DUCKWEED AQUACULTURE

A NEW AQUATIC FARMING SYSTEM FOR DEVELOPING COUNTRIES

Paul Skillicorn, William Spira, and William Journey

A WORLD BANK PUBLICATION

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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, Professor Guy Alaerts of the International Institute for Hydraulic and Environmental Engineering Delft, the Netherlands, reviewed the section on Wastewater Treatment, and illustrations were provided by Ms. S. Gray of Auburn.

Harinder S. Kohli
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Europe, Middle East and North Africa Region

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 13 – 38 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. 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

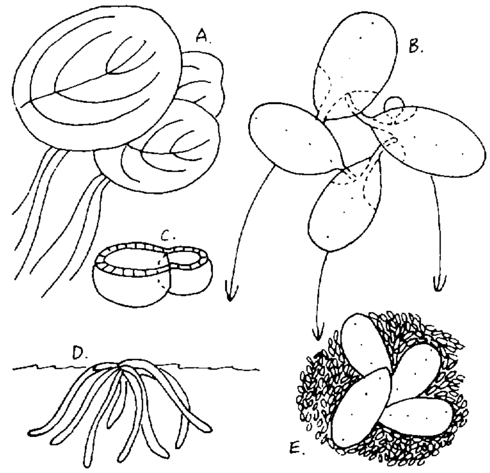

Figure 1. Duckweed, the smallest flowering plants
Genera: A. Spirodela B. Lemma C. Wolffia
D. Wolfiella E. Lemna with Wolffia

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. Data were obtained from

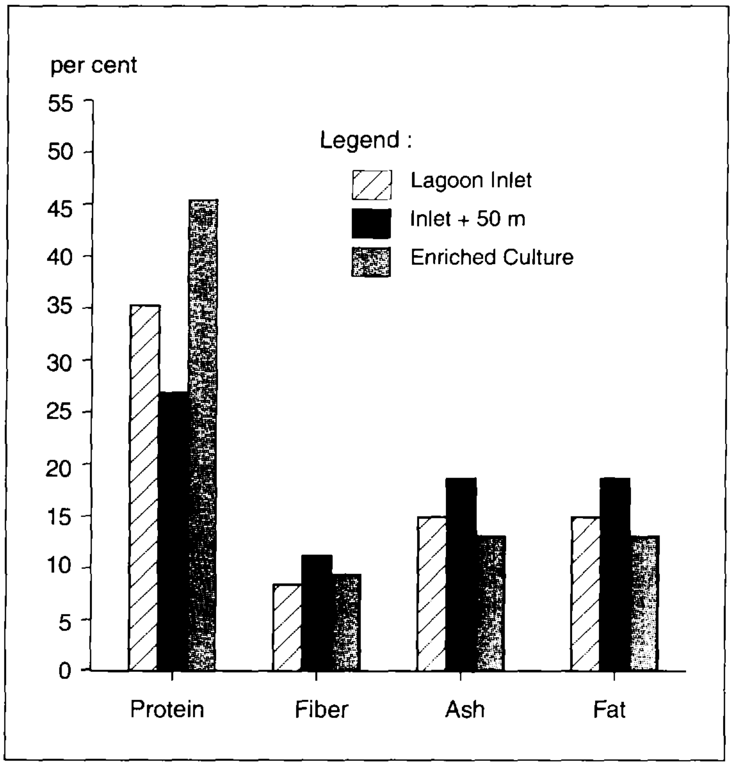

Figure 2. Composition of duckweed from three sources

Source: Mbagwu and Adeniji, 1988

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 compares the lysine and methionine concentrations of proteins from several sources with the FAO standard recommended for human nutrition.

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

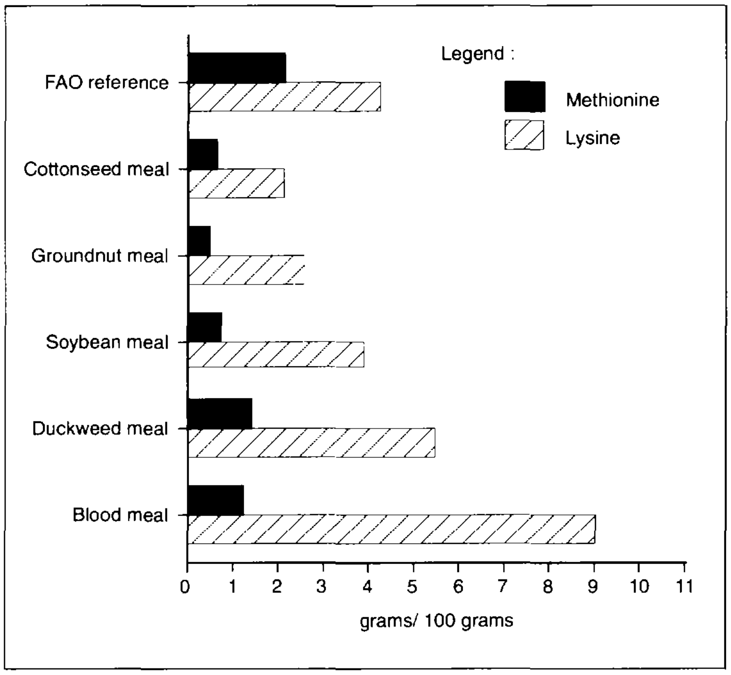

Figure 3. Comparison of lysine and methionine content of protein from various sources

Source: Agagwu and Adeniji,, 1988

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. This is economically important because of the relatively high cost of the pigment supplement in poultry feed.

