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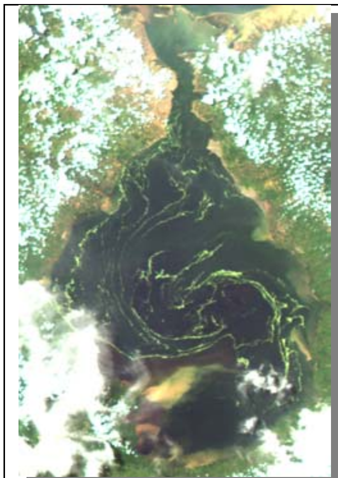
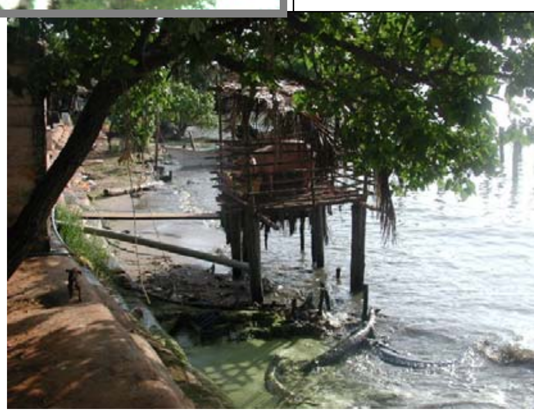
The duckweed invasion of Lake Maracaibo: An evaluation of the causes and proposals for future action




By

Professor R A Leng
Dr T R Preston
MSc Lylian Rodríguez

The University of Tropical Agriculture Foundation – UTA

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El crecimiento explosivo de lemna en el Lago Maracaibo: Evaluación de las causas y Propuestas para el futuro

Reporte presentado a:

Por

Fundación Universidad para la Agricultura Tropical (UTA)

Ronald A Leng, PhD, DSc, Profesor Emeritus
Thomas R Preston, PhD, DSc
Lylian Rodríguez, MSc

www.utafoundation.org

Finca Ecológica UTA -TOSOLY
AA #48, Socorro, Santander, Colombia

Contents

Executive summary

Lake Maracaibo, the largest lake in South America, covers 12,000 square kilometres and contains approximately245 billion cubic meters of water. In the past 3 months a proportion of the lake has become covered with a floating aquatic plant which has recently been identified as a member of the *Lemnacea, Lemna obscura.*

The purposes of the present assignment were two-fold: (i) to investigate the causes of the present duckweed bloom and provide a strategic plan to avoid future problems; (ii) to provide recommendations on the potential development and use of the duckweed biomass, with special emphasis on assisting the rural poor.

In order to understand the underlying causes of the duckweed bloom, the following aspects were analysed: changes in the topography of the lake in recent times; sources of pollution by key nutrients entering the lake; supply of water to the lake and its currents; biology of the particular aquatic plant; the behaviour of fresh water entering saline water bodies.

In many parts of the world, there are areas in seas and of lakes that are too low in oxygen to support life. These areas are expanding rapidly and at alarming rates. World-wide there are 146 such "dead zones", 43 of which occur in coastal waters of the USA. Since 1960 the number of dead zones has more then doubled, usually in line with increased agricultural inputs to land-based crop production with subsequent increased discharge of fertiliser in run-off water. It is considered that the circumstances relating to the development of Dead Zones in oceans or lakes represents a model that helps to explain the phenomena of the duckweed bloom on Lake Maricaibo. It is suggested that such a model could help to predict the "worst case" scenario, should no actions be taken to remedy pollution of the Lake.

The hypothesis is that the salinity in the lake has risen because of the dredging of the canal entrance. The inflow of water to the lake from rivers, together with the drainage from areas of human activity, is of low salinity and remains in the surface layer above the main body of saline water. The inflow of water from the Catatumbo River appears to be responsible for the direction of the Maracaibo current, which flows initially in the upper layer and picks up surface nutrients from various point sources with little mixing with the main body of the water in the lake. The stratified layer of fresh water entering from the Catatumbo River first passes major areas of human activity along the south west and west shoreline picking up concentrated nutrients that support high growth rates of duckweed. This phenomenon will be enhanced by the surges of water as the rains intensified. Around the lake there are thousands of ponds, ditches and small streams [Zone A) that have high concentrations of nutrients shortly after the commencement of the rains. These sites are the sources of the nutrient-rich duckweed, which spill over into the lake and are carried by the Maracaibo current picking up nutrients from the point sources of pollution (Zone B). In this zone (B) protected bays and other sheltered areas could support optimum growth of duckweed but probably do not produce enriched duckweed. The duckweed originating from Zone B continues to grow as the Maracaibo current carries it as a raft to the nutrient-poor areas in the lake (Zone C). At the same time as the surface water moves towards the northern part of the lake, the action of the waves and currents breaks down the stratification and further depletes the nutrient availability. The growth of the duckweed slows, nutrients are mobilised and eventually the death rate exceeds the rate of formation, and the duckweed mat slowly disappears. Some duckweed when blown by wind and wave action can re-enter the polluted areas of lower saline content along the whole shoreline and will rejuvenate prolonging the life cycle on the lake's surface.

The first priority is to reduce the inflow of nutrients into the lake as these have been accumulating, as shown by the tendencies in concentrations of nitrogenous materials [Figure 10]. Although the average level of nitrogen in the water is relatively low, the duckweed can continue to grow because of the nutrients accumulated in Zones A and B. The relatively low concentrations of nutrients in the body of the lake are nevertheless important as this allows the plant to survive longer on the lake surface.

A second reason for lowering the pollution entering the lake is to eliminate the potential for an algal bloom to develop in the surface water and possibly creating a 'Dead Zone' as has occurred in the Gulf of Mexico. The area of high priority is that between Ceuta and Cabimas because of the probability that this is the major source of nutrients entering the surface layer. The reason for this suggestion is that these areas are the first to receive the surface flow of fresh water driven by the Catatumbo River. A third reason is that other aquatic plants [eg: *Elodea*] appear to have become established in recent years with potentially serious consequences for the fishing industry.

The large biomass of decaying duckweed may create some areas of hypoxia in the lake but unlike algae the duckweed rafts are continuously moving over the lake's surface and dead duckweed will be spread over the whole lake. As only 15% of the lake was covered a dead zone is unlikely as indicated by the fact that there have been no kills of the fish. However a bigger bloom could be disastrous leading to the death of the lake and could occur with increasing levels of pollution and in similar climatic conditions.

Treatment of sewage water should be targeted as a first priority, but run-off of any sort from urban populations also should be controlled. The sewage treatment should include duckweed "polishing" ponds in order to ensure a low level of phosphorus in the discharged water. The resultant duckweed biomass, with a few precautions, could be used by local farmers as a source of animal feed.

Simultaneously in the same areas other source of pollution should be targeted, particularly small lagoons and water bodies associated with animal and human use. In these areas the development of duckweed farming should be initiated with integrated crop animal farming systems as are described later in this document.

The productive use of duckweed as animal feed is reviewed. It is shown that duckweed of high quality (>35% crude protein in the DM) can substitute for soya bean meal in diets for ducks and chickens; that it increases the growth rate of pigs when added to traditional diets; and that it probably has potential as a protein source for ruminants.

Appropriate research to be carried out includes: testing of the hypothesis that the nutrient-rich duckweed originates in small water bodies areas surrounding the lake and the concept of the stratified layer of fresh water above the saline water; evaluating systems of using duckweed to remove nutrients from black water in large and small scale water purification systems; using duckweed of low nutrient content as substrate for biodigesters and earth worms and as compost; and validating use of high-quality duckweed as animal feed.

Key words: Duckweed, Lemna spp, dead zones, fish, livestock, feed, stratification, Maracaibo, saline fresh water stratification, black water, contamination

Background

Lake Maracaibo, the largest lake in South America, covers 12,000 square kilometres and contains approximately245 billion cubic meters of water. In the past 3 months a proportion of the lake has become covered with a floating aquatic plant which has recently been identified as a member of the *Lemnacea, Lemna obscura* but there are potentially other members of this family present including *Lemna minor.*

The floating weed was first observed in January 2004 when it covered from 1 to 2% of the lake's surface and built up to a maximum density in April-May when it appeared to cover approximately 14% of the lake. At the time of writing this report [July 10th 2004] it appears to have decreased to about 10% coverage of the lake's surface. The duckweed moves around the lake in large rafts of material, carried by the counter clockwise currents in the lake and according to wind speed and direction. Thus many areas experience a period where the immediate area is covered by weed, which is then suddenly removed to another area.

The lake's counter clockwise currents, which result from the inflow of water from the Catatumbo River [provides 60% of the total fresh water input into the Lake] in the south western part of the lake, and the tidal flow through the channel to the Gulf of Venezuela in the north tends to concentrate the rafts of duckweed at the centre of the lake. This has distracted many people into believing that the origin or source of duckweed is at the centre. As will be discussed later this is probably incorrect and the origin is the shores and hinterland areas of the lake.

The obvious presence of the weed has alarmed environmentally concerned persons and organisations, as it has been recognised as a major indicator of pollution of the lake with mineral nutrients. This may be true to some extent but the circumstances of the invasion of the weed in the lake may not be so important per se, but is an early warning of problems to come if the lake's pollution rate is not controlled. The lake has a self-cleaning action brought about from the flow of water from the south of the lake through a dredged channel to the Gulf of Venezuela.

Members of the small scale fishing industry have become alarmed that the pollution may affect the viability of their industry and there have been reports that the weed has been responsible for increasing the difficulties of fishing from small boats whose engines become clogged with the weed. The indications are that up to now the fish biomass is not decreasing. The major problem for the fishing community is in finding ways to undertake their customary activities, and the aesthetic problem that the duckweed at times surrounds their shoreline and their fishing areas, which are transient. The appearance of other aquatic weeds that are submerged [*Elodia*] is also indicative of changing ecological aspects of the lake. The submerged aquatic plants mainly *Elodia* and balls of fibrous materials [referred to as boletoes] clog the fishing nets and many small fish and crustacean are difficult to separate and perish in the discarded materials. One fisherman claimed that for a catch of 35kg of prawns he discarded some 3000kg of weeds .These appear, however, to have gone unnoticed.

