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The Utilization of Emergent Aquatic Plants for Biomass Energy Systems Development

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FOREWORD

Emergent aquatic plants, such as reeds, cattails, and bullrushes, are highly productive and are potentially significant resources for alcohol and solid fuel production. It has been estimated that if one-half of the 65,600 mi^2 of marshland in the United States were used for emergent biomass energy plantations, approximately 5% of present total national energy requirements might be met. Additionally, existing brackish or saline ground water supplies could conceivably double this number.

Before such predicitons can be realized, important technological and environmental difficulties must be resolved. This report presents the results of a study performed to assist the Solar Energy Research Institute (SERI) in its preparation of a plan for the development of emergent aquatic biomass energy systems. The work was performed under subcontract to SERI with funds provided by the Biomass Energy Technology Division of the U.S. Department of Energy.

Lawrence P Raymond

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EXECUTIVE SUMMARY

The objective of this program was to conduct a review of the available literature pertaining to the following aspects of emergent aquatic biomass:

- identification of prospective emergent plant species for management
- evaluation of prospects for genetic manipulation
- evaluation of biological and environmental tolerances
- examination of current production technologies
- determination of availability of seeds and/or other propagules, and
- projections for probable end-uses and products.

Species identified as potential candidates for production in biomass systems include *Arundo donax*, *Cyperus papyrus*, *Phragmites communis*, *Saccharum spontaneum*, *Spartina alterniflora*, and *Typha latifolia*. If these species are to be viable candidates in biomass systems, a number of research areas must be further investigated. Points such as development of baseline yield data for managed systems, harvesting conceptualization, genetic (crop) improvement, and identification of secondary plant products require refinement. However, the potential pay-off for developing emergent aquatic systems will be significant if successful.

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INTRODUCTION

For the past decade, a broad objective of the United States government has been to develop a degree of energy self-sufficiency, particularly replacing petroleum-based products with equivalent products derived from alternative resources. Other important criteria of these alternative resource systems are that they should:

- maintain a positive energy balance, and
- be a profitable venture.

Recently the Aquatic Species Program (ASP) was established to implement a plan to develop, demonstrate, and commercialize aquatic biomass energy systems for maximum contribution to U.S. energy supplies.

One of the plant categories assigned to the ASP is the emergent aquatic group. This group is characterized by:

- photosynthetic aerial portions above the water surface,
- basal portions rooted in the water substrate, and
- occupation of the shallow waters of the marginal zone from the wet shore to a depth of about one meter.

The ASP has estimated that the total U.S. marshland area extends over some 17 million hectares. Therefore, assuming a reasonable yield of biomass with low energy requirements and production costs, the emergent aquatic species systems may supply a small, but significant quantity of energy and fiber.

It has long been recognized that the primary production of emergent aquatic communities are among the highest found in either the tropic or temperate regions. However, this high level of productivity has created problems, i.e., burdening of waterways, interfering with navigation, irrigation, disease and insect control, fisheries production, and water quality. The goal must be to manage emergent aquatics for beneficial uses such as the production of fuel, fiber, feed, or fertilizer.

From a botanical and an ecological perspective, much research has been conducted on emergent aquatic species. However, from a resource utilization and management standpoint, little work has been performed and it is difficult to extrapolate information of use from these previous botanical/ecological studies.

The objective of this first-phase study is to conduct a review of the available literature pertaining to the following aspects of emergent aquatic plant biomass:

- identify prospective emergent plant species for management,
- evaluate prospects for genetic manipulation, focusing on improvement of yield, biological and environmental tolerances, and physico-chemical properties,
- examine biological and environmental tolerances,
- examine current emergent aquatic systems in order to identify modern agronomic technologies which might be applicable to production of this biomass resource,
- determine availability of seeds and/or propagules for planting managed stands, and
- project probable end-uses and products.

Included along with these considerations is a preliminary economic assessment of the potential of emergent aquatic biomass systems and the selection of the six most promising candidate species for biomass energy systems development. A glossary of several terms used in the report is provided at the end of the text.

BOTANICAL CONSIDERATIONS

Several botanical considerations are pertinent to developing optimally managed systems of emergent aquatic species. These considerations include growth habitat, growth habit, morphology, and genetics. In addition, noting the common name, or, as often is the case, common names, applied to a species avoids the confusion associated with synonomy. Tables 1 and 2 provide botanical information for 27 emergent aquatic species.

Growth Habitat

The natural growth habitat of a plant indicates the possible managed environments to which the species may be adapted. Examining the habitats of emergent aquatic species reveals potential application to a wide range of managed systems.

Some species, such as Scirpus robustus, are halophytic, i.e., able to grow in saline substrates. Other species, e.g., Zizania palustris, are salt sensitive and grow best in nonsaline conditions. Many emergent aquatic plants exhibit natural adaptation to both freshwater and saline environments. A particularly good example is Spartina cynosuroides which is found in salt, brackish, and fresh tidal marshes. The cosmopolitan species Typha angustifolia also grows in both fresh and brackish water. Certain emergent aquatic species are endemic to specialized environments. For instance, some species of Carex survive in sphagnum bogs, Scirpus acutus grows well in calcareous regions, and Sparganium eurycarpum is found chiefly in argillaceous substrates.

