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ALGAE AND AQUATIC WEEDS AS SOURCE OF ORGANIC MATTER AND PLANT NUTRIENTS FOR WETLAND RICE

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Algae and aquatic weeds are possible sources of organic manure; they are usually as rich in nutrients as or richer than many green manures. However, their high water content (92% on the average) has been the major deterrent to the commerical use of aquatic weeds.

Algae and aquatic weeds developing in rice fields have both beneficial and detrimental effects. Nitrogen-fixing blue-green algae provide free N. Their growth can be encouraged by inoculation. The photosynthetic biomass growing in floodwaters acts as a trap for C and N released by the soil into the water and recycles it in an available form. On the other hand, algae and aquatic weeds compete with rice for space, light, and nutrients. Their biomass varies with cultural practices, but it is rarely higher than 1 t dry weight/ha.

In irrigation canals and water sources, algae and aquatic weeds can develop large biomasses (1-13 t dry weight/ha). Because they have mainly detrimental effects, their use as organic manure requires integrated management, permitting the reclamation of water bodies. The practice of incorporating composted aquatic plants has been developed mainly for dryland crops. Little is known about its potentialities in wetland rice, except in China. Detrimental effects such as weed dispersal and concentration of toxic products are possible.

The wetland rice ecosystem comprises a water layer in which a photosynthetic biomass of algae and aquatic macrophytes develops in addition to rice. Rice fields are connected, through irrigation canals, to reservoirs, rivers, and ponds, which are colonized by similar vegetation. Most of the aquatic plants developing in rice fields, irrigation canals, and water sources are weeds.

In a field, weeds compete with the crop for nutrients, space, and light. The importance of controlling weeds is emphasized in popularized books (see Vergara

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1979, Moody 1981). Detrimental effects of the lack of weed control range from a slight decrease in yield to intensive damage. In paddy fields in India (Bhubaneswar), a biomass of 9-15 t *Chara* (fresh weight)/ha caused yield losses of more than 30% (Misra et al 1976). *Limneocharis* and water hyacinth invading paddy fields in Sri Lanka were reported to take large areas out of production (Kotalawa 1976). Subsistence farmers in the wet lowlands of Bangladesh annually face disaster when rafts of water hyacinth, weighing up to 300 t/ha, float over their rice paddies in floodwater; as the floods recede, the weeds remain on the germinating rice, killing it (Panel on Utilization of Aquatic Weeds 1976). The effects of *Salvinia* and *Pistia* have been reported to be similar (Kotalawa 1976). The photosynthetic aquatic biomass also increases the pH of submersion water, causing losses of N fertilizer by volatilization (Vlek and Craswell 1979).

Blue-green algae (BGA) have been sometimes cited as "weeds" in water-seeded rice because their growth pulls seedlings down into the water or mud (Smith et al 1977). However, the possible detrimental effects of BGA are negligible compared with the free N input provided by their N-fixing activity. The usefulness of these microorganisms in rice cultivation is clearly demonstrated in the literature (Roger and Kulasooriya 1980). Similarly, azolla, sometimes classified as a weed, has tremendous potential as a biofertilizer.

Whereas in the fields the photosynthetic biomass of aquatic plants can have both detrimental and beneficial effects, their presence in irrigation canals and water reservoirs seems to have a mainly detrimental effect. They reduce the water flow in canals and the utility of reservoirs for water storage, irrigation, and fish production. They also increase losses of water by transpiration from their leaves (National Science Research Council of Guyana and National Academy of Sciences, USA 1973; Varshney and Singh 1976).

Shortages of food and fertilizers and large expanses of aquatic weeds often exist in the same locality (Boyd 1974). Utilization of aquatic weeds from water bodies as a manure is an integrated management strategy permitting, at the same time, the reclamation of the water body and the fertilization of a crop with an organic manure frequently rich in N, P, and K. Moreover, aquatic plants can possibly be used to remove nutrients from waste-water effluents. Pilot studies with *Eichhornia* indicated that up to 29 t dry weight/ha can be produced in ponds receiving additional nutrients (Wahlquist 1972).

This paper deals with non-N-fixing algae and aquatic weeds. Little emphasis is given to N-fixing BGA, as they were recently extensively reviewed (Roger and Kulasooriya 1980, Roger and Reynaud 1982). Azolla is covered elsewhere in this volume.

NATURE OF FRESHWATER ALGAE AND AQUATIC WEEDS

Aquatic plants are classified as algae or macrophytes.

Algae are primitive plants devoid of true leaves or seeds. They reproduce vegetatively and through spores. Morphologically, three types can be distinguished:

- Phytoplanktons include microscopic single-celled, colonial, and simple filamentous forms; bloom-forming species such as *Microcystis* and *Anabaena* belong to the phytoplanktons.

- Filamentous algae such as *Cladophora* (cotton mat type), *Spirogyra* (slimy and green type), and *Hydrodictyon* (water net type) frequently form scum.
- Higher algae such as *Chara* and *Nitella* resemble vascular plants, grow as anchored species, and possess stems and branches.

Physiologically algae can be classified into N-fixing and non-N-fixing forms:

- N-fixing algae belong exclusively to the blue-green group, which are procaryotic. Their growth provides free N to the ecosystem.
- Non-N-fixing algae comprise part of the BGA and all the eucaryotic algae.

In a review on algal weeds and their chemical control, Das (1976) cited *Chara, Spirogyra*, *Oscillatoria*, *Nitella*, *Oedogonium*, *Cladophora, Pitophora, Rhizoctonium*, and filamentous algae without specific names. It appears that only filamentous and higher algae are considered weeds.

Aquatic macrophytic weeds are usually divided into three groups:

1. Submerged weeds produce most of their vegetative growth beneath the surface, rooted to the soil.
2. Surface (or floating) weeds have a majority of their leaves and flowers near the surface of water. Both rooted and free-floating species occur in this group, characterized by special parenchymatous tissues for buoyancy.
3. Emersed or marginal weeds growing in shallow water or wet soils.

