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Duckweed - a potential high-protein feed resource for domestic animals and fish

R A Leng, J H Stambolie and R Bell

Centre for Duckweed Research & Development University of New England Armidale, NSW 2351

Summary

Duckweeds have received research attention because of their great potential to remove mineral contaminants from waste waters emanating from sewage works, intensive animal industries or from intensive irrigated crop production. Duckweeds need to be managed, protected from wind, maintained at an optimum density by judicious and regular harvesting and fertilised to balance nutrient concentrations in water to obtain optimal growth rates. When effectively managed in this way duckweeds yield 10-30 ton DM/ha/year containing up to 43% crude protein, 5% lipids and a highly digestible dry matter.

Duckweeds have been fed to animals and fish to complement diets, largely to provide a protein of high biological value. Fish production can be stimulated by feeding duckweed to the extent that yields can be increased from a few hundred kilograms per hectare/year to 10 tonnes/ha/year.

Mature poultry can utilise duckweed as a substitute for vegetable protein in cereal grain based diets whereas very young chickens suffered a small weight gain reduction by such substitution. Pigs can use duckweed as a protein/energy source with slightly less efficiency than soyabean meal.

Little work has been done on duckweed meals as supplements to forages given to ruminants, but there appears to be considerable scope for its use as a mineral (particularly P) and N source. The protein of duckweeds requires treatment to protect it from microbial degradation in the rumen in order to provide protein directly to the animal.

The combination of crop residues and fresh duckweeds in a diet for ruminants appears to provide a balance of nutrients capable of optimising rumen microbial fermentative capacity. These diets can, therefore, be potentially exploited in cattle, sheep and goat production systems particularly by small farmers in tropical developing countries.

KEY WORDS: Duckweeds, Lemna spp, cultivation, composition, fish, livestock, nutrition

The plant and its habitat

Duckweed species are small floating aquatic plants found worldwide and often seen growing in thick, blanket-like mats on still or slow moving, nutrient-rich fresh or brackish waters. They are monocotyledons of the botanical family Lemnaceae and are higher plants or macrophytes, although they are often mistaken for algae.

Duckweeds grow at water temperatures between 6 and 33°C. Many species of duckweed cope with low temperatures by forming a turion and the plant sinks to the bottom of a lagoon where it remains dormant until warmer water brings about a resumption of normal growth.

Duckweeds have structural features that have been simplified by natural selection. A duckweed leaf is flat and ovoid. Many species have adventitious roots which function as a stability organ and which tend to lengthen as mineral nutrients in water are exhausted.

Compared with most plants, duckweed leaves have little fibre (5% in dry matter of cultivated plants) as they do not need to support upright structures. Roots, however, appear to be more fibrous. As a result the plant has little or no indigestible material even for monogastric animals. This contrasts with many crops such as soya beans, rice, or maize, where approximately 50% of the biomass is in the form of high fibre, low digestibility residues.

Duckweed species are adapted to a wide variety of geographic and climatic zones. They are found in all but waterless deserts and permanently frozen areas. They grow best in tropical and temperate zones and many species can survive temperature extremes.

The natural habitat of duckweed is the surface of fresh or brackish water which is sheltered from wind and wave action. They do not survive in fast moving water (>0.3 m/second) or water unsheltered from wind which is an important attribute as they do not become weeds in water ways.

The best nutritional situations for duckweed growth are in waters with decaying organic material, providing it with a steady supply of nutrients. A dense cover of duckweed inhibits competing submerged aquatic plants, which require solar energy for growth and they can also often exclude algae from bodies of water.

Growing duckweed and its nutritive value

The best conditions for cultivation of duckweed simulates the favoured natural environmental niche, namely a sheltered lagoon or a lagoon with surface partitions to prevent wind from blowing the plants onto the banks causing conditions of self shading and competition for nutrients. For high growth rates, nutrients must be made available, at a rate commensurate with growth, being derived either from organic or mineral fertilisers added daily.