Natural stands of emergent aquatic plants are found in both permanent and intermittent water bodies. Justicia americana grows on the shores and banks of streams, and in streambeds. It flourishes best, however, in 15 to 45 cm of water. On the other hand, Paspalum vaginatum survives on dry, sandy beach soils subject to inundation by brackish or seawater seepage. In further contrast, Phalaris arundinacea grows in marshes, wet meadows, and along streams and shores.

The natural habitat of a species serves as a useful guide for determining which plants are best suited for certain managed systems. However, it is important to note that a plant's indigenous environment does not necessarily exclude it from a contrasting or modified managed habitat.

TABLE 1. BOTANICAL CHARACTERISTICS OF EMERGENT AQUATIC SPECIES

Species	Common Name(s)	Classification	Growth Habitat	Growth Habit	Morphology	Genetic Characteristics	References
Arundo donax L.	Giant reed, carrizo, bamboo reed	Monocot, family Poaceae	Along irrigation ditches, on sand bars and levees, occasionally in marshes	Erect culm, 1-4 cm in diameter, 2-8 m tall, often in large clumps, branching the second year	Herbaceous perennial; leaf blades to 6.8 cm wide; roots fibrous, arising from creeping rhizomes; flowers perfect, in dense terminal panicle up to 6 dm long	Varieties recognized	71 12 48 148
Butomus umbellatus L.	Flowering rush, grassy rush, water gladiolus	Monocot, family Butomaceae	In mud, shallow to deep water, along wet shores	Erect stem, to 1.2 m tall	Herbaceous perennial; leaf blades erect, up to 1 m long; rootstock fleshy, bearing tubers; rhizomatous; flowers perfect, in umbel		133 12 71
Carex rostrata Stokes	Beaked sedge	Monocot, family Cyperaceae	Shallow water, wet shores, swamps	Spongy culms 0.3-1.2 m tall	Herbaceous perennial; leaf blades 2-12 mm broad, equalling or exceeding culms; roots fibrous; rhizomatous; monoecious; flowers imperfect; spike inflorescence	Varieties, hybrids recognized	133 71
Cyperus esculentus L.	Yellow nutsedge, yellow nutgrass, chufa	Monocot, family Cyperaceae	In shallow ponds and lakes, gravel bars along streams	Culms 15-65 cm long	Herbaceous perennial; leaf blades attached to basal half of culm; roots fibrous; creeping rhizomes, some with tuber like thickenings; flowers perfect; spike inflorescence		12 48 133
Cyperus papyrus L.	Papyrus, paper plant, Biblical bulrush	Monocot, family Cyperaceae	Banks and shores, in quietly flowing water up 0.9 m deep	Thick, woody culms, 1.2-4.6 m tall	Herbaceous perennial; basal leaves reduced to sheaths; rhizomatous; flowers perfect, umbellate inflorescence		12
Distichlis spicata (L.) Greene	Seashore salt grass, spike grass	Monocot, family Poaceae	Saline marshes, alkaline substrates, coastal areas	Erect culm, 0.1-1.2 m tall	Herbaceous perennial; leaf blades narrow, 0.5-1.5 dm long; roots fibrous; extensively rhizomatous; dioecious; short, dense panicle inflorescence	Varieties recognized	133 71
Eleocharis dulcis (Burmf.f.) Trin.	Chinese water chestnut, matai	Monocot, family Cyperaceae	Imbedded in bottom mud or sand, in shallow water or in areas subject to periodic inundation; freshwater and brackish marshes	Numerous erect, terete, septate, culms, 0.3-1.5 m tall	Herbaceous perennial; essentially leafless; rhizomatous; elongate stolons terminating in rounded corms 2.5 cm long, 3.7 cm in diameter; monoecious; flowers imperfect, in terminal spikes	Varieties recognized	12 89

TABLE 1. (Continued)