The unknown issues, associated with the sudden appearance of large rafts of duckweed on the lake, have resulted in calls for finding ways to get rid of the duckweed from the lake, and to investigate the reasons for the appearance of the large volume of weed [the purpose of the present task]. The reaction of the authorities, charged with preserving the lake's ecology, have been to organize the physical removal of the duckweed from those parts of the lake of immediate concern to the local communities, and to simply place it in heaps on the edge of the lake. This is resulting in decomposition of the duckweed and eventually the run-off of nutrients which will re-enter the lake, thus adding to the pollution, with the production of hydrogen sulphide gas and subsequently sulphuric acid.
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There have been some reports of dermatitis in people who have had to go into the water where duckweed is concentrated. As will be discussed later this is probably associated more with the decomposing duckweed than the fresh plant.

Duckweed is recognised in other parts of the world as a valuable resource that can be used to purify water bodies [in the USA/Europe/Australia] and the resultant biomass has been shown to have potential use as a food for domestic animals [In South America and in Asia] and even a source of vitamins and protein for humans (in Cuba).

Objectives

The purposes of the present assignment were two-fold:

1. To investigate the causes of the present duckweed bloom and provide a strategic plan to avoid future problems
2. To provide recommendations on the potential development and use of the duckweed biomass.

The problem

In order to understand the underlying causes of the duckweed bloom it is necessary to appreciate the following aspects of:

- changes in the topography of the lake in recent times
- sources of key pollutants entering the lake
- supply of river water to the lake and its currents
- biology of the particular aquatic plant
- behaviour of fresh water entering saline water bodies

Blooms of aquatic flora, particularly algae, are major problems in many aquatic ecosystems. In many cases this has resulted in eutrophication of large areas where nutrient-rich fresh water enters saline waters. Large areas of oceans polluted with run-off of mineral nutrients in rivers suffer periodic algal blooms that lead to development of "Dead Zones".

We believe that the circumstances relating to the development of Dead Zones in oceans or lakes represent a model that helps to explain the phenomena of the duckweed bloom on Lake Maricaibo. It is suggested that such a model could help to predict the "worst case" scenario, should no actions be taken to remedy pollution of the Lake. The first section of this report describes the underlying reasons for the development of Dead Zones in the world's oceans. The immediate comparison is with the Dead Zone that appears each spring in the Gulf of Mexico, leading to large areas that are devoid of fish and other aquatic life. The dead zone in the Gulf of Mexico presently occupies 21,000 square kilometres, which is almost twice the size of Lake Maracaibo.

Dead Zones in the World's Oceans and Lakes.

Occurrence of dead zones

In many parts of the world, there are areas in seas and of lakes that are too low in oxygen to support life. These areas are expanding rapidly and at alarming rates. World-wide there are 146 such "dead zones", 43 of which occur in coastal waters of the USA. Since 1960 the number of dead zones has more then doubled, usually in line with increased agricultural inputs to land-based crop production with subsequent increased discharge of fertiliser in run-off water.

The world's largest dead zone is in the Baltic Sea followed by the seasonal one in the Gulf of Mexico. The explanation of the development of the dead zone in the Gulf of Mexico has important implications for Lake Maracaibo and also for the Gulf of Venezuela, because it ultimately receives the water from the Lake.

The hypoxic zone in the Gulf of Mexico is a seasonal phenomenon. It spreads from the point of entry of the Mississippi River and extends to a area of 22,000 square kilometres. It was first recorded in 1970 and has since occurred every 2 to 3 years increasing in size each time. It now occurs annually, commencing with spring rains.

The dead zone appears each spring as the Mississippi and Atchafalaya rivers empty into the Gulf bringing nutrient-enriched waters from the catchments. The nutrient load promotes the rapid growth of algae and creates hypoxic and anoxic areas devoid of fish and other sea creatures.

Hypoxic [<2 mgO_2 /litre] or anoxic[zero oxygen] conditions in the sea arise from two sets of circumstances.

- **Stratification of fresh and saline water**. The first step is when the fresh water from the Mississippi river enters the saline waters of the Gulf. The fresh water being less dense then the saline waters forms a surface layer. Normally the wind would churn the water and mix these layers as they move across the surface; however, during the summer months the weather is calm and the fresh water remains stratified in the top layer. Under these circumstances, the lower saline layer is cut off from the supply of oxygen from the surface and the oxygen levels are decreased in the saline bottom layer.

- **Growth of photosynthesising plants or algae in the nutrient-rich upper layer** The second feature in the development of hypoxia is that the rich nutrients from the river are not significantly diluted in the water accumulating as a surface layer. The levels of minerals in this layer, particularly nitrogen and phosphorus, are such that they support rapid algal growth and a huge increase in carbohydrate-rich biomass. The growth of algae is rapid because nutrients are not limiting. With no other impediments to growth (eg: factors such as disease and predation by other organisms), the rate of increase in algal biomass may be close to exponential and a bloom of algae suddenly appears in the surface layers of the water. Unlike lemna which may be dissipated by wind, these algae remain concentrated in the water. Algae have a finite life cycle and die or are consumed by fish. The algal biomass and detritus "rain down" into the lower level of saline water. The organic matter in the saline layers is decomposed by aerobic microbes and this depletes the oxygen level below that which supports life. Mobile fish leave the area or die and bottom inhabitants such as crustaceans perish. The bottom layers become anoxic and anaerobic organisms complete the degradation process leading to accumulation of organic acids [which lowers the pH] and liberation of methane and hydrogen sulphide gases.

The "dead zone" persists until some climatic phenomena disrupt the stratification of the water layers and mixing occurs lowering the concentration of nutrients in the upper layer and re-establishing the oxygen concentration in the deeper water. The cause of the dead zone is quite clear. It is a result of:

- human activities that increase levels of nutrients in the river water
- the physics of mixing of fresh and saline waters and
- the climatic conditions that pertain to the time of year when the dead zone forms

The catchments of the Mississippi River covers enormous areas and most polluting nutrients come from run-off from nitrogen and phosphate fertilisers used in crop production, predominantly grain production. Untreated or inadequately treated sewage is probably the second largest source of mineral contaminants.

Application of knowledge of the cause of dead zones to the duckweed problem on Lake Maracaibo

Characteristics of the Lake

Prior to the development of the oil industry in the 1950s the channel into the Gulf of Venezuela was shallow and flows of seawater were restricted. The salinity of the lake was very low. Salinity increased following dredging which was done to accommodate access by large sea-going tankers.

The Catatumbo River, which enters the lake at the south-western point, delivers 60% of the water flowing into the lake. This flow of water together with the tidal pulses of saline waters through the northern channel has produced a characteristic current, [which we will call the Maracaibo Current] that is counter clockwise. The current appears to be stronger at the surface, and this may enhance or induce stratification of the fresh water inflow at the surface of the lake creating similar stratification phenomena as seen in the Gulf of Mexico.

Associated with the Maracaibo Current is the development of a concentrated cone of saline water at the centre of the lake, that would also tend to reduce mixing of the surface water with water from the depth of the lake. Water from the Catatumbo River is picked up by the current and flows in a counter clockwise direction across the lake from the entry point on the south west corner.

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Climate

Rainfall is extremely high in the southern part of the lake and in the catchments of the Catatumbo River. Annual rainfall decreases from the south to the north of the lake. Heavy rains in the catchments of the Catatumbo River and the southern half of the lake will decrease salinity of the surface layer, particularly the early un-seasonal rains that occurred this year.

Nutrient content of lake water

The average concentrations of key nutrients in the lake water have risen from the 1950s, in particular nitrogen, which has increased from 0.001 to 1.0 mg N / litre, and phosphorus. These levels are high but they are not excessive. But they only represent mixed lake water [ie: at the centre of the lake].

Research in 1979 indicated that human activity at that time had created a number of point sources of pollution entering the lake, due to inadequate disposal of sewage and waste from industry. These analyses indicated that there was no apparent nutrient pollution from oil spills or residues from related activities [Figure 1]. However, the dispersants used on oil slicks contain sufficient phosphorus to be of concern particularly when oil leaks are excessive.

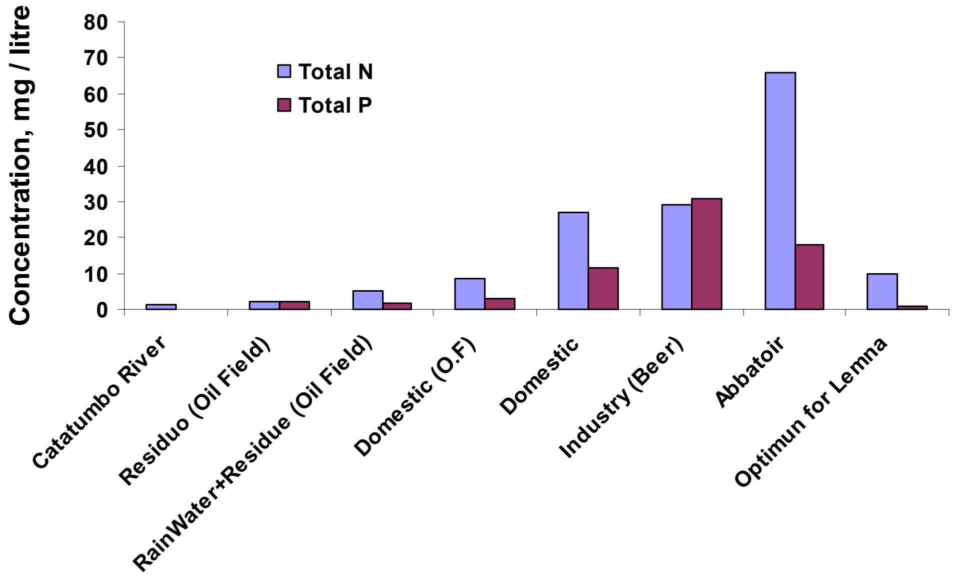


Figure 1: Concentration of N and P in different sources of contaminated water (1979)

Since these analyses were done, the population of the shoreline has increased enormously stimulated by the development of the oil industry. The major cities are Maracaibo with around 1.5 million people, followed by Cabimas [population 250,000] and Ciudad Ojeda [150,000]. Only about one sixth of the sewage from these cities is receiving some treatment before entering the lake. It was estimated that approximately 10,000 litres /sec of sewage enters the lake and only 1,600 litres per second receive some treatment [ICLAM 2004]. The analysis of water samples taken at sites around the lake [ICLAM 2004] close to population densities show that phosphorus and nitrogen levels are 2 to 3 times higher on the average compared with those from the centre of the lake or the Catatumbo River [Figures 2 and 3].

In Figures 2 and 3 the levels of phosphorus or nitrogen that would be needed for Lemna to grow optimally [growth] or to grow optimally and also accumulate high levels of phosphorus and protein [quality] are also shown so as to indicate areas where there is potential for lemna to grow.

