad smells and unpleasant physical aspect, higher TSS load in the effluent due to algal growth, and a potential danger of percolation if a concrete lining is missing. The formation of a crust on the water surface after a few months may reduce odours, algal growth and favour anaerobic conditions. In venting the effluent 0.5 m below the surface, the floating material is hindered from moving to subsequent treatment processes.

Sludge from primary treatment should, if possible, be analysed for heavy metals and organic toxins. If found to meet established standards, it can be used, after stabilisation, as a fertiliser in agriculture.

Latrines of the pour-flush type (Phot.1, Figs. 2 and 3) were used for nutrient supply to duckweed ponds in villages. In the examples shown, the water-sealed pit and the submerged bamboo case serve as some kind of pretreatment stage for anaerobic digestion. Moreover, they prevent faeces and ablution material for anal cleaning from freely floating around in and on the pond.

At village level, some kind of pretreatment can be achieved by anaerobic decomposition of excreta in the containment structures of pour-flush-type latrines.

Figure 2. *Low-cost pour-flush latrine. Excreta is collected and digested in the submerged bamboo case placed directly in the duckweed pond releasing nutrients through diffusion (PRISM).*

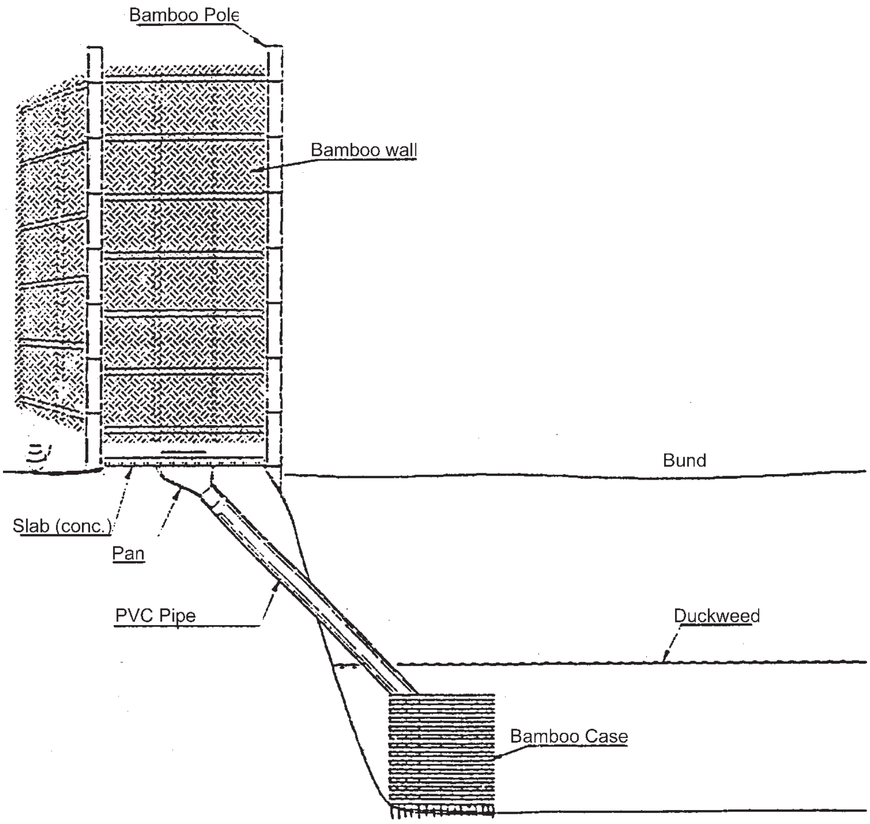
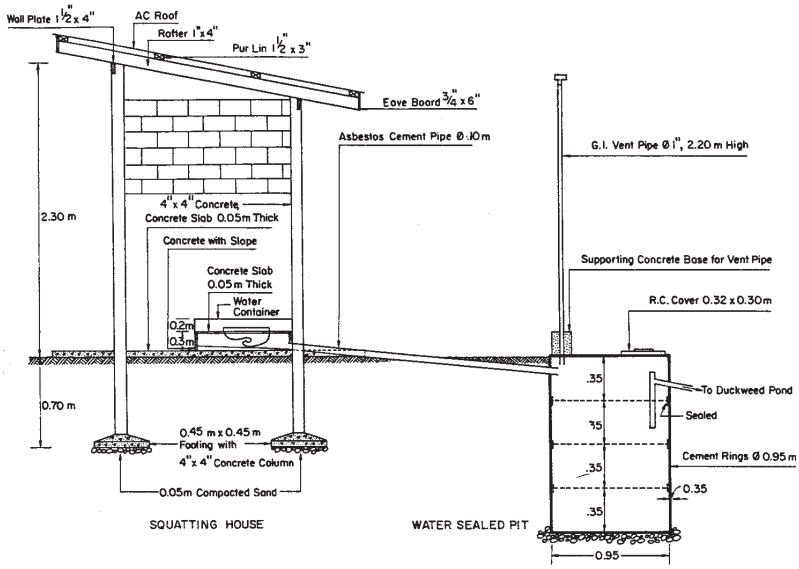


Figure 3. *Family/village level pour-flush pit latrine. Settleable solids sink to the bottom of the water-sealed pit where they undergo anaerobic decomposition. The liquid effluent overflows from the pit into the adjacent duckweed pond, while sludge remains at the bottom of the pit from where it has to be removed periodically (Edwards et al. 1987).*



Pond Design

As aforementioned, two basic principles for pond design and operation are used for duckweed treatment, namely plug-flow and batch systems.

Plug-flow design is suitable for treatment of large and regular wastewater flows originating from communities and peri-urban areas.

A plug-flow (continuous flow through) design (Phot. 2) seems to be the more suitable treatment option for larger wastewater flows originating from communities and (peri-)urban areas, as it ensures an improved and more continuous distribution of the nutrients. A plug-flow design also enhances the contact surface be-

Photograph 2: *Duckweed-covered serpentine plug-flow lagoon in the USA for tertiary treatment of effluent from three facultative lagoons followed by a wetland buffer. Design flow is reported at 19,000 m³/d, with peak flows reaching 38,000 m³/d. (Photograph: Lemna Corp. 1994).*

tween wastewater and floating plants, thereby, minimising short-circuiting. To ensure plug-flow conditions, a high plug-flow length to width ratio of 10:1 or more is necessary (Hammer 1990). Alaerts *et al.* (1996) reported excellent treatment results with a length to width ratio of 38:1. Moreover, a narrow, channel-like design allows easier access to the water surface for operation and maintenance work.

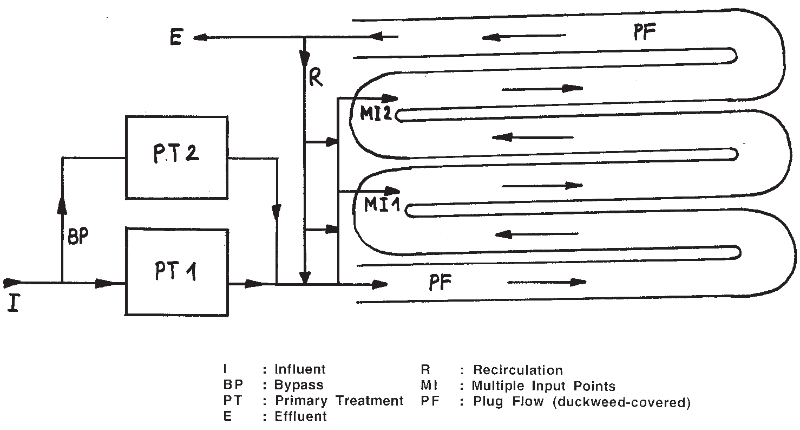
In a plug-flow system, duckweed productivity, nutritional value and nutrient removal efficiency decline gradually with increasing retention time. Depletion of nutrients causes plants to visually become brownish at some stage in the plug-flow runway, to grow slower and take up less nutrients per time than plants in the initial stages of the plug-flow. Furthermore, their protein content drops and their fibre content increases. At this point, the two so far parallel running processes of efficient wastewater treatment and high duckweed production begin to diverge. Yet, if this occurs at the very end of a duckweed plug-flow system and if the required effluent standards are met, the objective of combined wastewater treatment and production of high quality feed is attained.

Duckweed can be used for combined wastewater treatment and production of high protein biomass up to the point where nutrient limitation diverges the two so far parallel running processes.

However, reliable design guidelines are missing to dimension a duckweed plug-flow lagoon in such a way that nutrient starvation occurs at the very end of the system. The system could, therefore, either be oversized if effluent standards are already met at early fractions of total retention time, leaving most of the system's surface underused with regard to protein production, or undersized where effluent standards are not met at the end of the plug-flow. Thus, an ideal duckweed plug-flow system should include both multiple wastewater input points and a recirculation system (Fig. 4).

To achieve optimum treatment efficiency and protein production, an ideal plug-flow design should include multiple wastewater inlet points and allow recirculation of the final effluent.

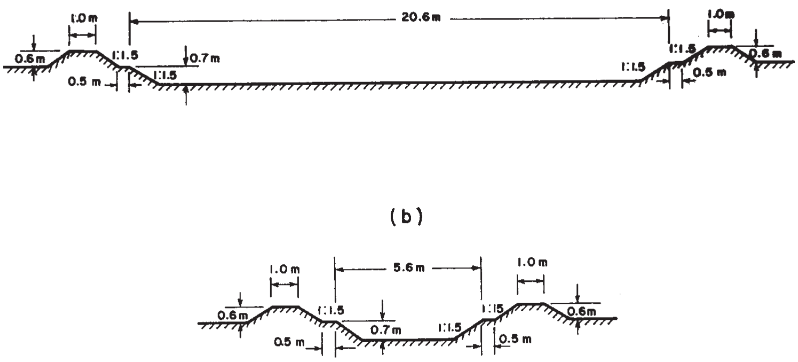
Figure 4. *Ideal plug-flow system for combined duckweed-based wastewater treatment and protein production.*



Batch-operated ponds (Phot. 3, Fig. 5) are a feasible option for introduction of duckweed aquaculture in villages where already existing ponds can often be used and, thus, save capital costs for extra earth work. In comparison with a continuous flow through system, duckweed growth may be enhanced near the nutrient inlet points as a result of reduced nutrient mixing and distribution. A narrow pond design allowing duckweed harvesting from the embankment is also favoured here.

Photograph 3: *Batch-operated pond for duckweed cultivation at village level showing dense duckweed cover and pour-flush latrine influent for nutrient supply in the background (Bangladesh).*

Figure 5. *Example of batch-operated pond for duckweed cultivation at village level. (100 m^2 at 0.5 m depth). (a) length and, (b) width section of duckweed pond (Edwards et al. 1987).*



Hydraulic Retention Time (HRT)

Hydraulic retention time in duckweed treatment systems should amount to at least 20 days to ensure acceptable pathogen removal.

The HRT is dependent on the organic, nutrient and hydraulic loading rate, depth of the system and harvesting rate (Metcalf and Eddy 1991). To ensure acceptable pathogen removal and treatment efficiency, comparatively long retention times in the range of 20 to 25 days are postulated for duckweed (plug-flow) systems (Metcalf and Eddy 1991).

Water Depth

The critical factor with respect to water depth is to ensure vertical mixing in the pond to allow the wastewater to be treated to come into contact with the duckweed fronds for nutrient uptake and BOD degradation through attached microbial populations. An outlet structure is recommended in order to vary the operating depth (Metcalf and Eddy 1991).

Reported pond depths range from 0.3 to 2.7 m up to even 5 m (Lemna Corp. 1994). The majority of authors report an optimal depth ranging from 0.4 to 0.9 m, implying that a maximum depth of one meter is sufficient for acceptable temperature buffering. Higher depths are also a feasible option for systems with relatively low BOD loads, a low recirculation rate and high land costs. Shallow system depths are, however, better suited for high organic loads, a high recirculation rate and for regions with inexpensive land prices.

Both shallow and deeper pond depths are currently being applied, depending on organic load and land availability.

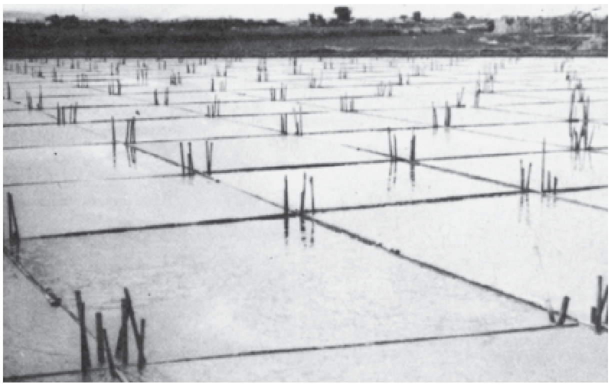
Organic Loading Rate

Average organic loading rates expressed in terms of BOD_5 for plant systems without artificial aeration should not exceed 100 to 160 kg/ha·d in order to obtain an effluent quality of 30 mg BOD/l or less (Metcalf and Eddy 1991, Gijzen and Khondker 1997). Odours can develop at lower loading rates, especially where the sulphate concentration in the wastewater is greater than 50 mg/l. It seems that duckweed is less suitable for the treatment of wastewaters containing high BOD loads.

Duckweed systems alone appear to be less suitable for treating wastewaters containing high BOD loads.

Wind Protection

Since duckweed is very susceptible to wind drifts and water currents, stabilisation of the plants on the water surface is of prime importance. In regions with moderate winds, drifts are prevented through floating grids dividing the pond surface into cells or compartments. Floating bamboo poles divided into small square or rectangular areas of 2 to 5 by 4 to 8 meters are most commonly



Photograph 4: *Large-scale commercial duckweed cultivation on organically polluted surfacewater in the city of Chiai, Taiwan (1985), showing floating bamboo square grids on the water surface to prevent duckweed from drifting. (Photograph: Edwards et al. 1987).*

Photograph 5: *A high density polyethylene grid system is used for duckweed stabilisation on the water surface in the shown duckweed-based polishing lagoon in the USA. It receives 500 m^3/d of combined municipal, septic and industrial wastes after pretreatment in an aerated lagoon. (Photograph: Lemna Corp. 1994).*

used (Phot. 4). The size of the grid is determined by mean wind conditions and, in the case of flow through systems, by maximum projected flow velocity in the system. The higher the wind and flow velocities, the smaller the cells and the higher the system's costs. With a design life of around two years and an average per hectare cost of about US$ 500, a bamboo grid systems offers a feasible solution to the problem of wind drifts (PRISM 1990). Furthermore, vegetation on the pond embankment contributes to dispersing and protecting against wind.

Lemna Corporation has developed a patented UV-stable high density polyethylene grid system (Phot. 5). The square shaped grids have a surface area of 25 to 50 m^2 and a reported design life of several years. This robust grid system is resistant to environmental extremes, however, the per hectare costs of such a system appear to be too high for low-income countries (PRISM 1990). For middle-income countries, a more durable and expensive grid system may be an economically more feasible option on a long term than a less expensive bamboo grid system which has to be replaced frequently.

Operating Considerations

Labour Requirement for Duckweed Farming

Duckweed aquaculture is a highly labour-intensive farming method requiring skilled labour and sophisticated management.

Duckweed survives a wide range of environmental extremes, but grows best in a narrow band of optimum growth conditions. Maintenance of these optimum conditions requires regular, skilled and experienced labour, as well as sophisticated management. Therefore, duckweed(-fish) farming is highly labour-intensive and needs almost daily attention throughout the year. This may be a

Photograph 6 (top) : *Transport of fresh duckweed in a wickerwork basket to the weighing station and adjacent fish pond, using a wooden board, a bamboo pole and strings for suspension of the basket (Bangladesh).*

Photograph 7 (left): *Freshly harvested duckweed grown on diluted sewage is filled into a wickerwork basket, where it remains for some time to allow some water drainage and pathogen removal by sunlight irradiation (Bangladesh).*

Photograph 8: *Determination of duckweed wet weight using a spring scale and record keeping (Bangladesh).*

Photograph 9: *Distribution of fresh sewage-grown duckweed into floating bamboo feeding zone of fish pond. The feeding zone prevents the floating duckweed from being undiscovered by fish through dispersal in the fish pond (Bangladesh).*

reason why duckweed aquaculture has, so far, not become a major waste reuse option in developing countries.
The availability of labour resources is generally not the limiting factor. Especially in areas where agricultural labour is seasonally underemployed, duckweed cultivation can create an alternative employment opportunity. However, recruiting of people for wastewater-based duckweed farming may become difficult in regions where the tasks related to excreta reuse have a very low employment status (WHO 1989).

Initial work may include earth work for pond excavation, sealing of ponds, planting of vegetation on the embankment as protective measure against heat and wind, duckweed seed stock collection from locally adapted wild colonies, seeding of duckweed, construction of wastewater and freshwater supply installations like open or closed channels, pumps, access ramps for septage trucks, or installation of latrines.

Operational and maintenance work includes harvesting (Phot. 6), weighing (Phot. 8), and transport of plants (Phot. 7), feeding of duckweed and supplementary feed to animals like fish (Phot. 9), heat and wind stress management, pest control, nutrient supply, water level maintenance, floating grid maintenance, pump operation and repair, maintenance of the duckweed cover, pond repair, periodic desludging, bookkeeping, to name but only the most important tasks. Standard monitoring of chemical wastewater parameters and pathogens is recommended whenever feasible.

Work related to animal cultivation, as in the case of integrated duckweed/animal farming, may account for a large part of total labour input, especially for pisciculture. Fish stocking, harvesting, transport and marketing, pond excavation, sealing and repair, water supply, feeding, fertilising ponds, continuous fish growth and health monitoring, aeration measures when concentrations of dissolved oxygen become critical, night-time guarding against theft, and bookkeeping are the most important tasks in pisciculture.

The vegetation grown on the pond embankments requires irrigation, fertilisation, weed removal, pest management, harvesting, transport, and marketing.

Four to five workers were employed for daily operation and maintenance of a sewage-duckweed-fish system (0.6 ha of duckweed-covered lagoon, 0.6 ha of fish ponds) in Bangladesh.

Harvesting of Duckweed

Regular harvesting of duckweed is essential to continuously remove nutrients or toxins from the system and to maintain a productive and nutritive crop.