Species	Common Name(s)	Classification	Growth Habitat	Growth Habit	Morphology	Genetic Characteristics	References
Juncus effusus L. (*J. polyanthemus* Buchenau)	Soft rush, Japanese mat rush	Monocot, family Juncaceae	Meadows and lake shores, freshwater peaty swamps, bogs and marshy areas; areas which maintain a few inches of water for prolonged periods	Erect stems, 0.3-1.8 m tall, in dense tussocks	Herbaceous perennial; leaves involucral; rhizomatous; flowers perfect, in cymose clusters	Varieties exist	12 71 133
Juncus roemerianus Scheele	Rush	Monocot, family Juncaceae	Brackish ditches, coastal marshes	Erect culms 0.5-1.5 m tall	Herbaceous perennial; leaves terete, hard; rhizomatous; flowers perfect, in cymose clusters		71 48
Justicia americana (L.) Vahl	American water willow	Dicot, family Acanthaceae	Beds, shores, banks of streams, best in 15-45 cm of water	Prostrate and erect stems from 0.3-1.5 m high, depending on water depth	Herbaceous perennial; leaf blades 0.8-2 dm long; roots fibrous, primarily adventitious; abundant, thick, superficial rhizomes; stoloniferous; flowers perfect	Varieties recognized	146 48 71
Paspalum vaginatum Swartz	Seashore paspalum, sheathed paspalum, salt water couch	Monocot, family Poaceae	Dry, sandy beach soils; especially suited to areas subject to inundation by brackish or seawater seepage, rarely in coastal sub-brackish ponds	Culms 5-25 dm long, creeping and freely rooting	Herbaceous perennial; leaf blades stiff, 2.5-15 cm long; rhizomatous; flowers perfect; panicle inflorescence		48
Phalaris arundinacea L.	Reed canarygrass	Monocot, family Poaceae	Marshes, wet meadows, along streams and ditches, shores	Erect culm, 0.6-2 m tall	Herbaceous perennial; leaf blades 0.6-2 cm wide; roots fibrous; rhizomatous; flowers perfect; panicle inflorescence; fruit 3-4.2 mm long, 0.7-1.5 mm wide	Forms, hybrids recognized	71 133 12
Phragmites communis Trin. (*P. australis* (Cav) Trin. ex Steud)	Common reed, carrizo	Monocot, family Poaceae	Fresh to alkaline marshes, pond margins, ditches, along shores of lakes and streams	Erect culm, 1.5-6 m tall	Herbaceous perennial; leaf blades linear, 1.5-6 dm long, 1-6 cm wide; rootstock coarse; rhizomatous; stoloniferous; flowers staminate or perfect, in large, terminal panicle up to 4 dm long	Varieties recognized	72 12 133
Saccharum spontaneum L.	Wild sugar cane	Monocot, family Poaceae	Along river banks	Culms slender, hard, pithy; ranges from small tufted forms 35 cm high, to erect forms over 8 m tall	Herbaceous perennial; leaf blades 100-200 cm long; aggressively rhizomatous; flowers perfect; tassel inflorescence	Variable forms, hybrids recognized	153
Scirpus acutus Muhl.	Hardstem bulrush	Monocot, family Cyperaceae	Shallow ponds, lakes, sloughs, marshes, tule marshes, calcareous regions	Culm hard, 0.5-3 m tall	Herbaceous perennial; usually bladeless; rhizomatous; flowers perfect; panicle inflorescence	Forms recognized	71 133

TABLE 1. (Continued)

Species	Common Name(s)	Classification	Growth Habitat	Growth Habit	Morphology	Genetic Characteristics	References
Scirpus americanus Pers.	Three-square rush, shore rush, swordgrass	Monocot; family Cyperaceae	Shallow water or sandy shores of lakes, ponds, streams, and along seashore; most abundant in saline, brackish or alkaline waters	Culms scattered, 0.03-1.5 m high	Herbaceous perennial; leaf blades 0.5-6 dm long; stout, elongate rhizome; flowers perfect		71 133
Scirpus fluviatilis (Torr.) Gray	River bulrush	Monocot; family Cyperaceae	In sloughs, borders of ponds, lakes and large streams (usually calcareous)	Erect culm, 0.7-2 m tall	Herbaceous perennial; leaf blades flat; rhizome elongate, moniliform with thick corm-like enlargements; flowers perfect		71 133
Scirpus robustus Pursh	Stout bulrush	Monocot; family Cyperaceae	Brackish or saline ponds, seacoasts	Culms 0.7-1.5 m tall, leafy to summit	Herbaceous perennial; leaf blades flat, 2-4 dm long; rhizomatous; flowers perfect	Forms recognized	71
Scirpus validus Vahl (= S. lacustris)	Great bulrush, soft-stem bulrush	Monocot; family Cyperaceae	Brackish or fresh shallow water and marshes	Culm 0.5-3 m tall	Herbaceous perennial; usually bladeless; stout, scaly rhizome; flowers perfect, in panicle	Varieties, forms recognized	71 133
Sparganium erectum (L. (S. romosum Huds.)	Bur reed	Monocot; family Sparganiaceae	Paludal	Erect stem, to 1.5 m tall	Herbaceous perennial; leaf blades ribbon-like; roots fibrous, clustered; rhizomatous; monoecious; flowers imperfect, in heads, lower heads pistillate, upper heads staminate; achene fruit.		71 12 133
Sparganium eurycarpum Engelm	Bur reed	Monocot; family Sparganiaceae	Paludal, sloughs, shallow water; chiefly in argillaceous or basic substrates	Erect stem, 0.5-1.5 m tall	Herbaceous perennial; leaf blades ribbon-like, stiff; roots fibrous, clustered; clustered; rhizomatous; monoecious; flowers imperfect, in heads, lower heads pistillate, upper heads staminate; achene fruit		133 12 71

TABLE 1. (Continued)