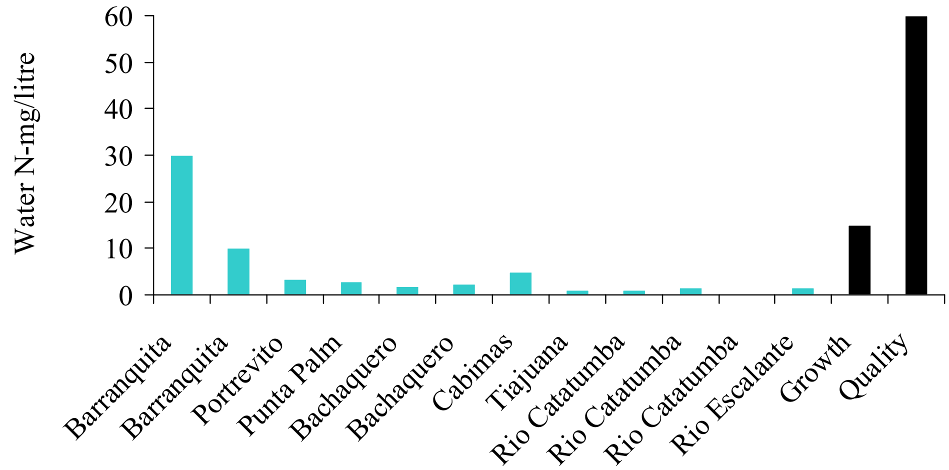


Figure 2: N concentration in water samples [mg/10litres water] at various sites in lake Maracaibo (Source: ICLAM)

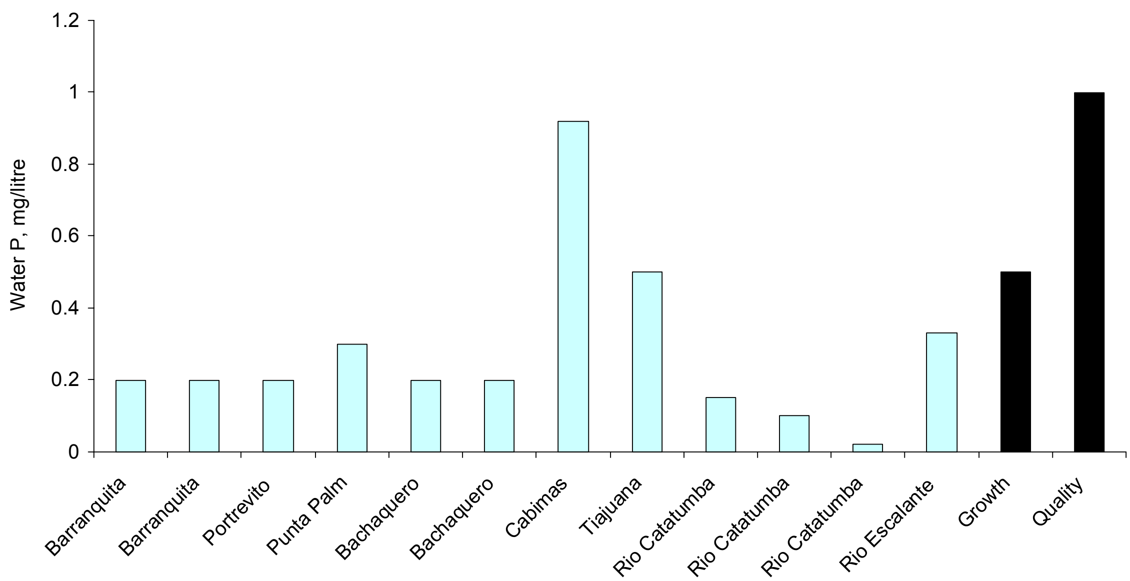


Figure 3: P concentration in water samples at various sites in lake Maracaibo (Source: ICLAM)

Lake surroundings

Most of the lake is surrounded either by grazing or waste land. It is mostly flat country with numerous small rivers, man-made drainage ditches, small to medium lagoons [some of which dry out in the dry season]. Many of these water bodies are presently covered by duckweed. There are small villages with houses close to the shoreline or on piles over the water the waste from which goes directly, or via a pond, into the lake. Animal densities appear to be low, and are dominated by grazing cattle and goats, but free range poultry and pigs are found in the villages and there are some intensive livestock operations. .

Development of large scale prawn farming is just commencing and if water returned to the lake is untreated this represents a future major point source pollution site.

Catatumbo River

The Catatumbo River provides 60 to 70% of the fresh water entering the lake. It's catchments are mainly in Colombia. The concentrations of P and N in the river water are approximately the same as in the mixed water in the lake as a whole, thus the river does not appear to be a major source of pollution.[Figures 2 and 3].

Pertinent aspects of the biology of duckweed

Introduction

Duckweed or Lemna are the common names given to the simplest of flowering plants that grows ubiquitously on fresh and polluted water throughout the world. It grows year round in the tropics on water with traces of nutrients to support its growth. Duckweeds can grow on the surface of mud or in water from a few millimetres deep to any depth provided the water is still and the temperature in the water is between 6 and 33 ^oC. Higher temperatures that particularly occur in shallow water will cause growth to cease and the plant to die. The optimum pH for growth appears to be around neutral but duckweeds will grow within the range of 5.5 to 8. They are adapted to shaded areas and on open water may become heat-stressed in full sunlight.

Duckweeds belong to 4 genera: Lemna, Spirodelia, Wolfia and Wolfiela. They vary in size, presence or absence of roots and some 40 species are known throughout the world. All of the species have minute oval to round fronds from about 1mm to 1 cm in diameter. Under ideal conditions all species can multiply rapidly. Reported time for doubling the biomass is from 16 hours to 2 days under good conditions and may extend up to 10 days when conditions are unfavourable.

Duckweeds reproduce by a process of producing daughter fronds which separate from the plant and in turn produce further fronds. There are some peculiarities in growth patterns as these are cyclical, and under constant conditions duckweed mats are seen to wane and then re-grow . This appears to be a result of the finite life of the fronds which produce the daughter fronds that either progressively increase or decrease in size with each budding. Thus growth follows a cyclic pattern, which causes the duckweed mat on a closed pond to apparently shrink and then suddenly bloom or show explosive growth. This is a mechanism which presumably allows the plant to take advantage of flushes of nutrients through the aquatic ecosystem. This latter ability is important when duckweed on the lake's surface is blown by wind from nutrient-poor water, in the body of the lake to nutrient-rich sites close to the shore line, where it can reinvigorate its nutrient status.

Aspects of duckweed biology pertinent to the hypothesis

Nutrient load and growth

Duckweeds just as any photosynthesising organism need a range of mineral elements to grow including N, P and K and other macro- and micro-minerals. The primary limitations to growth are normally nitrogen and phosphorus. Duckweeds will grow on water with minimal concentration of nutrients but at slow rates. They accumulate minerals when flushes of nutrients become available and continue to grow by mobilising these when water nutrient levels are too low to sustain normal growth.

The ability of duckweed to store phosphorus was demonstrated where duckweeds were grown on a range of diluted sewage water [Figure 4].

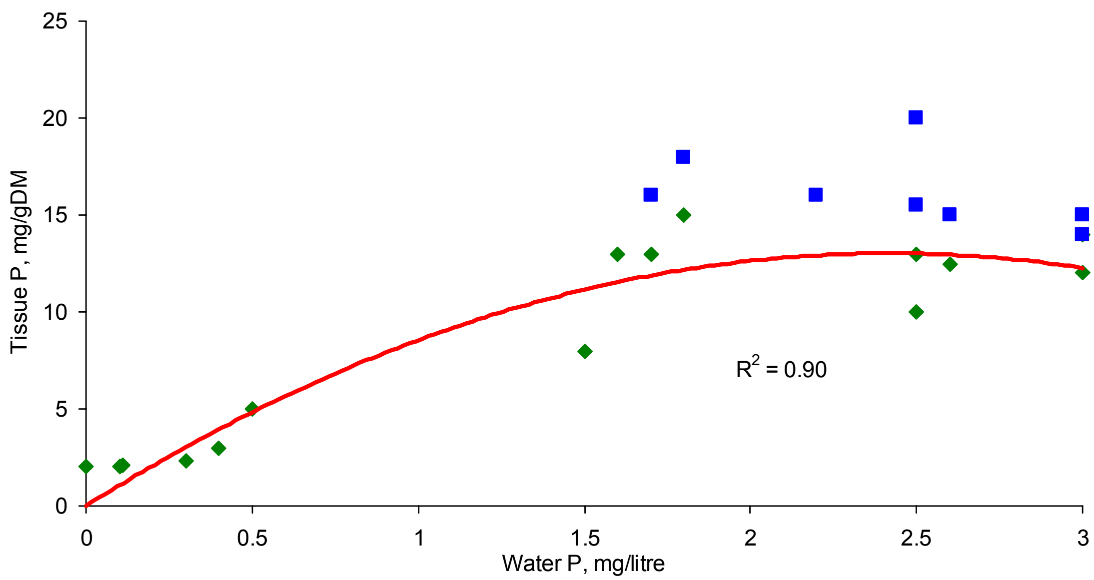


Figure 4: Growth and composition of duckweed [Original crude protein 38% in DM] when transferred to sewage water (Source: Leng 1999)

When levels of nitrogen in the water are high, duckweeds store nitrogen as protein. Ammonium ions are the most useful N source but ammonia is toxic to duckweed when the pH of the water rises to the point when there is free ammonia. The capacity of duckweed to store protein with increasing nitrogen content of water is shown in Figure 5.