Productivity differs among aquatic plants according to this classification. Ambasht and Ram (1976) studied the vertical distribution of dry matter and chlorophyll in different aquatic communities and distinguished three types of productivity: 1) the upright triangle type, represented mainly by emersed plants (e.g., *Eleocharis*), whose photosynthetic biomass is concentrated just above the basal layer; 2) the inverted triangle type, represented by submerged plants (e.g., *Hydrilla* or *Najas*), whose photosynthetic biomass is greatest in the 20-40 cm of the top layer of water body; 3) the flag type, represented by floating species (e.g., *Nymphea*), whose photosynthetic organs are concentrated on or above the water surface.

Lists and identification keys for common aquatic weeds are provided in several handbooks (e.g., Weldon et al 1979). Recently a list of major weeds of rice was published by Moody (1981).

Most of the important submerged weeds belong to the genera *Hydrilla*, *Myriophyllum*, *Ceratophyllum*, *Egeria*, *Elodea*, *Najas*, *Potamogeton*, *Vallisneria*, and *Chara*. Among floating weeds, water hyacinths (*Eichhornia* spp.), *Salvinia* spp., water lettuce (*Pistia stratiotes*), and duckweeds (Lemnaceae family) are the most common. The classification of a plant as a weed depends not only on the area but also on the method of crop cultivation. For example, submerged plants like *Chara* and *Hydrilla* are not considered main weeds in transplanted rice (Moody 1981). On the other hand, in areas where rice is directly seeded, they are considered detrimental (Mukherji and Laha 1969, cited by Das 1976).

Weeds can also be indirectly detrimental by inhibiting more or less the biological N fixation by BGA. Negative correlations have been observed between the N-fixing BGA biomass and the submerged weeds biomass (Roger and Kulasooriya 1980) or

Table 1. References reporting biomass of planktonic algae in paddy fields and in fresh waters.

Reference	Location	Dry wt (kg/ha)	Fresh wt (kg/ha)	Remarks
Institute of Hydrobiology Academia Sinica (1978)[a]	Paddy field, China		7,500	After inoculation
Mahapatra et al (1971)[a]	Paddy field, India	3 - 300 32	60 - 6,000 600	Green algae dominant N-fixing BGA dominant
Muzafarov (1953)[a]	Paddy field, USSR		16,000	Total algal biomass
Reynaud and Roger (1981)	Uncultivated submerged sandy soil		41,000	Total algal biomass
Roger and Reynaud (1977)[a]	Paddy fields, Senegal		2 - 6,000 2 - 2,300	Total algal biomass N-fixing algal biomass
Saito and Watanabe (1978)	Paddy field, Philippines	2 - 114		
Singh (1976)[a]	Paddy field, India	480	9,000	*Aulosira* bloom
Srinivasan (1979)[a]	Paddy field, India		100 - 2,100	
Watanabe et al (1977)[a]	Paddy field, Philippines	177	24,000	*Gloeotrichia* bloom
MacKenthun (1962)[b]	Lake, USA	110 - 400		Phytoplankton
MacKenthun (1971)[b]	Lake, USA	112 - 400 224		Phytoplankton Attached algae
Forest (1965)[a]	Upland soils, USSR		40 - 100	For comparison
Patnaik and Ramachandran (1976)	Fish pond	10 ml phytoplankton/ liter water		Mycrocystis bloom

[a]Cited by Roger and Kulasooriya (1980). [b]Cited by Little (1979).

the floating weeds biomass (Srinivasan 1982). But whether these were due to antagonism or to competition as well as to the inhibitory organism is still unknown.

QUANTITATIVE EVALUATIONS OF THE PHOTOSYNTHETIC AQUATIC BIOMASS

Aquatic plants in the paddy field must compete with rice; therefore their biomass differs largely from that in irrigation canals and water sources, where they can occupy the whole available area.

Paddy fields

Very little literature is available on the productivity of the floodwater in paddy fields. In the Philippines, Saito and Watanabe (1978) reported a net primary production of the flood community of 50-60 g C/m^2 in 90 days. The standing crop of algae ranged from 2 to 114 kg fresh weight/ha while the maximum standing crop of submerged weeds (*Najas* spp. and *Chara* spp.) was 400 kg dry weight/ha. The primary production of the floodwater community was equivalent to productivity values in eutrophic lakes, and the total gross primary production of the floodwater community during the cropping period corresponded to 10% of that of the rice plants in a fertilized plot and to 15% of that in a nonfertilized plot. A similar value was reported by Yamagishi et al (1980).

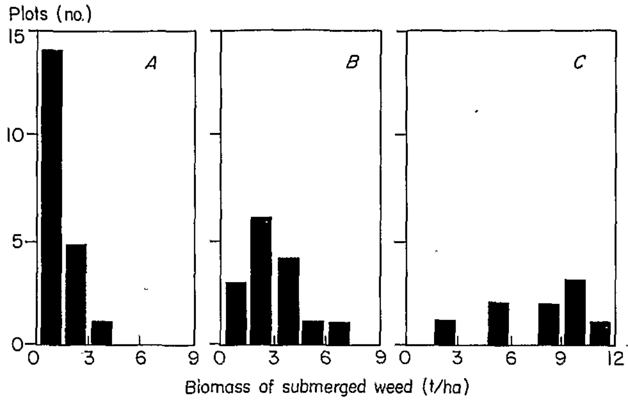
Probably because of technological difficulties in estimating algal abundance, quantitative evaluation of algal biomass in kilograms per hectare is also scarce. From the available data, summarized in 1980 by Roger and Kulasooriya, it appears that algae can develop a biomass of several tons (fresh wt) per hectare (Table 1). From the highest BGA biomass recorded in a paddy field (480 kg dry wt/ha), and assuming a protein content of 30-50%, it appears that under favorable conditions, a N-fixing algal bloom may contribute 30-40 kg N/ha. Reported data on N fixation related to BGA were summarized by Roger and Kulasooriya (1980). The estimated amount of N fixed varied from a few to 80 kg/ha and averaged 27 kg/ha per crop.