Species	Common Name(s)	Classification	Growth Habitat	Growth Habit	Morphology	Genetic Characteristics	References
Spartina alterniflora Loisel	Saltwater cordgrass	Monocot; family Poaceae	Shallow water, salt marshes along seacost	Erect culm, 0.1-2.5 m tall	Herbaceous perennial; leaf blades to top of culm, succulent, tough, 0.4-1.5 cm wide; rhizomes flaccid; flowers perfect, may be proterogynous; spike inflorescence	Pronounced varieties recognized	133 71 48
Spartina cynosuroides (L.) Roth	Salt reed grass	Monocot; family Poaceae	Salt, brackish to fresh tidal marshes	Erect culms 1-3 m tall	Herbaceous perennial; leaf blades 1-2.5 cm wide; rhizome hard, deep, 1-2 cm thick; flowers perfect, may be proterogynous; spike inflorescence	Varieties recognized	133 71 48
Spartina patens (Ait) Muhl	Salt meadow grass, high water grass, marsh hay	Monocot; family Poaceae	Saline marshes, brackish shores	Erect culm, 1.5-8 dm tall, arising primarily from matted marcescent shoots from preceding season	Herbaceous perennial; leaf blades 0.5-2 dm long; rhizomes slender, wiry; flowers perfect, may be proterogynous; spike inflorescence	Varieties recognized	133 71 48
Typha augustifolia L.	Narrow-leaved cattail, soft flag	Monocot; family Typhaceae	Bay, marshes, marl lakes; in both fresh and brackish, basic or alkaline water	Erect stem, 0.75-1.8 m tall	Herbaceous perennial; leaf blades linear, sheathing, 3-8 mm wide; rootstock thick, branching; extensively rhizomatous; monoecious; flowers imperfect, in dense, terminal spike, 2-4 dm long, lower flowers pistillate, upper staminate; individual fruit minute, on a long stalk, witn a single seed; in fruit, spikes 0.6-1.5 cm in diameter, 0.3-1.5 dm long	Hybrids recognized	68 133 71
Typha latifolia L.	Common cattail, cossack asparagus, nailrod, broad-leaved cattail	Monocot; family Typhaceae	Shallow bays, slouohs, marshes, springs	Erect stem, 1-3 m tall	Herbaceous perennial; leaf blades linear, sheathing, 0.6-2.5 cm wide, 9.5-33 cm long; rootstock thick, branching; extensively rhizomatous; monoecious; flowers imperfect, in dense, terminal spike, lower flowers pistillate, upper staminate; individual fruit minute, on a long stalk, with a single seed; in fruit, spikes 0.7-3.5 cm in diameter	Hybrids recognized	133 12 71

TABLE 1. (Continued)

Species	Common Name(s)	Classification	Growth Habitat	Growth Habit	Morphology	Genetic Characteristics	References
Zizania palustris L. (*Z. aquatica* var. *augustifolia*	Annual wild rice, Indian rice, wild oats, water oats	Monocot; family Poaceae	In water and mud of springs, marshes, lakes and ponds	Simple or basally branching, culms 1.5 m tall	Herbaceous annual; leaf blades flat, 4-15 mm wide; many prop roots from lower nodes; monoecious; flowers imperfect, in branched panicle inflorescence, staminate spikelets mostly on lower branches, pistillate spikelets on upper branches; caryopsis cylindrical, 15-20 mm long	Several varieties recognized	71 133 12 48 166

TABLE 2. GEOGRAPHICAL DISTRIBUTION OF EMERGENT AQUATIC SPECIES

Species	Geographical Distribution
Arundo donax L.	Introduced from Med. region to Ark. and Tex., w. to s. Calif., occasionally on e. Coast from Md. s; also in trop. Am; generally in warmer areas of the world
Butomus umbellatus L.	Naturalized (from Euras.) to N. Am.; in U.S., N.Y., Vt., n. O., Mich.
Carex rostrata Stokes	Greenl. to Alas., s. to Del., Ind., N.M., Ariz. and Calif.; indig. to N. Am.
Cyperus esculentus L.	W. Asia and Afr.; Am., n. to Que., Ont., Minn., Ore. and Alas.; probably adv. in Tex.; widespread in the new world, especially in warmer parts.
Cyperus papyrus L.	N. and trop. Afr.
Distichlis spicata (L.) Greene	e. Tex., Can. to Mex. along coast; W.I., S. Am.; indig. to N. Am.
Eleocharis dulcis (Burmf .f.) Trin	Trop. e. Asia, Pac. Is, Madag., w. Afr., cultivated in s. coastal U.S.
Juncus effusus L. (*J. polyanthemus* Buchenau)	Euras., Aust., N. Zeal., e. and s. Afr., Japan; N. Am. in Okla., s and s.e. Tex., N. M., Ariz.; indig. to N. Am.
Juncus roemerianus Scheele	Coastal states, Md to Tex; indig. to N. Am.
Justicia americana (L.) Vahl	Ga. to Tex., n. to Que., Vt., N.Y., Ont., Wisc., Mo., Kan,; indig. to N. Am.
Paspalam vaginatum Swartz	Widespread in warm coastal areas of the world; in Am., n. to N. C. and Gulf States
Phalaris arundinacea L.	N. Am. from N. B. to Alas., s. to N. C., Okla., Ariz.; Euras.; indig. to N. Am.