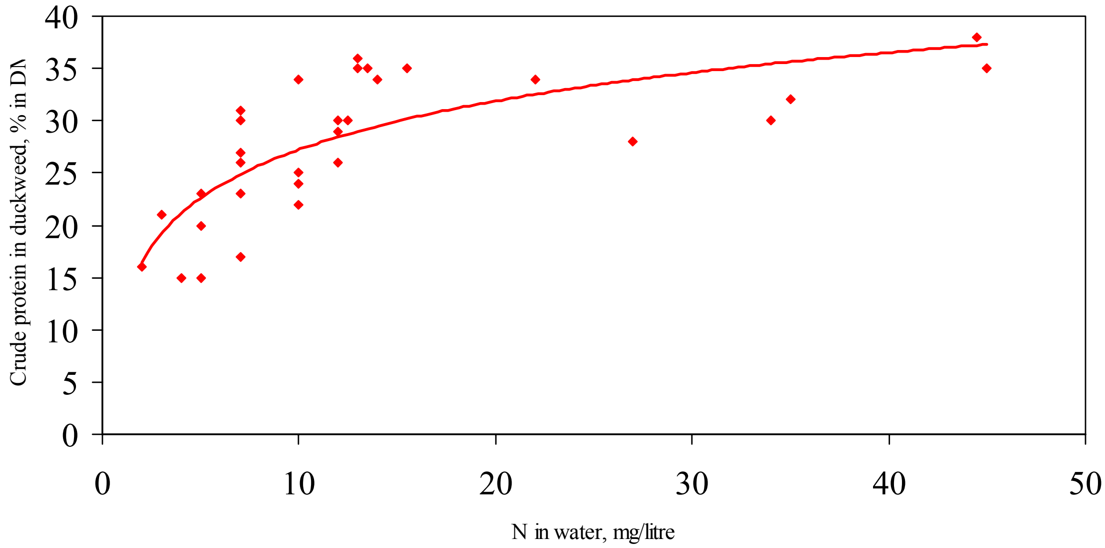


Figure 5: The crude protein concentration in duckweed depends on the level of N in the water, provided the P level is above 1 mg/litre (Source: Leng 1999)

Duckweeds that have been grown on water with high nutrient status, when transferred to water with low or no nutrient content, will continue to increase in biomass but mobilise both phosphorus and nitrogen [from protein] in order to continue to grow [Figures 6 and 7]. However, this increase in growth is composed of carbohydrate. Part of the increase in weight following the transition from high nutrient water to low nutrient water is in growth of root material.

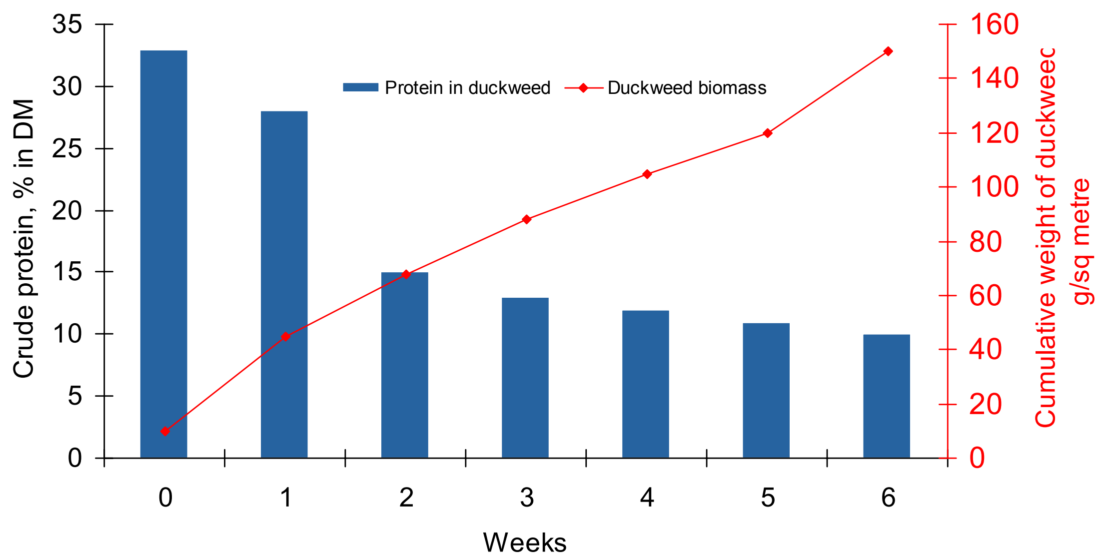


Figure 6: Duckweed, of high protein content initially, will continue to grow on water low in nutrients but the growth is entirely in carbohydrate (Source: Leng 1999)

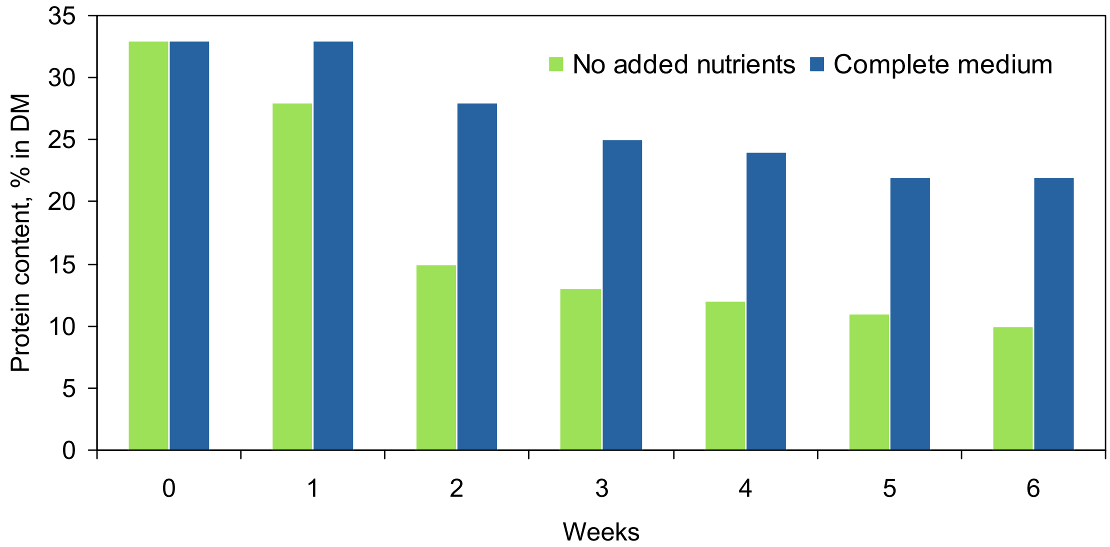


Figure 7: Protein content of duckweed grown in water with or without added nutrients [NPK] (Source: Leng 1999)

Research carried out in Australia [Table 1] has shown that for optimum quality of the duckweed biomass as a feed resource (ie: high crude protein and phosphorus), concentrations of both N and P in the water must be considerably higher than requirements for optimum growth. The conclusions from the above discussion are that when N and P concentrations are lower than required for optimum growth rate, the plant mobilises protein and phosphorus that allow it to continue to grow. Part of this growth is in the form of elongated roots which facilitates the scavenging for minerals when these are in low concentration. This helps to explain why:

- root length and protein content are inversely related; and
- when there is an explosive bloom of duckweed on the lake surface, in the form of a mat with long roots, this has its origins in the nutrient enriched water bodies as discussed below (eg: Zones A and B)

Table 1: Concentrations of N and P in the water for optimum growth and optimum quality (content of nutrients) of duckweed

	P [mg/litre]	**N [mg/litre]**
Optimum growth	>0.5	10-20
Optimum quality	1	60

The hypothesis for the sudden appearance of large areas of duckweed on Lake Maracaibo.

The clues

1. The mixed water of the lake contains levels of N and P [about 1mg N/litre and 0.02 mg P/litre] that can only support the slow growth of duckweed

2. The duckweed in mats on the lake has a very low crude protein concentration [range of 8 to15% in DM], whereas most of the samples taken from ponds in the hinterland, and in sheltered coves or from duckweed mats blown into shoreline areas contaminated with sewage, approach the enriched levels of 30 to 35%
3. The lake was highly saline prior to the beginning of the rains, and was especially so in the "hipolimnio" (or cone) at the centre of the lake,
4. Rains were particularly heavy and came earlier then usual at a time when the lake was highly saline. Large amounts of water entered the lake in the south west corner from the Catatumbo River
5. In 1979, the analysis of water from various sites in the lake indicated point sources of pollution with N and P, with the highest levels apparently associated with areas of human activity and industry
6. The duckweed plant has evolved a capacity to respond rapidly with explosive growth rates when high concentrations of nutrients become available.
7. Duckweeds that are depleted of nutrients can recoup nutrients when entering nutrient-rich waters and begin to re-grow. At these times the plant sheds its roots particularly in water with low oxygen content.[Studies at the University of Zulia confirmed this point].
8. The commencement of the rains would create thousands of habitats enriched with nutrients that had previously been concentrated in them during the dry season
9. The colour of the duckweed on the main body of the lake is yellow which is another indication of low nutrient content but within these yellow areas there are small patches of green duckweed indicative of the rejuvenated plants that had been blown there from nutrient-enriched areas.

The hypothesis

The salinity in the lake has risen because of the dredging of the canal entrance. The inflow of water to the lake from rivers, together with the drainage from areas of human activity, is of low salinity and will remain in the surface layer above the main body of saline water. The inflow of water from the Catatumbo River is responsible for the direction of the Maracaibo current, which flows initially in the upper layer and picks up surface nutrients from various point sources with little mixing with the main body of the water in the lake. This phenomenon would be enhanced by the surges of water in the river as the rains intensified.

Around the lake there are thousands of ponds, ditches and small streams [Zone A) that have high concentrations of nutrients shortly after the commencement of the rains. These sites are the sources of the nutrient-rich duckweed, which spill over into the lake and are carried by the Maracaibo current, picking up nutrients from the point sources of pollution (Zone B). In this zone (B) protected bays and other sheltered areas could support optimum growth of duckweed but probably do not produce enriched duckweed. The duckweed originating from Zone B continues to grow as the Maracaibo current, wind or wave action, carries it as a raft to the nutrient-poor areas in the lake (Zone C). At the same time the action of the waves and currents breaks down the stratification and further depletes the nutrient availability. The growth of the duckweed slows, nutrients are mobilised and eventually the death rate exceeds the rate of formation, and the duckweed mat slowly disappears. However, the life span of the duckweed on the lake surface may be prolonged when the rafts of plants enter point sources of pollution. The schematic representation of this is shown in Figure 8, while the aerial photographs (Photos 1, 2, 3 and 4) demonstrate the practical outcome.