Duckweed reproduction is primarily vegetative. An individual leaf may go through 10 divisions over a period of 10 days to several weeks before the original plant senesces. Duckweeds can double their mass in between 16 hours to 2 days under optimal nutrient availability, sunlight, and water temperature. This is faster than almost any other higher plant. Under experimental conditions their production rate can approach an extrapolated 183 metric tonnes/ha/year of dry matter although yields are closer to 10-20 tons of DM/ha/year under real-world conditions (Table 1).

The growth pattern resembles the exponential growth of unicellular algae more than that of higher plants and this confers a high potential for production as a livestock feed resource.

Growth rates of duckweed colonies will be reduced by a variety of stresses: such as 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. However, when conditions are good, duckweed contains considerable protein, fat, starch and minerals which appear to be mobilised for biomass growth when nutrient concentrations fall below critical levels for growth. The reported nutrient densities in duckweed therefore vary according to conditions of growth (Table 2).

Table 1: Some reported yields of duckweed dry matter under a variety of growth conditions

Location	DM Yield (tonnes/ha/yr)	Source
SUB OPTIMUM ENVIRONMENT		
Thailand	10-11	Hassan and Edwards (1992),

		Landolt & Kandeler (1987)
Israel	10-17	Porath *et al* (1979)
Russia	7-8	Landolt and Kandeler (1987)
Uzbekistan	7-15	Landolt and Kandeler (1987)
Germany	16-22	Landolt and Kandeler (1987)
India	22	Landolt and Kandeler (1987)
Egypt	10	Landolt and Kandeler (1987)
Southern States - USA	2-23	Culley and Epps (1973), Rusoff *et al* (1980), Reddy and DeBusk (1985), Landolt and Kandeler (1987)
NEAR OPTIMUM ENVIRONMENT		
Southern States - USA	27-79	Mestayer *et al* (1984)
Israel	36-51	Oran *et al* (1987)

Fresh duckweed contains about 92-94% water. Fibre and ash content are higher and protein content is lower in duckweed colonies that grow slowly.

The concentration of nutrients in dry matter of a wild colony of duckweed growing on nutrient-poor water typically is 15 to 25% protein and 15 to 30% fibre.

Duckweed grown under ideal conditions and harvested regularly will have (in dry matter) a fibre content of 5 to 15%, a crude protein content of 35 to 43%, and a polyunsaturated fat content of about 5%, depending on the species involved (Table 2).

Table 2: Nutrient contents of duckweed harvested in Armidale (Stambolie and Leng 1994)

	N*.25	Fat	Fibre	Ash
		-----------% in DM----------		
Natural lagoon	15-35	4.4	8-25	15
Grown on Armidale sewage	40-43	5.4	5	13

Growth conditions

Unlike most plants, duckweed tolerates relatively high concentrations of salts (up to 4000 mg/litre total dissolved solids). Nutrients are absorbed through all surfaces of the duckweed leaf.

There are at least three methods of fertiliser application including broadcasting, dissolving in the water column of the plot, and spraying a fertiliser solution on the duckweed mat. Efficient crop management strategies need to maximise fertiliser uptake and at the same time minimise fertiliser losses, particularly nitrogen, while also maintaining the pH of the water in the range of 6-8.

Duckweed survives from pH 5 to 9, but grows best over the pH 6.5 to 7.5 range. Ammonia, in the ionised form is the preferred N substrate for duckweed. An alkaline pH shifts the ammonium-ammonia balance toward the un-ionised state and results in the liberation of free ammonia which is toxic to duckweed at high concentrations (>100 mg NH_3/litre).

As a generalisation, duckweed growth is controlled by temperature and sunlight more than nutrient concentrations in the water. At high temperatures, duckweeds can grow rapidly down to trace levels of P and N nutrients in water.