The quantity and frequency of duckweed harvesting plays a major role in the treatment efficiency and nutritional value of the plants. Regular harvesting ensures that the accumulated nutrients or toxins are permanently removed from the system. Because younger plants show a better nutrient profile and higher growth rate than older plants, regular harvesting is important to maintain a healthy and productive crop. Laboratory results from Whitehead and Bulley (in Reddy and Smith 1987) revealed that under conditions of high nutrient loading, an increase in the cropping rate resulted in improved nutrient removal. At lower nutrient loading rates, the cropping rate should be reduced. An almost complete cover should remain on the pond surface after plant harvesting.

Optimum standing crop density to achieve highest productivity is site specific.

The standing crop density, which realises the highest duckweed productivity, will determine the harvesting frequencies and amounts. The correlation between standing crop density and absolute biomass productivity peaks at some optimal density and gradually declines as increasing density inhibits growth through crowding. Optimal standing crop densities are site-specific and have to be determined through practical experience (Skillicorn *et al.* 1993).

Alaerts *et al.* (1996) reported a standing crop density of 1600 g(wet wt)/m^2 for a duckweed-covered sewage lagoon in Bangladesh. Koles *et al.* (1987) reported an optimum standing crop density for treatment of nutrient-rich algae culture (fertilised with pig excreta) effluent in Florida of 1250 g(wet wt)/m^2. Lower standing crop densities of 400 to 800 g(wet wt)/ m^2 were reported by PRISM (unpublished), DWRP (1996), and Skillicorn *et al.* (1993). Each cell should be harvested back to optimal standing crop density at rates dependent on the plants' productivity. Reported harvesting frequencies and amounts vary widely (Tab. 2).

Table 2. *Harvesting frequencies and amounts as reported by different authors.*

Application level	*Species*	*Harvesting frequency (days)*	*Amount harvested (in % of standing crop)*	*Reference*
Community level Bangladesh	*S. polyrrhiza*	1	10-25%	Skillicornet *al.* (1993), PRISM
Laboratory-scale	*S. polyrrhiza, L. minor*	1	10%	Whitehead and Bully in Reddy and Smith (1987)
Community level Bangladesh	*S. polyrrhiza*	2 (wet season) 3 (dry season)	____	Alaerts *et al.* (1996)
Large-scale Commercial level Taiwan cities	*Lemna, Wolffia*	7	80%	Edwards *et al.* (1987)
Village/family level Thailand	*S. polyrrhiza*	11.3 (mean)	____	Edwards *et al.* (1987)
Pilot-scale	*Spirodela, Lemna*	1-3	25%	Edwards *et al.* (1992)
Large-scale	*Lemnaceae*	weekly (nutrient removal) monthly (secondary treatment)	____	Metcalf and Eddy (1993)
Pilot-scale	*L. gibba, S. punctata*	biweekly	____	Koles *et al.* in Reddy and Smith (1987)

The choice of harvesting technique is dictated by system design and by labour and equipment costs. For shallow ponds, the most simple harvesting techniques include manual skimming of the plants from the pond surface with a net (Phots. 10 and 11), or moving the floating plants to one corner of the pond with a bamboo pole and removing them with baskets (Phot. 12). Two people were reported to require 3.5 hours for manual harvesting of duckweed from a 0.3 ha pond in Taiwan. Large-scale harvesting in industrialised countries is carried out with mechanical harvesting machines requiring, however, deep ponds (Phot. 13).

Relief of Heat Stress

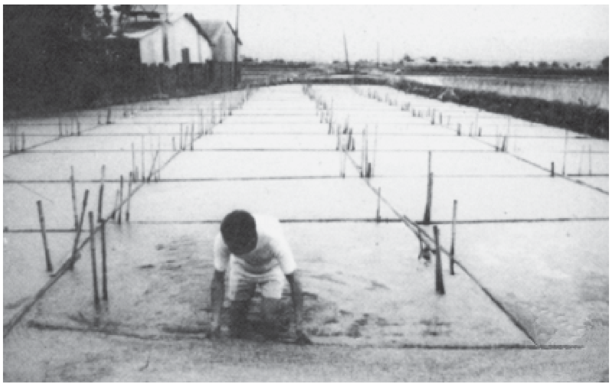
As aforementioned, duckweed growth rapidly declines at temperatures above 31 °C to 35 °C, as the plants experience severe heat stress. Relief of heat stress during extremely hot days can be achieved by manual dunking of the plants and by splashing or spraying them with a fine mist of water. This is an efficient and immediate way of lowering temperatures by 5 °C to 10 °C, though quite intensive in terms of work.

Duckweed experiences severe heat stress at temperatures above 31 °C to 35 °C. Manual dunking of plants, planting of shading vegetation on the pond embankment and an increase in the water volume of ponds can relieve from heat stress.

Cultivation of plants on the embankments of the ponds will shade the duckweed cover and protect it from direct sunlight. In addition, the sale of the co-produced plants, such as papaya, ba-

Photograph 10: *Manually harvested sewage-grown duckweed using a net (Bangladesh).*

Photograph 11: *Manually harvested duckweed using a net. The pond is fertilised with human excreta, supplied by the pit's overflow of the pour-flush pit latrine shown in the background (Thailand). (Photograph: Edwards et al. 1987).*



Photograph 12: *Manually harvested duckweed grown on organically polluted surfacewater using a bamboo pole to move the floating duckweed to the pond's corner for removal (City of Chiai, Taiwan). (Photograph: Edwards et al. 1987).*

Photograph 13: *Diesel-powered mechanical harvester for biomass removal in larger duckweed-based wastewater treatment lagoons in the USA. (Photograph: Lemna Corp. 1994).*

nana, sugar cane, bamboo, etc., can generate additional net income.

Another alternative to buffer high temperatures is to increase water depth up to 150 cm. Increased water volume and the inflow of cool groundwater have a buffering effect and significantly lower peak temperatures. The availability of sufficient and suitable water resources can be problematic and result in a cost increase. Since ponds must be designed to hold a meter or more of water, the pumping costs will increase significantly. The increased water pressure of raised water levels may accelerate water loss through percolation (PRISM 1990).

Removal Mechanisms

Duckweed wastewater treatment systems are, at their core, conventional facultative pond systems. They differ from the latter, however, in that they a) achieve a higher nutrient removal from the wastewater by harvesting the biomass, b) work to inhibit rather than to encourage algal growth, c) may have an aerobic zone of only a few centimetres in comparison to facultative ponds with aerobic zones of up to one meter in depth, and d) undergo only slight variations in temperature, dissolved oxygen concentrations and pH which show wide diurnal fluctuations in facultative ponds. These more consistent conditions are believed to favour the continuous growth of degrading microbial populations (Lemna Corp. 1994, PRISM unpublished).

Environmental conditions and treatment processes prevalent in duckweed-covered lagoons differ significantly from those encountered in facultative ponds.

The following paragraphs contain a brief description and discussion of the removal mechanisms for TSS, BOD, nitrogen, phosphorous, heavy metals, and organic toxins, as assumed by various authors. Removal of pathogens is discussed separately under Chapter Three, pp. 45.

TSS Removal

TSS are removed mainly by sedimentation and biodegradation of organic particles in the pretreatment and duckweed pond system. A minor fraction is absorbed by the roots of the duckweed fronds, where organic particles undergo aerobic biodegradation by microorganisms, and part of the degraded products is assimilated by the plants.

Two characteristics of duckweed treatment systems are believed to play an important role in TSS removal. A complete mat of duckweed inhibits penetration of sunlight and subsequent growth of algae. Large amounts of algae contribute significantly to TSS concentrations. Though algae take up considerable amounts of N, P and other nutrients and may, therefore, contribute to their removal, the nutrients are released again by biodegradation when algae settle, die off and become available again for algal growth. A dense mat of duckweed can, therefore, reduce algal contribution to TSS. This is one of the reasons why a complete duckweed cover is essential for treatment efficiency of duckweed systems. Compared to facultative ponds, a second, more uncertain factor favouring sedimentation of TSS in duckweed systems is attributed to the quiescent conditions prevalent in the water column under the duckweed cover, as a consequence of the more consistent vertical temperature profile.

Algal contribution to TSS is low in duckweed systems since penetration of sunlight is greatly reduced by a dense duckweed cover inhibiting subsequent algal growth.

BOD Removal

The mechanisms of BOD removal in duckweed ponds and the relative contribution of the plants towards BOD removal are far from being fully understood. Generally, it can be said that BOD is substantially removed by both aerobic and anaerobic microorganisms associated with the plants' surfaces, suspended in the water column and present in the sediment. Landolt and Kandeler

BOD is aerobically digested by microorganisms attached to the duckweed fronds. Anaerobic processes are responsible for BOD removal in the sediment.

(1987) reported the direct uptake of small hydrocarbons by duckweed, however, heterotrophic growth probably plays a minor role in total BOD removal.

Aerobic degradation of BOD may be less important in duckweed systems than in water hyacinth systems due to lower oxygen supply and smaller plant surface area for attached bacterial growth.

Aerobic BOD removal is assumed to be less important in a duckweed treatment system than for example in a water hyacinth system. Aerobic BOD removal depends on oxygen supply and surface area available for attached bacterial growth. *Lemnaceae,* however, possess a relatively small surface area for attached growth of mineralising bacteria compared to other aquatic macrophytes with larger submerged root and leaf surfaces (Zirschky and Reed 1988). The dense cover of duckweed on the water surface would also inhibit both oxygen from entering the water by diffusion from the air and photosynthetic production of oxygen by phytoplankton as a result of the poor light penetration (Culley and Epps 1973, Brix and Schierup 1989). According to Zirschky and Reed (1988), BOD removal could even decrease in ponds covered with duckweed because of the limited oxygen transfer into the water.

Alaerts *et al*. (1996), however, found that with a BOD loading rate of 48-60 kg/ha·d, a water depth of 0.4-0.9 m and a HRT of about 20 days, the water column in a duckweed-covered sewage lagoon system always remained aerobic. Surprisingly, the authors calculated an aeration rate through the duckweed-covered surface of 3-4 gO_2/m^2, which is slightly higher than oxygen transfer through an uncovered surface (Srinanthakumar *et al.* 1983). This leads to the conclusion that aerobic conditions occur at least in the top layer of a duckweed pond within and under the plant cover due to photosynthetic production of oxygen and surface aeration. Interesting results were also observed by Koerner *et al.* (1998) who reported that COD removal was significantly faster in the presence of duckweed than in its absence. They believe that the structure of duckweed surface and the way oxygen is supplied are important elements, since the positive influence of a living duckweed population on COD removal could not be simulated by artificial plastic duckweed surfaces and oxygen pumps.

Depending on the organic loading rate, water depth and HRT, the prevalent redox conditions in a duckweed-covered pond system can become anoxic to anaerobic. In this case, the main factors responsible for BOD removal in duckweed treatment systems are probably similar to those described for the anaerobic zone of facultative ponds (Reed *et al.* 1988). Step cascade aeration prior to discharge is a low-energy possibility for reaeration of an effluent containing low levels of dissolved oxygen.

Nitrogen Removal

The nitrogen balance in a duckweed treatment system is determined by plant uptake, denitrification, volatilisation of ammonia, microbial uptake, and sedimentation. Regarding the relative importance and kinetics of the different removal processes, overall conclusions are either unknown or difficult to draw, as determining factors like nitrogen availability, redox and pH conditions are largely dependent on N and BOD loading rates, including specific design and operation of a duckweed treatment system.

Besides plant uptake, denitrification and volatilisation of ammonia are quantitatively relevant processes for nitrogen removal in duckweed systems.

Existing results suggest that approx. 50 % (± 20 %) of the total nitrogen load is assimilated by duckweed, while the remaining nitrogen is removed by indirect processes other than plant uptake of which nitrogen loss to the atmosphere by denitrification and volatilisation of ammonia are suggested to play a major role (Alaerts *et al.* 1996, Gijzen and Khondker 1997, Koerner and Vermaat 1997).

Particularly in ponds with aerobic and anaerobic environments favouring microbial nitrification and denitrification, ammonium (NH_4^+) is first oxidised to nitrate (NO_3^-) and subsequently reduced to atmospheric nitrogen (N_2) which is released from the system.

At alkaline pHs above 8, the ammonium-ammonia (NH_3) balance shifts towards the unionised form which results in a loss of nitrogen through volatilisation of ammonia. Besides, ammonia is toxic to duckweed.

It is unknown how far nitrogen fixation by cyanobacteria, which can form a symbiontic relationship with *Lemnaceae* (Duong and Tiedje 1985), contributes to the overall nitrogen balance in a duckweed treatment system.

Phosphorous Removal

Plant uptake and sedimentation are quantitatively relevant for phosphorous removal in duckweed systems.

In a duckweed treatment system, phosphorous is normally removed by the following mechanisms: plant uptake, adsorption to clay particles and organic matter, chemical precipitation with Ca^{2+}, Fe^{3+}, Al^{3+}, and microbial uptake. Except for plant uptake, the latter three mechanisms cause a storage of phosphorous in the system. As no volatile intermediates such as N_2 or NH_3 as in the case of nitrogen are formed, ultimate phosphorous removal is only possible by plant harvesting and dredging of the sediment.

The plants' uptake capacity depends largely on the growth rate, harvesting frequency and available *ortho*-PO_4^{3-}, the favoured form of phosphorous for duckweed growth. In the warmer season when the growth rate is highest, phosphorous removal rate is also highest. The uptake of phosphorous by duckweed is enhanced by frequent harvesting and adequate pretreatment of raw wastewater to release organically bound *ortho*-PO_4^{3-}.

Besides plant uptake, adsorption and precipitation are probably the other dominant mechanisms for phosphorous removal in a duckweed treatment system. These particle/sediment-water phase interactions are very complex and depend on the redox potential, pH and concentrations of reactants. Aerobic conditions contribute to the precipitation of phosphorous through oxidised forms of Fe and Al. However, phosphorous is again released under anaerobic conditions prevailing in the sediments.

Removal of Heavy Metals and Organic Compounds

Since duckweed are capable of accumulating high amounts of heavy metals and organic compounds, its use is to be limited to only wastewater treatment.

As aforementioned, *Lemnaceae* can tolerate and accumulate high concentrations of heavy metals and organic compounds with accumulation factors ranging between multiples of 10^2 and 10^5. As regards this particular duckweed characteristic, Landolt and Kandeler (1987) cite over 60 references. It seems that the concentration factor for heavy metals is much higher at low metal concentrations.

This fact suggests a possible use of duckweed for efficient removal of metals from wastewaters. It is, therefore, important that the plants are harvested at regular intervals to prevent the metals from settling on the sediments with the decaying duckweed. The duckweed thus produced should under no circumstances be used in food production (Gijzen and Khondker 1997). As reported, heavy metals can be regained from the plant tissues through low temperature caronization (Niklas 1995). Potential applications for removal of chromium from wastewaters of leather processing industries or removal of arsenic for drinking water purification are worth investigating.

Toxins may enter a duckweed aquaculture systems not only through (industrial) wastewaters, but also through additional water resources such as surface or groundwater.

Compared to Swiss sewage sludge and compost standards, heavy metal analysis of a duckweed plug-flow lagoon using an anaerobic sedimentation pond for pretreatment in Bangladesh revealed acceptable concentrations of lead, cadmium, chromium, copper, nickel, mercury, and zinc in duckweed and in the sludge of the sedimentation pond (Iqbal 1995). The wastewater was of domestic origin. The sediment of the plug-flow was not analysed. The major sink for the aforementioned metals was the sludge of the sedimentation pond and not the duckweed, except for copper and arsenic which showed higher concentrations in duckweed than in sludge. High concentrations of arsenic in duckweed used as fish feed, are of serious concern as it is highly toxic for humans. Arsenic was introduced into the system through the additional supply of groundwater during the dry season. The duckweed produced during the dry season, when sewage is diluted with groundwater, should no longer be fed to fish until the risk of arsenic accumulation in the food chain is assessed. Geogenic arsenic contamination of groundwater is a severe calamity in Bangladesh.

In case of nutrient depletion, the “polishing theory” sustains that starved plants begin to process great amounts of water in search of growth nutrients. In this process, they absorb virtually all chemical substances present in the wastewater. During this polishing process, organic toxins and heavy metals are most likely to be absorbed. It is interesting to note that this theory can only be partially supported by the study: concentrations of lead, chromium and nickel were about twice as high in duckweed harvested from the polishing zone (last section downstream of the plug-flow where nutrient depletion occurs) than in duckweed harvested at the inlet of the plug-flow (wastewater inlet). The cobalt and cadmium concentrations were about the same. For copper and arsenic, however, concentrations in duckweed were about five to six times higher at the plug-flow's inlet than at its outlet.

Organic toxins enter a duckweed treatment system mainly via the (industrial) wastewater, but also through external sources such as pesticides sprayed against duckweed pests (see Chapter Four, pp. 51), contaminated additional water resources, and to an unknown fraction also via rain and air deposits.

Biodegradation of a few organic compounds in duckweed systems was also reported. It is assumed that duckweed does not directly contribute to the biodegradation process, but indirectly via the provision of additional oxygen for associated bacteria. Anaerobic degradation of organic xenobiotics in the water column and the sediment of duckweed treatment systems is also likely to occur.

Certain organic xenobiotics may to some extent, undergo microbial degradation in duckweed systems.

Federle and Schwab (1989) reported the efficient biodegradation of alcohol ethoxylate and mixed amino acids by the microbiota associated with *Lemna minor*. Linear alkyl benzene sulphonate was not biodegraded by the same microbial population.

Mosquito and Odour Control

The results of several studies on the effects of duckweed on mosquito breeding appear to be contradictory (Gijzen and Khondker 1997). Positive, negative and no effects were reported by the references in Landolt and Kandeler (1987). A positive effect of a duckweed cover on the decrease of mosquito larvae was reported for *S. punctata* (Furlow and Hays 1972), *L. minor* (Angerilli and Beirne 1980), *Wolffia* (Bentley 1910), and *Spirodela* (Culley and Epps 1973). The authors suggest that a complete duckweed cover acts either as physical barrier and hinders the mosquito larvae from reaching the surface for oxygen uptake, or that the plants release compounds which are toxic to the larvae (Bentley 1910, Judd and Borden 1980). A possibly reducing effect of duckweed on mosquito breeding may positively contribute to the acceptance of duckweed farming systems in areas where mosquitoes are a nuisance and a vector of serious human diseases like malaria or dengue.

There are indications that a dense mat of duckweed acts as physical and chemical barrier against mosquito larvae and odour development.