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 han-

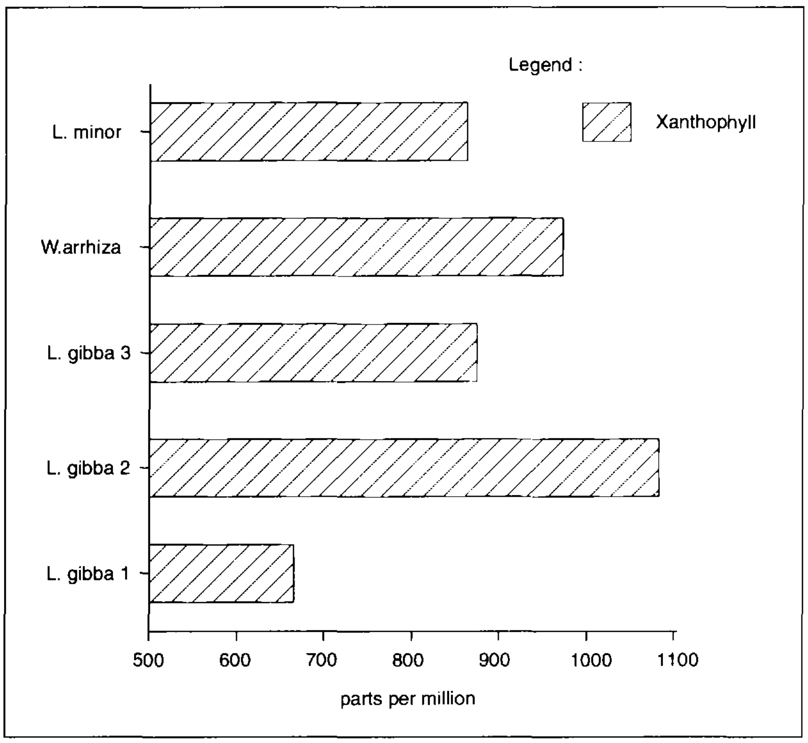

Figure 4. Pigment content of several samples of duckweed growing wild on wastewater

Source: Skillicorn, et al., 1990

dling 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.

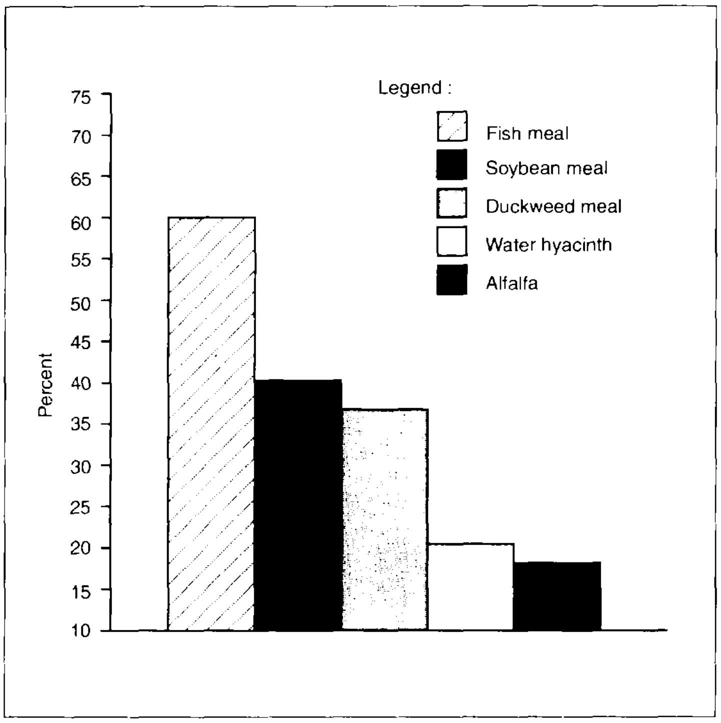

Figure 5. Protein content of various animal feedstuff ingredients

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.

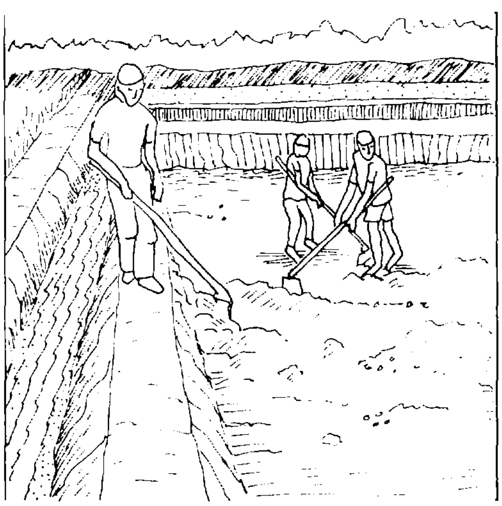

Figure 6. Making a duckweed culture pond

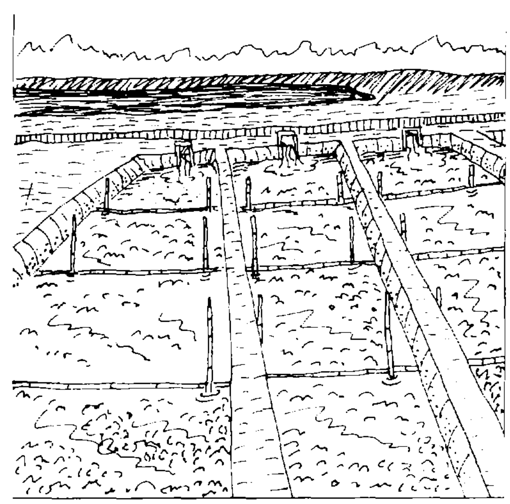

Figure 7. Protecting duckweed from wind and wave action

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* 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

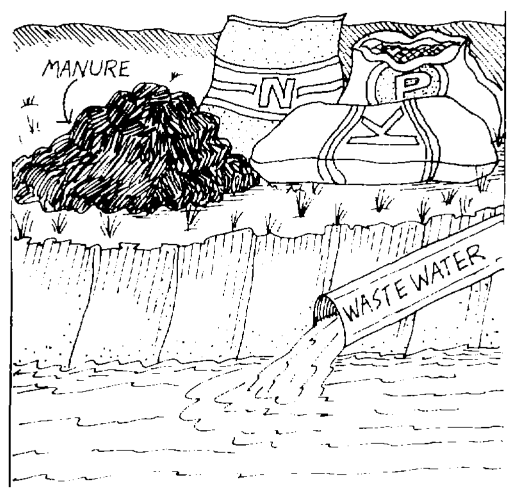

Figure 8. Nutrients for duckweed can come from fertilizer or organic wastes

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

Table 1. Daily Fertilizer Application Matrix (kg/ha)						
	Daily production of fresh plants per hectare					
Fertilizer	*500 kg*	*600 kg*	*700 kg*	*800 kg*	*900 kg*	*1,000 kg*
Urea	10.00	12.00	14.00	16.00	18.00	20.00
TSP	2.00	2.40	2.80	3.20	3.60	4.00
Muriated potash	2.00	2.40	2.80	3.20	3.60	4.00
Sea salt	4.50	5.40	6.30	7.20	8.10	9.00

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.

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/m^2 of has been shown, in the Mirzapur experimental program, to yield daily incremental growth of between 50 to 150 $g/m^2/day$. 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 production.