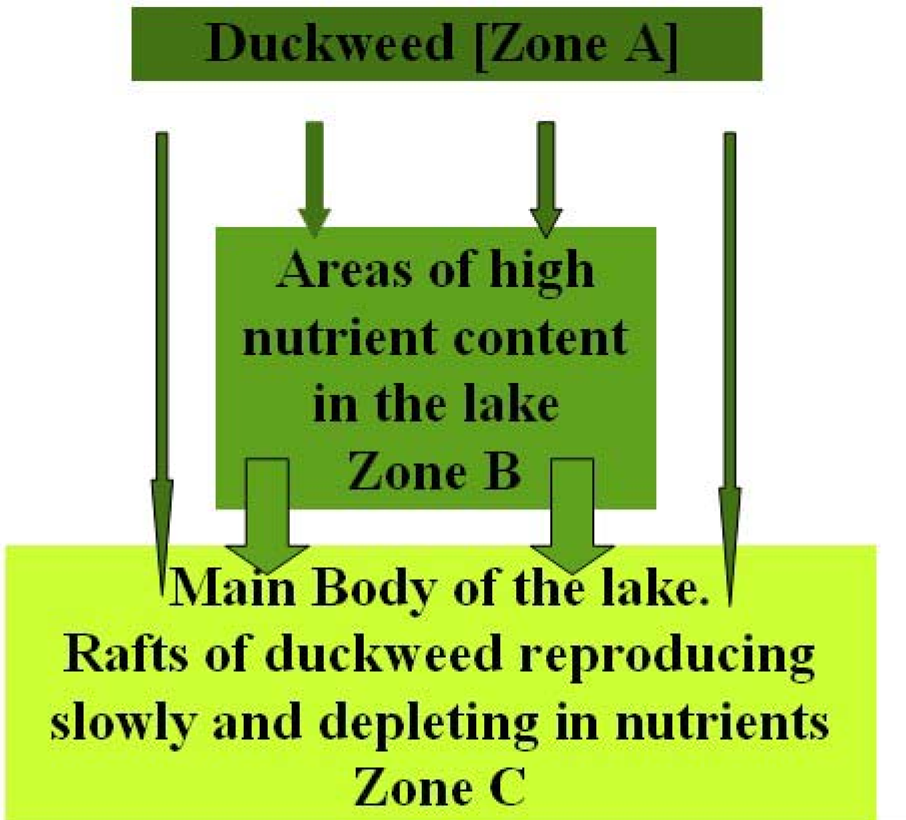


Figure 8: The predicted flow of duckweed from sites outside the lake (Zone A) to areas of high nutrient concentration inside the lake (Zone B) and finally to the main body of the lake (Zone C), where the duckweed continues to grow (slowly and mainly in the form of carbohydrate) by catabolizing its nutrient stores finally dying when these nutrients are fully depleted

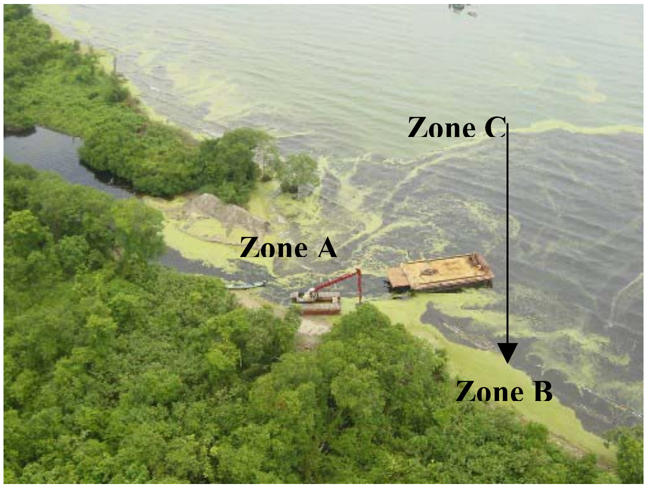


Photo 1: Sites of growth of the duckweed


Photo 2: A raft of duckweed in Zone C.

Photo 3: Sheltered bays favour the growth of duckweed in polluted water spread by the Maracaibo current

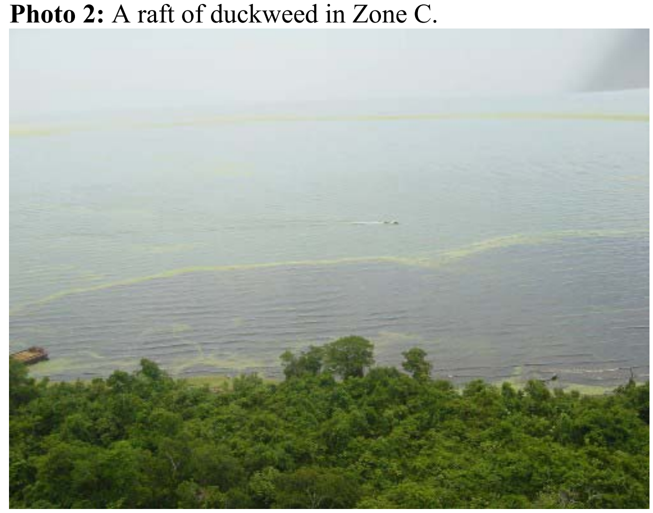


Photo 4: Duckweed dispersing over the lake surface, showing the influence of the Maracaibo current moving the polluted water along the shore line

A simple model of the duckweed bloom

The potential explosive nature of the duckweed bloom can be illustrated (Figure 9) by applying known rates of growth (time to double the biomass) and making some assumptions, as to the time spent in the different zones:

- In the early rains duckweed grows at a maximum rate in Zone A [doubles the biomass each 24hours] for 10 days
- Nutrient-rich duckweed enters Zone B where it remains for 10 days and continues to grow at half the maximum rate [doubles the biomass every 2 days] supported by its own nutrients and the nutrients from the point sources of polluting water before entering zone C
- In zone C it mobilises its protein and minerals to grow at a slower rate [doubles the biomass every 8 days] over 40days

On the basis of these assumptions, it appears that only 0.38 ha of duckweed would be needed in the land-based growth areas to give rise after 10 days to 195 ha in Zone A, then growing to 6,250 ha in the polluted areas [Zone B], which drifts into Zone C where it will continue to grow slowly and over 40 days could cover 200,000 ha (approximately 15% of the Lake surface. [Figure 9]. The extent of any rejuvenating process is not considered but could be expected to decrease the time for doubling of the duckweed in rafts and prolong the time for the duckweed to senesce.

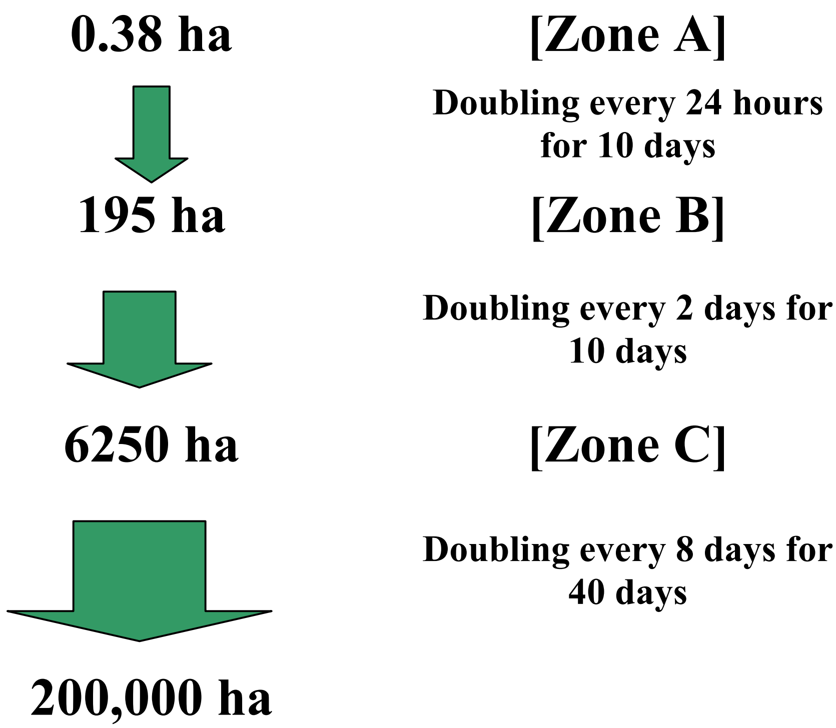


Figure 9: Diagram illustrating the potential of duckweed to grow from small areas in sites mostly outside the lake to eventually cover 15% of the lake surface in a total period of 60 days..

Photo 5: Illustration of the large areas outside the Lake with active growth of “high-quality” duckweed (Zone A)

Recommendationsns for Action on the Lake

The first priority is to reduce the inflow of nutrients into the lake as these have been accumulating, as shown by the tendencies in concentrations of nitrogenous materials [Figure 10]. Although the average level of nitrogen in the water is relatively low, the duckweed can continue to grow because of the nutrients accumulated in Zones A and B. The low concentrations of nutrients in the body of the lake are nevertheless important as it allows the plant to survive longer on the lake surface.

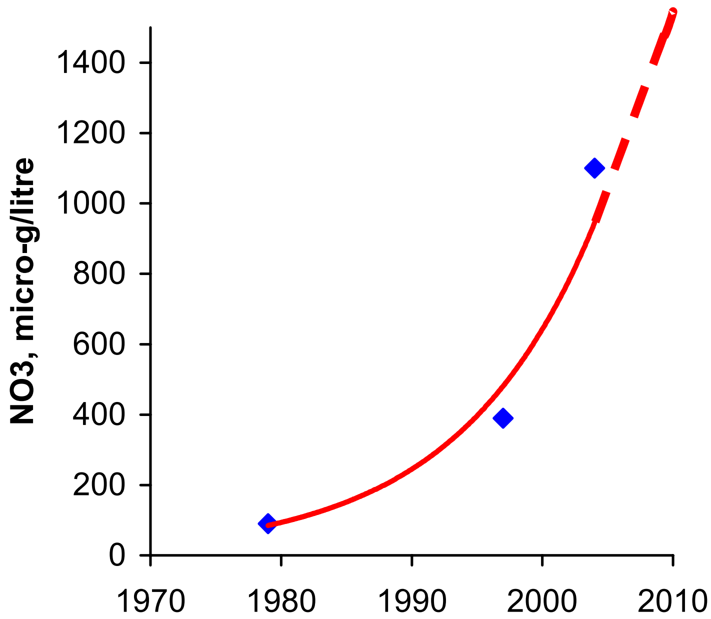


Figure 10: Changes in the concentration of nitrate in the water in Lake Maracaibo from 1970 to the present time

A second reason for lowering the pollution entering the lake is to eliminate the potential for an algal bloom to develop in the surface water and possibly creating a 'Dead Zone' as has occurred in the Gulf of Mexico. The area of high priority is that between Ceuta and Cabimas because of the probability that this is the major source of nutrients entering the surface layer. The reason for this suggestion is that these areas are the first to receive the surface flow of fresh water driven by the Catatumbo River. A third reason is that other aquatic plants [eg: *Elodea*] appear to have become established in recent years with potentially serious consequences for the fishing industry. The biomass of duckweed on the lake surface will produce eutrophication as it dies and descends to the bottom of the lake. The consequences may not be great because of the rapid movement of the biomass around the lake spreading the contamination throughout the lake and thus preventing localised concentrations of decaying biomass. However, a larger bloom in coming years could create hypoxia throughout the lake with serious consequences.