The nitrogen content, however, seems to increase over the range from trace ammonia concentrations to 7-12 mg N/litre when the N x 6.25 is maximised at around 40% (see Table 3). Urea is a suitable fertiliser which is rapidly converted to ammonia under normal conditions.

Table 3: The influence of the concentration of N in culture water on crude protein in duckweed (*Spirodela spp*) grown on diluted effluent from a piggery. The P levels varied from 0.2-6.1 mg P/litre (Leng *et al* 1994)

N in water		N*6.25 (% in DM)				
(mg/litre)	Total samples	5-20	20-25	25-30	30-35	35-40
		Number in each N*6.25 range				
0-5	7	3	3			
5-10	13	3	4	3	3	2
10-15	12		2	2	2	6
15-20	3					3
20-25	2				1	1
25-30	2					2
30-35	0					
35-40	0					
40-45	2					2

Fast growing duckweed on nutrient-rich water is a highly efficient sink for both phosphorus and potassium, but little of each is required for rapid growth. Muriate of potash and superphosphate are commercial sources of potassium and phosphorus that are widely available in most countries and have been used where duckweed has been farmed. Duckweed growth is not particularly sensitive to potassium or phosphorus once an adequate threshold has been reached. The effect of water phosphorus content on duckweed phosphorus concentration is shown in Table 4. Thus duckweed efficiently concentrates P and could be an important source of P particularly for grazing ruminants in the tropics where P- deficiency is widespread. Duckweeds concentrated P up to 9 mg P/g duckweed DM in the studies reported in the literature. However, recent research showed that levels of up to 1.4 mg P/g duckweed DM have been recorded (Stambolie and Leng, 1994) (Figure 2).

Table 4: The relationship between the quantity of P in duckweed and the concentration of P in water. Values below 1.5 mg P/litre of water are Sutton and Ornes (1975); the higher values are from research in this Centre (Stambolie and Leng 1994)

P in water	Total	P (mg/g DM)						
(mg/litre)	samples	0-2	2-4	4-6	6-8	8-10	10-12	12-14
		Number in each P range						
0-0.5	6	3	3					
0.5-1.0	1	0	0	1				
1.0-1.5	2	0	0	0	0	1	0	2
1.5-2.0	2	0	0	0	0	0	0	2
2.0-2.5	3	0	0	0	0	1	0	2
2.3-3.0	1	0	0	0	0	0	0	1

Trace mineral requirements for duckweed growth are unknown although it appears the plant is able to concentrate some trace minerals more than 500,000 times. Sea salt has been regarded as a good source of trace minerals to use in duckweed farming. In work in these laboratories, molasses which is a concentrated plant juice has been used to safe guard the trace mineral requirements of duckweed.

Management systems for duckweed

Duckweed species are able to survive extremely adverse conditions. Their growth rate is, however, highly sensitive to the major nutrient balances in the water. 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 and therefore the initial research requirements are concerned with when to fertilise, harvest, and buffer; how much to fertilise and to harvest; and which nutrients to supply. Judicious management should be aimed at: (i) maintaining a complete and dense cover of duckweed; (ii) low dissolved oxygen; and (iii) a pH of 6- 7. A total crop cover suppresses algal growth, which minimises CO_2 production from algal respiration and prevents its elevating effect on pH.

Any waste organic material can be used to supply duckweed with nutrients. The most economical sources are wastewater effluents from homes, food processing plants, cattle feedlots, and intensive pig and poultry production. 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 at suitable levels. All wastewater containing manure or night soil must undergo an initial treatment by holding it for a few days in an anaerobic pond, before using it to cultivate duckweed. There is an additional need when using such sources of nutrients to reduce solids and prevent the formation of a floating mat.