The potential productivity of aquatic weeds in rice fields seems to be higher than that of algae (Table 2). The biomass of submerged weeds (mainly *Chara* and *Najas*) was studied in 44 plots at the IRRI farm by Kulasooriya et al (1981). Results (Fig. 1) show that the population of submerged weeds under a rice crop at the end of tillering had a mean biomass of about 1 t/ha (range, 0.4-3 t fresh weight/ha) and that it increased at maturity to a mean of 3 t/ha (range, 0.2-4.5 t/ha). The highest values, which ranged from 2.7 to 12 t/ha, with a mean of 7.5 t/ha, were recorded in fallow plots. Twenty measurements of floating and emersed weeds in planted fields at the tillering stage gave a mean value of 1.7 and a maximum value of 4.1 t fresh weight/ha. Measurements conducted by the IRRI Agronomy Department over 9 crops in 3 years (De Datta, personal communication) gave similar values, ranging from 70 to 2,400 kg dry weight and averaging about 500 kg dry weight. In some cases, submerged weeds seem able to develop a very high biomass. Mukherji and Ray (1966, cited by Das 1976) reported that the growth of *Chara* and *Nitella* is favored by high temperatures (27°-35° C) and a slightly alkaline reaction of water. According to them, clear days with most of the rainfall at night, which allow the muddy water to clear in the day and light to penetrate the water, helped in their rapid

Table 2. Standing crops and productivity of some aquatic macrophytes.

Species	Standing crop (t/ha)		Productivity (t dry wt/ha)	References	Remarks
	Fresh wt	Dry wt			
Chara spp.[b]	9 - 15			Misra et al (1976)	Rice fields, India
Chara nitella[b]	5 - 10			Mukherji and Laha (1969)	Rice fields, India
Ceratophyllum demersum[b]		6.8	9.0	Boyd (1974), Gaudet (1974)	Temperate lake, USA
Hydrilla verticillara[b]			2.5	Steward (1970)[a]	Florida, USA
Najas guadalupensis[b]		1.1		Boyd (1974)	USA
Najas and *Chara*[b]		0.4		Saito and Watanabe (1978)	Rice fields, Philippines
Nymphoides aquaticum[b]		1.8		Boyd 1974	USA
Sagittaria subulata[b]			23.2	Steward (1970)[a]	Florida, USA
Sagittaria eatonii[b]			27	Gaudet (1974)	Subtropical spring
Thalassia restudinum[b]			33.5	Steward (1970)[a]	Puerto Rico
Total submerged vegetation	1 - 3			Kulasooriya et al (1981)	Rice fields, Philippines
"	7.5			Kulasooriya et al (1981)	Fallow rice field
"	25 - 350			Gupta (undated)	Weedy canal
Eichhornia crassipes[c]	250	12.8	36.8/167	Gratch 1968[a]/Steward (1970)[a]	Louisiana, subtropic
Marsilea quadrifolia[c]	2.32			Srinivasan (in press)	Fallow fields, India
Myriophyllum verticillatum[c]		2.4		Boyd (1974)	USA
Nelumbo lutea[c]		1.0		Boyd (1974)	"
Nuphar advena[c]		0.8		Boyd (1974)	"
Pistia stratiotes[c]	20	4.6		Boyd (1974)	"
Potamogeton pectinatus[c]		2.2		Boyd (1974)	"
Alternaria philoxeroides[d]		7.4		Boyd (1974)	"
Cyperus papyrus[d]		2.7 - 4.6	83.5	Gaudet (1974), Steward (1970)[a]	Tropics
Eleocharis quadrangula[d]		7.2		Boyd (1974)	USA
Justicia americana[d]		7.1		Boyd (1974)	"
Orontium aquaticum[d]		2.4		Boyd (1974)	"
Phragmites communis[d]			32.5	Steward (1970)[a]	Romania
Sagittaria latifolia[d]		7.3		Boyd (1974)	USA
Typha latifolia[d]		15.3	51.5	Boyd (1974), Steward (1970)[a]	Minnesota, USA

[a]Cited by Little (1979). [b]Submerged. [c]Floating. [d]Emergent.



1. Distribution of biomass of submerged weeds (fresh weight, t/ha) among A) 20 plots at end of tillering (the plots had been hand weeded 4 weeks before the measurement), B) 15 plots at harvesting stage (no weeding was performed), and C) 9 fallow plots at harvesting stage of rice.

and luxuriant growth (5-10 t fresh weight/ha) on very large areas (about 50,000 ha in India). The biomass produced by *Chara* was reported to be 9-15 t fresh weight/ha by Misra et al (1976). Floating weeds also attained a very high biomass in Tamil Nadu (India). In Thaujavur Delta, submergence of fields during the fallow period encourages the growth of many aquatic weeds. Among such weeds, *Marsilea quadrifolia* is difficult to control and can develop a biomass of around 25 t fresh weight/ha (average of 44 locations; Srinivasan 1982).

Irrigation canals and water sources

Little is known about the productivity of planktonic algae in fresh water. Densities of microcystis blooms observed in India (Cuttack) by Patnaik and Ramchandran (1976) ranged from 7 to 17 ml/liter. Assuming a colonized water layer of 20 cm, this leads to values of 14-30 t fresh weight/ha.

It can be assumed that the mass of algal cells per unit area in a culture or a natural ecosystem would not increase beyond a value that is probably determined by natural shading of the cells. Extrapolation of data from laboratory cultures indicates a maximal biomass of 2.75 t dry weight/ha (Roger and Reynaud 1979).

Much more is known about higher algae and macrophytes. Their very high productivity is frequently mentioned. A classical example is the water hyacinth; in one experiment 2 parent plants produced 30 offspring after 23 days and 1,200 at the end of 4 months (Holm and Yeo 1980). Water hyacinth has an average doubling time (vegetative reproduction) of 12.5 days during the warm season in the US; *Salvinia*, in open water at the edge of a mat, grows faster and can double the area it covers in 8.6 days (Holm and Yeo 1980). However, Sculthrope (1967) has discussed the mistaken notion that luxuriant submerged or floating macrophytes are unusually productive. The rapid spread of some weeds gives the observer the impression of phenomenal growth, but such vegetation is necessarily buoyant and contains very little dry matter. For example, the amount of dry matter produced in a *Hydrilla* mat averages only 2.25-4.5 t/ha; the plant is 96% water, and mats are often limited to about 60 cm in thickness, because the density of the canopy eliminates all light and reduces growth beneath that level (Holm and Yeo 1980). According to Gaudet (1974) there is now adequate proof that in terms of dry weight such plants are not very productive compared with other plant communities.