Treatment of sewage water should be targeted as a first priority, but run-off of any sort from urban populations also should be controlled. The sewage treatment should include duckweed "polishing" ponds in order to ensure a low level of phosphorus in the discharged water. The resultant duckweed biomass could be used by local farmers as a source of animal feed

Simultaneously in the same areas other sources of pollution should be targeted, particularly small lagoons and water bodies associated with animal and human use. In these areas the development of duckweed farming should be initiated with integrated crop animal farming systems as are described later in this document.

Prawn farming should be rigorously controlled to prevent a major point source pollution. The requirement is that the water in the ponds should be treated to remove N and P to the levels found in the lake, before being discharged into the lake and / or should be recycled.

Satellite monitoring of both duckweed growth and potential algal blooms should be continued.

Mapping of the stratification of fresh and saline water

The extent of the stratification layer of fresh water is likely to vary from year to year depending on the timing of the onset of the rainy season, the extent and patterns of the rainfall and the churning effects of the wind. The stratified layer may at times cover only small areas but could extend to the whole lake area. It is therefore very necessary to begin research to map the stratification areas so as to be able to set priorities for initiation of sewage and other treatment works around the shore line. The map of the stratification layer will also be important in terms of the sites for construction of prawn farms on the lake edge.

Activities with the community

Cañada de Urdaneta

Visits were made to several communities to asses the situation with respect to the presence of the duckweed in the lake. In “Cañada de Urdaneta” it was found that sewage water was going directly into the lake and there was no waste management. Duckweed was not seen as a big problem; however, there were comments about a different kind of aquatic plant coming every year to the shorelines. A citizen in this community pointed out that chickens had been consuming duckweed for over two months.

“Black water” pipe lines going directly to the Maracaibo Lake

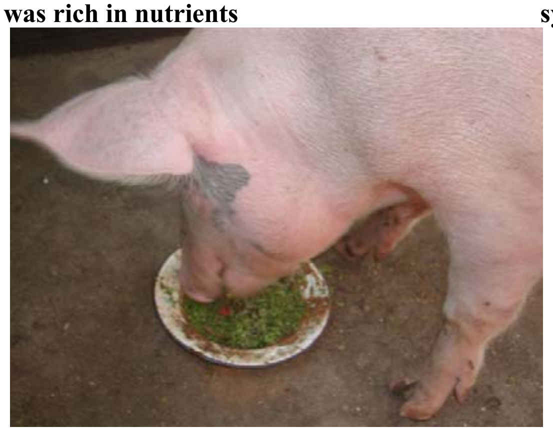
Chickens eating duckweed on the beach

Curaride

In Curaride, most of the population visited were fishermen; however, there were activities involving other animals, such as pigs which were found to be housed in precarious conditions with no system to recycle the excreta. There was no treatment of the waste water at any level. Demonstrations were made on the feeding of duckweed to the pigs.

A pig pen built over the water; duckweed accumulated in this area was rich in nutrients

Waste water treatment is not present in this system



Demostration of duckweed as feed for pigs

La Rosita/ Potrerito

A visit was made to a cattle farm (La Rosita/ Potrerito) where the owner mentioned that duckweed was present for over 40 years in the surrounding areas of the lake. Duckweed was growing in an irrigation pond despite the fact that the water source was a well. The water from this pond was distributed for irrigation in the grass fields by a flooding system.

Irrigation pond; a means of distribution of duckweed into many areas

Duckweed grows well in shaded areas

Barranquitas

A community of Barranquitas was visited and it was found that there was presence of other aquatic plants in the lake. Fishermen mentioned that these plants started to appear about three years ago and that they have been a real problem as the separation of shrimp and crabs had become very laborious and it was also pointed out that to get 25 kg of shrimp there are 700 kg of waste composed of small fish (about 7 kinds of non commercial fish) and three types of aquatic plants (elodea and two other kinds named locally as "limo"). Evidently it is a sign of pollution in the lake and in addition the "waste" is thrown in the lake after the valuable fish is separated. It is a potential source of protein for pigs and these aquatic plants could be used as substrate for earthworms or larvae production.

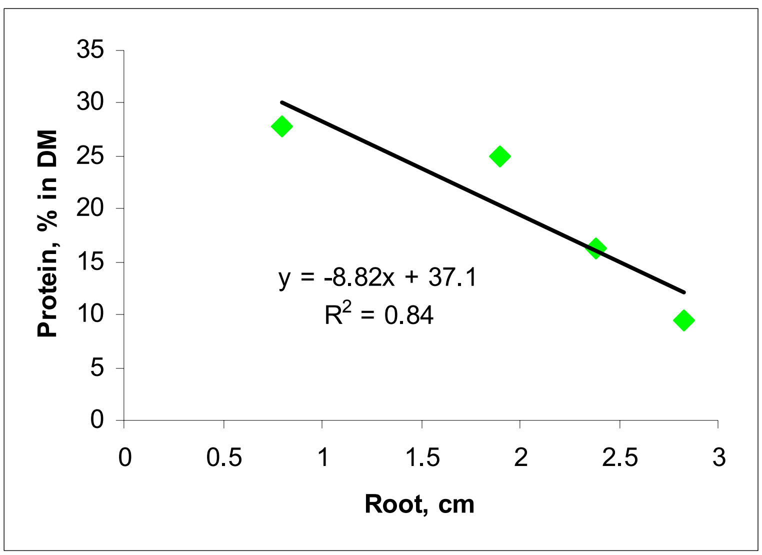
"Waste residue" after separation of shrimps and crabs

25 kg shrimp per 700 kg waste

An aquatic plant called locally "limo"

Pollution caused by the "waste residue" thrown in the shoreline

Samples of duckweed were taken from different points, Nitrogen analyses were done and the root length was measured. The results were similar to published data, with a close relationship between root length and protein content.



Relationship between root length and protein content in samples taken in Barranquitas community in Maracaibo lake

There was a field day where demonstrations were made on the use of duckweed as animal feed. Experiments were started on the duckweed silage and use of duckweed as substrate for earthworms. A small "waste water" treatment plant was set up "the plastic biodigester".

There was also a demonstration on preservation methods for the "waste residue" from shrimp selection and it was explained that it could be used as animal feed and mainly as a source of protein for pigs..

"Feeding duckweed to pigs"

Installation of the plastic biodigester unit as part of the waste water treatment plant

Demonstration on the use of duckweed for feeding sheep

Two kinds of duckweed: "high quality" and "low quality" as substrate for earthworms

Fresh duckweed with maize bran for local chickens

Using different levels of "black water" to fertilize duckweed

Molasses to preserve the waste from separation of shrimps and crabs

Mixtures of duckweed / elodea and sheep manure as substrate for earthworms

During this field day many activities were started with the community and the CIARA extension group is responsible for following up the results. The community was enthusiastic in learning how to use the duckweed for their benefit.

Duckweed as animal feed

Introduction

The use of duckweed as poultry feed has been recognized by many authors (Haustein *et al*., 1987, 1990; Islam *et al.,* 1997; Rodriguez *et al*., 1997, Leng, 1999; Samnang, 1999). Duckweed has a high crude protein content and a well-balanced amino acid profile and is also a good source of vitamins and minerals (Landolt *et al*., 1987; Men *et al*., 2001). Even though the moisture content of duckweed can be the first limiting factor for chickens, duckweed can play an important role in poultry feeding.

Early work with duckweed as a protein source for poultry was done in Peru using dehydrated duckweed (Hatfield et al 1987, 1990, 1994). Up to 25% replacement of conventional protein sources with duckweed gave good results in growing and laying birds of improved strains. However, due to the difficulties of dehydrating a plant with 95% water, more recent work in Vietnam was done with fresh duckweed.

Duckweed for fattening ducks

Growth rate of ducks was reduced when fresh duckweed replaced roasted soya beans as the protein source (Figure 11), however the low nutritive value of the duckweed (26.3% crude protein in DM) could have been a limiting factor.

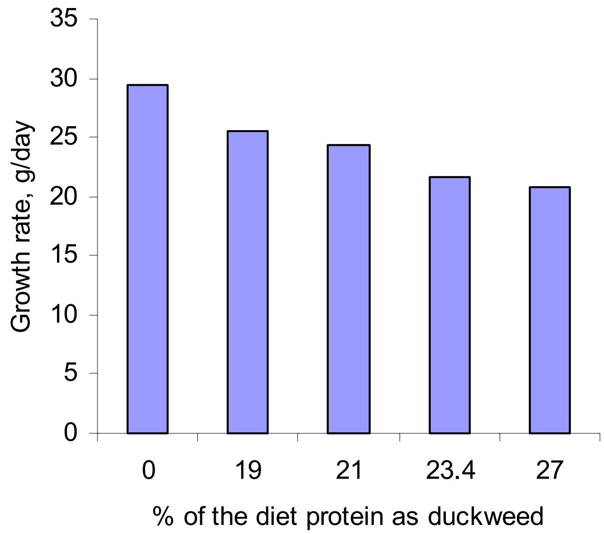


Figure 11: Growth rate of ducks fed sugar cane juice supplemented with increasing proportions of fresh duckweed (26.3% crude protein in DM) replacing roasted soya beans as the protein source (Becerra et al 1993)

This was confirmed in a later trial using duckweed with 39.6% crude protein in DM (Figures 12 and 13), when final weights of ducks and growth rates were the same using only fresh duckweed compared with soya bean meal as the supplementary source of protein in diets based on broken rice.

Figure 12: Final live weight of ducks fed broken rice and increasing amounts of fresh duckweed replacing from 27% to all the soya bean meal (Source: Bui Xuan Men et al 1993)

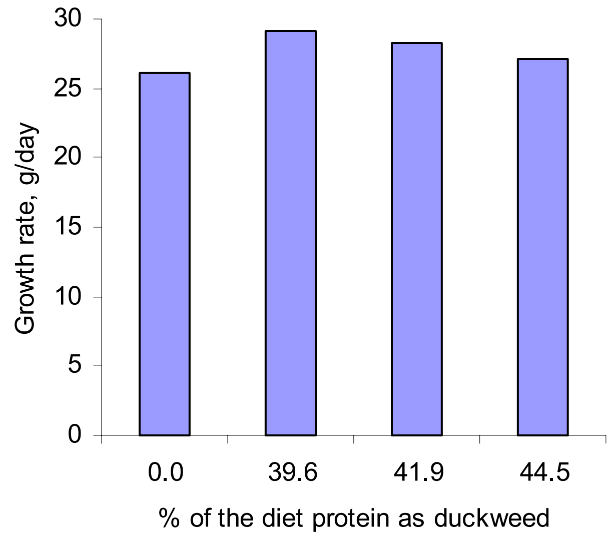


Figure 13. Growth rates of ducks fed broken rice and increasing amounts of fresh duckweed replacing soya bean meal (Source: Bui Xuan Men et al 1993)

Duckweed in diets of growing pigs

In Vietnam, pigs of the local Mong Cai breed showed different degrees of adaptation to consumption of duckweed, when given free access to fresh duckweed and sugar cane juice. Growth rate was directly related to the amounts of duckweed consumed (Figure 14).