Duckweed-based wastewater treatment systems

The basic concept of a duckweed wastewater treatment system is to farm local duckweeds on the wastewater which needs to be treated. 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 following the harvesting of a proportion of the crop. Depending on the wastewater, the harvested crop may serve as: (i) an animal feed; (ii) feed supplement supplying protein and minerals; or (iii) fertiliser. However, it may have to be decontaminated prior to feeding to animals if heavy metals are present in the water as these are concentrated by the duckweed.

Maintenance of efficient duckweed growth requires an even distribution of a thick layer of plants across the entire lagoon surface. Initial research has shown that there is a range of plant densities that supports optimum growth rate for prevailing conditions. In this case harvesting to maintain approximately 1kg duckweed wet weight per m^2 resulted in an extrapolated average yield of 32 tonnes DM/ha/year.The upper density appears to be that at which crowding limits growth (above 1.2 kg wet weight/m^2) and the lower density (<0.6 kg wet weight/m^2) is when growth is insufficient to prevent algal blooms.

Using duckweed as a feed/supplement

The composition of duckweed depends on the nutrient content of the water and the prevailing climatic conditions. A range of values for the composition of duckweed is shown in Table 2. Harvested duckweed plants contain up to 43% protein on a dry weight and may be used without further processing as a complete feed for fish.

Duckweed protein has a better array of essential amino acids than most vegetable proteins and more closely resembles animal protein (Hillman and Culley 1978). It is, therefore, a source of high quality protein to be exploited for domestic animal production. Duckweed grown on nutrient-rich water has a high concentration of trace minerals, K and P and pigments, particularly carotene and xanthophyll, that make duckweed meal an especially valuable supplement for poultry and other animals, and it provides a rich source of vitamins A and B for humans.

Use of duckweed in fish nutrition

A major limitation to fish farming is that meals high in protein with high biological value are expensive and often locally unavailable. Duckweeds grown on water with 10-30 mg NH_3-N/litre have a high protein content (around 40%) of high biological value (Hillman and Cully 1978; see Table 2). Fresh duckweed is highly suited to intensive fish farming systems with relatively rapid water exchange for waste removal (Gaigher *et al* 1984) and duckweed is converted efficiently to liveweight by certain fish including carp and tilapia (Hepher and Pruginin 1979; Robinette *et al* 1980; Van Dyke and Sutton 1977; Hassan and Edwards 1992).

A tilapia culture strategy investigated under a World Bank project in Bangladesh was as follows:

A duckweed lagoon with a standing crop of duckweed is harvested and placed fresh into a second lagoon containing a mixed size tilapia culture. The pond is harvested twice weekly and the fish sorted into various groups for return to the lagoon or sale. Under these circumstances the average yield of fish per hectare of lagoon is estimated at around 10 tons annually using only duckweed as the supplement to the naturally available fish feed (Skillicorn *et al* 1993).

Table 5: The effects of feeding tilapia increasing levels of duckweed. Tilapia were held in static water in concrete tanks (Hassan and Edwards 1992). The fish initially weighed approxinmately 41g

Feeding rate Lemna (g DM/kg fish)	Survival rate of fish (%)	Mean LW gain (g/d)	Conversion of Lemna 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

In recent more detailed studies in Thailand, Hassan and Edwards (1992) have grown tilapia in static-water concrete tanks and fed them on two species of duckweed, *Lemna perpusilla* and *Spirodela polyrrhiza* at levels of 0, 25, 50 or 75g duckweed DM per kg wet weight of fish. The duckweeds were relatively low in protein (approx 24% CP). The Spirodela was poorly consumed whereas Lemna was rapidly ingested by fish. The growth rate and feed conversion rates for Lemna-fed tilapia are shown in Table 5.

Duckweed is a convenient feed for fish. Its attributes are:

- It can be readily grown locally often in waste ponds that are polluted.
- It can be fed fresh and since it floats, by judicious setting of the rates of application it may be totally used by fish.
- It is used very efficiently by fish such as tilapia and carp but other species might well cope with duckweed as a component of the diet since it is particularly low in fibre and high in protein when

grown under ideal conditions.