The gaseous products resulting from anaerobic decomposition in the sediment and water column are responsible for odour development. It is assumed that the aerobic duckweed mat acts as chemical and physical barrier against odours. Hydrogen sulphide (H_2S) oxidises for example to sulphuric acid (H_2SO_4) within the aerobic plant mat (Lemna Corp. 1994).

Removal Efficiencies

Reliable data on removal efficiency in full-scale duckweed treatment systems is practically inexistent.

The most relevant study on removal efficiencies in a full-scale duckweed treatment system in a low-income country was published by Alaerts *et al.* (1996). The study focused on a 0.6 ha plug-flow sewage lagoon covered with *Spirodela* for 2000-3000 inhabitants in Bangladesh. The lagoon received the effluent of an anaerobic sedimentation pond with a HRT of 1-3 days. The plug-flow's depth increased from 0.4 to 0.9 m with a HRT of about 20 days. Table 3 shows the typical loading rates, influent and effluent concentrations, including reduction in concentration of the lagoon during the study period (dry/winter season).

Table 3. *Typical wastewater parameters of a duckweed-covered plug-flow lagoon during the dry/winter season in Bangladesh. The values in parentheses are based on a 4-year monitoring (1990-1994). Influent data was corrected for dilution effect caused by groundwater supply. Concentrations of NH_4^+ and NO_3^- are expressed in mg N/l. The concentration of o-PO_4^{3-} is given in mg P/l. Values were corrected for a leakage-free lagoon (Alaerts et al. 1996).*

Parameter	*Loading rate (kg/ha·d)*	*Influent (mg/l)*	*Effluent (mg/l)*	*Reduction in concentration (%)*
BOD_5	48-60	125 (80-160)	5 (8)	96 (90-95)
Kjeldahl-N	4.2	10.5	2.7	74
Total P	0.8	1.95	0.4	77
o-PO_4^{3-}	----	0.95 (0.5-2.5)	0.05 (0.05-1)	95 (90-95)
NH_4^+	----	8 (3-20)	0.03 (0.1-1)	99 (90-99)
NO_3^-	----	0.03 (0.05-1)	0.05 (0.05-1)	----

A duckweed-covered lagoon in Bangladesh treats domestic sewage of relatively low strength to a quality meeting tertiary wastewater effluent standards.

The system performs extremely well with regard to the studied chemical wastewater parameters and meets tertiary effluent standards.
Mention should be made that the lagoon suffered from substantial leakage during the dry season with a loss of about 30 % of total nutrient input. Furthermore, the influent BOD concentration was lower than typical values encountered in most developing countries, as a significant portion of the community's BOD discharge was not captured by the collection system.

The contribution of duckweed towards total nutrient removal in the system was around 46 % for phosphorous and about 42 % for nitrogen. When corrected for leakage, the authors calculated that duckweed harvest would remove 60-80 % of the total N and P load.

About 80-90 % BOD removal and about 90 % of total nutrient uptake by the duckweed were already reached within 7.3 days actual retention time, indicating that the system could accommodate higher organic and nutrient loads.

Table 4 contains promotional information by Lemna Corp. on removal efficiencies. This data has to be interpreted with reservation as Lemna Corp. uses artificial aeration for gross BOD and TSS reduction, and nitrification reactors with fixed media for bacterial growth as modular options for their treatment facilities.

Table 4. *Reported treatment efficiencies of Lemna Corp. facilities (Lemna Corp. 1994).*

Parameter	*Influent*	*Effluent*	*Removal (%)*
BOD (mg/l)	200-600	<30-10	85-98
TSS (mg/l)	250-700	<30-10	88-98
Ntot (mg/l)	40-80	<20-5	50-93
NH_3-N (mg/l)	10-50	<10-2	0-96
Ptot (mg/l)	10-20	<5-1	50-95

Table 5 lists nitrogen and phosphorous uptake rates for duckweed as reported by different authors. The results are, however, not comparable due to differences in climate, operating conditions, incomplete mass balances, and species.

Table 5. *Nitrogen and phosphorous uptake rates (g/m^2·d) by duckweed (Gijzen and Khondker 1997, completed).*

Region	*Species*	*N uptake (gN/m^2·d)*	*P uptake (gP/m^2·d)*	*Reference*
Italy	*L. gibba / L. minor*	0.42	0.01	Corradi *et al.* (1981)
CSSR	Duckweed	0.2	------	Kvet *et al.* (1979)
USA	*Lemna*	1.67	0.22	Zirschky and Reed (1988)
Louisiana	Duckweed	0.47	0.16	Culley *et al.* (1978), Culley and Myers (1980)
Minnesota	*Lemna*	0.27	0.04	Lemna Corp.
Florida	*S. polyrrhiza*	------	0.015	Sutton and Ornes (1977)
Florida	*S. polyrrhiza*	0.15	0.03	Reddy and DeBusk (1985)
India	*Lemna*	0.50-0.59	0.14-0.3	Tripathi *et al.* (1991)
Bangladesh	*S. polyrrhiza*	0.26	0.05	Alaerts *et al.* (1996)

The area required for phosphorous removal is greater than for nitrogen removal. A reduction of the total phosphorous level to 1 mg/l, as proposed for strict water effluent standards in the USA, is unlikely to be achieved with duckweed alone (Culley and Myers 1980), as duckweed is unable to significantly reduce nutrient concentrations in waters with N and P levels below 4 mg/l (Rejmankova 1982). As phosphorous is mostly the limiting factor (Landolt 1996), P reduction to 1 mg/l may require a supplementary addition of N (Koles *et al.* 1987) or the use of a mixture of plants with similar climatic but different nutrient requirements (see Chapter Four, pp. 47).

Reduction of total P concentration to 1 mg/l is unlikely to be achieved without supplementary addition of nitrogen, as phosphorous is mostly the limiting factor for duckweed growth.

Comparison of Duckweed Systems with Other Treatment Systems

Duckweed treatment systems are less robust and simple to operate than waste stabilisation ponds. However, the generation of valuable biomass may offer a competitive advantage of duckweed systems over waste stabilisation ponds, and make up for their highly labour-intensive operation disadvantage.

Comparison with Waste Stabilisation Ponds

Where land is available at reasonable costs, waste stabilisation ponds are usually the wastewater treatment method of choice in warm climates (Mara 1976, Arthur 1983). They should be arranged in a series of anaerobic, facultative and maturation ponds with an overall HRT of 10-50 days, depending on temperature and required effluent quality. Simplicity, low cost and high efficiency of stabilisation pond systems compete with the generation of a net income derived from a qualitatively high feedstuff obtained from duckweed treatment systems. The disadvantage of both systems is their large land requirement. Table 6 compares the two types of pond systems.

Table 6. *Comparison between waste stabilisation ponds (WSP) and duckweed treatment systems (WHO 1989, Alaerts et al. 1996, Asano 1998).*

Criterion	*WSP*	*Duckweed treatment system*
Robustness	• Extremely robust • High ability to absorb organic and hydraulic shocks	High BOD loads need appropriate pretreatment
Capital costs	Low	25% higher than for WSP (*Source:* PRISM)
Labour requirements for operation and maintenance	• Low labour requirements • Unskilled, but supervised labour is sufficient • Extreme simplicity of O&M	• Highly labour intensive • Requires skilled labour • Sophisticated management necessary
BOD removal efficiency	>90%	>90%
Nutrient removal efficiency	Ntot: 70-90%, Ptot:30-50%	Ntot and Ptot >70%
TSS removal efficiency	Low, because of algae in the final effluent	High, due to inhibition of algae
Pathogen removal efficiency	High	Mainly unknown, but good preliminary results
Valorisation of biomass	None	• Use as animal feed • Revenue generation

Comparison with other Aquatic Macrophytes

Various aquatic macrophytes were studied as low-cost options for combined secondary (BOD removal) and tertiary (nutrient and final pathogen removal) wastewater treatment and nutrient reuse. Most of the work was done on water hyacinth (*Eichhornia crassipes*), some focused on pennyworth (*Hydrocotyle umbellata*), water lettuce (*Pistia stratiotes*) and waterfern (*Azolla sp.*).

The advantages of duckweed over other water plants are the following:

- Duckweed grows rapidly and is capable of nutrient uptake under a wide range of environmental conditions. Compared to most other aquatic plants, it is less sensitive to low temperatures, high nutrient levels, pH fluctuations, pest, and diseases (Dinges1982).
- Duckweed and its associated microorganisms are capable of absorbing and disintegrating a number of toxic compounds (Landolt and Kandeler 1987).
- Duckweed has been observed to efficiently absorb heavy metals (Landolt and Kandeler 1987). This characteristic may be detrimental if duckweed is used as feed.
- When grown on nutrient-rich waters, duckweed has a high protein and a relatively low fibre content and is, thereby, suitable for use as high-quality feed supplement.
- Harvesting of duckweed plants from the water surface is easy.
- A complete duckweed cover on the wastewater may efficiently prevent the growth of algae in the water body and result in a clear effluent of low TSS content.
- The presence of a dense duckweed mat has been reported to decrease and control the development of mosquito and odour in a wastewater body.

Landolt and Kandeler (1987) report that of all aquatic macrophytes, *Lemnaceae* have the greatest capacity in assimilating the macroelements N, P, K, Ca, Na, and Mg, however, this may not be supported by other literature sources. The data presented in Table 7 suggests that nutrient removal rates for duckweed are comparatively slower than for other aquatic plants and, therefore, longer retention times will be necessary to reduce nutrient concentrations to specific discharge limits. Gijzen and Khondker (1997) state that despite of contradictory data, it is an established fact that duckweed has a high nutrient removal efficiency.

The reported nutrient removal rates for duckweed may be lower than for other aquatic macrophytes used in wastewater treatment.

Table 7. *Nitrogen and phosphorous uptake rates by different floating aquatic macrophytes during summer and winter months in central Florida (DeBusk and Reddy 1987 and Reddy and DeBusk 1985).*

Plant	*N uptake ($g/m^2 \cdot d$)*		*P uptake ($g/m^2 \cdot d$)*	
	Summer	*Winter*	*Summer*	*Winter*
Water hyacinth	1.30	0.25	0.24	0.05
Water lettuce	0.99	0.26	0.22	0.07
Pennywort	0.37	0.37	0.09	0.08
Duckweed *(S. polyrrhiza)*	0.15		0.03	

Water hyacinth has been widely used for its extremely high nutrient uptake capacity (Tab. 7). However, no economically attractive application of the harvested biomass has so far been identi-

Duckweed treatment systems offer an alternative to water hyacinth systems in terms of tolerance to low temperatures, mosquito and odour problems, harvesting, nutritional value, use of biomass, and water loss through evapotranspiration. However, water hyacinth systems are more suitable for treatment of high BOD loads.

fied. In addition, water hyacinth only grows efficiently in tropical climates. Its use is restricted to regions with an even more pronounced temperate or seasonal climate than required for duckweed cultivation. A specific comparison of duckweed with water hyacinth for wastewater treatment and biomass use is presented in Table 8.

Table 8. *Comparison between duckweed and water hyacinth for wastewater treatment and biomass use as reported by various authors.*

Criterion	*Duckweed*	*Water hyacinth*
Tolerance to low temperatures	Higher	Lower, more restricted to warm climates
Nutrient uptake capacity	• High, but smaller contact area with the wastewater surface • High tolerance to high nutrient concentrations	Higher, due to greater contact area with the wastewater through root hairs
BOD removal efficiency	• Lower, because of smaller surface area for attached bacteria growth and lower oxygen supply • Lower tolerance to high BOD concentrations (<200 mg/l)	• Higher, because of larger submerged suface area for attached bacteria growth and higher oxygen supply to the root zone • Treatment of wastewater with very high BOD concentrations reported (>1000 mg/l)
Removal capacity of organic xenobiotics and heavy metals	High	High
Mosquito and odour problems	Probably positive effect on mosquito and odour control	In non-aerated and aerated aerobic systems a lesser problem. In facultative anaerobic systems a major problem
Harvesting	• Easier • Can be done manually (labour-intensive) and mechanically	• Complicated, because plants are bulky and interconnected over large distances • Mechanical harvesting equipment necessary
Nutrient profile (in % dry weight) when grown on wastewater	• Protein (30-45%) • Carbohydrate (35%) • Fiber (7-14%) • Fat (3-7%) • High vitamin and mineral content	• Protein (10-25%) • Carbohydrate (37-52%) • Fiber (17-20%) • Fat (1-3%)
Use of biomass	• High quality food supplement for fish and poultry • Land application • Composting • Methane and ethanol fermentation • Medicinal plant	• Hardly consumed at all by herbivorous fish • Technical processing feasible as animal food supplement, but unlikely because of high costs • Land application • Composting • Paper production • Biogas digestion
Water loss through evapotranspiration (ET)	Lower ET rates compared to open water (20-30% reduction)	Equal or increased ET rates compared to open water

Chapter Three

Public Health Aspects

Pathogens, heavy metals and organic toxins are the major public health aspects of concern. The, thereby, related health risks affect three main categories of people: Firstly, the workers who are in direct or indirect contact with the wastewater during operation and maintenance of a duckweed treatment system, and when handling and processing the system's outputs, such as duckweed, fish or sludge. Secondly, the consumers of the system's products, such as fish (mainly), but also chickens and ducks which are contaminated with pathogens and can contain high concentrations of toxins due to their bioaccumulation in the food chain. Thirdly, the population, especially children, living in the vicinity of the treatment ponds. Many people belong to more than one of the aforementioned categories, in some cases even to all three of them and will, thus, be at increased risk.

Particularly workers, but also the population residing near duckweed treatment systems and consumers of its products, are exposed to potential health risks through disease transmission by pathogens and toxic effects of heavy metals and organic xenobiotics accumulating in the food chain.

As it is difficult to entirely exclude direct contact with wastewater during work routine (Phots. 14 and 15), such as duckweed harvesting, dunking and transport, the pond workers belong to the highest risk category and are especially exposed to parasitic infections. Workers should be urged to adopt a high level of personal hygiene and receive basic health training to ensure that they understand the nature of risk and adopt available countermeasures. Pond design and surrounding vegetation should possibly allow operation and maintenance work to be carried out from the pond embankment (Phot. 16). Use of gloves, wellington boots and/or high-body waders is rare (Phot. 17), as they hinder

Workers should be urged to adopt a high level of personal hygiene.

Photograph 14: *Workers come into direct contact with diluted sewage of low strength during duckweed harvesting. They thoroughly wash themselves with soap and groundwater after harvesting routine is completed. So far, they have not shown any symptoms of disease transmission after 4 years of employment. Formerly, harvesting was performed from the plug-flow's embankment, but turned out to be too inconvenient and time-consuming.*

Photograph 15: *Filling of fresh duckweed into sacs using bamboo poles and wickerwork baskets. Workers come into direct contact with the organically polluted surfacewater used for duckweed cultivation (Taiwan 1977). (Photograph: Edwards et al. 1987).*

Photograph 16: *Fresh duckweed is placed into sacs and excess water squeezed out manually. Duckweed was grown on organically polluted surfacewater. The worker is using high wellington boots and gloves to protect himself from direct contact with the wastewater (City of Tainan, Taiwan). (Photograph: Edwards et al. 1987).*

Photograph 17: *Appropriate pond design and unconstrained access to the pond, allows manual harvesting of duckweed from the pond embankment, and prevents direct contact with the faecally polluted pond water (Thailand). (Photograph: Edwards et al. 1987).*

free and specific movements necessary for skilled duckweed farming, and because they are inconvenient to wear in warmer climates.

Some user groups in Bangladeshi villages have developed their own protective measures against contact with pond water: they form a kind of floating platform from bamboo poles or use a large bamboo stick for dunking (DWRP 1996). In some cases, boats are used for duckweed harvesting in larger ponds.

Viewed from a public health perspective, the limited number of health educated workers operating the system at increased risk will be of benefit to the population at large through the removal of faecal contamination. This is particularly true for community and (peri-)urban treatment systems.

To reduce the risk of pathogen transfer to consumers of animals fed on sewage-grown duckweed, removal of intestinal organs, repeated washing with safe water and thorough cooking is recommended.

Transfer of pathogens from animals fed with excreta-grown duckweed can be significantly reduced through the removal of intestinal organs, repeated washing with safe water and thorough cooking. However, traditional eating habits of raw meat or fish are very difficult to alter. The introduction of fish not eaten raw (for example tilapia) to such areas is also a possible alternative. However, even this preventive measure will not entirely eliminate customary practices, especially in small-scale subsistence aquaculture (WHO 1989). The physical separation of duckweed (grown on wastewater) and fish (raised in freshwater) cultivation in a two-pond system may lower health risks, as only indirect pathogen contamination of fish via duckweed is possible. However, due to bioaccumulation of toxic compounds, indirect wastewater use does not lower the risk of contamination.

Local residents should be informed that duckweed-covered ponds are fertilised with excreta and wastewater, in order to forbid their children from playing or swimming in them, and prohibit its use for bathing, cooking and other purposes. Warning notices should be posted by ponds adjacent to roads, especially if they are unfenced (WHO 1989).

Use of water for bathing, washing of clothes and cooking from excreta and wastewater-fertilised duckweed ponds should be prohibited.

Transfer of Pathogens

Pathogens of concern include helminths, bacteria, viruses, and protozoa. Almost no literature is available on the transfer of pathogens from duckweed farming systems (Gijzen and Khondker 1997). The few studies conducted so far have not revealed serious public health risks, however, further research is necessary and ongoing.

There is a priority research need to asses the risk of pathogen transfer in wastewater-duckweed-animal farming systems.

Feachem *et al.* (1983) mention three potential health risks associated with the aquacultural use of excreta and wastewater: a) passive transfer of excreted pathogens by fish and cultured aquatic macrophytes, b) transmission of trematodes whose life cycles involve fish and aquatic macrophytes (principally *Clonorchis sinensis* and *Fasciolopsis buski*) and c) transmission of schistosomiasis. These health risks are given for direct reuse of excreta and wastewater. In such systems, fish and aquatic macrophytes for human consumption are raised in ponds directly fertilised with excreta for which tentative microbiological pond water guidelines were set at 0 viable trematode eggs per litre and $<10^4$ faecal coliforms per 100 ml (WHO 1989). The same guideline values have to be considered when the final effluent of a duckweed treatment system is reused for irrigation purposes and fish pond topping. However, the potential health risks associated with the indirect reuse of excreta in duckweed farming systems are unknown. Microbiological quality guidelines are missing for different pathogens on excreta-grown duckweed fed to fish, poultry and mammals.