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 bamboo's, 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 also been developed. 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,

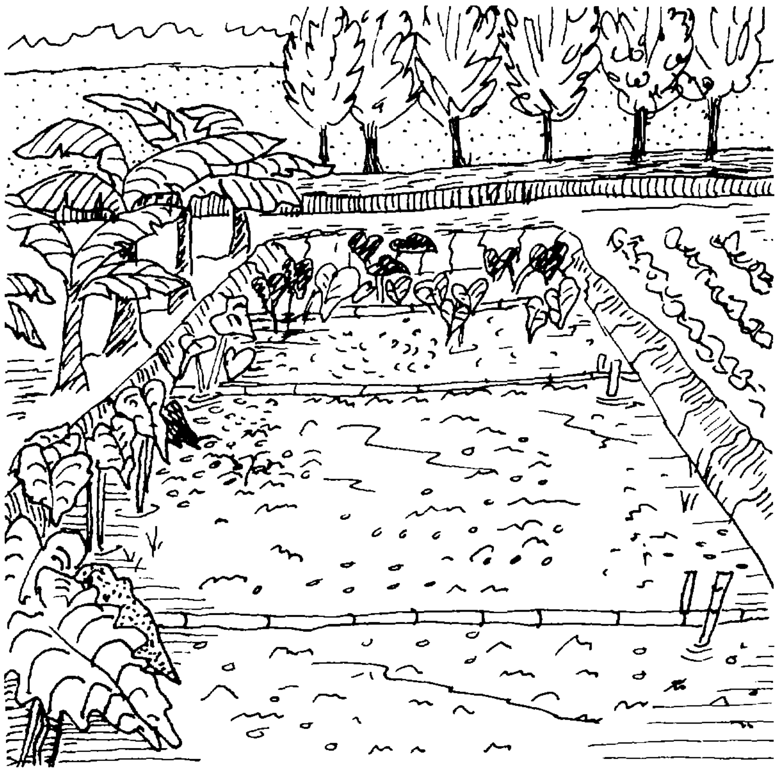

Figure 9. Co-cropping with terrestrial plants mimics duckweed's natural environment and increases cropping intensity

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.

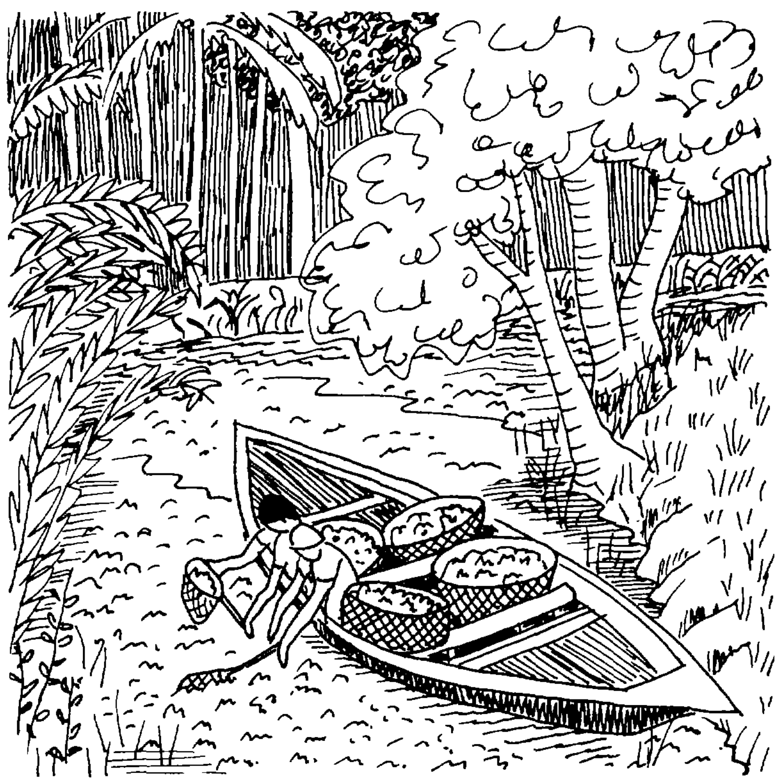

Figure 10. Collecting duckweed seedstock

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.

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/m^2 (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 8^0 C. As surface temperatures rise above 33^0 C at the Mirzapur experimental programs, local varieties of 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 m^2 that is used to lift a section

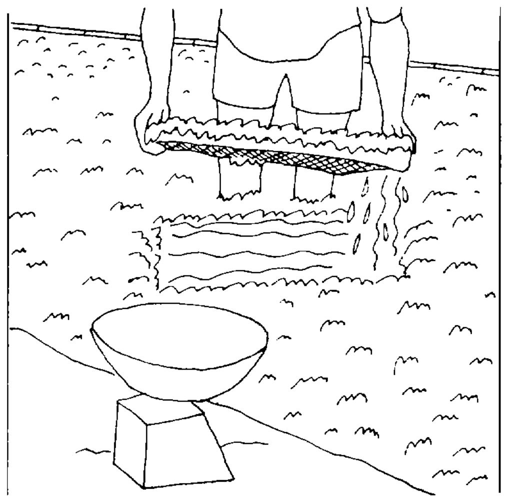

Figure 11. Growth in excess of the optimal stocking density should be harvested regularly to promote rapid growth

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 $g/m^2/day$—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.