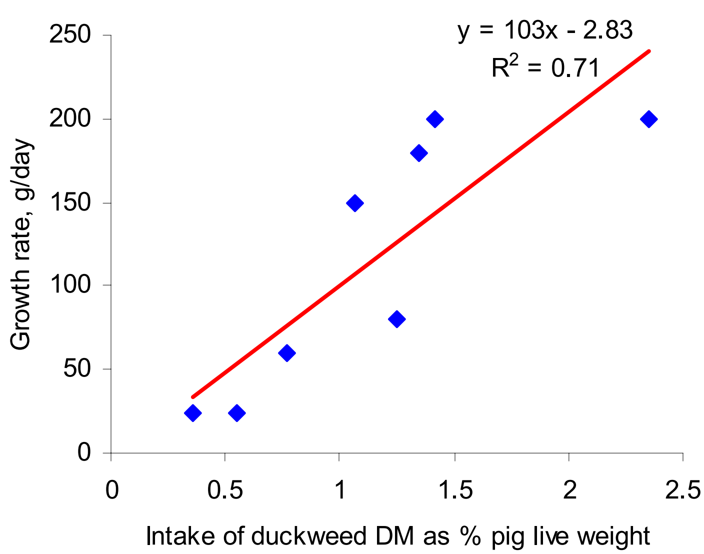


Figure 14: Growth rate of Mong Cai pigs with free access to sugar cane juice and fresh duckweed (Source: Rodriíguez and Preston 1996)

In small family farms in Hue province (Vietnam), there were consistent improvements in growth rate of crossbred pigs when the traditional diet (rice by-products and cassava root meal) was supplemented with 2 kg/day of fresh duckweed (Figure 15).

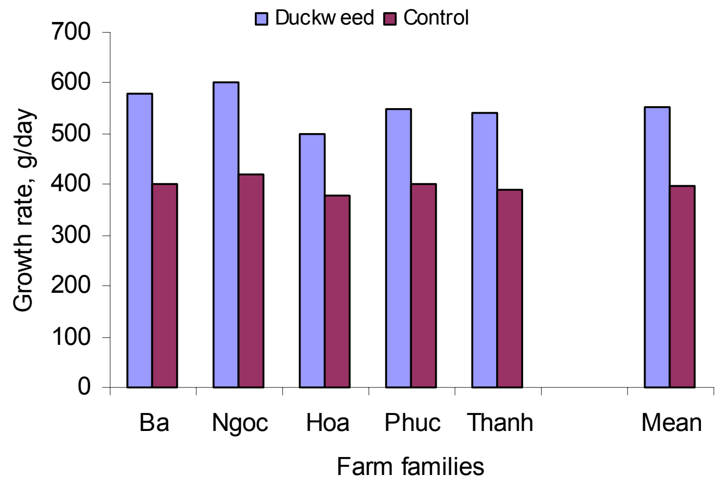


Figure 15: Growth rates of crossbred pigs in 5 farm households in Vietnam showing the advantage of supplementing the traditional diet with fresh duckweed (Source: Du Thanh Hang 1998)

Duckweed for local chickens

As with the experiments on ducks, the approach with growing chickens and laying hens, has been to give free access to fresh duckweed at the same time varying the level of soya bean in the basal diet composed of broken rice (Nguyen Thi Kim Khang et al 2004a,b, c). The data in Figure 16 show that chickens readily consume duckweed to compensate for reducing proportions of soya bean meal in the basal diet.

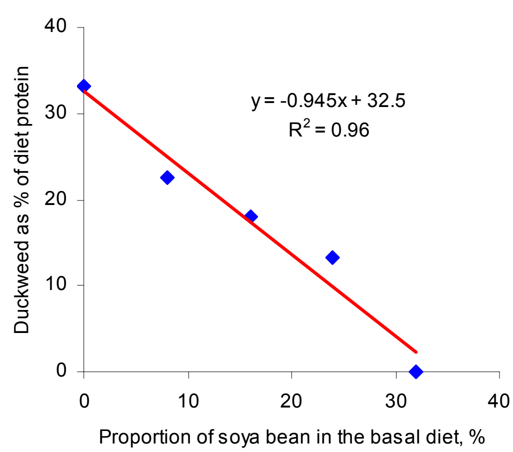


Figure 16: Reducing the proportion of soya bean in the basal diet induced increasing intakes of duckweed in growing chickens (Source: Nguyen Thi Kim Khang et al 2004b)

Older chickens responded better than younger ones with higher growth rates when offered access to fresh duckweed and decreasing levels of soya bean (Figures 17 and 18).

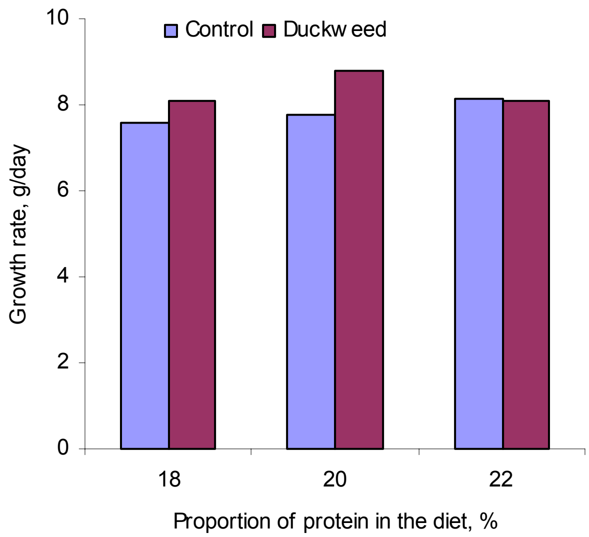


Figure 17: Response to supplementary fresh duckweed (37.3% protein in DM) by local breed chicks from 1 to 30 days of age, according to protein level in the basal diet

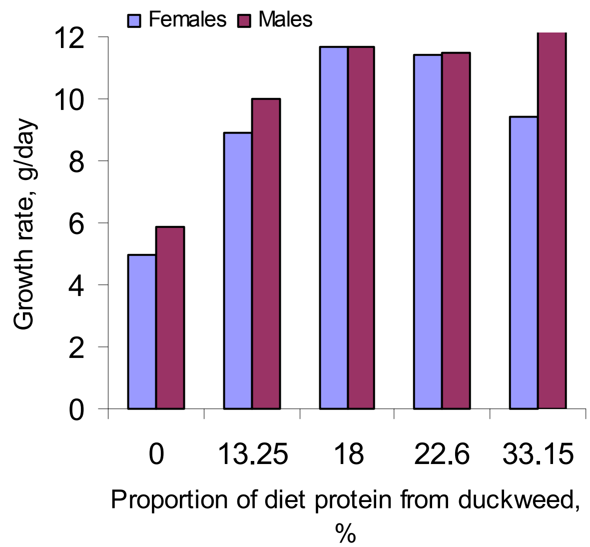


Figure 18: Response by local breed chickens from 5 to 15 weeks of age according to protein provided by duckweed (37.3% protein in DM)

Egg production was increased (Figure 19) when local birds had free access to fresh duckweed and decreasing levels of soya bean meal in the basal diet.

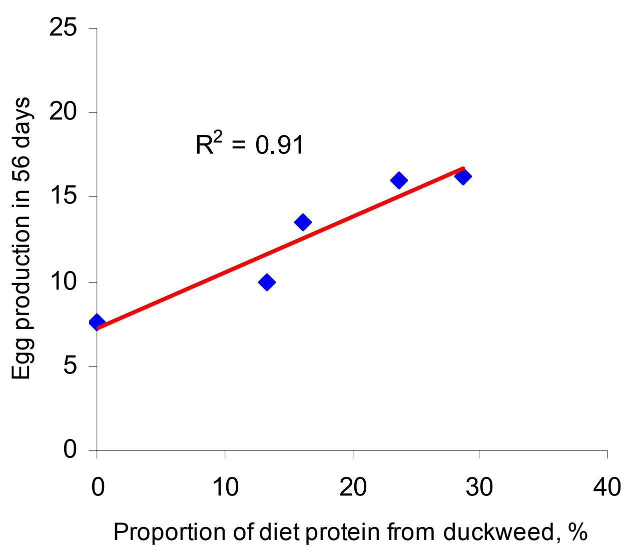


Figure 19: Egg production in local birds in response to replacement of soya bean meal by fresh duckweed (Source: Nguyen Thi Kim Khang and Ogle 2004)

Hatching rate was also improved when the birds had access to duckweed during the laying period (Figure 20).

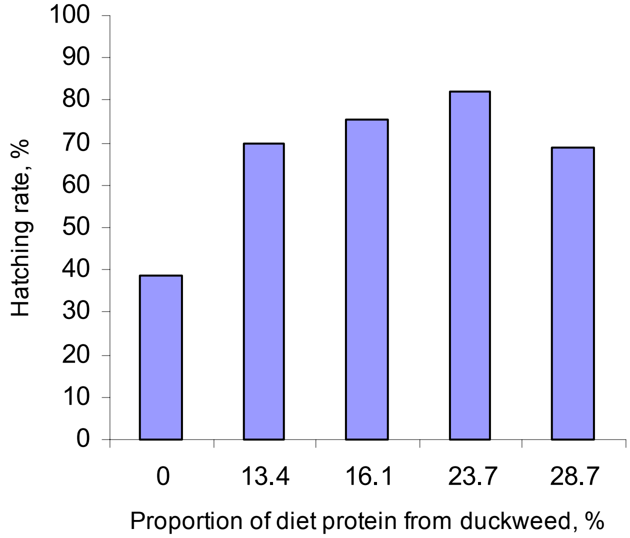


Figure 20: Effect of free access to fresh duckweed on hatchability of eggs from local birds (Source: Nguyen Thi Kim Khang and Ogle 2004c)

Duckweed for fish

Growth rates of different species of carp in ponds supplemented with fresh duckweed in Bangladesh (Figure 21) showed that silver carp and catla carp showed the best response.,

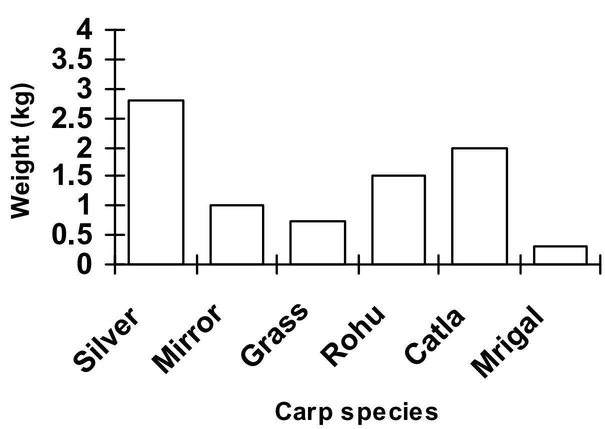


Figure 21: Average weight of fish after 13 months in polyculture with fresh duckweed supplementation in Bangladesh (Source: Skillicorn et al 1993)

In Thailand, *Tilapia* responded linearly in growth rate and feed conversion to supplementation with duckweed at the rate of 30 g duckweed DM per 1 kg fish live weight (Table 2).