- It is relatively inexpensive to produce or may be regarded to have no cost where the opportunity costs of family labour are not taken into consideration.

Use of duckweed in pig and poultry production

It seems reasonable to assume that village pigs, horses or ruminants could be fed on freshly harvested duckweed. For most applications with poultry, dried duckweed would be preferable. Research with ducks has been surprisingly lacking but it could be expected that duckweed would provide an ideal wet supplement to any high energy diet.

Research on using duckweed in the diets of domestic animals has been surprisingly scarce, perhaps because of the difficulties of growing sufficient duckweed under experimental conditions. However, with knowledge of how to grow duckweed efficiently; that is the levels of minerals in water that are needed, how often to harvest and the density that must be retained in the residual crop -- a yield of 10-20 tonnes dry matter/ha/year containing say 40% protein can be reasonably and easily achieved. Thus there are major opportunities to grow duckweed as a crop for animal production purposes, but research on preparation and drying is needed to facilitate the uptake of the technology particularly in the poultry industry.

Poultry nutrition studies

The potential nutritional value of duckweed in poultry diets has long been recognised (Lautner and Mueller 1954; Musaffarov 1968; Abdullaev 1969). Dehydrated duckweed has been used to replace alfalfa (lucerne) meal as a protein source in conventional poultry diets. Chickens fed 10% dehydrated duckweed had superior weight gains to those fed conventional protein sources. However, variable responses are often reported depending on the source of the duckweed which can be high protein/low fibre or low protein/high fibre depending on the nutrients in the growth medium.

Layer performance and egg quality in birds fed Lemna meal (from sewage water) at levels of 0, 25 and 40% inclusion in a conventional ration are shown in Table 6.

Table 6: Production levels of egg-laying birds at 18 weeks on conventional base diet containing varying proportions of dehydrated *Lemna gibba* meal (33% N x 6.25 in DM). Metabolizable energy and protein intake were consistent across treatments (Haustein *et al* 1988)

	Level of dehydrated duckweed, %		
	0	25	40
Feed consumption (g/d)	131	131	125
No of eggs/ week/ hen	5.9	5.9	5.6
Mean egg wt (g)	64.2	63.1	63.6
Feed conversion (g DM/g egg)	2.41	2.47	2.38
Live weight gain (g)	40	114	-118

Recent studies have demonstrated that the growth of very young broiler chickens may be retarded with increasing levels of *Lemna gibba* dehydrated meal in the diet (Haustein *et al* 1992b) whereas layer hens produced effectively (Haustein *et al* 1990a) and older broiler birds had excellent growth when fed relatively high levels of *Lemna gibba* meal. Thus there is a need to be conservative when using Lemna protein meals with young birds.

Undoubtedly duckweed can replace conventional protein and energy sources in chicken diets up to 25% of the total dry matter without jeopardising a high level of production. This indicates that duckweed of known chemical analysis can be used in least-cost ration formulation for both poultry meat and egg production.

Pig nutrition

Table 7: The live weight of pigs fed three levels of Lemna meal to replace a conventional protein meal in a cereal-based diet balanced to the same protein/energy intake (Haustein *et al* 1992a)

Time	Level of Lemna meal in diet (%)		
(days)	0	5	10
	(Live weight, kg)		
1	6.9	6.8	6.8
10	9.4	9.2	9.1
20	13.4	11.9	11.2
30	17.4	14.6	13.2
40	23.8	19.5	17.2

Little work appears to have been done on the feeding of duckweed to pigs perhaps because of the difficulties under experimental conditions of obtaining sufficient meal for such studies. Research with a low protein/high fibre duckweed meal (23% N x 6.25 and 7.5% fibre in DM) showed that replacing conventional protein sources in diets for growing pigs reduced production and increased feed required per unit growth (Haustein *et al* 1992a). Growth rates of pigs on different levels of duckweed meal are shown in Table 7.