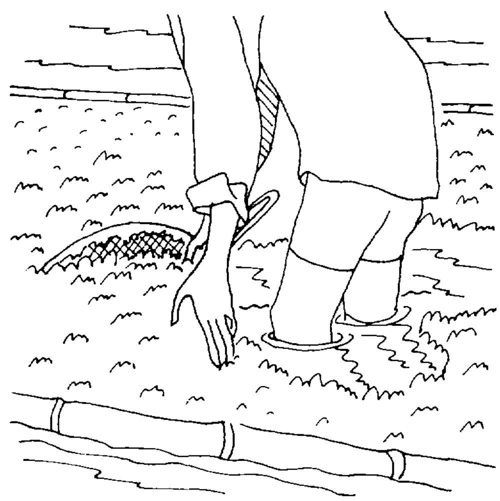

Figure 12. Harvesting by skimming with a dip net

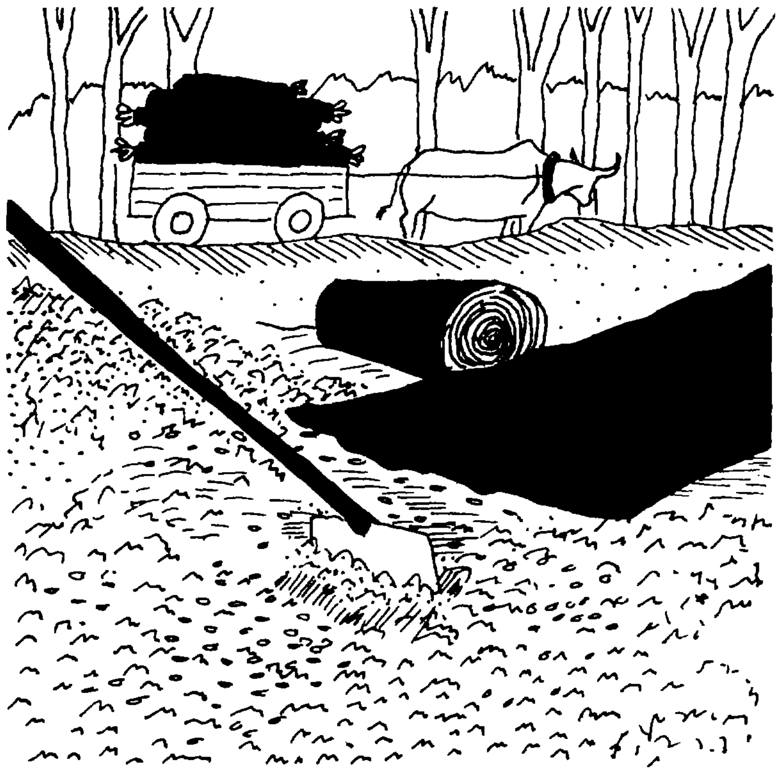

Figure13. Drying duckweed in the sun and bagging dried meal in opaque plastic bags

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.

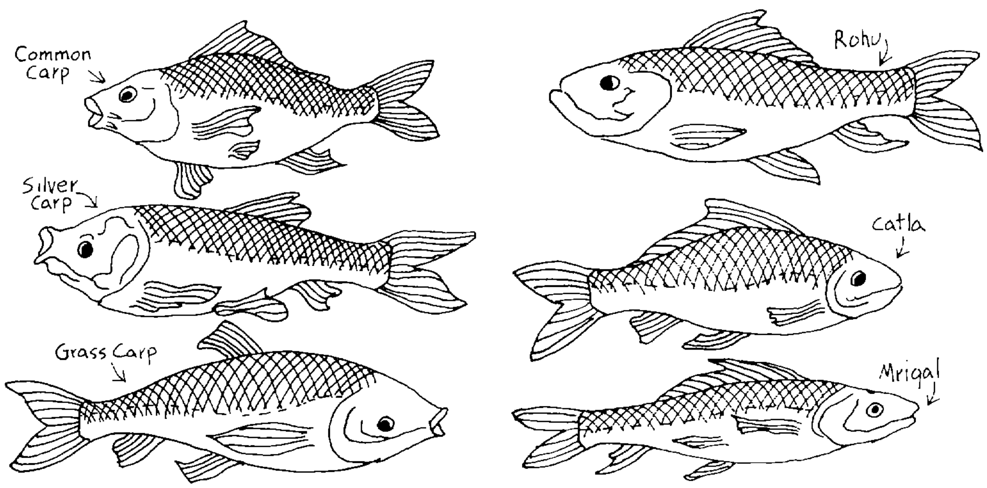

Figure 14. Chinese and Indian carp species

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:

$FERTILIZER_{CHEM}$ -> $PLANKTON_{FEED}$ -> *FISH*

is more efficient with respect to inputs than:

$DUCKWEED_{FEED}$ -> *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:

[$OXYGEN_{AVAIL}$] $FERTILIZER_{CHEM}$ -> $PLANKTON_{FEED}$ -> *FISH* -> $FECES_{FERT}$ -> NH_3, $PLANKTON_{FEED}$ -> *FISH* -> $FECES_{FERT}$ -> *NH3*, $PLANKTON_{FEED}$ ... ..**[$OXYGEN_{MIN}$]**

is less efficient with respects to inputs and oxygen than:

$duckweed_{feed}$ -> *fish* -> $feces_{feed}$ -> *fish* -> **[$oxygen_{avail}$]** $feces_{fert}$ -> $plankton_{feed}$ -> *fish* -> $feces_{fert}$ -> NH_3, $plankton_{feed}$ -> *fish* -> $feces_{fert}$ -> NH_3, $plankton_{feed}$ -> ... ..**[$oxygen_{min}$]**

In the duckweed model, the entire cycle of:

$duckweed_{feed}$ -> *fish* -> $feces_{feed}$ -> *fish* ->

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[1] 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".

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

[1]All dollar amounts are US$

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.

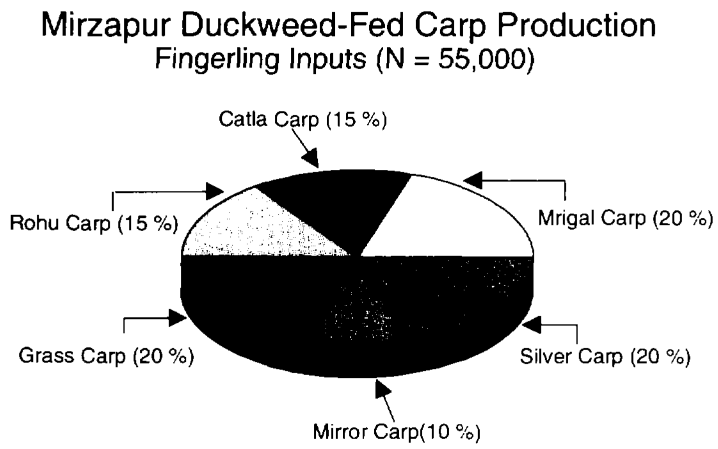

Figure 15. Fish inputs (1989-90)