Table 2: The effects of feeding increasing levels of duckweed to tilapia. The tilapia initially weighed approximately 41 g (Source: Hassan and Edwards 1992).

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

Duckweed for ruminants

There has been little research on feeding duckweed to ruminants, mainly because larger quantities are required compared with needs of smaller monogastric animals. There are indications from research in Australia that fresh duckweed, because it remains intact in the rumen and it is small, may partly escape undigested from the rumen, thus offering potential as a source of "bypass" protein (J V Nolan, Personal communication). Demonstrations on the farm of a fishing community in Barranquitas showed that sheep and cattle readily consumed fresh duckweed (Photos 6 and 7).

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Photo 6: Sheep consuming fresh duckweed on the farm of a fishing community in Barranquitas

Photo 7: Cattle eating fresh duckweed in Barranquitas

Proposed areas of research

The following are suggested main areas of research and development:

- Testing the hypothesis for the appearance of the duckweed bloom on Lake Maracaibo
    - Mapping the Maracaibo current
    - Identifying point sources of pollution and the movement of the current
    - Satellite monitoring of algal and duckweed blooms
    - Examination of "boletoes" and demonstration of the cycle involved in rejuvenating exhausted duckweed in sewage water

- Developing systems for using duckweed in water treatment plants
    - Major lagoons and small community systems
- Evaluating productive uses of duckweed of low nutrient status (as harvested from the lake surface)
    - Potential for rejuvenation of "old" duckweed for feed use
    - As substrate in biodigesters
    - As a mulch for fruit trees etc
    - As compost [soil conditioner]
    - As substrate for earth worms

[Note the duckweed heaps on the shore line should be tested for the latter three uses and should be exported immediately from the lake edge for such purposes]

- Evaluating productive uses of nutrient-rich duckweed for animals. Feeding trials with:
    - Ruminants
    - Pigs
    - Poultry
    - Capybara
    - Rabbits
    - Fish
- At a later stage research of a more basic nature should be undertaken to
    - Extract the protein
    - Determine the levels of bypass protein

Research to test the hypothesis for the appearance of the duckweed bloom on Lake Maracaibo

- Establish the presence of stratified layers of water from the mouth of the Catatumbo River [now and during and following the dry season]
    - Measure the salt content in water in 0.5 m intervals from the surface to 3m
- Analyse water for N and P in samples taken at all points of entry of (black) water into the lake and 50m from these source in the direction of the Maracaibo current

- Measure N and P content of duckweed in samples taken from Zones A, B and C at various parts of the Lake
- On a fairly large scale[100 litre vessels] test the potential for low nutrient density duckweed to store nutrients when introduced onto enriched water
- Analyse samples from roots and compare with “boletoes” from Baranquitas

Developing systems for using duckweed in water treatment plants

- Establish small scale models of lagoon systems to collect and clean black water.
    - Measure water concentration of N and P levels at various sites in and along the lagoon. Compare colour, content of N and P and root length in duckweed growing in the lagoons.
    - Initiate studies to add supplementary minerals (mainly N) at points in the lagoon to optimise duckweed growth
    - Study effects of harvesting duckweed on nutrient density in the water

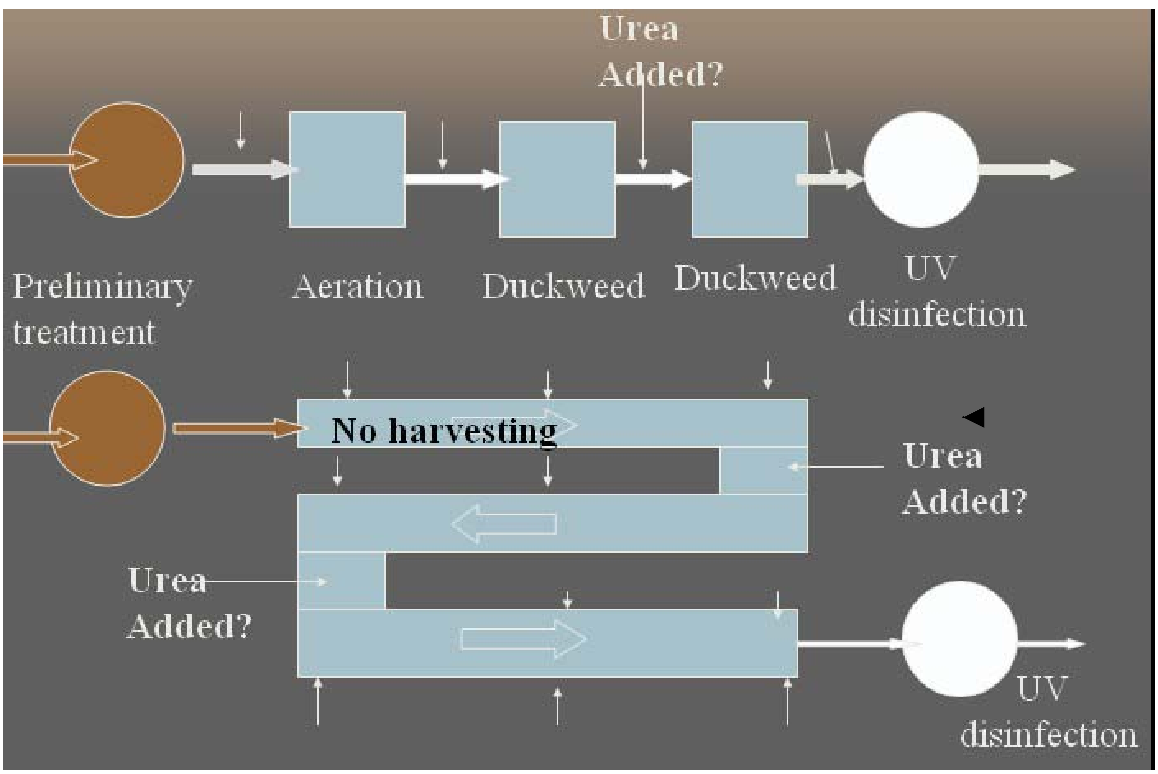

Figure 22: Examples of small scale models of lagoon systems to collect and clean black water (short arrows indicate points to sample for N and P.

Evaluating productive uses of duckweed of low nutrient status (as harvested from the lake surface)

As substrate in biodigesters

Build tubular plastic biodigestor and inoculate with pig or cattle manure

- Charge with fresh duck weed (3 kg as DM daily plus 40 litres water for every 1 m^3 of biodigester liquid volume). Measure gas output (see Santhy et al 2003 for details of method) and percent methane in the gas. Measure total N and NH_4-N in effluent.
- Dig pit in ground and fill with fresh duckweed. Cover with plastic sheet fitted with gas escape pipe and measure gas production and composition of methans; and DM, N and NH_4-N in residue.

As mulch and compost

- Plant areas of fodder trees and shrubs (eg: cassava) or fruit trees (eg: oranges)
    - Mulch with duckweed 1 m diameter circle around the tree with 0, 2, 4 or 6 kg fresh duckweed
    - Measure growth rate of shrubs / trees

- Make mounds of duckweed say 1 m high.
    - Turn each mound over at intervals 1, 2, 3 days during 21 days
    - Using same principles as for mulch apply over 1 meter diameter around the tree / shrub, increasing amounts of compost

As substrate for earth worms

- Put 10 cm layer of recently harvested earth worms with compost
    - Add 10 cm layer of fresh duckweed, or duckweed from heaps on the side of the lake that have begun to decompose, at intervals according to rate at which the worms digest the duckweed
    - Measure worm biomass yield
    - Assess fertiliser value of the worm casts for vegetable production or other crops in the same way as for mulch and compost

Or

- Put alternate adjacent rows of earth worms (plus compost) and fresh duckweed
    - Add more duckweed according to rate of digestion by the earth worms
    - Measurements as above

Evaluating productive uses of nutrient-rich duckweed for animals

Growing the duckweed

- Prepare small ponds (n=4) for growing the duckweed using plastic film (Photos 8 and 9). Fertilize with biodigester effluent at rates of 2 (2 ponds) or 4 (2 ponds) litres effluent/m^2/day.

- Harvest duckweed from 50% of pond surface area each day. Measure yields in fresh and dry basis and content of N.

Photo 8: Preparing the duckweed pond with plastic film

Photo 9: Introducing the duckweed

Cattle and sheep (grazing system)

- Feed fresh duckweed at levels of 3, 6 and 9 kg per 100 kg live weight
  - Record weight gains during dry and wet season
- Prepare silage from duckweed after sun-drying for 24 hours, adding molasses at 5% of estimated DM of duckweed. Store for 21 days.
  - Repeat above experiment

Cattle and sheep (in confinement)

- Offer duckweed fresh or as silage ad libitum plus:
  - No supplement
  - Rice straw (1 kg per 100 kg live weight)
  - Rice straw (2 kg per 100 kg live weight)

Ducks

- Select duckweed of high quality (>35% of crude protein in DM)
  - Local breed of ducks of one week of age (6 groups of 10 ducklings in each)
  - Two treatments (3 groups of 10 animals in each group) and each treatment
    - Control: Rice bran (polishings) (or other local energy source or household food waste) ad libitum
    - DW: as for control plus fresh duckweed ad libitum in separate feeder
  - Measure intakes and live weights every week over 8 weeks

Chickens (Growing and Laying)

- Use local (Criollo) birds and apply same treatments as for ducks
    - Measure intakes, growth and egg production

Growing pigs

- Use same treatments as for ducks and chickens
    - Measure live weights and feed intakes over 84 day period beginning with weaned animals of about 20 kg live weight

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