Species differ greatly in inherent ability to produce dry matter. Large floating plants may have large standing crops, and values of dry matter above 10 t/ha are commonly encountered in *Eichhornia crassipes* (Table 2). Other floating and submerged plants normally have standing crops with dry matter values ranging from 1 to 5 t/ha. More information on productivity and standing crops of aquatic plants can be obtained from Little (1979).

COMPOSITION OF ALGAE AND AQUATIC WEEDS

In 1953, Milner pointed out the scarcity of information on the composition of freshwater algae, which is still true today. Table 3 gives the composition of some freshwater microalgae and shows how variable the composition of a species can be. But the range of variation in the composition of *Chlorella* may be mainly due to the fact that no other plant species has been subjected to such extensive experimentation regarding the effects of environmental conditions and chemical composition. Other species might show as much variation as *Chlorella* (Milner 1953).

Despite the abundance of literature on the role of BGA in paddy soils, very little is known about their composition. From the analysis of 22 strains (Table 3) it appears that BGA have a low dry matter content, and their average protein content might not be as high as previously thought (Fogg et al 1973). In fact, mucilagenous BGA can develop very impressive blooms, but the corresponding N content may be low. A *Nostoc* biomass of 13 t fresh weight/ha, which corresponds to an almost continuous layer of colonies, 1-4 cm in diameter, frequently has a total N content of less than 5 kg/ha (Roger, unpublished).

Because of increasing interest in the pollution problems in water bodies, more information is available on the composition of higher algae and aquatic weeds. C. E. Boyd has probably done the most comprehensive analyses of aquatic macrophytes, culminating in an extensive review (Boyd and Scarsbrook 1975) in which data from 35 papers on temperate species were tabulated. Little (1979) summarized papers on both tropical and temperate species and concluded that the ingredients of aquatic plants other than water are similar to those of dryland plants.

A high water content is certainly the overwhelming characteristic of aquatic plants. Little and Henson (1967) presented results suggesting an average water content of 92%. By comparison, terrestrial forage plants contain 70-90% water.

A second characteristic of aquatic plants is a high content of ash (Sculthorpe 1967), which varies with location and season. Sand, silt, and encrusted carbonates often account for much of the mineral content. Although silt is most frequently removed during analysis, in practice it represents part of the chemical composition of the harvest. Submerged macrophyte communities contain, on the average, 21.3% ash on a dry weight basis; floating communities average 11.5% (Sculthorpe 1967); and upland plants usually contain less than 10%.

Table 3. Composition of some freshwater algae.

Species[a]	Dry wt (% fresh wt)	Ash (% dry wt)	Ash-free dry wt (%) Protein	Carbohydrate	Lipid	C:N
Chlamydomonas spp.		4.74	36.3	58.2	5.5	8.2
Anabaenopsis spp.		9.35	45.5	45.6	8.9	6.8
Oikomonas termo[a]		5.08	33.5	45.8	20.7	9.7
Stichococcus bacillaris (sample A)		6.50	62.3	25.8	11.9	5.3
Stichococcus bacillaris (sample B)		11.24	22.6	38.5	38.9	15.8
Chlorella pyrenoidosa (sample A)		3.45	58.0	37.5	4.5	5.3
Chlorella pyrenoidosa (sample B)		3.46	8.7	5.7	85.6	49.1
Av		6.26	38.1	36.7	25.1	14.3
Median		6.50	36.3	38.5	11.9	8.2
Composition of 22 strains of blue-green algae[b]		*Composition of 22 strains of blue-green algae*[b]				
Average	3.85		34.2[c]	43.1[c]		7.6
Highest value	8.50		51.6	68.4		13.0
Lowest value	0.18		21.2	19.9		4.8

[a]Adapted from Milner (1953); [b]Strains belonging to the following genera: *Anabaena* (5), *Aulosira* (1), *Calothrix* (3), *Fishcherella* (3), *Gloeotrichia* (2), *Nostoc* (6), *Oscillatoria* (1), *Tolypothrix* (1) (Roger, Tirol, and Watanabe, unpublished); [c]% of dry wt.

Table 4. Variability of the composition of water hyacinth.[a]

	Number of data	Mean	Lower value	Higher value	CV (%)[b]
Dry matter (% fresh wt)	13	7.79	4.50	12.00	23.7
N (% dry wt)	9	1.86	1.03	3.70	42.9
P (% dry wt)	8	0.36	0.10	0.63	43.9
K (% dry wt)	7	3.35	1.81	4.40	28.8
Crude proteins (% dry wt)	8	13.36	6.50	19.8	32.9
Ash (% dry wt)	6	13.40	11.90	25.6	28.3

[a]Data used for calculations have been collected from the papers summarized by Little (1979) in Chapter 3 of his *Handbook of utilization of aquatic weeds*. Data given on a fresh weight basis without indication of dry matter content of the plant have been recalculated on a 7.79% dry matter basis. [b]Variance expressed as a percentage of the mean.

A third characteristic of aquatic plants is the large variability of composition (as in algae), which is influenced by the composition of the water in which they grow. Lawrence and Mixon (1970) have shown how aquatic plants growing in water containing ample quantities of N, P, and K will exploit the situation by "luxury consumption" of these elements, far in excess of the amount they need for healthy growth. An extensive example was the K uptake by *Alternanthera philoxeroides*: in one case consumption was 20 times the content of plants grown in unfertilized pools (7.3% vs 0.36%). Table 4 shows the variability of the composition of water hyacinth. Table 5 is a compilation of data on the composition of some common aquatic weeds. It appears that aquatic weeds contain appreciable quantities of N, P, and K and, on a dry matter basis, have similar N and P contents to those of alfalfa but a higher K content. The amounts of Mg, Na, S, Mn, Cu, and Zn in aquatic weeds growing in nature are generally quite similar to those in terrestrial plants. However, aquatic plants are often richer in Fe and Ca than forage plants (Panel on Utilization of Aquatic Weeds 1976). The amount of all mineral elements can be exceptionally high in aquatic plants grown in sewage or agricultural and industrial waste water.

DECOMPOSITION AND AVAILABILITY OF PRODUCTS TO RICE

Mechanisms of release of nutrients

Living aquatic plants continuously excrete appreciable amounts of dissolved organic matter, including soluble nutrients (Kristritz 1978). Laboratory experiments have frequently shown that BGA liberate large portions of their assimilated nitrogenous substances; however, the large amounts recorded may be a methodological artifact due to osmotic shock in resuspending the cells or to physical damage of the algal material. No information on the exudation of organic compounds by BGA in field conditions is available (Roger and Kulasooriya 1980).