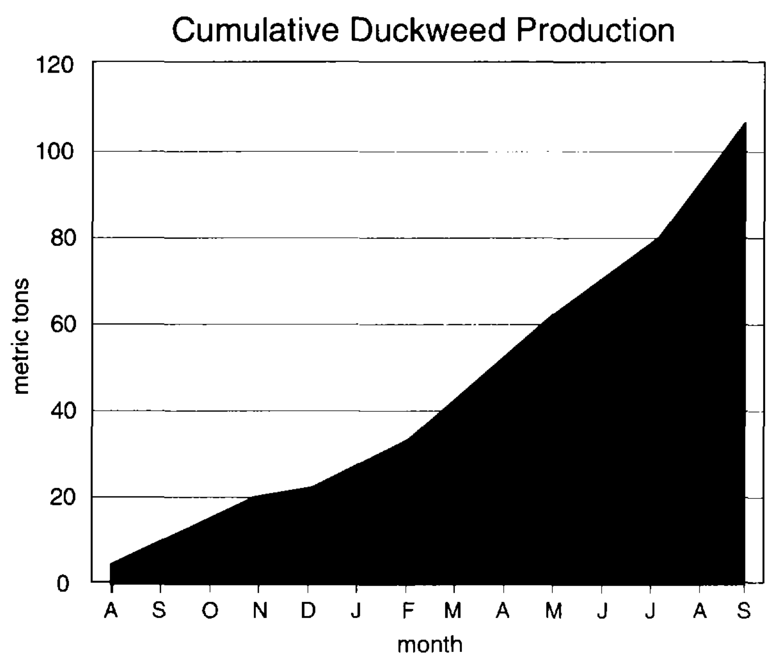

Figure 16. Duckweed inputs (1989-90)

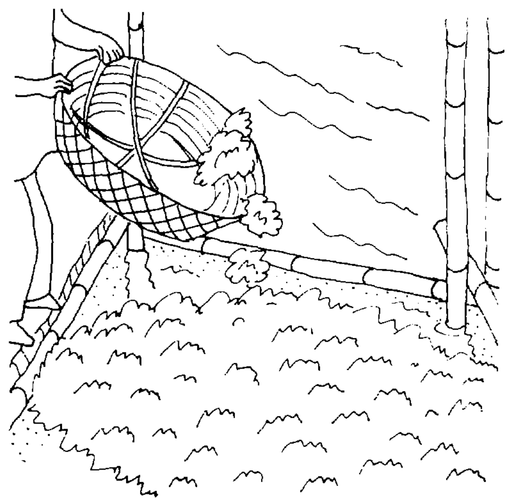

Figure 17. Fresh duckweed from the culture pond is fed directly to carp in the fish pond

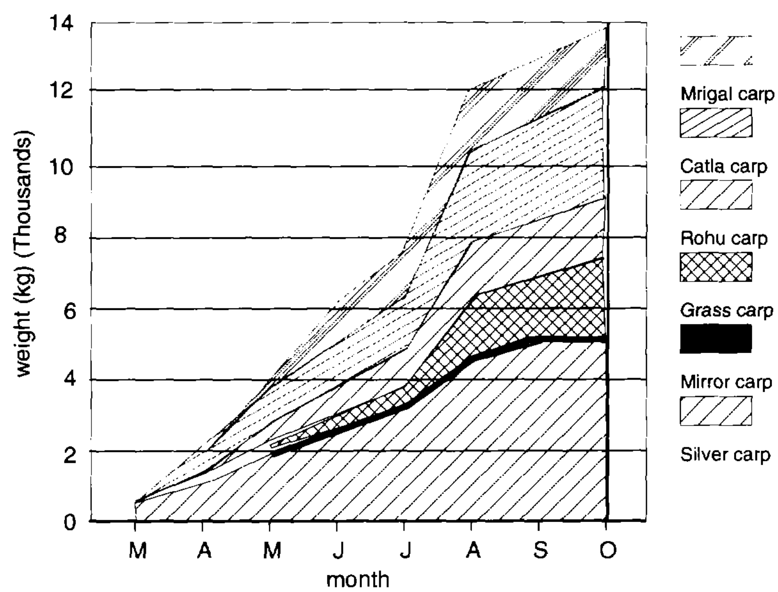

Figure 18. Weight of fish caught (1990)

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 m^2 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

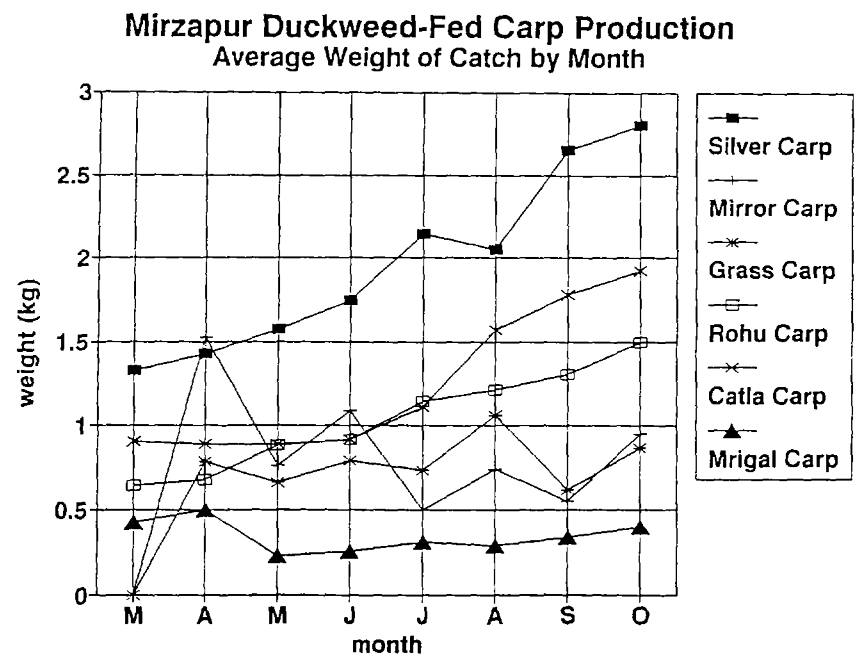

Figure 19. Average weight of fish catch by month in Mirzapur duckweed-fed carp production tests (1990)