TABLE 2. (Continued)

Species	Geographical Distribution
Phragmites communis Trin [*P. australis* (Cav) Trin. ex Steud]	Most of the warmer parts of the world; Aust., Afr., S. Am.; N. Am. from N.S. to B.C., s. to Fla. and Calif.; originally from Euras; (N. Am. variety - *Berlandièri* (Fourn) Fern.).
Saccharum spontaneum L.	Widely distributed in trop. and temp. regions, Afr., through the Middle East, to India, China, Taiwan and Malaysia, through the Pac. to New Guinea.
Scirpus americanus Pers.	Nearly throughout temp. parts of the world; Fla., to Tex., n. to Nfld., Que., s. Ont., Mich., Wisc., Minn. and Nebr.; indig. to N. Am.
Scirpus acutus Muhl.	Eur., much of temp. N. Am., s. to Gulf States, Chih., Coah and Calif.; indig. to N. Am.
Scirpus fluviatilis (Torr) Gray	Que., to Sask. and Wash., s. to Va., Ind., Ill., Mo., Kans., N.M., Calif.; indig. to N. Am.
Scirpus validis Vahl	Nfld. to S. Alas., s. to N.S., N.E., L.I., Ga., Tenn., Mo., Okla., Tex., N.M. and Calif.
Scirpus robustus Pursh	Fla., to e. Mex., n. to Mass. and Calif.; W.I., e. S. Am.; indig. to N. Am.
Sparganium erectum L.	Euras. to cen., Sib
Sparganium eurycarpum Engelm.	Nfld. to B.C., s. to Va., Mo., Okla., N.M., Ariz. and Calif.; indig. to N. Am.
Spartina alterniflora Loisel	Native to e. coast of N. Am. from Maritime Provinces to Tex., and also S. Am. from Gui. to Arg.; introduced in Wash., and in Fr. and Eng.;
Spartina cynosuroides (L.) Roth	Coasts from Mass. to Tex.; indig. to N. Am.

TABLE 2. (Continued)

Species	Geographical Distribution
Spartina patens (Ait) Muhl	Shores of Great Lakes and Gulf coasts; cont. N. Am., and W.I.; also s. Fr., Corsica and It.; indig. to N. Am.
Typha augustifolia L.	Euras., Asia, Am.; in N. Am., N.S., and s. Me. to s. Que. and Ont.; s. to S.C., W. Va., Ky., Mo., Nebr. and Tex.; also in Calif.; indig. to N. Am.
Typha latifolia L.	Euras., Asia; in N. Am., Nfld. to Alas., throughout most of U.S. into Mex.; indig. to N. Am.
Zizania palustris L.	n. U.S. and Can., Que. to N. Dak., s. to N.Y. and Nebr.

Abbreviations

Adv., adventive
Afr., Africa
Alas., Alaska
Am., America
Arg., Argentina
Ark., Arkansas
Ariz., Arizona
Aust., Australia
B.C., British Columbia
Calif., California
Can., Canada
Cen., Central
Chih., Chihuahua
Coah., Coahuila
Cont., continental
Del., Delaware
Eng., England
Eur., Europe, European
Euras., Eurasia
Fla., Florida
Fr., France
Ga., Georgia
Greenl., Greenland
Gui., Guyana
Ill., Illinois
Ind., Indiana
Indig., indigenous
Is., islands
It., Italy
Kan., Kansas
Ky., Kentucky
L.I., Long Island
Madag., Madagascar
Mass., Massachusetts
Md., Maryland
Me., Maine
Medit., Mediterranean
Mex., Mexico
Mich., Michigan
Minn., Minnesota
Mo., Missouri
N., north or northern
N.Am., North America
N.B., New Brunswick
N.C., North Carolina
N.Dak., North Dakota
N.E., New England
Nebr., Nebraska
Nfld., New Foundland
N.M., New Mexico
N.S., Nova Scotia
N.Y., New York
N. Zeal., New Zealand
O., Ohio
Okla., Oklahoma
Ont., Ontario
Ore., Oregon
Pac., Pacific
Que., Quebec
Sask., Saskatchewan
S., south or southern
S. Am., South America
Sib., Siberia
Temp., temperate
Tex., Texas
Trop., tropical
Va., Virginia
Vt., Vermont
W., west or western
Wash., Washington
W.I., West Indies
Wisc., Wisconsin

Growth Habit

Growth habit influences the adaptation of plant species to managed systems, especially in regard to agronomic practices. The stem height and stem arrangement of the various plant species should be taken into account when making agronomic decisions such as optimum planting configurations, cultivation practices, and foliar harvesting methods. Emergent aquatic species vary considerably in growth habit. Justicia americana, for example, possesses both erect and prostrate stems from 0.3 m to 1.5 m high depending on water depth. The culms of Paspalum vaginatum are 0.5 to 2.5 m long, creeping, and freely rooting. In contrast, the erect culm of an individual Phragmites communis plant ranges from 1.5 to 6 m in height. Juncus effusus, alternatively, grows in dense clumps, its stems 0.3 to 1.8 m tall.