Excretion of nutrients by aquatic plants is particularly pronounced in senescent plants and, undoubtedly, the largest proportion of nutrients tied up in plant tissues would be released after death (Kristritz 1978). Nutrients are released after death mainly because of microbial decomposition. However, Otsuki and Wetzel (1974) demonstrated under laboratory conditions that 30-40% of the net production of the submerged freshwater angiosperm *Scirpus subterminales* was released as dissolved organic matter on autolysis; most of the autolytic organic matter was released within 5 days under both oxic and anoxic conditions.

A laboratory study by De Pinto and Verhoff (1977) illustrated the two mechanisms by which algae populations may decay under dark aerobic conditions — endogenous respiration by the algal cells themselves and decomposition by microorganisms. Active bacterial decomposition proved to be the more important mechanism by far. In the same study, the viability of the bacteria-free algal cultures after 70 days in the dark, with no net P regeneration, was regarded as an indirect proof that bacteria not only can decompose algae but, under certain circumstances, can cause the termination of an algal bloom. However, whether the lytic bacteria act as pathogens, and thus are the primary cause of decline, or act as saprophytes, decomposing the dead algal material resulting from other primary processes, remains a question (Fallon and Brock 1979).

Table 5. Composition of some aquatic weeds.[a]

Aquatic weed	Dry matter (% fresh wt)	Protein[b]	N[b]	P[b]	K[b]
Chara vulgaris		7.92	1.27[d]	0.19	0.84
Ceratophyllum spp.	8.50		3.3	0.47	5.9
Elodea canadensis[c]	9.03		3.29	0.51	3.26
Hydrilla spp.[c]	8.00	17.1	2.7	0.28	2.9
Lagarosiphon spp.[c]	8.90		3.54	0.53	2.56
Lemna minor		17.86	2.87[d]	0.17	1.20
Myriophyllum[c]			2.81	0.43	1.75
Nuphar variegatum		15.70	2.52[d]	0.23	1.62
Pistia stratiotes	5.9	13.2	2.1	0.30	3.5
Potamogeton spp.[c]			2.51	0.33	2.28
Typha spp.[c]			1.37	0.21	2.38
Vallisneria spp.[c]		13.5	2.14	0.20	5.70
Water hyacinth[c]	7.8	13.4	1.86	0.36	3.35
Av			2.48	0.32	2.86
Alfalfa hay	15		2.7	0.26	1.77

[a]Data from Boyd (1969, 1970), Fish and Will (1966), Lancaster et al (1971), Lawrence and Mixon (1970), Lin et al (1975), and Riemer and Toth (1969) – all cited in Little (1979). [b]As % of dry matter. [c]Av value. [d]Extrapolated from protein content (Protein = 6.23 × N).

Susceptibility to decomposition

The decomposition rate depends on the environment, the species, and the physiological state of the plant.

Survival of microbial bodies incorporated into the soil was studied by Casida (1980). The cells died more quickly when nutrients were added to the soil, whereas survival increased at lower temperature. At 20° C, 62% of the added cells were alive 1 week after incorporation, but at 37° C no living cell was observed after 1 week.

The susceptibility to microbial decomposition of 14 algal species was assessed by Gunnison and Alexander (1975) in pond water and with inocula from several environments. Some of the algae were destroyed in short periods, but others withstood microbial digestions for more than 4 weeks. The production of toxins did not account for the resistance of those algae not readily destroyed microbiologically. The suitability of the cell as a substrate for microorganisms was correlated with the longevity of three susceptible and three resistant algae. The differing susceptibility to decomposition may be related to the relative biodegradabilities of specific components of the algal walls like polyaromatic compounds.

The decomposition, by the action of various soil bacteria, of four nitrogen-fixing BGA at two different physiological stages was examined by Watanabe and Kiyohara (1960). Within 10 days of incubation with the most active strain (*Bacillus subtilis*), about 40% of the N from autolized cells and 5% of the N from fresh cells were converted to NH_4^{+2}.

Regeneration of nutrients in floodwater

Most of the experiments concerning regeneration of nutrients from algae and aquatic plants have been conducted either in the laboratory or in enclosures replaced in situ. Therefore, the test samples were cut off from the circulation occurring under natural conditions, and the validity of the results are limited by this "enclosure effect."

Studies in which field- or laboratory-grown algae were placed in the dark and the changes in N, or P, or both, were monitored for varying periods were summarized by Foree et al (1970). They reported three general stages of activity with nutrient regeneration:

1. the stage immediately after dark conditions — usually the first 24 hours — during which either a release to or absorption from solution or a release followed by an absorption of nutrients took place;
2. a stationary stage over a period of several days during which net nutrient regeneration was zero; and
3. the stage in which active nutrient regeneration occurred with a net release of nutrients to the solution, lasting a few hundred days.

The N and P regeneration of algae in dark aerobic (44 strains) and dark anaerobic (21 strains) conditions was studied by the same authors (Foree et al 1970) for periods ranging from 40 to 360 days. In aerobic conditions, on the average, 50% of the initial N and P was regenerated but the extent of regeneration ranged from zero to nearly 100%. In anaerobic conditions, the extent of N and P regeneration averaged 40% and 60%, respectively, with a range similar to that for aerobic decomposition.

The dark aerobic decomposition of batch unialgal cultures inoculated with a natural bacterial community was studied in detail by De Pinto and Verhoff (1977). The P regeneration values obtained ranged from 31 to 95% (mean 74%), with higher percentages of release associated with higher initial cellular P. The conversion of particulate organic N to NH_4^{+2} ranged from 51 to 94% (mean 74%). The incubation periods required for stabilization of the system varied from 29 to 55 days, about one-third of which was bacterial lag time. The P regeneration followed a pattern that indicated three stages:

1. after the algae were subjected to a darkened environment, a rapid release of P to solution associated with endogenous respiration, followed by an immediate absorption by the remaining cells;
2. a stationary lag phase lasting several days, during which there was a build-up of bacteria and no net P regeneration; and
3. when the viable algal population had been significantly reduced, an associated active P regeneration with a net release of orthophosphate to solution.