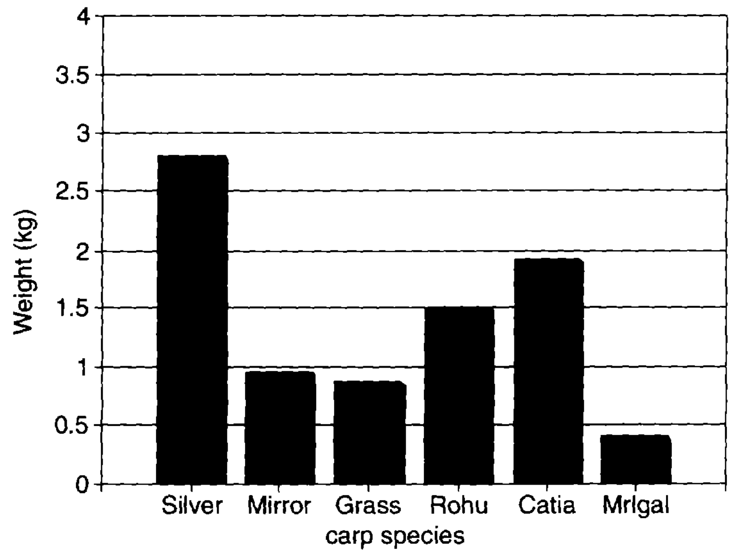

Figure 20. Average weight of fish catch after 13 months

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. Biweekly 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

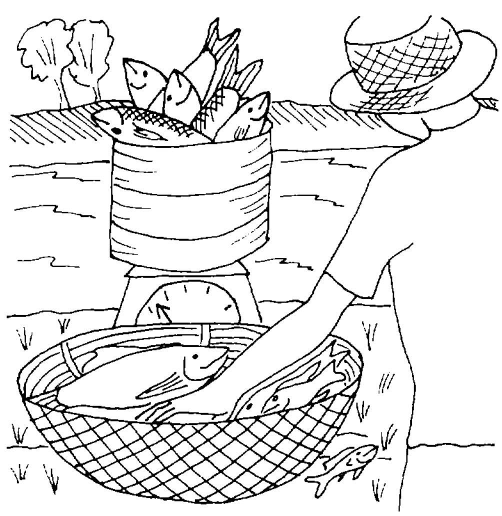

Figure 21. Market-size fish are selected and weighed

(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

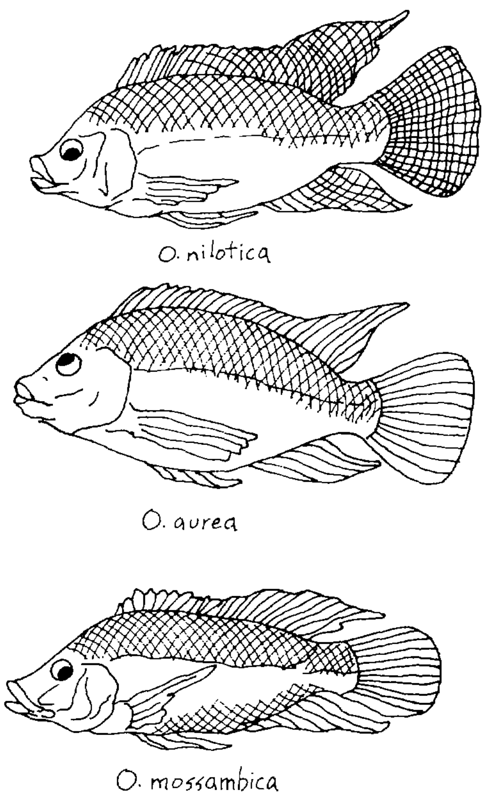

Figure 22. Major tilapia species

do not grow below 16^0 C and do not survive temperatures below 10^0 C. Unlike carp, they have no "floating" intramuscular bones, making it easier for the diner to separate bones from flesh.

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 four basic approaches to management of tilapia populations: monosex culture, intensive culling, production in brackish water 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

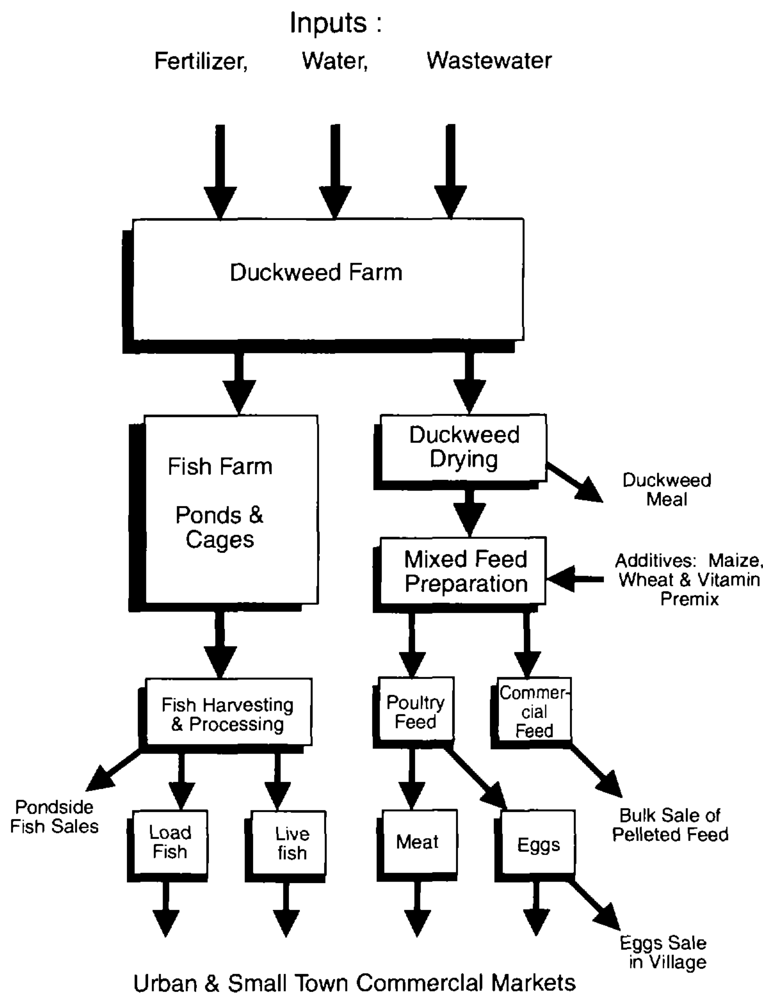

Figure 23. Product flows in integrated farming of duckweed, fish and poultry

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 under existing pricing arrangements in Banglasesh, 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.

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

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 (for terminology see Box 1). 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 percent 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 by-product. Providing accumulated toxin and heavy metal levels are not high,[1] the harvested duckweed biomass may be used as the

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

Box 1. Wastewater Treatment

Origin of wastewater

In cities and urbanised areas sewers and, sometimes, open-air drains convey wastewater from the households, from workshops or even some factories. The sewers often also drain away rain water to prevent flooding. This *municipal sewage* has a more or less typical composition all over the world, though locally characteristics reflect the activities in the drainage area.