Morphology

Vegetative and reproductive morphological features offer several criteria useful for assessing the application of emergent aquatic species to managed systems. Length of the life cycle, for instance, varies among the species. Zizania palustris is an annual, requiring replanting each year of production. Many others, such as Phragmites communis and Sparganium erectum, are rhizomatous perennials and may not require replanting as long as an adequate portion of below ground propagative material remains after harvest.

Whether a species produces rhizomes not only influences potential methods of propagation but also suggests the possibility of augmenting biomass harvested above-ground with below-ground plant parts. These plant parts may, reportedly, compose over 50% of the total plant biomass of some emergent aquatic species. (Sculthorpe, 1971; see Table 5, Physiological Considerations.)

Reproductive morphological features vary greatly among emergent aquatic species. Distichlis spicata is a dioecious plant, its unisexual flowers gathered in dense panicles. Phalaris arundinacea also possesses a panicle inflorescence; however, its flowers are perfect. In further contrast, Typha latifolia is monoecious, producing imperfect flowers in a dense, terminal spike, the lower flowers pistillate, the upper flowers staminate. The reproductive morphology of some Spartina species is of special interest since their flowers may be proterogynous, i.e., the stigma of an individual flower may be ripe for pollination before the anthers of the same flower mature. These reproductive characteristics influence the out-crossing potential, and, consequently, the genetic variability of the species, indicating possibilities for crop improvement. (See Crop Improvement Section.)

Genetics

Genetic considerations of interest to the development of emergent aquatic species as crop plants include intraspecific variation and hybridization potential. For example, Phalaris arundinacea, a species which is capable of hybridization, exhibits both varieties and forms. Similarly Spartina alterniflora possesses several pronounced varieties. This information provides an index of the existing and potential diversity within a species, which can be exploited in crop development programs. (See Crop Improvement Section.)

PHYSIOLOGICAL CONSIDERATIONS

Unlike commercial terrestrial crops, the physiology of emergent aquatic plants has not been well documented, particularly under managed (controlled) systems. The paucity of information is not a function of the complexity of the emergent aquatic plant physiology and/or metabolism; these species have simply not received much attention in terms of their potential as managed crops. Because of their niche in the aquatic system, the emergent aquatic plants respond to environmental stimuli in a different manner than do the floating or submerged aquatic plants. As stated in the introduction, emergent aquatic plants have aerial leaves and a gaseous source of carbon dioxide, which makes them resemble terrestrial plants, but they are normally free from restrictions imposed by water supply (Westlake, 1975). The physiological considerations of emergent aquatic plants include information regarding carbon utilization, i.e., photosynthetic pathway, ranges of growth rates, and rates of net production, along with limited information on percent dry weight of the plant components, and the ratio of the aboveground to belowground biomass. Other topics discussed under the physiological considerations are water utilization, nutrient absorption, and the influence of environmental factors such as light, temperature, and salinity on the growth of emergent aquatic plants.

Carbon Utilization

The presentation of the carbon utilization data must first be prefaced with a number of qualifying statements. The data summarized in Table 3 are a collection of numbers obtained under a wide range of environmental conditions and levels of agricultural management. References are listed so that the interested reader may go beyond the data summarized in this report to find the specific conditions of the study. Secondly, data regarding carbon utilization by emergent aquatic species has been difficult to obtain. The determination and interpretation of biomass changes remain the primary basis for estimations of the annual productivity of emergent aquatic plants, but difficulties have arisen with stands with stable or irregularly changing biomass (Westlake, 1975). Furthermore, translocation and accumulation of carbon in the below-ground organs tends to complicate analyses.

Table 3 highlights the carbon utilization data of the selected emergent aquatic plants. It can be noted that the emergent aquatic plants contain both C_3 and C_4 photosynthetic pathway species. The very great photosynthetic advantage of C_4 to C_3 species appears to be attenuated under conditions where water is not limited. Also, since conditions for optimum growth of C_3 and C_4 species are quite different, valid comparisons of their performance can hardly be made.

Generally speaking, the values obtained for the annual rate of net production of the emergent aquatic plants are quite impressive. Several species, in fact, exhibit yields exceeding those of corn and sweet sorghum, which range from 15 to 33 tons of dry matter per hectare. The higher recorded yields of emergent aquatic plants may be a function of three possibilities, among others. These include: (1) water is not limiting in the emergent aquatic plant production system, (2) the length of the growing season of the emergent aquatics is longer because of their perennial nature, and/or (3) the current level of experimental methods does not accurately measure productivity. Only further testing of productivity levels, analyzing both above and below ground portions under highly controlled conditions, will resolve this point.

Table 4 summarizes the data collected concerning percent dry weight of the plant components of emergent aquatics. Two critical points must be considered as one views Table 4. Firstly, the potential problem of dewatering the emergent aquatic biomass may not be as great as anticipated. Data indicate that the percent dry weight of emergent aquatic plants is in the range of their terrestrial counterparts and higher than the floating and submerged aquatic plants (5 to 15 percent dry weight). Secondly, the percent dry weight of a plant species is highly dependent on a number of factors, such as plant age or time of harvest during the day. Therefore, data may vary over a relatively large range. However, this type of information is critical in a systematic approach to crop development, particularly from a transportation and energy balance perspective.