Further research is needed to show how duckweed can be used as the protein source in diets for pigs. Studies using wet and dry duckweed and conventional (grain-based) or non-conventional feeds (eg: sugar cane juice or molasses) are urgently needed. If systems based on non-conventional feeds were to be successful they would support small farm enterprises of great significance (see Preston and Murgueitio 1992).

Ruminant nutrition

Very little literature is available on the utilisation of duckweeds by ruminants. Duckweeds grown on nutrient-rich waters have the potential to be of high nutritional value particularly for the young or lactating ruminant and preliminary observations suggest that they might form the basis of a supplement to diets based on mature biomass such as crop residues, mature grass or pasture. Even the high water content, softening the straw, let alone the nutrients they provide would facilitate the use of straw by ruminants.

However, unlike the case for monogastric nutrition where feed analyses are indicative of nutrient availability to the animal, the compounding of diets for ruminants needs to take into account microbial activity in the rumen which can alter the availability of nutrients from duckweed when consumed and digested. Ruminants fed mature biomass such as straw are generally deficient in a range of minerals and ammonia for efficient fermentative digestion of the straw in the rumen and in addition for maximum efficiency of feed utilisation they require supplements containing proteins that escape the rumen environment to be digested in the intestines.

With ruminants, therefore, it is necessary to describe the nutritional role that is required of the duckweed before assessing its feeding value. There are some preliminary attempts to use duckweed as a supplement to ruminant diets, however, there is a major research need ahead. A duckweed:maize silage diet (2:1) produced higher growth rates in Holstein heifers (about 200 kg LW) than a maize silage:concentrate:grass diet, without any detrimental effects (Rusoff *et al* 1978).

Special research needs for ruminants

Depending on the nutrient level in the culture medium, duckweeds may be an important source of trace minerals and phosphorus, but if the protein is readily fermentable in the rumen the dietary amino acid supply to the animal will be minimal. In recent studies, Smith and Leng (1993) incubated duckweed meal in rumen fluid where it was rapidly fermented with the production of ammonia, indicating the extensive degradation of duckweed protein. Treatment with heat, formaldehyde or xylose had little or no effect on the rate of release of ammonia indicating that duckweed protein is difficult to protect from rumen degradation or that a large proportion of the crude protein is as peptide, amino acids and other non-protein-N compounds (unpublished observations). It is likely therefore that duckweed will be initially used as a source of essential microbial nutrients to enhance the efficient fermentative digestion of straw in the rumen. Research is needed to protect the protein before its value as a bypass protein source can be estimated. However, the critical scarcity of protein resources in tropical countries indicates a need for feed technology research to enhance the use of duckweed as a direct protein source for ruminants and thus add value to the duckweed (see Leng 1990).

Conclusions

Proteinaceous feed resources are generally in short supply, and in addition are usually the most costly components of the diets of most animals in developing countries. Duckweed presents a protein source that is of great potential for feeding to domestic animals and particularly fish.

The nutrients in the water upon which the duckweed is grown critically affect its nutritional value particularly for monogastric animals where the fibre and protein contents of the duckweed are important elements. For ruminants, high levels of duckweed are not so crucial but feed processing to ensure the protein bypasses the rumen is probably necessary.

The potential for duckweed resides in its use as a sole fish feed or a component of fish diets where it can be used at the site of production for fish cultivation.

Duckweed appears to be potentially a major resource for the poultry industries of developing countries and could be incorporated into poultry diets on a least cost basis.

Duckweed meal may have great potential to blend with non- conventional diets based on inexpensive carbohydrate sources that can be used by pigs and ducks. With the possibilities for growing it with high protein and fat content, it would then blend extremely well with sugar cane juice or molasses and with other low-protein root or tuber producing carbohydrate crops such as cassava and sweet potatoes. These unconventional diets lend themselves to small scale integrated farming operations that include pigs.

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