Parts of cities which are not connected to the sewer network, and towns and villages without sewers, have to rely on open channels to drain kitchen sullage, and on septic tanks and soaking pits to have the heavily contaminated toilet ('black') wastewater percolate into the soil.

Factory discharges are very specific per industry sector with regard to their quantity and composition.

Wastewater composition and purpose of treatment

The following categories of water contaminants can be distinguished:

- organic substances which can be degraded by bacteria with the help of oxygen dissolved in the water (BOD); too much of these substances depletes oxygen in the water rendering it septic and unfit for human or animal use;

- nutrients (nitrogen and phosphorus) which make plants and algae grow profusely to the extent they endanger normal use of the water (*eutrophication*);

- heavy metals and organic micropollutants, generally from factory discharges, which may be toxic ('toxins') to plants, animals and humans; and

- pathogenic (disease causing) micro-organisms which abound in human excremental and black wastewater.

The purpose of treatment can be public protection (keeping pathogens away from the habitat, or killing them by disinfection), protection of environmental quality (removing oxygen consuming substances, and toxins) or achievement of water quality and ecological standards (nutrient removal).

Elements of wastewater treatment

'Primary' treatment aims at removing settleable and floating matter in a simple settling tank; up to 40 percent of pollution can be removed (but not all BOD nor nutrients or toxins). 'Secondary' treatment conventionally uses bacteria and forced oxygen adduction to remove the remainder of oxygen consuming substances and is traditionnally the most expensive component of the system. Only the additional 'tertiary' stage, applying chemical or biological methods, is also able, at a considerable expense, to remove nutrients and part of the toxins. Finally, pathogen reduction can only be achieved fully by 20 - 25 days impoundment, as in a duckweed system, or by chemical disinfection.

sole feed input for fresh-water pisciculture, and as up to 40 percent of poultry feed. This biomass might also be useful for a variety of other domestic animals.

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) achieve removal of oxygen consuming substances and pathogenic organisms to an extent comparable to algae based lagoons; but (c) without having the disadvantage of large amounts of algae being washed out of the system as suspended solids.

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.[2]

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, though the system has not been optimized—notably the required surface may prove lower than the present situation. Treating an average flow of 125

[2]Duckweed systems can vary in depth from half a meter to three or more meters, but this requires further study. System design should balance detention time—for pathogen reduction—against land and excavation costs, nutrient removal targets and the feasibility of chlorinating the final effluent. All things being equal a duckweed system having the same depth and detention time as a conventional facultative lagoon system will provide a higher overall level of treatment—for pathogen, nutrient and suspended solids removal. Secondary effluent standards can be achieved with between 0.3 and 1.0 m^2 per person, and advanced tertiary standards with 2.5 to 4.0 m^2 per person. This contrasts well with the facultative lagoon requirements of between 1.8 and 2.8 m^2 per person to achieve close to *secondary effluent standards.*

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*[1]
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[2]

1. This turbidity unit standard is roughly equivalent to total suspended solids (TSS) times two.
2. 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.

m^3/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.[3]

Table 2 shows typical influent, primary effluent and duckweed system effluent data for the Mirzapur experimental wastewater treatment plant.

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 hundred cubic meters per day to over 30,000 m^3/day.[4]

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.

[3] The wastewater effluent from the Kumudini Hospital complex (Mirzapur), with BOD of 120 mg/l, is not typical of most developing country wastewater streams which are commonly more polluted. 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.
[4] 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 and not used as food or forage. In such situations the duckweed system should be operated to optimize the combined "value" of achieved effluent quality and duckweed crop.

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.[5]

Harvested duckweed plants contain up to 45 percent 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.[6]

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.

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

[6] 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.*

Primary system The primary phase of the duckweed wastewater treatment system in a simple and cheap basin, which receives all the raw wastewater influent. This phase in itself is a quite common primary sedimentation, but should be designed to release the maximum amount of nutrients from the settled matter; in the subsequent phase, duckweed will thrive on these nutrients. 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.

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.[7]

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 percent 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

[7] 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.

desludging. This will, of course, require temporary 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 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. In villages and rural towns without sewer infrastructure, the primary phase in the duckweed system may be deleted. A structure should be organized which motivates village dwellers to make use of well designed and maintained latrines situated on the banks of the duckweed lagoon. The purpose is to get as much excreta, containing valuable nutrients directly into the lagoon rather than having them deposited in the neighbourhood or in pit latrines. The system consists of just one deep pond for duckweed production; excrements settle down quickly to the bottom where they gradually decompose. Of course, crop collection requires more careful procedures to prevent contamination.

Duckweed plug flow system The essential element of a duckweed wastewater treatment facility is the duckweed system itself. It consists of a shallow, lined[8] 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.

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.

[8] 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.

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.[9]

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[10] and compounds with herbicidal properties can have a similar effect but this 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.

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.[11]

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

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[9] Refer to Sections one and two for specific information on optimal conditions for duckweed cultivation.

[10] 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.

[11] 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.

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[12] and choice of system operation intensity.

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 m^2 to 50 m^2.

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

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

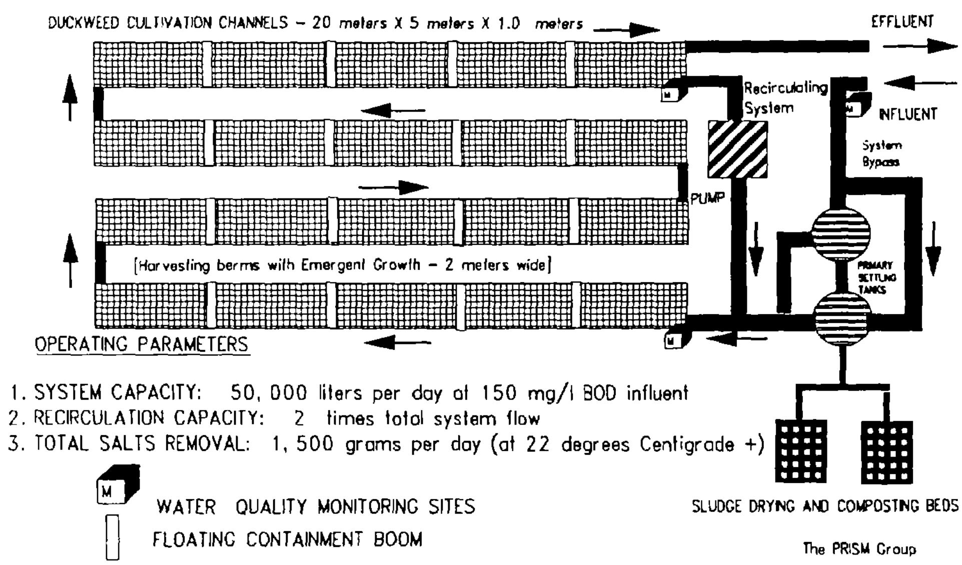

Figure 24 Model duckweed wastewater treatment system using floating containment barriers