TABLE 3. PHYSIOLOGICAL CHARACTERISTICS OF EMERGENT AQUATIC SPECIES.

Species	Photosynthetic Pathway	Ranges of Rates of CO_2 Assimilation mg $dm^{-2}h^{-1}$	Ranges of Crop Growth Rates g m^{-2} d^{-1}	Rate of Net Production t Dry Matter ha^{-1} yr^{-1}		REF
				Above Ground	Below Ground	
Arundo donax L.				12-38		180
Butomus umbellatus L.				15-25		180
Carex rostrata Stokes				5-10	2-4	18
Cyperus esculentus L.	C4			10-23	1-5	15
Cyperus papyrus L.	C4	26	50	30-50		95, 158, 180
Distichlis spicata (L.) Greene	C4*		5-10	7-15	4-14	52, 96, 173, 180
Eleocharis dulcis (Burmf .f.) Trin.					7-18	89
Juncus effusus L.	C3*					51, 92
Juncus roemerianus Scheele	C3	15-25		17-34	1-13	51, 92
Justicia americana (L.) Vahl			25-48	10-25		51, 92, 180
Paspalum vaginatum Swartz	C4			3-7		26
Phalaris arundinacea L.	C3	15-30		8-20		82, 180
Phragmites communis Trin.	C3	15-30	25-48	15-35	1-14	22, 23, 74, 92, 134, 180
Saccharum spontaneum L.	C4	50-60	18-37	15-40		93, 153
Scirpus acutus Muhl.	C3*			9		30
Scirpus americanus Pers.	C3*			4-9	4-18	30
Scirpus fluviatilis (Torr.) Gray	C3*					30, 182
Scirpus validus Vahl	C3*			1-2	3-5	51, 57
Scirpus robustus Pursh.	C3*			11		51, 57
Sparganium erectum L.			12-36	15-35		180
Spartina alterniflora Loisel	C4		5-10	5-22	1-8	51, 92, 134, 157, 173
Spartina cynocuroides (L.) Roth	C4		5-10	4-22	1-13	51

TABLE 3. PHYSIOLOGICAL CHARACTERISTICS OF EMERGENT AQUATIC SPECIES, (Continued).

Species	Photosynthetic Pathway	Ranges of Rates of CO_2 Assimilation mg $dm^{-2}h^{-1}$	Ranges of Crop Growth Rates g m^{-2} d^{-1}	Rate of Net Production t Dry Matter ha^{-1} yr^{-1}		REF
				Above Ground	Below Ground	
Spartina _patens_ (Ait) Muhl	C4		5-10	5-24	1-2	51, 173
Typha _augustifolia_ L.	C3		25-48	10-30	9-36	134, 150, 151, 152, 180
Typha _latifolia_ L.	C3	22-34	25-48	11-33	14-26	122, 134, 150, 151, 152, 180
Zizania _palustris_ L.	C3*			2-4	>1	166

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* Information not found on photosynthetic pathway; however, other species within the given genus exhibit the identified pathway.

TABLE 4. DRY WEIGHT CONTENT OF EMERGENT AQUATIC SPECIES

Species	Percent Dry Matter		References
	Above Ground	Below Ground	
Arundo donax L.	43		148
Eleocharis dulcis (Burmf .f.) Trin.		22-40	89
Juncus effusus L.	31		33
Justicia americana (L.) Vahl	11-18	11-18	27
Phragmites communis Trin.	25-46		22, 23
Saccharum spontaneum L.	15-30		93
Scirpus americanus Pers.	16-23		30
Typha augustifolia L.	22	23	150, 151, 152
Typha latifolia L.	23-31		150, 151, 152

In Table 5 data are presented concerning the ratio of above-ground to below-ground biomass in selected emergent aquatic species. In many cases, it is quite difficult to assess the ratios, and the separation between rhizomes (which contain a high percentage of starch) and roots is not well delineated. Furthermore, the factors which influence the ratio, while having been identified, have not been well correlated with quantified crop response. What is clear is that a large quantity of usable plant biomass is accumulated below the soil surface and it will be integral to either find an efficient way to harvest this material or to breed plants with a greater above-ground to below-ground biomass ratio.

Water Utilization

In developing managed systems for utilization of emergent aquatic species for fuel and/or fiber, a criterion for plant species selection will be efficient use of water. At first glance, this criterion might appear paradoxical for emergent aquatic plants. However, when one considers future systems for development, water use efficiency is critical due to water being a finite resource.

Very little information regarding water utilization by emergent aquatic plants has been acquired during this phase of work but generalizations can be made.

The utilization (production) of emergent aquatic plants will lead to a greater use of water in a system than if no plants were grown and the surface of the water body was exposed. This result is a function of increasing the effective evaporative surface area of the system by increasing the plant leaf area. In essence, plants are analogous to the role played by a wick. However, although more water may be used with a plant cover, it is used more efficiently if benefits can be obtained by the utilization of the grown plant matter.