Tentative microbial guidelines for direct reuse of excreta and wastewater do exist, however, health guidelines for indirect reuse via duckweed are lacking.

Islam *et al.* (1996), who monitored faecal coliforms in a plug-flow lagoon covered with duckweed, observed a reduction from $4.57x10^4$/ml in the raw wastewater to values below 10^2/ml after treatment with duckweed (99.78 % removal). Despite these promising results, it does not provide any information on the relative contribution of duckweed on coliform removal or survival (Gijzen and Khondker 1997). Although different strains of *Vibrio cholerae,* including strains associated with cholera epidemics were isolated from duckweed, water, fish gills and intestine, and from the soil, the duckweed-wastewater-fish cultivation was considered a safe system (Kabir 1995, Islam *et al.* 1996).

Studies in Thailand and Bangladesh revealed promising results regarding faecal coliform removal in two-pond duckweed-fish systems.

Edwards *et al.* (1987) monitored aerobic bacteria (standard plate count), total and faecal coliforms, bacteriophages, *Salmonella*, and helminths in a duckweed-tilapia system using pour-flush water-sealed pit latrine effluent for duckweed culture at family/village level (Tab. 9). The authors concluded that the system was

A hundred-fold accumulation of bacteria by duckweed from excreta-loaded pond water was observed.

safe from a health point of view. Concentrations of faecal and total coliforms were about a hundred times higher on duckweed than in duckweed pond water, thereby indicating a concentration effect of bacteria by duckweed. Although the contents of the digestive tract of fish showed relatively high concentrations of aerobic bacteria and total and faecal coliforms, most samples of fish muscle tissue were negative for all microbiological tests, and judged safe for human consumption following gutting, washing and thorough cooking. Fish and duckweed were cultivated in separate ponds.

Table 9. *Concentrations of microorganisms monitored at village level excreta-fed duckweed-fish systems in Thailand. Spirodela polyrrhiza was selected in Trial 1, whereas a mixture of Lemna perpusilla and Wolffia arrhiza was used in Trial 2 for duckweed cultivation.*

Test	*Water-sealed pit*		*Duckweed pond water*		*Duckweed*		*Fish pond water*	
	Trial 1	*Trial 2*	*Trial 1*	*Trial 2*	*Trial 1*	*Trial 2*	*Trial 1*	*Trial 2*
Stnd. plate count (number/l)	$1.8x10^8$	$1.5x10^6$	$1.9x10^4$	$2.6x10^4$	$2.1x10^7$	$1.8x10^7$	$4.0x10^3$	$4.7 x10^3$
Total coliforms (MPN index/100 ml)	$6.7x10^7$	$1.1x10^7$	$1.5x10^4$	$1.2x10^4$	$1.8x10^6$	$1.5x10^6$	$3.4x10^3$	$2.9x10^3$
Faecal coliforms (MPN index/100 ml)	$3.6x10^7$	$8.1x10^6$	$7.0x10^3$	$6.0x10^3$	$5.4x10^5$	$4.8x10^5$	$2.0x10^3$	$3.3x10^2$
Bacteriophage (MPN index/100 ml)	$1.8x10^5$	$2.8x10^6$	$2.2x10^2$	$2.7x10^3$	2.8x10	$1.5x10^3$	7.1	3.0x10

Efficient coliform removal mechanisms of sunlight (UV) and high pH values, as encountered in stabilisation ponds, are absent in duckweed-covered lagoons for lack of light and algal growth.

Efficient removal of coliforms is known from conventional lagoon treatment systems without floating aquatic macrophytes. Direct sunlight and an increase in pH due to algal growth are believed to be possible factors responsible for coliform die off in such systems. These beneficial effects are not prevalent in a pond system completely covered by duckweed which cuts off light and suppresses algal growth. A study in Egypt by Dewedar and Bahgat (1995) actually showed no decline in faecal coliforms under a dense duckweed cover over a period of (only) 5 days, whereas faecal coliforms in dialysis sacs exposed to direct sunlight decayed at a rate of 0.177/h. However, an analysis of studies on removal performance of *E. coli* in lagoons covered by various species of floating macrophytes (Alaerts *et al.* 1990) suggests that water temperature and hydraulic retention time are more determining factors. The effects of sunlight, pH and other parameters on bacterial and viral removal have to be investigated further in comparative studies using ponds with and without duckweed (Gijzen and Khondker 1997).

Helminths and their ova usually settle and die off in pond systems with long hydraulic retention times. These processes will probably be similar in duckweed-covered ponds. The quiescent conditions under a duckweed cover possibly favour the settling of helminths and TSS (Gijzen and Khondker 1997).

The quiescent conditions prevalent under a duckweed cover are believed to favour the sedimentation of helminths and their ova.

Transfer of Heavy Metals and Organic Compounds

As clearly shown, *Lemnaceae* can tolerate and accumulate high concentrations of heavy metals and organic compounds at accumulation factors ranging between multiples of 10^2 and 10^5.

Little specific information is available on the health risks associated with bioaccumulation of toxins in fish and other animals fed on duckweed grown in (industrial) wastewater. Krishnan and Smith (1987) report acceptable levels of heavy metals and pesticides in fish grown in sewage stabilisation ponds. Nevertheless, a potential health risk through bioaccumulation of toxins must be assumed even if some animals such as fish possess specific proteins which bind and eliminate certain heavy metals or metabolise toxins.

A potential health risk through the transfer of organic and inorganic toxins by animals consumed must be assumed due to high accumulation of such compounds in the duckweed feed.

From a health point of view, a strict separation of domestic and industrial wastewaters containing critical substances for duckweed culture is recommended if possible. The duckweed cover or sections of it grown on wastewater contaminated with heavy metals and organic toxins should, under no circumstances, be used anymore for food production, but rather be disposed off as safely as possible for example in bottom-sealed landfills.

Chapter Four

Particular Growth Constraints

Several problems partially limiting duckweed cultivation have emerged in practice. The major ones, as aforementioned, are drying up of ponds during the dry season and lack of water. This leads to wide seasonal variations of duckweed productivity and wastewater treatment efficiency. A second major problem is caused by the insufficient supply of nutrients required at relatively high concentrations for the rapid growth of duckweed. Other practical problems occasionally encountered are algal blooms, insect and fungal infestations and contamination of ponds by other aquatic macrophytes.

Insufficient Supply of Nutrients and Alternative Nutrient Sources

Insufficient nutrient supply was reported as a major growth constraint in two studies at rural level in Thailand (Edwards *et al.* 1987) and Bangladesh (DWRP 1996) using family latrine effluent as a nutrient source. Low nutrient concentrations are a minor problem in well-dimensioned community and peri-urban facili-

An insufficient supply of nutrients is a major problem, particularly at village level, since relatively high nutrient concentrations are required for duckweed growth.

ties where nutrient availability is higher and more regular. *Lemnaceae* need relatively high concentrations of nutrients for optimal growth (Tab. 10).

Table 10. *Range of nutrient concentrations in waters with Lemnaceae (Landolt 1996). Chemical elements in mg/l, conductivity in µS/cm.*

Parameter	*Absolute range*
pH	3.5 - 10.4
N	0.003 - 43
P	0.000 - 56
K	0.5 - 100
Conductivity	10 - 10900
Ca	0.1 - 365
Mg	0.1 - 230
Na	1.3 - >1000
HCO_3	8 - 500
Cl	0.1 - 4650
S	0.03 - 350

Phosphorous is mainly the limiting factor for duckweed growth.

Nutrient uptake is highest at relatively high concentrations of nutrients. At nitrogen and phosphorous concentrations below 4 mg/l, however, nutrient uptake strongly declines (Rejmankova 1982). Edwards *et al.* (1992) observed that pond water with less than 3 mg/l TKN and 0.3 mg/l TP did not support normal growth of *Lemna perpusilla* and *Spirodela polyrrhiza*. The limiting factor in waters for Lemnaceae growth is mainly phosphorous (Landolt 1996). Long-term growth of *Spirodela polyrrhiza* is, for example, only possible with a minimum phosphorous concentration of 0.4 mg/l (Lueoend 1983).

The reason for the comparatively high nutrient demand of duckweed resides in the fact that the nutrients are absorbed by the lower surface of the fronds which are rather small compared to that of the root hairs of other plants (Landolt and Kandeler 1987).

A mixture of aquatic plants, including different duckweed species, with similar climatic requirements but different nutrient level demands is suggested for nutrient removal at limiting phosphorous concentrations and continuous biomass production under conditions of low nutrient supply.

Landolt (1996) suggests the use of a mixture of plants with similar climatic requirements but lower nutrient level demands, such as for example different duckweed species (*L. minuta*), *Azolla*, or *Salvinia*, as a possible solution for nutrient removal at low concentrations. This, of course, would also be an option to sustain plant production during periods when nutrient supply is lower. Moreover, Zirschky and Reed (1988) assume that a mixture of different species is less susceptible to diseases and pests than a monoculture.

Natural selection generally shifts the composition of the plant community to the one best suited to the prevalent climatic and nutrient conditions. In Bangladesh for example, the growth of *Azolla* was observed in excreta-fed duckweed ponds at village level. The mixture of duckweed and *Azolla* was used as feed for a carp polyculture. However, initial stocking with *Lemna* and *Spirodela* of a wastewater lagoon receiving domestic sewage from a community in the same country gradually shifted to a monoculture of *Spirodela*.

Lemna Corp. optimises treatment efficiencies of their systems by addition of nutrients and micro-nutrients. As phosphorous is the limiting factor for duckweed growth, the addition of N was suggested for reduction of total P down to 1mg/l (Koles *et al.* 1987) to meet U.S. EPA discharge limits for tertiary treatment.

Owing to their comparatively high N, P, K, and Ca contents, human faecal matter and, particularly, urine seem a most suitable nutrient source for duckweed cultivation (Tab. 11). Rashid (1993) showed that for cultivation of duckweed in a 1000 m^2 shallow pond, human faecal matter and urine from 29-50 people are sufficient to sustain a high duckweed production rate.

Human excreta, in particular urine, is a most suitable nutrient source for duckweed growth.

Edwards *et al.* (1992) used septage as a fertiliser for duckweed cultivation. The septage was pumped by municipal vacuum trucks from residential septic tanks in the city of Bangkok and transported to the experimental ponds at AIT, where it was directly loaded without further treatment at weekly intervals into four 200 m^2 (20x10m) ponds at a rate of 2 m^3 septage per 200 m^2. The municipal septage, with a mean 1.9 % dry matter, 941 mg/l TKN, and 119 mg/l TP content, was reported to be an effective fertiliser for duckweed cultivation.

Low-strength septage was reported to be an effective fertiliser for duckweed cultivation.

The sole use or the addition of inorganic chemical fertilisers like urea (as nitrogen source), TSP (triple super phosphate as a source for both phosphorous and calcium), MP (muriated potash as a source for potassium), and unrefined sea salt (as a source for trace elements) for duckweed cultivation is practised in Bangladesh. This may be a solution for short periods of acute nutrient shortage in the waste streams, however, it increases costs significantly in the long run.

Various other readily biodegradable organic wastes with a sufficiently high content of nutrients could be potentially used in addition to human excreta for duckweed cultivation (Tab. 11). Wastes from kitchen and bathroom, food, dairy and fish processing industries, from slaughter houses, urban refuse, animal manure, biogas effluents, composted agricultural and market wastes, etc. are mentioned as potential nutrient sources (Gijzen and Khondker 1997). The same authors also suggest the use of inorganic and nutrient-rich waste streams originating from fertiliser industries (ammonium production), soap factories, pharmaceutical companies, etc.

Various readily biodegradable organic and inorganic wastes, containing a high level of nutrients, are potential sources of nutrients for duckweed cultivation.

The choice of (additional) nutrient sources is largely dependent on the local situation pertaining to available quantity, quality, degree of required pretreatment, and market value.

***Table 11.** Moisture, organic and mineral content of some organic wastes expressed in % dry matter (Gijzen and Khondker 1997).*

Nutrient Source	*Moisture*	*Dry org. matter*	*C*	*N*	*P_2O_5*	*K_2O*	*CaO*	*Reference*
Human faecal matter	65-80	88-97	40-55	5-7	3-5.5	1-2.5	4-5	Rashid (1993)
Human urine	93-96	65-85	11-17	15-19	2.5-5	3-4.5	4.5-6	Rashid (1993)
Urban refuse	10-60	25-35	12-17	0.4-0.8	0.2-0.5	0.8-1.5	4-7.5	Rashid (1993)
Water hyacinth compost	85-95	_	_	1.9	1	2.9	4.6	Haider *et al.* (1984)
Cow dung (fresh)	85	_	_	0.4	0.02	0.1	_	Quddus and Talukder (1981)
Cow dung (compost)	_	_	_	0.5	0.3	0.2	0.3	Haider *et al.* (1984)
Pig manure (fresh)	80	_	_	0.55	0.5	0.45	_	Quddus and Talukder (1981)
Poultry (fresh)	_	_	_	1.6	1.5	0.85	_	Quddus and Talukder (1981)
Digester effluent (charged with pig manure)	_	6.5	_	3.4	_	_	_	Rodriguez and Preston (1996)

Ammonium concentrations above 50 mgN/l combined with pH values above 8 were reported to inhibit duckweed growth.

Not only the shortage of nutrients can limit duckweed growth, but also an oversupply of nitrogen at higher pHs. Koles *et al.* (1987) observed an important duckweed die off at ammonium-N concentrations above 50 mg/l, especially at pHs above 8. At high pHs, ammonium is transformed into the gaseous ammonia (NH_3) which is toxic to duckweed. Therefore, high concentrations of NH_4^+ at high pHs should preferably be avoided by dilution and pH buffering.

Algal Blooms

Algal blooms resulting from an incomplete duckweed cover and allowing penetration of sunlight into the water column, may cause severe damage and even duckweed die off.

Light penetration in the water column and subsequent competition of nutrients and space by algae can become a nuisance when the duckweed mat is incomplete due to disturbances or poor growth. The amount of duckweed harvested is an important factor in algal blooms. If too much duckweed is harvested, algae may start to grow. Refer to Chapter Two, pp. 30, for more detailed information on harvesting frequency and quantity.

Edwards *et al.* (1987) reported that the filamentous green alga *Spirogyza* bloomed in duckweed ponds fed with family latrine effluent. The farmers removed the filamentous algae manually, but the algae grew rapidly, became entangled with the duckweed roots and the duckweed fronds turned in colour from green to yellow. In several ponds, duckweed stopped growing and died. Although the ponds were cleaned from dead duckweed and algae and restocked with healthy duckweed, algal blooms reoccurred in most cases.

In another study (Edwards *et al.* 1992), algal blooms of both filamentous algae (mostly the blue-green alga *Oscillatoria* and the green alga *Oedogonium*) and phytoplankton (mostly the blue-green alga *Microcystis*) were reported as one of the most important factors constraining growth of duckweed with septage. The former was more harmful to duckweed as it clogged and wrapped itself around plant roots, causing the fronds of duckweed to shrivel and finally die. Attempts were made to kill algae by the algicide copper sulphate at a concentration of 2 mg/l. Algal growth was inhibited, but duckweed turned yellowish in colour. By changing the harvesting strategy, to maintain an almost complete duckweed cover on the pond surface, algal blooms did not reoccur. However, when algal infestation became severe, it was necessary to clear the pond and restock it with fresh duckweed.

Similar problems with filamentous algae were reported by DeBusk *et al.* (1976) and Lin (1982).

Insect and Fungal Infestation

Insect larvae and fungal infestation may cause severe damage and even death of duckweed.

Though duckweed growth is reported to be less sensitive to pests and diseases compared to most other aquatic plants (Dinges 1982), insect infestation can cause severe damage and even death of the plants. Fungal infestation inhibits growth.

A study in Thailand revealed that occasional insect infestation by larvae of *Nymphula* (Order Lepidoptera, Family Pyralidae) or/and by the waterlily aphid *Rhopalosiphum nymphaeae* (Order Homoptera, Family Aphididae) caused heavy damage to duckweed. Infestation by *Nymphula* was more frequent than by aphids. In one case, *Nymphula* infestation caused the death of plants within two weeks. Insecticide was applied to duckweed whenever insect infestation was observed and carried out weekly until the infestation was under control. Sevin-85 (carbaryl) at 5 g/5 l, dimethoate at 7.5 ml/5 l, ambush-100 (pyrethroid) at 5 ml/5 l water were alternately used to prevent insect resistance (Edwards *et al.* 1987).

In the same study, fungal infestation occurred in many ponds and inhibited the growth of duckweed. The fungal infestation resulted in a leaf spot disease and was probably caused by *Mylothecium,* which is also a parasite of the aquatic mosquito fern, *Azolla*. Infestation was brought under control by a weekly application of the fungicide Thane-45 (carbamate) at a concentration of 7.5 g/5 l water.

Insect (and possibly fungal) infestation by lepidoptera larvae (summer) and aphids (winter) was reported to affect duckweed yields at irregular intervals, causing decreased duckweed production in Bangladesh. At demo farm level, insect infestation was controlled by alternate application of different insecticides like Malathion and Nogos. At rural level, farming groups mentioned insect damage and diseases as the third reason for seasonal variations in duckweed production after lack of water and high temperatures (DWRP 1996).

Farmers, who commercially cultivated duckweed in Taiwan, reported that insects cause no problems to the crops and regarded insect damage as unimportant (Edwards *et al.* 1987).

Application of biocides to control insect and fungal infestation of duckweed is critical due to their extremely high and rapid uptake by duckweed and possible transfer into the food chain. Pesticides designed for agricultural use may behave differently in aquatic systems.

Application of insecticide and fungicide does indeed represent a health risk, since lipophilic organic compounds are known to bioaccumulate in the lipids of the cell membranes of duckweed and to excrete inside the cells. *Lemna minor,* for example, accumulates DDT up to 800 times (Vrochinski *et al.* 1970 in Landolt and Kandeler 1987). Studies of other pesticides revealed that the concentrations were about 1000 times higher in duckweed than in water (Landolt and Kandeler 1987). When fed to animals like fish, the residual pesticide can penetrate the food chain.

Regular residue analyses of duckweed and fish are recommended, yet they are often not always feasible in low-income countries for lack of necessary sophisticated analytical equipment. Biocides should be correctly applied (dosage, protective measures during application) and plants harvested several days after biocide application.