The regeneration pattern for N seemed to be less complicated than that for P. All organic N regenerated appeared first as NH_4^{+2}; then a portion of the NH_4^{+2} was converted to NO_3 by nitrification. The state of P regeneration during the active phase of decomposition (3rd phase) depended on the initial P level, whereas N regeneration was a direct function of the amount of organic decomposition.

Studies dealing with the release of nutrients from decomposing aquatic macrophytes (Jewell 1971, Nichols and Keeney 1973, Kristritz 1978, Rho and Gunner 1978) have dealt also to different extents with the effects of the nutrients on the surrounding microflora, including algae. Kristritz (1978), who studied recycling of nutrients in an enclosed aquatic community of *Myriophyllum spicatum*, reported that total suspended bacterial biomass represented an average of 10% of the total organic N and P pool of the water column. Decaying *Myriophyllum heterophyllum* released NH_4^{+3} and phosphate in concentrations sufficient to promote algal growth. The oxidation of NH_4^{+2} by resident nitrifiers had a striking impact on microfloral succession. Nitrification was accompanied by a decrease in pH and thereafter by a decline in the numbers of bacteria and protozoa. Subsequently, coincident with the accumulation of nitrite and nitrate, the numbers of the resident green algal communities rose dramatically.

Mineralization in soil

Mineralization of some algae and weeds under flooded conditions was studied by Mitsui (1954). Nitrogen contents varied from 2.2 to 6.6%, C contents from 39 to 44%, and C-N ratios from 6.6 to 20.1. The order of the accumulation of ammonium N followed the order of C-N ratios as long as the incubation period remained within 34 days. *Lemna* (floating weed; C:N = 6.6) accumulated the largest ammonium N whereas *Spirogyra* (filamentous green alga; C:N = 20.1) had even less than the check. However, a result contradictory to this "C:N rule" was quoted by Rho and Gunner (1978): "Though Boyd (1973) reported a higher nitrogen content of phytoplankton tissue than that of macrophytes, the decomposition of macrophytes was found to be more complete and to occur at twice the rate of phytoplankton (Jewell 1971)."

The rate and degree of nitrification, under aerobic conditions, of different aquatic weeds added to soil was studied by Riemer and Toth (1971) for 8 weeks. Considerable variations were observed, with rates ranging from high values (40-60% for *Nuphar advena* and *Lemna minor*) to low and even negative values (*Potamogeton pulcher*, *P. cordata*, and *Sparganium*). Some tissues not only showed poor nitrification but inhibited nitrification (old plants of *Phragmites*). It was also concluded that some aquatic weeds may be composted for agricultural use without added N.

Effects on soil organic matter

Little is known about the nature of humus derived from algae and aquatic weeds. Their content of lignin, which is a major substance producing humus, seems to be low. Values ranging from 2.9% in *Hydrodictyon* (green alga) to 6.18% in *Hydrilla verticillata* (submerged weed) were recorded by Mitsui (1954), whereas ordinary green manures usually range from 9 to 24%.

Decomposition and humification of algal cells was studied by Verma and Martin (1976) using six strains of BGA and one green alga labeled with ^{14}C. After 22 weeks of incubation of the whole cell in a sandy loam, between 61 and 81% of the added C had evolved as CO_2. Over 50% of the residual ^{14}C activity in the soil was not extractable with 0.5% NaOH.

Analysis of sedimentary organic matter from a cyanobacterial (BGA) mat by Disnar and Trichet (1981) indicated a wealth of amino acids and carbohydrates and a paucity of aromatic structures. Dzumaniyazou (1979) reported that green and blue-green algae stabilized humic acids and increased the content of humus and of free amino acids in an irrigated soil.

Availability of the decomposition products to rice

Besides indirect evidence such as an increase in rice yield after algae or weeds were incorporated into the soil, there is very little information about how much and when nutrients released by this kind of manure are made available to the rice plant.

In a laboratory experiment, Wilson et al (1980) recovered from a rice crop 37% of the N from ^{15}N-labeled *Aulosira* spp. spread on the soil and 51% of the N from the same material incorporated into the soil.

Recently, uptake by rice of ^{15}N from a *Nostoc* strain was studied in pot and field experiments at IRRI (Tirol et al, in press). The availability of ^{15}N from BGA incorporated into the soil was 23-28% for the first crop and 27-36% for the first and second crops. Surface application of the algal material reduced ^{15}N availability to 14-23% for the first crop and 21-27% for the first and second crops. The pot experiment demonstrated that for the first crop algal ^{15}N was less available than $(NH_4)_2SO_4$, but for two crops its availability was very similar. That indicates the slow-release nature of algal N; however, the very low C-N ratio (5-8) of BGA gives it better N availability than that of organic fertilizers such as farmyard manure. After two crops, 57% of ^{15}N from BGA and 30-40% of ^{15}N from $(NH_4)_2SO_4$ remained in the soil, suggesting that algal N is less susceptible to losses than mineral N.

Shi et al (1980) studied the N availability of ^{15}N-labeled *Azolla*, *Astragalus sinicus*, and water hyacinth to rice and to a following crop of wheat. Water hyacinth had 1.53% N, a 21.3 C-N ratio, and 11.1% lignin. Twenty-five percent of the N from water hyacinth was absorbed by the first crop and 4.5% by the second. Nitrogen from water hyacinth was more available for rice than N from *Azolla*, and less available than N from *Astragalus sinicus*.

The foregoing results indicate that:

- Algae and aquatic weeds show great variations in their decomposition rate and in the conversion of plant N to NO_3^- by soil microorganisms (Gunnison and Alexander 1975, Mitsui 1954, Riemer and Toth 1971).
- The extent of the decomposition of algae and aquatic weeds, and the consequent regeneration of N and P into the water in a soluble form are similar in aerated and nonaerated conditions (Foree and McCarty 1970, Jewell and McCarty 1971, Rho and Gunner 1978).
- The relative regeneration rate of P from the algae (Golterman 1964) and from the macrophytes (Rho and Gunner 1978, Kristritz 1978) is much higher than that of N.
- Humus resulting from the decomposition of algae is poor in aromatic structures; because of their paucity in lignin, a similar characteristic for the humus from aquatic plants, especially submerged ones, can be expected.
- If the decomposition of the photosynthetic biomass occurs in the floodwater, the nutrient regeneration, along with many other parameters, can markedly affect the dynamic seasonal succession of the phytoplankton, but availability of the nutrient to the rice plant is poor (Tirol et al, in press).