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 harvesters 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

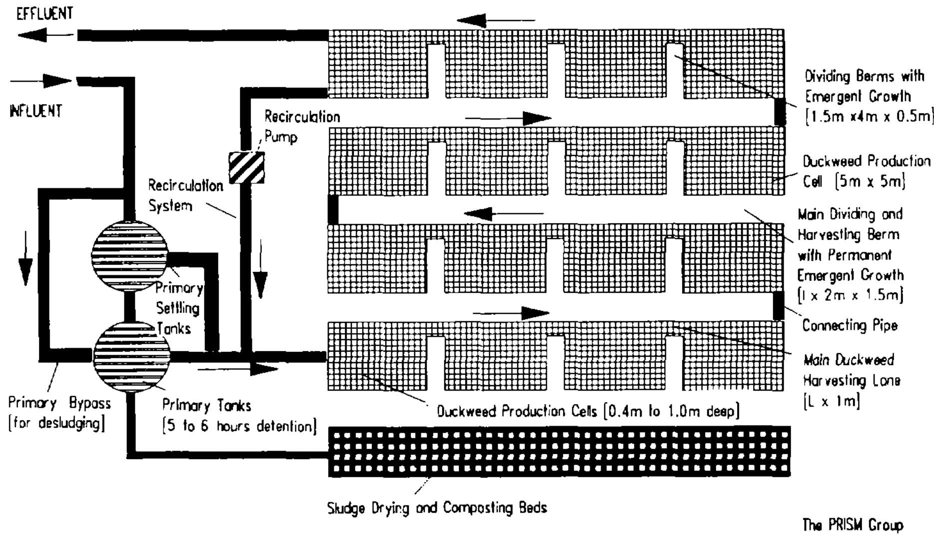

Figure 25 Model duckweed wastewater treatment system using earthen berms for crop containment

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 remove 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[13] with high toxin and heavy metal content.

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 USF-DA (United States Food and Drug Agency) food standards prohibiting human consumption.[14]

Duckweed wastewater polishing Effluent from a polishing treatment plant has normally received a series of expensive treatments. Duckweed plants do, also, 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 percent; 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 virtually everything still present in the wastewater.

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[13] Duckweed wastewater treatment systems are, nevertheless, capable of efficient toxin and heavy metals removal in a polishing process described under "Duckweed Wastewater Polishing" below.

[14] 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.

Polishing units, necessarily, form the final stage of a duckweed wastewater treatment system. The polishing function takes place in the final stretch of a duckweed wastewater plug flow system. In instances of wastewater with 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.

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.[15]

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[15] 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.

A secondary advantage of the duckweed system in this respect lies in the very low concentrations of suspended and dissolved organic matter in its effluent, when compared to regular algae based treatment lagoons. As described earlier, removal of organic pollution takes place efficiently. In addition, growth of algae, always hard to remove from water, is inhibited by the shade created by the duckweed layer on the pond surface. If the necessity arises to produce an effluent totally free of pathogens, such effluent can be disinfected safely by chemical chlorination; chlorination of water containing too much organic substances produces carcinogenic trihalomethane, which should be avoided.

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[16] 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.

Commercial systems In the United States, a commercial duckweed based wastewater treatment process has been approved by the U.S. Environmental Protection Agency for funding in municipal applications, which has now been applied, under varying conditions, in over sixty distinct locations throughout the United States, Europe and Latin America. The 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 trop-

[16] 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.

ical. Such systems compete favorably against mechanical wastewater treatment systems[17] 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.

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.

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

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, dried 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 Hectare 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	$4,063
Fingerlings		$457	$489	$523	$560	$599
Pond Preparation		$429	$459	$491	$526	$562
Water		$571	$611	$654	$699	$748
Labor		$712	$762	$815	$872	$933
Miscellaneous		$57	$611	$654	$699	$748
Total Recurrent Costs		$5,840	$6,249	$6,686	$7,154	$7,655
INCOME						
Sale of Fish		$15,000	$16,050	$17,174	$18,376	$19,662
NET INCOME	($17,271)	$9,160	$9,801	$10,487	$11,221	$12,007
CALCULATIONS (5 year investment)						
Internal Rate of Return	50%					
Net Present Value	$20,141					
Break Even Point	1.8 years					
ASSUMPTIONS (per year)						
Labor	2,601 hr					
Water	60,000 m^3					
Fingerlings	20,000					
Production	10 tons					

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					
Duckweed Seed Stock	$71					
Total Fixed Costs	$3,285					
Total Working Capital	$486					
Total Capital Requirements	$3,771					
Recurrent Costs						
Fertilizer		$866	$927	$991	$1,061	$1,135
Supplies		$71	$76	$81	$87	$93
Bamboo, etc.		$171	$183	$196	$209	$224
Water		$286	$306	$327	$350	$375
Labor		$548	$586	$627	$671	$718
Total Recurrent Costs		$1,942	$2,078	$2,223	$2,379	$2,546
INCOME						
Duckweed Sale		$3,142	$3.362	$3,597	$3,849	$4,119
NET INCOME	($3,771)	$1,200	$1,284	$1,374	$1,470	$1,573
CALCULATIONS (5 years)	Hydroponic	With Wastewater				
Internal Rate of Return	23 %	52 %				
Net Present Value	$2,712	$4,757				
Break Even Point	2.9 years	1.8 years				
ASSUMPTIONS						
Fertilizer						
Urea	3,120 kg					
TSP	624 kg					
Potash	624 kg					
Salt	1,404 kg					
Water	30,000 m^3/year					
Labor	2,000 hours					
Production (wet weight)	110 tons					

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This publication is based primarily on a study performed at the Mirzapur Experimental Duckweed Site by The PRISM Group of Columbia, Maryland, U.S.A. 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.

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