Although no alternative strategies for duckweed pest control have been developed so far, entomological research is regarded as an important element in research proposals by scientific groups in the Netherlands and Bangladesh for example. A mixture of several duckweed species, as recommended by Zirschky and Reed (1988), would be less susceptible to infestations and diseases than a monoculture.

Chapter Five

Use of Biomass

The low fibre content and high nutritional value of duckweed makes it a quality feed or feed component for animals and possibly also for humans. On account of its high moisture and nitrogen content, it can also be used as organic fertiliser in agriculture by direct land application or via composting.

Application of duckweed as fish feed is the most frequent and best studied use of duckweed. Moreover, duckweed is also known as a feed for ducks, chickens, freshwater prawns, pigs, edible snails, horses, and ruminants like cattle and sheep, however, information on these applications is scarce.

Duckweed is mainly known as fish feed, but also as feed for ducks, chickens, prawns, pigs, snails, horses, and ruminants.

Nevertheless, the following factors restrict the use of sewage-grown duckweed for feeding and fertilising purposes (Gijzen and Khondker 1997):

- Due to efficient absorption of heavy metals and other toxic compounds, duckweed should be cultivated on wastewaters with extremely low concentrations of such compounds.
- Its high moisture content (about 95 %) increases its handling, transport (Phot. 18) and drying costs. This fact is less important in integrated systems where fresh duckweed is used on site.
- The genera *Lemna* and *Spirodela* may contain high amounts of calcium oxalate which may limit the use of certain species for non-ruminant or for human consumption.

Photograph 18: *Freshly harvested duckweed filled into 60 kg sacs awaiting collection by truck for transport to fish and duck farms (City of Chiai, Taiwan). (Photograph: Edwards et al. 1987).*

Due to preservation, storage and transport constraints the current use of fresh duckweed is often restricted to areas located near the farm. Depending on the target animal, duckweed can be fed fresh as the only feed or, as in the case of most animals, in combination with other feed components. Almost all the animals mentioned in the following chapters feed on fresh duckweed with the exception of poultry, such as chickens, which probably have to be offered dried duckweed.

Due to preservation and storage constraints, duckweed is mainly fed to animals in its fresh state, mostly as feed component of a mixed diet. Poultry will probably, have to be fed on dried duckweed.

Fresh duckweed can be stored temporarily in a cool, humid place, such as in a small tank or pool. The fresh material, which will begin to ferment at high temperatures after a few hours, can be preserved for several days if kept cool and damp (Skillicorn *et al.* 1993).

Small-scale solar drying is feasible, UV light, however, degrades the valuable pigments in duckweed.

Small-scale solar drying is possible by spreading the fresh material on the ground and exposing it to sunlight. UV light, however, degrades the valuable pigments in duckweed. Pigment losses of about one-third to one-half may be expected after two days in the sun (Skillicorn *et al.* 1993).

Lemnaceae have a very high moisture content. Therefore, desiccating duckweed with purchased energy is economically not feasible as large amounts of energy are required.

Developments of feasible procedures for large and medium-scale solar drying and pelleting are lagging behind. According to some critics, drying of duckweed, as component part of dry pelleted feed, is not economically possible. However, its use in moist pelleted feed should be studied (Edwards *et al.* 1987). Desiccating duckweed, whose moisture content amounts to about 92 to 94 %, with purchased energy, such as gas, oil, electricity or biomass, is not economically feasible as large amounts of expensive energy are required. The economic potential of the plant may not be fully realised until it can be economically reduced to a dried, compact commodity (Skillicorn *et al.* 1993). This requires solar drying and either pelleting, powdering or other potential preservation methods like ensilaging.

Duckweed is potentially suitable for pelleting.

The waxy coating on the upper surface of duckweed plants is a good binding agent for pelleting. It can be stored for five or more years in the form of dried pellets. Sealable, opaque plastic bags are recommended for long-term storage to protect dried pellets from humidity, insects, vermin, and direct sunlight (Skillicorn *et al.* 1993).

Nutritive Value and Productivity

In comparison with the FAO amino acid reference pattern, duckweed protein is of high quality and could improve the protein-supply in countries where people suffer from protein malnutrition.

The amino acid profile of duckweed compares favourably with the FAO reference pattern with the exception of methionine, which reaches only half of the percentage of the reference pattern, and tryptophane of which only traces can be detected (Russoff *et al.* 1980). Since duckweed protein resembles more closely animal protein (as found in meat, fish, eggs, and dairy products), it offers an effective supplement to grains for animal and human consumption, especially in countries where people suffer from protein malnutrition.

Duckweed contains valuable vitamins, pigments and minerals.

Other important components like minerals and vitamins are also found in *Lemnaceae*. Landolt and Kandeler (1987) reported that duckweed contains about 40 different minerals, including vitamins A, B_1, B_2, B_6, C, E, and PP. Especially the contents of vitamin E (20-40 ppm) and PP (40-60 ppm) are remarkably high (Muzaffarov *et al.* 1971). The fairly high concentrations of the pigments xanthophyll and carotene (Truax *et al.* 1972) deepen the yolk colour of chicken eggs and the skin colour of red tilapia.

Grown under nutrient-rich conditions, protein makes up between 30 and 40 % of the dry matter content, with average yields under real-scale conditions ranging somewhere between 10 to 30 t dry wt/ha·y (Tab. 12).

Table 12. *Duckweed productivity and protein content as reported by various authors in different parts of the world (Gijzen and Khondker 1997).*

Species	*Nutrient Source*	*Productivity (t dry wt/ha·y)*	*Protein (% dry wt)*	*Reference*
S. polyrrhiza	Domestic wastewater	35.5	_	Robson (1996)
S. polyrrhiza	Domestic wastewater	17-32	_	Alaerts *et al.* (1996)
L. minor	UASB - effluent	10.7	28.9	Vroon and Weller (1995)
L. gibba	Municipal waste	_	11.5-23	Oron *et al.* (1987)
L. gibba	Pretreated raw domestic sewage	55	30	Oron and Wildschut (1994)
L. gibba *S. polyrrhiza*	Domestic wastewater	10.9-54.8	30-40	Oron (1986)
S. polyrrhiza *L. perpusilla* *W. arrhiza*	Septage from septic tank	9.2-21.4	24-28	Edwards *et al.* (1992)
L. perpusilla	Septage from septic tank	11.2	_	Edwards *et al.* (1990)
Lemna	Domestic wastewater	26.9	37	Zirschky and Reed (1988)
Lemna	Domestic wastewater	_	40	Logsdon (1989)
S. polyrrhiza	Sewage effluent	14.6	29.6	Sutton and Ornes (1975)
S. polyrrhiza	Domestic sewage	17.6-31.5	30	PRISM valid. report
	Inorganic fertiliser	12.2-21.1	27	PRISM valid. report

Annual dry matter yields of duckweed under real-scale conditions in warmer climates range between 10 and 30 tons per hectare.

Productivity reported by various authors in different parts of the world varies from values as low as 2 t dry wt/ha·y to values over 50 t dry wt/ha·y. The wide variations are due to differences in species, climatic conditions, size of cultivation area, nutrient supply, and management. Some of the higher yield values are extrapolated from short-term and small-scale experimental systems operated under controlled growth conditions. These are not representative of real-scale conditions prevailing throughout the year. As aforementioned, by assuming a sufficient nutrient and water supply, an annual dry matter yield of about 10-30 t/ha, therefore, seems more realistic. Culley *et al.* (1978) report that best long-term productivities under natural conditions and in warm climate do not exceed 25 t dry wt/ha·y. Edwards *et al.* (1992) report that a productivity as high as 20 t dry wt/ha·y is perhaps a more realistic value for well-managed systems in the tropics.

Duckweed can yield about ten times more protein per hectare and year than soybean!

Assuming a mean annual yield of 17.6 t dry wt/ha·y, with a protein content of 37 % dry weight, a protein production of about 6.5 t/ha·y can be obtained. This per hectare protein yield is far higher than for most other crop plants, and about 10 times that of soybean (Tab. 13). This remarkable value for duckweed is not only attributed to its high growth rate and high protein content, but also to the fact that the entire biomass of duckweed is used as compared to only the seeds for most crops (Gijzen and Khondker 1997).

Table 13. *Comparison of annual and per hectare protein yields of duckweed and selected crops (adapted from Hillman and Culley 1978 in Gijzen and Khondker 1997).*

Plant/Crop	*Yield (t dry wt/ha·y)*	*Crude Protein (% dry wt)*	*Relative protein production**
Duckweed	17.6	37	100
Soybean	1.59	41.7	10.2
Alfalfa hay	4.37-15.69	15.9-17	11.4-38.3
Peanuts	1.6-3.12	23.6	5.7-11.3
Cottonseed	0.76	24.9	2.9

*Relative protein production: duckweed set at 100 units = 6.51 t dry wt/ha·y

Duckweed for Human Consumption

Wolffia arrhiza has traditionally been eaten in Myanmar, Laos, and northern Thailand (Bhanthumnavin and McCarry 1971). The duckweed cultivated in these areas is sold on local markets, however, since it is regarded as the “poor man’s food”, interest is apparently declining.

Use of duckweed for human consumption is not very popular as (pathogenic) organisms associated with duckweed are difficult to separate from the plants.

The use of *Lemnaceae* for human consumption has surprisingly not spread to other regions of the world. A possible explanation could be its high content of crystallised oxalic acid which has a negative effect on the taste. Another factor contributing to the low interest in duckweed as a potential food product for human consumption could be attributed to the fact that it is difficult to separate associated (pathogenic) organisms such as worms, snails, protozoa, and bacteria from the plant (Gijzen and Khondker 1997).

Duckweed as Fish Feed

Use of duckweed as fish feed is by far the most widespread application. Duckweed can be fed fresh as the only feed, or in combination with other feed components to a polyculture of Chinese and Indian carp species (Phot. 19) and tilapias (Phot. 20). Especially herbivorous and omnivorous fish such as grass carp (*Ctenopharyngodon idella*), silver barb (*Puntius gonionotus*) and tilapias (*Oreochromis sp*.) readily feed on duckweed.

Fresh duckweed is readily consumed by grass carp and tilapia.

Photograph 19: *Harvested Indian carp (Catla catla), 1.5 kg each, fed exclusively on duckweed. (Photograph: PRISM).*

Photograph 20: *Harvested tilapia (Oreochromis sp.) fed on sewage-grown duckweed and supplementary feed (Bangladesh).*

However, successful pisciculture on its own requires a high degree of skill, combining both know-how and experience. A delicate balance between fish density, feed and fertiliser inputs, and sufficient amounts of dissolved oxygen have to be maintained to reach high fish yields. The combination of duckweed and fish cultivation makes the system even more complex with strong interdependencies for example between availability and quality of duckweed feed and fish growth.

Combined wastewater-based duckweed-fish cultivation requires a high degree of skill.

Conversion efficiency of duckweed biomass into fish is represented by the feed conversion ratio FCR (g dry duckweed per g fish fresh weight). Table 14 contains an overview of FCRs as reported by various authors.

Table 14. *Duckweed to fish feed conversion ratios (in Gijzen and Khondker 1997).*

Duckweed species	*Fish species*	*FCR*	*Reference*
Lemna	Tilapia	1.6 to 3.3	Hassan and Edwards (1992)
Unknown	Grass carp 3g	1.6	Shireman *et al.* (1978)
Unknown	Grass carp 63g	2.7	Shireman *et al.* (1978)
Unknown	Unknown	1.1 to 5.3	Sutton (1976)
Unknown	Unknown	1.55 to 4.07	Baur and Buck (1980)
Unknown	Unknown	3.1 to 3.15	Hajra and Tripathy (1985)
Spirodela	Carp polyculture	1.2 to 3.3	PRISM, Bangladesh

Pisciculture using duckweed as the only feed was reported to be feasible, however, duckweed as a sole feed for fish tends to be a diet too low in fats and carbohydrates. Good results were obtained with a dry weight feed mixture of 50-60 % duckweed and 40-50 % supplementary carbohydrate-rich feed.

The reason for the very low values obtained by PRISM Bangladesh can be attributed to the addition of inorganic fertiliser to the fish ponds. Moreover, duckweed was not applied as a sole feed, but added to conventional feeds like oil cake and wheat bran. Though carp polyculture using duckweed as the only feed input was reported to be feasible (Phot. 21), there is some evidence that duckweed as a sole feed for fish is a diet too low in fats and carbohydrates. Recent findings for a balanced diet suggest a mixture of 50-60 % (dry weight) duckweed and 40-50 % (dry weight) fat and carbohydrate-rich feed (Gijzen, personal communication). Also Hassan and Edwards (1992) reported a decrease in crude lipid content of tilapia carcass, possibly attributed to the low fat content of fed duckweed (3-5 % of dry wt). They suggested energy-rich supplementary feed, such as rice

Photograph 21: *Harvesting of various carp species fed exclusively on duckweed. The vigorously jumping fish indicate healthy fish and good pond water quality. (Photograph: PRISM).*

bran, to avoid body lipid degradation as an energy source for metabolism.

With an average FCR value of 2.5 and a duckweed yield of 20 t(dry wt)/ha·y, a production of 8 t/ha·y of fish may be expected (Gijzen and Khondker 1997). This compares favourably with typical carp yields of 2 to 8 t/ha·y from well-managed, semi-intensive carp farms in Asia (Skillicorn *et al.* 1993).

Potential fish yields from carp polycultures fed on duckweed as feed supplement, compare favourably with carp yields obtained in Asia.

The smaller duckweed species like *Wolffia, Wolffiella* and *Lemna* were reported to serve as feed for fry and fingerlings. In China for example, excreta-grown *Wolffia* and *Lemna* are mainly used as feed for grass carp fingerlings (Edwards 1990).

Production of duckweed and fish in the same pond seems attractive in areas where land availability is low or competition for water bodies is high. Since a dense duckweed cover may reduce the oxygen supply to the water, this application should be tested with fish species tolerating low oxygen concentrations (Gijzen and Khondker 1997). The possible reducing effect on pathogen transfer in a two-pond system would be excluded in a one-pond system. The health hazards from a one-pond system are likely to be similar to those encountered with direct excreta reuse piscicultural systems.

Duckweed as Pig Feed

The limited information available on the application of duckweed as feed for pigs is contradictory. Haustein *et al.* (1992) reported a reduced meat production and lower FCRs for pigs fed on duckweed whose protein content amounted to 23 % and fibre content to 7.5 % dry matter. Schulz (1962) and Galkina *et al.* (1965), however, demonstrated a clearly positive effect on the weight gain of pigs when duckweed was added as a supplement to the normal diet. Comparative experiments using conventional diets and diets supplemented with high-quality duckweed are imperative (Gijzen and Khondker 1997).

Whether duckweed is a suitable feed for pigs is currently unknown.

Duckweed as Poultry Feed

As aforementioned, chickens are preferably fed on dried duckweed. The effect of the addition of duckweed to the feed of chickens has been studied by various authors with conflicting results. The overall tendency seems to be that small amounts (2-25 % of total dry matter fed) of duckweed in the diet stimulate the growth of chickens, while higher additions (> 40 %) of duckweed tend to decrease weight gain (Haustein *et al.* 1988). Several authors reported an increase in weight by 10 to 32 % for chicken fed with small amounts of duckweed (2-5 %) in addition to their regular diet (Mueller and Lautner 1954, Muzaffarov *et al.* 1968, Naphade and Mithuji 1969, Taubaev and Abdiev 1973). Shahjahan *et al.* (1981) obtained very good results with a 10 % addition of *Spirodela* to a mixed chicken diet. Other authors, however, did not observe an increase in weight by the addition of duckweed

Small amounts of dried duckweed are a suitable feed supplement for chickens.

to the chicken diet. When high portions of the diet were replaced by duckweed (50 %), even negative effects were observed (Muztar *et al.* 1976, Johri and Sharma 1980). Further studies comparing the effects of different *Lemnaceae* species at different feeding levels are necessary to draw definite conclusion of the nutritional value of duckweed for chickens (Gijzen and Khondker 1997).

Observations in Bangladesh and reports from Taiwan (Edwards *et al.* 1987) clearly revealed that ducks readily feed on fresh duckweed, often directly from the pond surface (Phot. 22). Application of duckweed as feed for ducks is practised at least to some extent in rural areas (Gijzen and Khondker 1997).

Photograph 22: *Excreta-fertilised duckweed pond at village level in Bangladesh showing dense duckweed cover with ducks feeding on duckweed from the pond surface.*

Duckweed as Ruminant Feed

Duckweed was reported to be a suitable feed for ruminants, however, the contribution of duckweed protein in ruminant nutrition is doubtful, as it is readily fermented by microorganisms in the rumen.

Several feeding experiments with duckweed as feed additive in regular diets for both cattle and sheep have been conducted by various authors. Russoff *et al.* (1977, 1978) reported that up to 75 % of duckweed could be fed to Holstein cattle without affecting the taste of milk. The weight gain of calves fed with a mixture of duckweed (67 %) and silage of corn (33 %) showed a daily weight gain of 0.95 kg, compared to only 0.5 kg weight gain when fed on a concentrate/corn silage diet. Culley *et al.* (1981) calculated that a 3.1 ha surface area of duckweed cultivation could provide sufficient protein to feed 100 dairy cattle.

Taubaev and Abdiev (1973) reported an additional weight gain of up to 27 % and 14 % for ram and sheep, respectively, upon feeding the animals 0.5 kg/day *Lemnaceae* in addition to their regular diet.

Leng *et al.* (1995) mentioned that the contribution of duckweed protein in ruminant nutrition is doubtful, as the duckweed protein is readily fermented by microorganisms in the rumen, and the amino acid supply to the animal, thereby, minimised. Preliminary tests showed that it may be difficult to protect duckweed protein from digestion in the rumen.

Duckweed as Agricultural Fertiliser

Use of *Lemnaceae* as fertiliser and soil improver on fields and gardens was reported for Angola (Welwitsch 1859), China (Tai-Hsingh *et al.* 1975) and Mexico (Lot *et al.* 1979). According to Lot *et al.* (1979), application of duckweed eventually contributed to a superior soil texture, including an improved water and cation exchange, and resulted in an annual harvest of 4 crops of vegetables or corn.

Duckweed can be used as an organic fertiliser in agriculture by direct land application or via composting.