AGRONOMICAL USE OF ALGAE AND AQUATIC WEEDS

In the paddy field, plants that can compete with the crop are usually removed, and the most common "use" of aquatic weeds is their incorporation into the soil during weeding.

One other possible technique is the use of BGA as a source of free N and organic matter for the crop. Literature concerning BGA and rice was summarized by Roger and Kulasooriya (1980). Since BGA were recognized to be one of the important N-fixing agents in the flooded rice soil, many trials have been conducted to increase rice yield by algal inoculation (algalization). Algalization has been reported to have a beneficial effect on grain yield in several countries; however, there are also reports indicating failure of algalization under widely different agroclimatic conditions. From the reports on field experiments, conducted mainly in India, it appears that, on the average, algal inoculation, where effective, caused about 14% relative increase in yield, corresponding to about 450 kg grain/ha per crop.

A method for producing algal inoculum easily adoptable by farmers has been developed and recommendations for field inoculation have been given (Venkataraman 1981). Unfortunately most of the experiments have been conducted on a "black-box" basis, where only the last indirect effect (grain yield) of an agronomic practice (algalization) was observed and the intermediate effects were not studied. Therefore, there are many uncertainties concerning the mechanism of action of BGA and the limiting factors for algal inoculation. In particular, it is still not known if the yield increase observed after algalization is simply due to an increase of N and organic matter in the soil resulting from the decomposing algae, or to some "auxinic effect" of exudation products, or both.

Plants that grow in irrigation canals (mainly submerged weeds and filamentous green algae) can also be incorporated into soil as a source of organic matter for rice. *Cladophora* and *Spirogyra,* two filamentous freshwater algae, were used by Pantastico and Rubio (1971) as manure for rice. A better increase in yield was obtained with dried algae than with fresh algae. *Spirogyra*, richer in N (5% dry weight), was more efficient than *Cladophora* (N = 2.39% dry weight). For an equivalent quantity of N, $(NH_4)_2SO_4$ was more efficient than dried algal material.

Because their NPK content is similar to that of many green manures used in dryland soil, partially dried aquatic plants that are composted can make a suitable soil fertilizer and conditioner. Several aquatic weeds have been used to make compost, mulches, and fertilizers, and a variety of methods are given in Little (1968). The same author (1979) recorded 26 papers dealing with this topic, among which 19 dealt with water hyacinth and only 3 with rice, clearly demonstrating the emphasis given to water hyacinth and dryland soils. The Indian Council of Scientific and Industrial Research (1952, cited by Little 1979) indicated that water hyacinth compost was eminently suitable for jute and rice fields. Subagyo and Vuong (1975, cited by Little 1979) reported that dead masses of *Salvinia molesta* stimulated the growth of rice seedlings in Indonesia.

Recently, Majid et al (1980) reported the effects of drained algae, composted aquatic weeds, and cow dung on a variety of crops including rice, soybean, sesame, brinjal, garlic, and onion. Drained algae and composted aquatic weeds yielded better results than cow dung in some experiments; in other experiments they were as good as cow dung. Field experiments indicated that rice yield has been increased by 24% through the use of composted *Eichhornia* in addition to the usual dose of chemical fertilizer. A recent note indicated that *Salvinia molesta* has been widely used by farmers in West Java as a soil additive in rice fields; 40 t/ha increased rice tillering by

30%. *Eichhornia crassipes* has also been used after being composted for 3-4 months (Soerjani 1980).

Aquatic weeds (mainly water hyacinth and *Pistia*), naturally growing or artificially grown, are used as organic manure for wetland rice in China (Nan Kin Institute of Soil Science 1978). In Hunan Province aquatic plants, mainly *Pistia stratiotes*, *Eichhornia crassipes*, and *Alternanthera sessilis*, are collected or grown for making compost or pig food (IRRI 1980). In Fujian Province high-yield trials were conducted with a wheat-rice-rice rotation using organic manures. Use of 75 t mud manure/ha per year gave yields between 7.5 and 11.8 t/ha per crop. Mud manure is prepared by mixing mud with aquatic plants (mainly *Eichhornia*), flooding for a while to permit an anaerobic decomposition, and then draining to permit an aerobic incubation. In the same area, trials to grow aquatic plants (*Pistia stratiotes, Japonica narcissus*, and *Azolla pinnata*) within wide rows of late rice were conducted. Chinese scientists indicated that non-N-fixing aquatic weeds collected N from paddy water, and the accumulated N was turned down into the soil.

Very little is known about the effect of incorporation of weeds or weed compost on soil properties. Dhar (1961) reported that incorporation of water hyacinth into paddy soil resulted in a N-fixing activity that was higher when basic slag (0.5% P_2O_5) was added and when the soil was exposed to the light. Depending on the treatment, N-fixation efficiency ranged from 18.2 to 33.5 mg N/g oxidized C.

Thus, it appears that aquatic plants have been used as a source of organic matter and nutrients mainly in dryland soils and that their potentialities on wetland soils are very poorly documented, except in China.

There are limitations and possible noxious effects of the use of algae and aquatic macrophytes. One limitation is the bulkiness of the material, despite the fact that in most places where tropical water weeds are a problem there is ample hot sunshine that could be used to dry the harvest. Little and Henson (1967) pointed out that the harvest of water weeds is commonly believed to be too extensive a job because of their high water content (92% on the average). To obtain the same dry matter of plant material from water weeds (8%), about twice as much fresh material is needed as lucerne (15%) or 2.5 times that of pasture grasses (20%).

A second possible limitation on the use of aquatic weeds in wetland soils is that they can aid weed dispersal through the irrigation system to the rice fields. Gupta (undated) pointed out that many cuttings and rhizomes of the weeds regain viability even after composting.