Chapter Six

Sociocultural Aspects

Besides skilful management, the feasibility and successful introduction of duckweed wastewater treatment/farming systems depends mainly on the acceptance and understanding of the technology by the user groups within a given sociocultural context. This chapter presents some country-specific experience with dissemination of duckweed aquaculture, and draws general conclusions where permissible. These general conclusions should be interpreted with caution, as cultural beliefs vary so widely in different parts of the world. Therefore, it is not possible to assume that existing practices of duckweed aquaculture can be readily transferred elsewhere.

Duckweed as a Novel Crop

With the exception of countries like Taiwan and China, where duckweed cultivation is traditional and has been carried out over decades, the introduction of duckweed as a novel and unknown crop is likely to be rejected at first. Duckweed farming is not only a novel farming method, but also a highly intensive one. Unlike traditional terrestrial crops, duckweed is an aquacultural crop. And unlike traditional crops requiring only sporadic attention, duckweed farming is a continuous process. The conventional agricultural cycle of planting, fertilising/crop maintenance, harvesting, processing, storage, and sale, spread over a growing season of a few months to two years, is compressed into a daily cycle in duckweed farming (Skillicorn *et al.* 1993). The initial rejection is likely to decrease with time. After about ten years of duckweed propagation in Bangladesh, the plant is now known throughout the country and accepted by rural farmers as a fresh feed component for pisciculture (PRISM unpublished).

Introduction of duckweed aquaculture as a novel farming method is likely to be initially rejected due to its labour-intensive, on-going and aquacultural nature.

Contact with Excreta and Wastewater

Human society has evolved very different sociocultural responses to the use of excreta, ranging from abhorrence through disaffection and indifference to predilection (WHO 1989).

In societies where excreta reuse is regarded as cultural or religious taboo, wastewater-based duckweed-animal farming is likely to be rejected.

In several African, American and European societies, human excreta is regarded as repugnant substances best kept away from the sense of sight and smell. Therefore, products which come into direct or indirect contact with excreta are likely to be considered as tainted or defiled in some way (WHO 1989). In such societies where excreta use is regarded as cultural or/and religious taboo, wastewater-based duckweed-fish farming is likely to meet with strong rejection.

In countries where excreta reuse is traditional, wastewater-based duckweed-animal farming may meet with less social resistance, however, farmers have to experience its advantages in order to give duckweed farming preference over established aquacultural techniques.

In contrast, both human and animal wastes have been used in aquaculture in countries like China, Japan and Indonesia. In such societies, intensive cultivation practices have evolved in response to the need of feeding a large number of people living in an area of limited land availability, and calling for the careful use of all resources available to the community, including excreta (WHO 1989). In such countries, excreta reuse through wastewater-based duckweed-fish farming will probably face less problems of social acceptance. However, the introduction of duckweed aquaculture as a novel farming method in societies where other (piscicultural) techniques have a long-lasting tradition, will probably be met with scepticism.

Indirect Excreta Reuse

Indirect reuse of excreta via duckweed may be of relevance to societies where direct reuse is socially unacceptable.

Edwards (1990) suggests that indirect reuse of excreta for food production could become of relevance to societies where direct reuse is socially unacceptable. Unlike direct excreta reuse, where fish is raised directly on human and animal wastes as practised for thousands of years in China for example, duckweed-fish production is physically separated by a two-pond system. As opposed to duckweed, fish raised for human consumption does not come into direct contact with the excreta. Therefore, duckweed acts as an intermediate in a lengthened food chain. Generally speaking, indirect excreta reuse involves two separate sequential processes; i.e., resource recovery using excreta and wastewater as fertiliser to cultivate duckweed, and resource use of the aquatic biomass in a separate system as animal feed to grow food for human consumption.

In Islamic societies, direct contact with excreta is abhorred since it is regarded as containing impurities (*najassa*) by Koranic edict. Its use is permitted only when the *najassa* have been removed (WHO 1989). Thus, it is possible that indirect use of excreta after treatment with duckweed will be met with less opposition. Of course, this cannot be generalised for all Islamic countries. The local sociocultural context will be the determining factor regarding acceptance or rejection of indirect excreta reuse through duckweed.

Village farmers in Bangladesh initially did not eat the fish, fed on excreta-grown duckweed which they produced.

The mainly Islamic villagers in Bangladesh initially rejected fish fed on duckweed-grown ponds fertilised with latrine effluents. Although the fish is raised indirectly on excreta, some farmers still do not eat the fish they produce themselves. Resistance decreased with time, however, it is likely to reappear when latrine-based duckweed-fish farming is introduced to villages where this farming method is unknown.

Positive Influence of Duckweed Farming on its Social Acceptance

Social acceptance of wastewater-based duckweed farming and its products may benefit from the potential advantages of the technology, such as income generation, improved nutrition and water quality, reduced odour problems, and possibly reduced mosquito breeding. Of course the opposite could also be true if for example a badly designed or operated system turns into a stinking and unpleasant site. Especially open sedimentation lagoons may produce bad odours and are likely to be met with the objection of those who live or work nearby.
In this context, it is interesting to note that a duckweed treatment system in Mirzapur (Bangladesh) has become a meeting place for the local population who enjoys its pleasant and park-like atmosphere (Skillicorn *et al.* 1993).

Income generation, improved nutrition and water quality, and reduced mosquito breeding may have a positive effect on social acceptance of wastewater-based duckweed farming.

Chapter Seven

Economic Aspects

Literature on reliable economic data analyses of real-scale duckweed farming is very scarce. Only a few economically feasible examples of sewage and excreta-based duckweed farming systems used at urban, demo farm and rural level were reported from Taiwan (Edwards *et al.* 1987) and Bangladesh (DWRP 1996/97).

Economically feasible duckweed farming systems were reported from Taiwan and Bangladesh.

Since fish production is the most widespread and well-documented application, it was chosen to exemplify animal production.

Integrated and Separate Duckweed-Fish Production

Until adequate storage technologies are developed, such as drying, pelleting, cold storage, ensilaging or others, the fresh duckweed has to be used within two to three days after harvesting. Therefore, duckweed cultivation is physically and geographically limited to the vicinity of the fish production area. Two approaches are known; i.e., the integrated production of duckweed and fish on the same premise by a single owner or group of owners, and the separate production of duckweed and fish by different owners with an intermediate market for the sale of duckweed.

Lack of storage technologies, such as pelleting or ensilaging limit the use of duckweed to its fresh form in the vicinity of cultivation area.

Integrated duckweed-fish production by a single owner group has the following advantages and disadvantages over separate production of duckweed and its subsequent sale to fish producers (Tab. 15):

Integrated duckweed-fish production yields higher profits in the long-term and is not dependent on market uncertainties of duckweed demand and supply in comparison with separate duckweed cultivation. The latter production system, however, is less complex to manage, requires less land, infrastructure and working capital, and is, therefore, exposed to a lower risk of capital loss through natural calamities, diseases and pests.

Integrated duckweed-fish farming requires sufficient land, an appropriate infrastructure and large sums of working capital, thereby, increasing the risk of capital loss through natural disasters like floods and droughts, diseases and pests. However, supply and demand of duckweed do not depend on market uncertainties. Although a market infrastructure for preservation and storage is necessary for both separate and integrated duckweed-fish production, it is less sophisticated for the sale of fresh duckweed. For integrated duckweed-fish production, access to urban and small-town markets for fish sale is desirable, while separate duckweed production only relies on local buyers of duckweed. Efforts and costs for duckweed transport are reduced in an integrated system. However, the complexity of the whole system, with two highly sensitive subsystems for maintenance and management of optimum growth conditions and strong system interdependencies are naturally higher in the case of integrated duckweed-fish farming. The greater risk of managing a more complex system at higher capital investment is set off by a substantial higher net return from the sale of fish produced by integrated duckweed-fish farming.

Physically separated production of duckweed and fish by different groups is a feasible option requiring, however, a good marketing infrastructure for storage and preservation of duckweed, transport of duckweed to the fish farms and protective trade agreements between the different production groups as described hereafter.

Formal short-term agreements between duckweed and fish producers on minimum price, supply guarantees and minimum purchase quantities are necessary to protect the interests of both sides in separate duckweed-fish production.

The current lack of storage technologies prevents the formation of a conventional duckweed market where supply and demand determine an equilibrium price. Protection of the interests of duckweed and fish producers through short-term agreements on duckweed minimum price over defined periods, including guarantees on supply and minimum purchased quantity, are necessary formal forms of linkage. Without price and supply guarantees on either side, duckweed producers retain little pricing leverage and remain vulnerable to arbitrary termination, while fish farmers are vulnerable to supply uncertainties (Skillicorn *et al.* 1993).

The presence of several groups of duckweed suppliers and buyers may create a more dynamic market and provide a buffer against fluctuations in duckweed supply and demand.

However, linked production between one duckweed and one fish producer may not provide a buffer against fluctuations in duckweed supply and demand. Linkage between groups of duckweed and fish producers appears to provide better conditions for duckweed-fish production. Supply shortage can also be buffered by guaranteeing adequate substitution and supplements for duckweed feed, like for example *Azolla,* water hyacinth, oil cake, or wheat bran. A market with several groups of duckweed suppliers and fish producers creates more dynamics with regard to price negotiations and eventually higher returns for duckweed producers, compared to a single fish producer's demand (Skillicorn *et al.* 1993).

As aforementioned, duckweed cultivation has significantly lower net returns than pisciculture. For example, at a price of US$ 0.03 per kg of fresh duckweed, a farmer in Bangladesh producing only duckweed can expect to net less than one-third of what the fish farmer to whom he sells the duckweed can earn from the same amount of land (Skillicorn *et al.* 1993).

Table 15. *Advantages and disadvantages of integrated and separate duckweed-fish culture (after Skillicorn et al. 1993).*

	Separate duckweed production	*Integrated duckweed-fish production*
Market dependencies of duckweed demand and supply	Formal agreements with fish producers are necessary on minimum price, supply guarantees and minimum purchase quantities	Not dependent on duckweed market uncertainties
Market infrastructure requirements for preservation, storage and transport	High, but no requirements for fish marketing Lower when fresh duckweed is traded	High, especially for fish marketing
Net financial return	Significantly lower, but more immediate	Higher, but profit only after 2-4 years
Risk of capital loss through natural disasters, diseases and pests	Lower	Higher
Complexity of the system, requirement of labour and management efforts	Lower	Higher
Requirements of land, infrastructure and working capital	Lower	Higher

The question of suitability between the integrated and separate farming model cannot be answered at this point. Both models are known to be practised. The prevalent local institutional, agricultural and socio-economical conditions will be the determining factor.

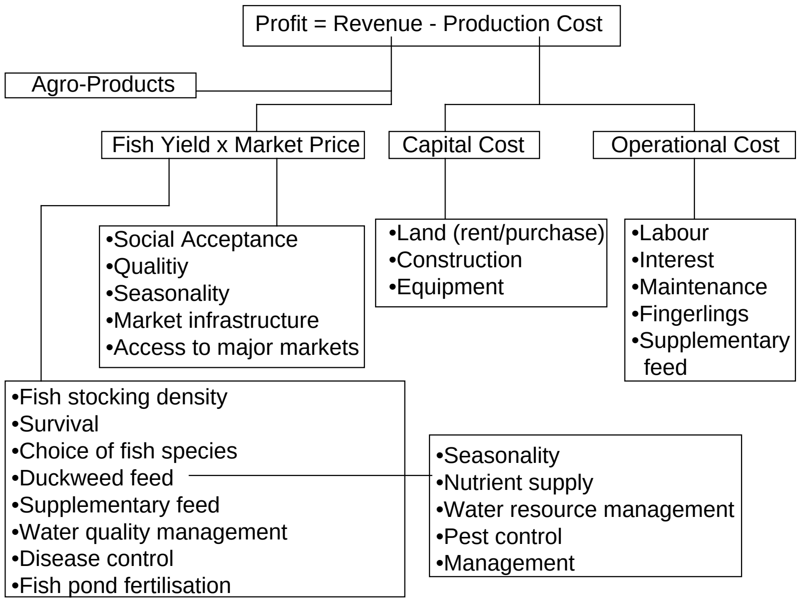
Separate production of duckweed was reported to be practised in Taiwan. Harvested duckweed was sold as feed for grass carps in sacs at 50 to 60 TwD per 60 kg sac, but also as a feed for chickens, ducks and edible snails. This was equivalent to about US$ 0.04/wet kg or US$ 1/dry kg duckweed in 1985. The sacs were transported by truck.

Integrated sewage/excreta-duckweed-fish production is practised in Bangladesh at demo farm and village level.

Economics of Integrated Wastewater-Duckweed-Fish Production

The major factors influencing the economics of integrated wastewater-duckweed-fish farming are summarised in Fig. 6.

Figure 6. *Major factors influencing the economics of integrated duckweed-fish production (adapted from Shang 1981, in Edwards et al. 1987)*



Based on the operating costs, sewage-duckweed-fish production at demo farm level proved to be profitable .

Based on the operating costs of 1994 and 1995, respectively, an economic analysis of the Mirzapur sewage-duckweed-fish system revealed that the system, covering a total area of 2 ha, earned a gross margin of 34,958 BdT and 62,597 BdT (Tab. 16). Interest fees on capital costs were not taken into consideration. The gross earnings do not include the revenue created by the sale of vegetables and fruit from the co-cropping vegetation. Besides, the value created by treating wastewater to an effluent quality meeting western standards was not taken into account either.

Table 16. *Operating costs for sewage-duckweed-fish production at Mirzapur demo farm of PRISM Bangladesh in the years 1994 and 1995 (DWRP 1996).*

Item	*1994*	*1995*
Duckweed production:		
Labour	31,200	31,200
Bamboo grids	3,500	3,500
Water supply	14,200	14,625
Others	34,200	37,800
Total operating cost (1)	83,100 BdT	87,125 BdT
Absolute production (0.6 ha)	149 t(wet wt)	182 t(wet wt)
Per kg operating cost	0.56 BdT/kg	0.48 BdT/kg
Per ha operating cost	138,113 BdT/ha	144, 803 BdT/ha
Fish production:		
Total operating cost (2) including (1)	216,700	244,670 BdT
Absolute production (3x0.2 ha)	6.2 t	7.57 t
Per ha production	10.3 t/ha	12.62 t/ha
Per kg operating cost	34.95 BdT/kg	32.32 BdT/kg
Gross earnings from fish sale (3)	251,658 (*)	307,267 BdT
Gross margin (3)-(2)	**34,958**	**62,597**

(*) calculated value, assuming same average price/kg fish as in 1995.
(2) in addition, total operating costs for fish production include costs for labour, lime, chemicals, fish pond fertiliser (urea), supplementary feed (mustard oil cake), fingerlings, and water supply.

The positive operating gross margin is remarkable, especially since wastewater treatment plants worldwide are generally never operated at a profit, as they rely on user-fees, contract revenues or on the sale of water to cover their costs. The Mirzapur sewage-duckweed-fish system is perhaps the only flow through sewage treatment plant in the world that is making a profit from its operation.

The Mirzapur sewage-duckweed-fish system is perhaps the only flow through sewage treatment plant in the world that is making a profit from its operation.

CHAPTER EIGHT

INSTITUTIONAL ASPECTS

Skillicorn *et al.* (1993) suggest the following institutional concept for propagation of duckweed aquaculture:

A first step for introduction and dissemination of duckweed farming in tropical and semitropical developing countries is to create institutional demo centres. During the first years, their task is to assimilate the existing knowledge about duckweed cultivation, to adapt this knowledge to the specific local conditions and increase it through research at demo farm level. In a second phase, when locally adapted farming protocols, design guidelines and end-use applications of the biomass are developed, the difficult process of introducing and disseminating the farming method to a wider audience can be initiated. The demo farms will then serve as training and know-how centres where individual farmers, farming cooperatives, government and NGO staff, as well as officials

An institutional concept to introduce and disseminate duckweed aquaculture is the creation of demo centres. These will in a first phase adapt the existing knowledge on duckweed aquaculture to the specific local conditions and, in a second phase, provide training, supervision, technical assistance, and credit support.

from other institutions will receive practical training and gain knowledge in duckweed aquaculture. Furthermore, they will provide continuous supervision, technical assistance and financial reinforcement to groups who are willing to adopt the technology with the support of extension workers. These demonstration centres should naturally receive financial aid from credit institutions capable of providing their credits directly to the duckweed and duckweed-fish (or other animals) farmers at low interest rates.

The role of the village extension worker for example is to ensure (1) that each participating farmer is trained in the latest farming techniques, (2) that he understands the continuous nature of the production process, (3) that he carries on with the good practice, and (4) that he continues to receive immediate payment for his daily product.
Receiving daily payment for daily production is a strong incentive for good practice. A farmer who fails to manage his crop adequately will experience an immediate drop in production and, hence, in income. He will not have to wait for months before facing the consequences of his action. Feedback is immediate and has a reinforcing effect on quality and level of effort.

Baseline Survey

A baseline study prior to introduction of duckweed farming technology should include evaluation of available land, water and human resources, existing farming systems, and identification of target groups.

Prior to introduction and dissemination of wastewater-based duckweed farming technology at rural and urban level, a baseline survey should evaluate if the specific local conditions provide an appropriate setting for duckweed farming. The following aspects should be considered in a baseline survey (DWRP 1997b):

Availability of resources

- Water bodies (ponds, river, wells, ditches, etc.)
- Water availability, quality and usage (annual fluctuations)
- Nutrients, their sources and availability
- Locally available animal and fish feeds
- Labour resources
- Domestic animals (fish, ducks, chickens, goats, etc.)

Existing farming systems

- Agricultural practices
- Animal production and animal products
- Nutrients, their sources and availability
- Flow of nutrients
- Use of existing resources
- Availability, cost and need of nutrients and feed
- Relative importance (time, economy) of different activities

Identification of target groups

- Present source of income
- Interest to participate in project activities
- Indication by the beneficiaries of their specific needs or interests

Credit Requirements

It seems obvious that credit support for wastewater-based duckweed-fish farming is essential. The intensive and continuous process needs a steady flow of investment. Skillicorn *et al.* (1993) report that credit for this kind of farming method is characterised by two features: (1) it is best disbursed continuously in small, productivity-based increments and (2) it is comparatively higher than the credit required for comparable conventional farming processes, especially when insufficient nutrient supply from the wastewater is compensated by applying costly inorganic fertilisers.

Credit requirements for wastewater-based duckweed-fish farming are comparatively higher than for comparable conventional farming processes.

The performance of credit programmes to support small farmers worldwide is poor. Loans seldom match real requirements, disbursements are slow, interests are exorbitant, and recovery rates are low. Beyond the more frequently cited structural deficiencies of the credit institutions themselves, common belief holds that a primary failing of agricultural credit programmes is the inability of farmers to manage their credit. Experience shows that farmers are likely to directly use the greater part of the credit received. Consequently, the higher the credit, the greater the amount used.

In the case of duckweed-fish production, the risk for farmers can be reduced through close technical and managerial involvement by the credit institution. Income from fish sales should flow through the credit institution before net payments are made to fish producers in order to add value to the production process by improving both production and marketing, and by continuously reinforcing good practice.

Promotion of Excreta-Based Duckweed-Fish Production in Rural Bangladesh

The aforementioned concept for duckweed propagation was derived from PRISM, a Bengali NGO. The institution is promoting integrated duckweed-fish production in the surrounding villages of their demo farms. Rural farming groups received credit, technical assistance and supervision by PRISM, and their extension workers resided in the assigned villages. Despite impressive achievements from the over 120 duckweed farming groups, a recent study (DWRP 1996) revealed some weaknesses of the chosen, so-called, “joint stock company” approach; i.e., it led to its abandonment and development of new group organisation models. The experience gained with the joint stock company approach can be of great benefit to rural duckweed propagation programmes. DWRP (1996) describes it as follows:

Through the formation of officially registered, so-called, “joint-stock companies”, PRISM, a Bengali NGO, developed an institutional model for promotion of excreta-based duckweed-fish cultivation at village level.

Shares were obtained by the company members through labour or land contribution.

Joint stock companies, comprising 10-15 members or shareholders, were formed and officially registered. Shares were obtained through land, labour or cash contributions. Labour contributions were compensated in cash or shares, land contribution was compensated in shares. One share was equivalent to one decimal of land (40 m^2) or 500 BdT. The net profit was distributed according to the respective number of shares held by the shareholders. PRISM received 10 % of the shares for their technical assistance.

Since land assigned to the company was registered under permanent ownership and taken as collateral security through power of attorney by PRISM for the disbursed loan, some members feared to lose control over their land.

The land assigned to the company was registered under permanent ownership and taken as collateral security through power of attorney by PRISM for the disbursed loan. Land and company registration required approx. 20,000 BdT. The amount was borne by and given to the company by PRISM in the form of a loan.

Most of the interviewed shareholders were not satisfied with the company concept. Since individual land transfer was made in the name of the company, members feared to lose their land forever.

As pond ownership was an initial criterion for selection of beneficiaries, participation of landless and marginal farmers was below target.

Selection of beneficiaries was initially based on pond ownership, particularly fish ponds which are usually larger than duckweed ponds and considered more valuable. This reduced participation of all those who do not own land or who own only a very small homestead like landless poor and women. For reasons of cultural and religious discrimination, women in Bangladesh usually do not own land or have little control over it.

Heterogeneous socio-economic background of company members caused decision-making power to lie with the rich members and favoured further build up of hierarchical structures.

The heterogeneous socio-economic situation of the company members caused decision-making power to lie completely with the rich members and favoured further build up of hierarchical structures. This led to a serious lack of coordination between the rich on one side and the poor and women on the other. The latter often had no idea about their savings, their actual number of shares, about the company's current economic condition, activities, and even about its actual concept.

High capital investment and high interest rates to be paid to PRISM exposed the members to high financial risk.

The high capital investment (approx. 280,000 BdT for a company formed by 10 farming members) and high interest rate (15 %) to be paid to PRISM put the members at great financial risk. As a result of this financial burden and damage caused by annual floods, several companies were not convinced of the company's profitability. Most of the interviewed members revealed that they had not yet received any cash benefits. If any profit was made, it was directly used to repay the loan. The members were not told that profit could be made only 3-4 years later. This was extremely disappointing for the poorer members, as they dispose of few other sources of income and require immediate returns on their contributions.

Some members continued to produce fish in their ponds but stopped sharing their yield with the companies. Some duckweed pond owners discontinued production of duckweed and started growing fish in their ponds. However, their waterbody was still owned by the company.

Quality of bookkeeping was often insufficient, as figures were not updated or inconsistent.

The company was managed by a board of directors composed of a chairperson, managing director, treasurer, and two general members. The managing director received a monthly salary from the company (800-1,000 BdT) and was responsible for record keeping and coordinating the company's activities. The quality of bookkeeping was often insufficient, as the figures were not updated and/or inconsistent in most companies. The extension workers were supposed to provide detailed accounts to the managing directors. Moreover, the record books were not understood by the poor members. Since company law required every company to be audited once a year by a qualified firm, an additional sum of about 3,000 BdT was required. In most cases, the management of the company was unable to prepare the accounts for the auditing firm.

Most companies contracted poor members as full-time labourers at a monthly salary of 1,000-1,200 BdT. Casual labourers were also employed at 35 BdT per working day. Sometimes, the wage labourers were not members of the company. Engagement of wage labourers was a good initiative to generate employment, although it increased production costs. The salary of a wage labourer was by far not sufficient to maintain his family, let alone save money to buy shares. Provision of employment to wage labourers to allow them to increase their shares failed its objective.

Demo farms served as training centres to the company and to the extension workers. Training was also given to NGO and government staff. A refresher course was also conducted for company members. Shareholders received training free of charge and also travelling allowances. The chairperson and the managing director were given first preference in the selection of trainees, while the daily activities were conducted by the untrained members or hired labourers. Most female members did not receive training as they are overburdened by a multitude of duties (raising of children, farming and domestic chores) and cannot leave home for a longer period of time.

The staff at the demo/training centres comprised one project director, one credit manager, three training officers, four area coordinators, and a number of village coordinators. Support staff like drivers, a cook and guards were also recruited. Employment of female staff in the demo centres was below 10 %.

In comparison with the sewage-duckweed-fish production system at Mirzapur demo farm, the village companies obtained lower duckweed and fish yields (Tab. 17).

Table 17. *Comparison of duckweed and fish production between PRISM joint stock companies and Mirzapur demo farm (DWRP 1996 and 1997a).*

	Duckweed production				Fish production	
	daily kg(wet wt)/ha·d		yearly t(wet wt)/ha·y		yearly t/ha·y	
	range	average	range	average	range	average
Village companies	7-444	162	2.5-162	59 (4.6)*	0.4-6.6	3.8
Mirzapur demo farm	<1200	>600	<260	>200 (15.6)*	5.6-12.6	>10
Fish production in Bangladesh	____	____	____	____	<3.6	2.1

*t(dry wt)/ha·y, assuming 7.8% dry matter content.

In comparison with other piscicultural projects in Bangladesh, joint stock companies obtained higher fish yields at higher production costs and, therefore, significantly lower rates of return on investment.

Even if fish yields were somewhat higher than those of the other aquacultural projects in Bangladesh applying lower quantum of inputs and capital, the rates of return of joint stock companies were generally much lower. This indicates high fish production costs of joint stock companies.

It should be noted that the production system at the demo farms is based on high capital investment from external donors and high labour input. It performs well, but it rather demonstrates what can be achieved under sophisticated management, maximum financial input, sufficient nutrient and water supply and high input of skilled labour than what is feasible on village level. Duckweed could not be grown year-round in the ponds of the village companies. Apart from poor management, several constraints also had a negative effect on duckweed-fish production at village level. The major ones include:

- Lack of water and duckweed (ponds dried up during the dry season, insufficient duckweed pond area)
- Floods
- Low nutrient supply

Others:

- Temperature extremes
- Insect damage/diseases (duckweed)
- High costs of supplementary fish feed
- Low fish prices (marketing problems)
- Fish diseases
- Poor quality of fingerlings
- Stealing of fish
- Shortage of oxygen in fish ponds

One of the major positive impacts of the project is the fact that people within the project area have now come to realise the importance of duckweed as a fish feed.

Interviews with villagers who were not members of a company revealed that most of them were familiar with the duckweed-fish culture activity and thought that it could yield a profit if applied correctly. One of the major positive impacts of the project is the fact that people within the project area have now come to realise the importance of duckweed as a fish feed. However, others indicated that they did not believe profits could be yielded in spite of the numerous efforts made. They were hesitant to apply the technology themselves. Some objected to the control of the rich shareholders over the poor members.

The study revealed that the households highly appreciate the installation of pour-flush-type latrines connected to the duckweed ponds, as they inhibit bad smells and reduce mosquitos and flies. However, they complained about pollution when duckweed ponds dry up.

The households highly appreciated the installation of pour-flush latrines connected to the duckweed ponds.

The fish production cycle did not coincide with the duckweed growing season; i.e., duckweed production was low when demand was high.

Interviews and observations indicated that marketing infrastructure for storage and preservation of fish was almost non-existent. Besides, the producers had little or no access to the major urban markets. Fish was either sold at the pond site to middlemen who mostly dictated prices or at local markets. A main weakness of the fish marketing system is the short period between harvesting and marketing during the winter months when most of the fish ponds dry up and, consequently, lower fish prices. Another weakness is the lack of a uniform weighing system.

Appropriate marketing infrastructure for storage and preservation of fish was practically non-existent.

An economic study revealed that only 7 of 44 companies yielded some net profit, the rest incurred losses on the basis of total costs. The fact that no dividends could be paid to the shareholders was particularly disappointing to the poor households, which not only lost control over their land, but were also left without an income. On the basis of operating costs, however, several companies showed substantial positive gross margins (operating profit). The major factors contributing to the net losses were: heavy investment costs per ha and company resulting in high interest and repayment charges, high expenses for supplementary feed inputs and fertilisers, low contribution of duckweed as a feed, and high company-related expenditures.

Only 7 of 44 companies proved that excreta-based duckweed-fish farming can be practised with a net profit. Financial loss of companies was attributed to high interest repayment charges and high expenses for supplementary fish feed and company-related issues.

The quantum of credit disbursed was quite high and surpassed the projected levels. The average loans per ha of fish pond exceeded 400,000 BdT. Such high investments against uncertain yields of fish and duckweed, and uncertain performances of newly-formed companies did not seem to be quite justified. Besides, recovery of credits was low (approx. 70 %).

It can be concluded that the high investment-driven, technology-oriented and top-down approach of the joint stock company concept as a group organisation model had to be abandoned because it did not correspond to the cultural and social reality of the beneficiary groups.

PRISM Bangladesh is currently developing new group organisation models based on the following study recommendations:

- People of a more or less homogeneous socio-economic status should be selected for group formation.
- Creation of formal (legal registration as a company) and also informal groups.
- No transfer of land owned by members to the company.
- Equal distribution of shares.
- Leasing of land from private owners or the government to allow landless poor and women groups to practise duckweed aquaculture.
- Reduction of credit investments.

Further recommendations include:

- Recruitment of female trainers to assist and supervise female groups.
- Provision of training at village level.
- Assuring detailed bookkeeping by close assistance.
- Regular village visits by demo farm staff for supervision and problem solving at field level.
- Lowering of fish production costs by increased reliance on duckweed as cheap fish feed. Reduction of expensive supplementary fish feed inputs. Replacement of costly inorganic fertilisers by cheaper organic waste as nutrient sources for duckweed production.
- Integration of duckweed aquaculture in existing farming systems.
- Development of marketing infrastructure for storage and preservation of fish to facilitate access of fish producers to the rural and urban markets.

Moreover, the following new technology approaches are being field-tested:

- Cultivation of both duckweed and non-duckweed-eating fish species like catfish and silver carp, in the same pond. Floating bamboo poles confine duckweed cultivation to one side of the pond leaving the other side uncovered for oxygen and light input.
- Use of cowdung as nutrient source.
- Only duckweed production (no fish production).

Individual farmers, family-based groups (consisting of two families), groups of landless people and groups with only female members, so-called "sister companies", are being tested. Individual farmers and pond owners receive a loan only for latrine construction and material (about 900 BdT per latrine). The members of the sister companies in Khulna produce only duckweed which they sell to the neighbour company. A mutually signed contract fixes amount and price (0.7 BdT/kg(wet wt)) of duckweed to be sold. The companies are currently leasing low-lying retaining water throughout the year which the owners are willing to lease as severe weed and salinity problems have rendered agricultural crop production impossible. Capital costs for pond excavation of 72,000 to 83,000 BdT per ha still require a high degree of investment. Another recommendation was to lease perennial/seasonal waterbodies, so-called «kash» lands from the Land Ministry or to use borrowpits under roads.

Chapter Nine

Past and Present Duckweed Activities Around the World

Taiwan

Small-scale duckweed cultivation is traditional in Taiwan and has been practised for a long time in ditches and ponds developed from paddy fields.

Edwards *et al.* (1987) reported the following duckweed cultivation practices in urban areas of Taiwan:

Commercial duckweed cultivation has been practised on a large scale in the cities of Tainan and Chiai for nearly 30 to 40 years. Duckweed in Tainan was cultivated in several areas over a total surface area of about 100 ha, the largest site covering 15 to 20 ha. In Chiai, duckweed was cultivated in two areas covering a total surface of about 20 ha. Since August 1985 the cultivated area has most likely decreased due to urbanisation. Whether duckweed is still cultivated today in Tainan and Chiai is unknown to the author.

Commercial duckweed cultivation has been practised on a large scale in two Taiwanese cities for nearly 30 to 40 years.

The ponds were fertilised once a week by lowering the water surface by about 7.5 cm and replacing the outflow with organically polluted grey to black surfacewaters. Ponds and water distribution channels were earthen structures. The ponds were drained and fed by gravity or/and pumps. The farmers reported that nightsoil had never been used. Concern was also expressed about contamination of surfacewater by factory effluents.

Paddy fields were turned into shallow ponds to cultivate *Lemna* and *Wolffia* throughout the year. The initial culture of *Spirodela* was replaced by *Lemna* and *Wolffia,* as fish and ducks were reported to prefer these species. Floating bamboo poles were used to divide the pond surface into small square or rectangular cells of 2 to 3 by 4 to 6 m.

Duckweed was harvested at weekly intervals by moving the floating plants to one corner of the pond with a bamboo pole. 80 % of the standing crop was harvested. If too much duckweed was harvested, the water turned green and the plants did not grow well. Two people were reported to require 3.5 hours to harvest 0.3 ha. The harvested duckweed was filled into wickerwork baskets to allow some drainage of water. It was packed in sacs holding 60 kg of wet duckweed. Water was periodically squeezed out by manually pressing down the top of the plants in the sac during harvesting.

The duckweed was sold fresh for 50-60 TwD per sac and used mainly as feed for small and large grass carp, but also as feed for chickens, ducks and edible snails. It was reportedly not fed to tilapia as it was too expensive. *Wolffia* was used as a first feed for grass carp fry, followed by *Lemna* when the fish were larger. The same practice is also reported from mainland China.

The data extrapolated from reported yields varied widely from 2.5 to 12.5 to 25.9 t dry wt/ha·y on the basis of a dry matter content of 4 % and year-round cultivation. Due to seasonal effects on duckweed growth, the winter yields made up only about 40 % of the summer harvest. Production was also reduced in the rainy season due to dilution of the organically polluted surfacewater. Insect damage was reported to be unimportant.

Mainland China

Almost no information was found on duckweed application in mainland China. China's long-standing tradition of direct and indirect reuse of waste for food production probably also includes the cultivation of duckweed.

In the Provinces of Kiangsi and Chekiang, *Wolffia* was reported to be cultivated from April to September, with an extrapolated annual yield of 14 t dry wt/ha (Gijzen and Khondker 1997).

Vietnam

A research group in Vietnam is studying the use of biogas digester effluents for duckweed cultivation.

Dr Preston's group at the University of Agriculture and Agroforestry in Ho Chi Minh City is studying duckweed applications on a research level as part of its M.Sc. programme on "Integrated Farming Systems for Sustainable Use of Renewable Natural Resources". The group's very interesting work focuses on the use of biogas digester effluents for duckweed cultivation. The biogas digester was charged with pig manure containing 6.5 % solids and 3.4 % nitrogen in the solids. Optimal levels of nitrogen in the duckweed pond water between 40 and 60 mg/l were surprisingly high. Duckweed production in the pilot pond (10 m^2) was reported to be 100 $g/m^2 \cdot d$ with a crude protein content of 35%.

Thailand

Research at AIT focused on the use of septage and excreta for duck-

The Asian Institute of Technology (AIT) in Bangkok has been involved in pilot-scale duckweed research for more than 15 years.

Activities started in 1981 with funds from ODA (1981-1984). Research continued under the project "Resource Recovery and Health Aspects of Sanitation" funded by the European Union's Science and Technology for Development Programme (1984-1986). The main objective of this project was to study the direct and indirect use of septage and excreta in aquaculture. The overall results showed that neither direct feeding of septage to fish, nor the combined system with duckweed production resulted in an economically attractive fish production system. However, septage reuse in aquaculture may be economically more attractive in countries with low labour costs and high fish market prices. The use of a duckweed-fish wastewater treatment system could result in substantial savings compared to an activated sludge system. The studied village/family excreta reuse duckweed/tilapia system may have a greater relevance if integrated in an urban excreta reuse system. Currently, AIT is not pursuing duckweed-related research as most of its questions have been answered (Edwards personal communication 1998).

weed cultivation.

Excreta-based duckweed-fish treatment systems may have greater relevance if integrated in urban excreta reuse systems than if used at village level.

PRISM Bangladesh

The NGO, PRISM Bangladesh, has set up since 1989 an impressive programme to develop and disseminate duckweed aquaculture in Bangladesh. A great deal of information cited in this report is based on conclusions from research studies at PRISM's project locations. PRISM has so far developed three so-called Shobuj Shona (Green Gold) Centres located in Mirzapur, Manikganj and Khulna. The centres serve as demonstration farms and training institutions for the promotion of integrated duckweed-fish production in the surrounding villages. The information cited in this chapter is taken from Gijzen and Khondker (1997), Alaerts *et al.* (1996), Iqbal (1995), and DWRP (1996 and 1997a).

Considerable experience with real-scale excreta and sewage-based duckweed-fish production at rural and community level was gained by the projects of PRISM Bangladesh.