A third limitation is that composting seems to be a recommendable precautionary measure because both fresh algae and aquatic weeds can release products toxic to rice when incorporated. Mats of BGA incubated anaerobically rapidly produced a large amount of volatile S compounds, including H_2S, methyl mercaptan, and dimethyl sulfide (Zinder et al 1977). In Sri Lanka, *Salvinia* growing in rice fields is buried during the preparatory stages. In marshy areas that helps in the aeration of the soil. On the other hand these buried plants decompose and liberate organic acids that are toxic to rice plants and create an unfavorable pH (Kotalawa 1976).

A fourth very important limitation is that certain stable pesticides, industrial chemicals, and heavy metals may be absorbed and retained by aquatic plants (Vance and Drummond 1969, Rose and McIntire 1970). Water hyacinths, in particular, have been shown to absorb large quantities of toxic materials, including heavy metals. Some filamentous algae appear to be especially efficient in accumulating pesticides; e.g., *Cladophora* concentrates DDT far more than other plants or animals (Meeks and Peterle 1967). Therefore, discretion should be used when considering use of aquatic weeds.

Incorporating organic matter from aquatic weeds is thus not invariably beneficial. Singh (1962) compared the effects of composts made from a number of aquatic weeds on the yield of different fruits. Composts of *Pistia Najas*, *Hydrilla*, and *Ottelia* gave higher yields than the control, but *Eichhornia* compost gave consistently lower yields than the control.

CONCLUSION

Algae and aquatic weeds that develop in rice fields and their related bodies of water constitute a source of organic matter and nutrients that can be used as manure for rice. Average standing crops of the aquatic photosynthetic biomass range from around 500 kg dry weight/ha in the fields to 1-5 t dry weight/ha in irrigation canals and water tanks. Higher values (30 t dry weight/ha) have been reported in bodies of water receiving farm or factory effluents. Planktonic algae usually have a lower productivity than aquatic macrophytes.

The average composition of aquatic macrophytes is 8% dry matter, 2-3% N (dry weight basis), 0.2-0.3% P, and 2-3% K. Planktonic algae have higher N contents, averaging 5%. On a dry weight basis, this composition is very similar to that of many green manures except for K in macrophytes and N in planktonic algae, which are higher. However, the high water content of aquatic weeds has been the major deterrent to their use.

In rice fields, the photosynthetic aquatic biomass exhibits both beneficial and detrimental effects. Nitrogen-fixing BGA provide a free input of N; they have other beneficial effects like auxinic effects on the rice plant, as well as antagonistic effects against some aquatic macrophytes. Their growth can be encouraged by inoculation. However, the mechanisms of action and the limiting factors are still poorly understood.

Other algae and aquatic weeds: 1) compete with rice for space, light, and nutrients; 2) may have detrimental mechanical effects on the germinating seeds and the young plants; and 3) increase the pH of the floodwater and cause N loss by volatilization. On the other hand, as photoautotrophs assimilate CO_2 evolved from the soil and return it in the form of algal cells and aquatic weeds, they prevent C loss. A similar role in partially preventing NH_4^+ loss is possible. In a gas-lysimeter experiment with two different soils, Vlek and Craswell (1979) recovered 18.5% and 29.5% of N added as urea in the algal biomass. With $(NH_4)_2SO_4$, only 0.5% and 6.3% of added N was recovered in algae.

Saito and Watanabe (1978) reported that the productivity and turnover rate of the aquatic community in a rice field were higher than those of rice roots. A gross primary production of 60-70 g C/m^2 in 120 days was recorded. A similar value (71 g C/m^2 in 114 days) was reported by Yamagishi et al (1980). It is likely that the contribution of the organic matter produced in the floodwater community is important quantitatively as well as qualitatively in recycling nutrients into available forms. Readily decomposable soil N increased in the surface layer during flooding (Kobo and Uehara 1943), and the amount of chlorophyll-like substances in rice soils was correlated with the increment in NH_4^+ production by air drying of soils, which is a good index of the N-supplying ability of the soil (Wada 1968). This suggests the possibility that the photosynthetic biomass contributes to readily decomposable organic matter (Saito and Watanabe 1978).

Nitrogen from algae and aquatic weeds is available to the rice plant; around 30% of N from incorporated BGA and water hyacinth was recovered in the first two crops. (Tirol et al, in press; Shi et al 1980).

Algae and weeds growing in irrigation canals and in other bodies of water may have very high productivity and are, in most cases, considered detrimental. Their use as a source of compost can effect the reclamation of the bodies of water. Such use has been developed mainly for dryland crops and, except in China, little is known about its potential for wetland rice. This aspect is reported in other sections of this symposium. The positive effects on grain yield have been reported, but detrimental effects like weed dispersal and concentration of pesticides and heavy metals are possible. Therefore, discretion should be exercised when considering use of aquatic weeds in wetland soils. Moreover, because of the bulkiness of aquatic weeds, their use will be strongly influenced by agroeconomic conditions, the facility of harvest, and the distance between the field and the places of harvesting and composting.

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DISCUSSION

PALANIAPPAN: Does the increased or decreased N content of the soil N or added nitrogenous fertilizers influence the rate of N fixation by blue-green algal forms?

ROGER: Addition of nitrogenous fertilizers at the beginning of the crop cycle inhibits the development of N-fixing algae. Laboratory experiments have clearly demonstrated the inhibitory effect of mineral N on the N-fixing activity of BGA. However, in the field this inhibition seems to be frequently only partial and decreases during the growth cycle because of the uptake of N by plants. Little is known about the organic N content of soil and the occurrence and activity of BGA.

NAGAR: Do you encounter the problem of the presence of heavy metals when you use water hyacinth as a source of organic matter and plant nutrients?

ROGER: The paper I presented is a review of the literature. We did not conduct any trials with water hyacinth. For more information, please refer to Little's handbook.

GAUR: What may be the cause of the very slow mineralization of BGA and *Chlorella* on soil although the C-N ratio is quite narrow (5-6) and they are poor in lignin?

ROGER: Algal material rich in akinetes or spores is less susceptible to decomposition than material comprising vegetative cells only. Also, there are differences among strains. However, from the few data available, it does not appear at all that BGA and *Chlorella* have a very slow mineralization rate.

PALANIAPPAN (comment): I have found that living or senescing leaf material, if allowed to decompose as it is, decomposes and releases its nutrient contents faster than leaf material subjected to decomposition after sun- or oven-drying. The delay observed in the current study could be due to the sun-drying of the N-fixing algal materials.