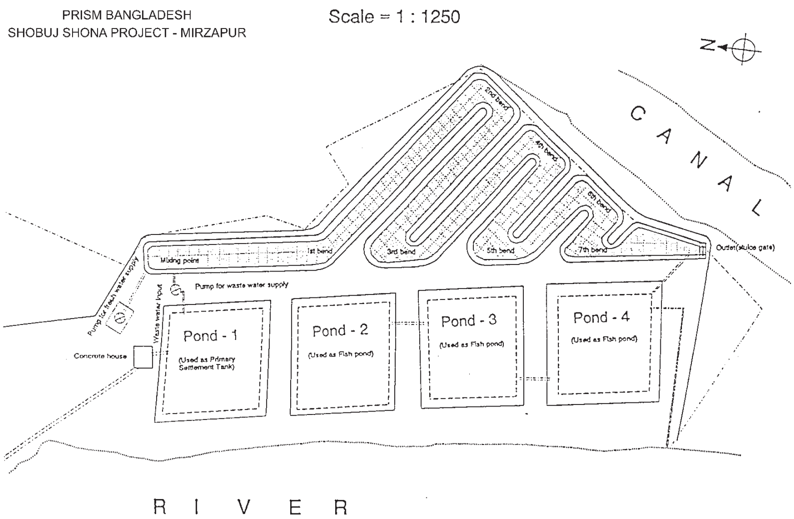
Mirzapur demo farm consists of one duckweed-covered sewage lagoon (0.6 ha), 17 fish culture ponds (total area 6.9 ha) and 66 small hydroponic duckweed ponds (total area 3.2 ha) fertilised by inorganic nutrients (Phot. 23). Manikganj demo farm operates 64 duckweed ponds (total area 1.97 ha) and 12 fish ponds (total area 2.93 ha). The duckweed ponds at Manikganj are fertilised mainly by inorganic fertilisers, however, some latrines are also directly connected to the ponds. Average daily production of duckweed in Manikganj amounts to about 535 kg/ha·d (about 10 t(dry wt)/ha·y), and fish production ranges between 4.92 to 9.88 t/ha·y.

Fig. 7 illustrates the duckweed-covered sewage lagoon preceded by a 0.2 ha sedimentation pond for removal of suspended solids, and adjacent 3 fish ponds (0.2 ha each) at Mirzapur demo farm. The fish ponds are fed by groundwater and by the final effluent of the plug-flow. The lagoon is designed as a serpentine plug-flow of 500 m length and 12.6 to 13 m width (Phots. 24 and 25). Its water surface covers an area of 0.6 ha. Depth increases gradually from 0.4 to 0.9 m at the outflow. The system

Photograph 23: *Groundwater/chemical fertiliser-based duckweed cultivation of PRISM Bangladesh at Mirzapur demo farm complex. Duckweed ponds with floating bamboo grids and co-crops on the embankments in the foreground, and main fish production pond in the background.*

treats 125 to 270 m^3/d of hospital, school and residential sewage produced by 2000 to 3000 people residing at the Kumudini hospital complex. The plug-flow is fed semi-continuously with the effluent of the sedimentation pond.

Figure 7. *Layout of duckweed-covered serpentine plug-flow lagoon, anaerobic sedimentation pond (Pond-1), and fish ponds (Pond-2, Pond-3, Pond-4) at Mirzapur demo farm of PRISM Bangladesh.*



As aforementioned, the lagoon not only suffers from substantial leakage during the dry season, with a loss of about 30 % of total nutrient input, but also from low influent BOD concentrations, as a significant amount of the community's BOD discharge is not collected. Since the plug-flow is over-dimensioned, intensive duckweed production is restricted to only about 60 % of the total surface area. On an average, 656±177 kg (wet wt)/ha·d

Photograph 24: *Duckweed-based sewage treatment lagoon of PRISM Bangladesh at Mirzapur showing one reach of the plug-flow channel under construction. (Photograph: PRISM).*

Photograph 25: *Inlet section of duckweed-covered plug-flow lagoon showing dense duckweed mat stabilised by a floating bamboo grid system and banana co-crops on the right pond embankment.*

could be harvested from February 1993 to March 1994. During the wet season, plant harvest can increase to 1000-1200 kg (wet wt)/ha·d. Annual duckweed production in 1994 and 1995 was reported at 213 t(wet wt)/ha·y and 260 t(wet wt)/ha·y, respectively. At a dry weight fraction of 7.8 %, this is equivalent to 16.6 and 20.3 t(dry wt)/ha·y.

PRISM adopted the old traditional Chinese carp polyculture concept, combining species with complementary feeding habits and living zones, to take advantage of all the feeding zones and food resources in a fish pond. A polyculture of different Indian (rohu, catla, mrigal) and Chinese (common, silver and grass carp) species is stocked at a density of 18,000-20,000 fish/ha. This combination of herbivorous, planktivorous and omnivorous fish makes efficient use of pond trophic zones. The polyculture can be divided into top, mid and bottom-feeding species. Distribution of the species is given in Table 18. Tilapia is not added to the ponds but enters the system by contamination and may contribute to about 40 % of the total fish production. PRISM has currently over eight years experience with duckweed-based carp polyculture. At Mirzapur demo farm, 60 % of all fish is directly sold at a discount to the Kumudini hospital and the remaining part is sold at the local market. Market prices are dependent on fish species: Rohu (58 BdT/kg) and mrigal (51 BdT/kg) seem more attractive, however, despite high stocking densities, the relative production of the two species tends to be low. Silver carp (34 BdT/kg) and tilapia (29 BdT/kg) seem to do very well but fetch a relatively low market price. Catla, grass carp, and common carp are sold at 48, 42, and 55 BdT/kg, respectively.

PRISM obtained comparatively high fish yields with a carp polyculture comprising Indian and Chinese carp species, and Tilapia fed on about 60 % sewage-grown duckweed and 40 % mustard oil cake (% dry matter).

Table 18. *Species distribution of carp polyculture for fish pond stocking as practised by PRISM Bangladesh.*

Species	*% of total stocking*
Catla catla (Catla)	20
Labeo rohita (Rohu)	20
Cirrhina mrigala (Mrigal)	20
Hypophthalmichthys molitrix (Siver carp)	15
Ctenopharyngodon idella (Grass carp)	20
Cyprinus carpio (Mirror carp)	5

Fish is produced in an annual cycle, with stocking in July and maximum harvesting from May to July. Harvesting is conducted throughout the year at irregular intervals varying between once a month to eight times a month. The experiments conducted only in 1990, using duckweed as sole fish feed, indicated that a fish yield of 6.6 t/ha·y could be obtained. Annual fish production using sewage-grown duckweed as a fish feed was reported at 10.58 t/ha·y in 1994 and 12.62 t/ha·y in 1995. These figures are high compared to Bangladesh or even international standards. However, these values were obtained with a mixed feed of sewage-grown duckweed and mustard oil cake at a dry weight ratio of 56-67 % and 44-33 %, respectively. Based on the total feed inputs (dry weight) and total fish production, FCR values of 2.8 (1994) and 3.3 (1995) were obtained. The reasons for these comparatively high FCR values were attributed to the non-addition of wheat bran - a good source of carbohydrates - to the feed mix, to overfeeding, loss of feed to the sediment, low water quality (oxygen, ammonia), theft of fish, and to the comparativley small size of fish ponds.

A Duckweed Research Project (DWRP) was initiated as a joint effort by the Governments of The Netherlands and Bangladesh in collaboration with PRISM and other institutions to test the technical and socio-economical feasibility of a wide range of duckweed-based production systems. Unfortunately, the DWRP was discontinued in 1997 due to structural and management problems.

The Ministry of Local Government and Rural Development is developing a “Bangladesh School and Community Sanitation Project” (SCSP) in partnership with the World Bank. The project includes a “Prefeasibility Study on Duckweed-Based Wastewater Treatment and Reuse” which is implemented by the International Institute for Hydraulic, Infrastructural and Environmental Engineering (IHE Delft, The Netherlands) in collaboration with PRISM Bangladesh. The objective of the prefeasibility study is to assess the possibility of introducing, on a demonstration basis, duckweed-based environmental sanitation into the SCSP design. The final report is expected to appear in March 1999.

India

The Indian NGO, Sulabh International, is involved in duckweed application in cooperation with the All India Institute of Hygiene and Public Health in Calcutta.

In April 1995, Sulabh started a demonstration project in Wazirabad (northern part of New Delhi), where Delhi Water Supply and Sewage Disposal Undertaking is operating 17 oxidation ponds (150 x 60 m each) for treatment of part of New Delhi's sewage. Of these 17 ponds, Sulabh is operating 4 ponds in series, using the first one for settling, the second and third for duckweed cultivation and pond four for fish production. Total HRT in the series of the four ponds amounts to 27-28 days. The aim of the project is to assess the economic feasibility of duckweed-based wastewater treatment. BOD of the influent ranges from 150 to 190 mg/l, whereas effluent levels after pond 3 are around 30 to 40 mg/l. The growth rate of duckweed is about 130 $g/m^2 \cdot d$, however, the presence of cyanobacteria as well as heavy oil and grease concentrations (>10 mg/l) were reported to seriously hamper duckweed growth. The duckweed ponds are covered mainly with *Spirodela*, as *Lemna* showed to be more sensitive to high light intensities. Another urban project is located at Halisahar in West Bengal. Both urban projects are funded by the Central Pollution Control Board.

Two Sulabh duckweed-fish production projects in rural areas are conducted in the states of Haryana and Orissa. The project in Orissa was funded by the Royal Danish Embassy (Rs. 1,943,480), the one in Haryana by the Ministry of Rural Areas and Employment (Rs. 1,246,000). The Haryana project was started in April 1996 in Gurgaon and Faridabad. The Orissa project was initiated in September 1996 in the villages of Budhalo, Indrapal, Brahmapur, and Srirampur. All the ponds used in the project are rain-fed and owned by local farmers.

UNDP/World Bank Regional Office in New Delhi compared different treatment options, including UASB, activated sludge and a duckweed-based treatment system for treatment of sewage from the city of Pondicherry. Due to additional household connections, the sewage flow is expected to increase about three times in the near future. The study concluded that a combined UASB, duckweed and fish production system can be installed at about 70 % of the costs of an activated sludge plant. Moreover, the duckweed-based system has the potential to generate, within a period of ten years, a net revenue equivalent to the initial investment costs. Operation and maintenance of the activated sludge process are also expected to be more expensive. In 1994, implementation had not yet started due to a lack of funds.

Another interesting wastewater treatment system is the Calcutta wetland system. According to Mara *et al.* (1993), the current fish yields may be increased 2-3 times if management is improved.

One of the options here could be the cultivation of duckweed in the initial stages of the wetland where high sewage concentrations are prevalent, and where the use of duckweed could sustain high fish yields in the rest of the wetland (Gijzen and Khondker 1997).

Lemna Corporation

The US-based company Lemna Corporation has been involved since the late eigthies in development and marketing of full-scale wastewater treatment plants and modules, using duckweed for tertiary post-treatment of aerated and non-aerated lagoon effluents. Lemna Corporation is divided into the two branches Lemna USA and Lemna International Inc. By February 1998, the company had installed over 125 treatment systems worldwide, with over 60 systems in the USA, of which 30 in Louisiana and over 40 outside the USA, of which 22 in Poland and others in Siberia (!), Sweden, China, and Mexico.

These facilities treat domestic and industrial wastewaters from small to medium-sized communities with daily flow rates ranging between 150 and 7000 m^3. Application of large-scale duckweed systems receiving peak wastewater flows of over 30,000 m^3/day from cities with a few 100,000 inhabitants are also reported. U.S. EPA has categorised the Lemna treatment system as an innovative/alternative technology.

The biomass produced in these treatment systems is generally not used as animal feed, but rather considered an undesirable by-product which is composted. This approach clearly focuses on duckweed as a wastewater purifier whose production is kept minimal, while allowing optimum treatment efficiencies. To minimise duckweed production, harvesting frequency is reduced to monthly intervals for secondary treatment, and weekly intervals for nutrient removal. Floating, mechanical harvesting machines are generally used for harvesting.

The company's projects in Eastern Europe and China suggest that the medium-tech approach of Lemna Corporation seems to be a feasible option for wastewater treatment in middle-income countries. The technical requirements, such as aeration pumps, high density polyethylene grids and mechanical harvesting devices, however, do not seem an appropriate solution for low-income countries as regards operation, maintenance and energy supply costs. To combine sanitation and the nutritional potential of duckweed, an optimum duckweed production allowing for acceptable treatment efficiency should be promoted rather than a minimum duckweed production as practised by Lemna Corp.

Chapter Ten

Priority Research Needs

A number of institutions in Bangladesh and elsewhere in the world have revealed the potential of duckweed aquaculture as a technology combining both wastewater treatment and fish production and, to a lesser extent, poultry, pig and livestock production. However, several key questions as regards the technical, institutional and socio-economical feasibility of duckweed-based treatment/farming systems remain to be answered before embarking on dissemination of the technology at rural and (peri-) urban level where prevalent local conditions provide the appropriate setting in developing countries.

The Duckweed Research Project (DWRP), a joint project of the governments of The Netherlands and Bangladesh, provides a comprehensive overview of the needs for applied research in development and testing of the technical and socio-economical feasibility of duckweed-based technologies in a developing country. Though the project was discontinued, the rationale and justifications which led to the identification of research topics are still valid. The priority research fields mentioned hereafter are to a major extent based on the research fields identified by the DWRP.

- Public health and environmental effects of duckweed treatment/farming systems
- Design and operation of duckweed-based pond systems for combined wastewater treatment and biomass production
- Economic assessment of wastewater-based duckweed farming models
- Sociocultural and institutional aspects of wastewater-based duckweed farming
- Duckweed production and feeding applications.

Public Health and Environmental Effects of Duckweed Treatment/Farming Systems

The key questions in this research field are:

- What are the public health and environmental effects of the introduction of duckweed-based systems?
- How can duckweed aquaculture be optimally combined with rural and (peri-)urban sanitation measures?

The research objectives should include:

- Assessment of the public health hazards of wastewater-duckweed-animal production systems with respect to pathogen transfer and accumulation of toxic compounds for different types of wastewater (domestic, industrial), animals (fish, poultry, livestock), products consumed (milk, eggs), and categories of people at risk (workers, consumers, residents). The contaminants of primary concern include pathogenic bacteria, parasites such as helminths, toxic compounds such as pesticides, and heavy metals such as chromium, nickel, led, zinc, copper, and arsenic accumulated in duckweed and possibly transferred to different organs and products of animals fed on it.

- Assessment of the effect of a duckweed cover on mosquito development in polluted still water bodies.
- Assessment of the relative contribution of duckweed to the survival or die-off of pathogens and parasites in duckweed-covered pond systems receiving domestic wastewater or latrine effluents, and comparison of the die-off rates in presence and absence of a duckweed cover.
- Assessment of the effects of duckweed on surface and groundwater quality in villages and other (urban) areas where ponds are polluted in a controlled (e.g. latrines connected to duckweed ponds) or uncontrolled way (waste dumping and indiscriminate defecation) through a combination of water quality analyses (dissolved oxygen, BOD, nutrients, pathogens, turbidity) and direct observations (algal blooms, odours, visual aspect).

Design and Operation of Duckweed-Based Pond Systems for Combined Wastewater Treatment and Biomass Production

The key questions in this research field are:

- How should a duckweed-covered pond system be designed and operated as regards quantity and strength of wastewater, to combine efficient treatment with optimum biomass production in rural and (peri-)urban systems?
- How can existing systems be further optimised?

The research objectives should include:

- Assessment and optimisation of existing duckweed-covered sewage and excreta treatment lagoons at rural and (peri-) urban level as regards efficient removal of contaminants (pathogens, BOD, nutrients, TSS, toxic compounds, etc.).
- Development of reliable plug-flow design and operation guidelines for wastewater treatment in peri-urban areas as regards maximum and minimum loading rates for BOD and nutrients, multiple wastewater input points, recirculation of final effluent, harvesting strategies, and duckweed productivity, including yield and quality as a function of hydraulic retention time.

Economic Assessment of Wastewater-Based Duckweed Farming Models

The key question in this research field is:

- What is the economic feasibility of different duckweed-based farming models under different realistic scenarios at village and (peri-)urban level?

The research objectives should include:

- Assessment of the profitability of different duckweed-based farming systems/models using methods like net present value, internal rate of return, and cost/benefit ratio. Environmental costs and benefits should possibly be incorporated in a profitability analysis.
- Provision of a sensitivity analysis of factors affecting the economic potential of duckweed-based systems.
- Assessment of the economic benefits for the target groups.

Sociocultural and Institutional Aspects of Wastewater-Based Duckweed Farming

The key questions in this research field are:

- Which institutional approaches are most suitable for dissemination of duckweed-based food production in a specific sociocultural context?
- Which target group structures or organisation models are most suitable for dissemination?
- Which sociocultural constraints influence the acceptance of duckweed systems and how can they be bypassed?

The research objectives should include:

- Evaluation of the acceptance of duckweed-based systems and products by rural and urban communities of a specific sociocultural background.
- Optimisation and testing of different target group organisation structures.
- Assessment of the impact of project implementations on the beneficiaries.

Duckweed Production and Feeding Applications

The key questions in this research field are:

- What kind of duckweed-based production systems can be developed and introduced in rural and (peri-)urban areas?
- How can available and under-utilised nutrient and land resources be optimally used in duckweed-based systems?
- Which farming system is most appropriate for incorporation of duckweed-based production?

The research objectives should include:

- Identification and testing of alternative nutrient sources, such as cattle dung, poultry droppings, biogas effluents, or food processing and industrial wastewaters for duckweed cultivation at rural and (peri-)urban level.
- Optimisation and stabilisation of duckweed production with respect to its yield and nutritional quality.
- Development and testing of preservation methods like solar drying, pelleting or ensilaging.
- Study of prevalent duckweed pests, such as insect larvae and fungi, and development of environmentally sound countermeasures to protect duckweed crops from infestation.
- Optimisation of the use of duckweed as fish feed with regard to feeding ratio (mixed feed), selection of fish species, cultivation method (mono or polyculture, continuous vs. batchwise fish production), FCRs, and use of duckweed as nursery fish feed (*Lemna* and *Wolffia*).
- Determination of the most appropriate duckweed form (dry or fresh) and feeding ratio (mixed feed or pure) for chickens, ducks, goats, and ruminants as regards digestibility, voluntary intake, FCRs, yield and quality of products (meat, eggs, milk).

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