Water use efficiency is defined as the crop yield divided by the evapotranspiration of the crop area. Many factors are known to influence water use efficiency, both physiological and agronomic. Physiologically C_4 plant species are more water use efficient than C_3 species and this

TABLE 5. RELATIVE PROPORTIONS OF DRY BIOMASS OF EMERGENT AQUATIC PLANTS

Species	Relative Proportions		References
	Above Ground	Below Ground	
Butomus umbellatus L.	>64	<36	76
Carex rostrata Stokes	50-77	23-50	18
Cyperus esculentus L.	69-80	20-31	95
Cyperus papyrus L.	78	22	15
Phragmites communis L.	>17	<83	22, 23, 76
Saccharum spontaneum Trin.	80-90	10-20	93
Scirpus fluviatilis (Torr.) Gray	25-66	34-75	181
Scirpus validus Vahl	40	60	15
Sparganium erectum L.	<70	>30	76
Typha augustifolia L.	30-50	50-70	76, 150, 151, 152
Typha latifolia L.	30-50	50-70	76, 181, 150, 151, 152
Zizania palustris L.	63-81	18-37	168, 181

fact has been documented in emergent aquatic species, as well as in terrestrial crops. Giurgevich and Dunn (1978) determined that, under summertime conditions, the water use efficiency of Spartina alterniflora, a C_4 species, was much greater than Juncus roemerianus, a C_3 species. Therefore, when efficient water use is a site specific need, a C_4 emergent aquatic plant may be advantageous.

Nutrient Absorption

Denny's (1972) schematic diagram (Figure 1) of factors contributing to nutrient absorption in aquatic macrophytes provides an interesting comparison of uptake in emergent versus submergent aquatic plants.

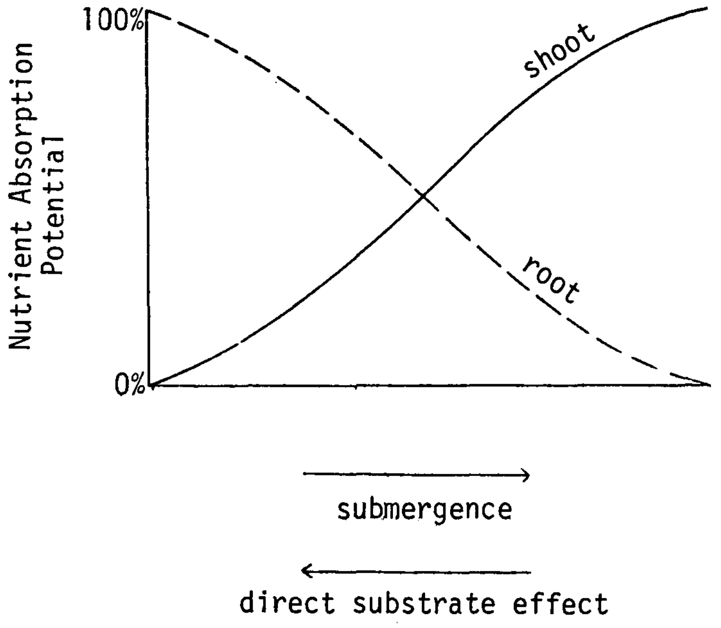

FIGURE 1. SCHEMATIC DIAGRAM OF THE TENDENCY FOR ROOT OR SHOOT NUTRIENT ABSORPTION BY AQUATIC MACROPHYTES

In accordance with Sculthorpe (1971), Denny's diagram indicates that the substrate provides most of the nutrients absorbed by emergent aquatic plants. Further the major absorptive site of emergents is the root system. As in terrestrial plants, salts travel upward through the vascular system and into ground tissue via lateral translocation.

Environmental Factors Influencing Growth

In this brief physiological analysis, the effects of light, temperature, and salinity on the growth of emergent aquatic species will be assessed.

Because of their unique morphological characteristics (see Botanical Considerations), the emergent aquatic species should respond to light in a manner similar to their terrestrial C_3 and C_4 counterparts. It is well recognized that emergent aquatic plant communities are some of the most productive canopies of the temperate zone. However, little detailed knowledge exists of their photosynthetic efficiencies (Dykjova, 1971). The effects of light on the growth of the emergent aquatics will require much further documentation if these species are to become commercialized.

The relationships of temperature and salinity on emergent aquatic plant growth have not been well correlated. Implications regarding optimum temperature regimes can be drawn from information highlighted in the geographical distribution (see Botanical Considerations). Salinity responses can be drawn from data regarding species habitat (see Botanical Considerations) and will be further elucidated under agronomic practices dealing with crop fertility requirements.

CHEMICAL CONSIDERATIONS

Chemical analysis of emergent aquatic species aids the identification of potential commercial uses and influences decisions regarding crop management and biomass processing systems. Table 6 compiles information pertaining to the chemical makeup of several emergent aquatic species. The chemical composition of corn and sunflower are provided for purposes of comparison. Most of the data refers to above-ground biomass. Unfortunately little data is available for the chemical composition of below-ground material. As is expected, different plant parts exhibit varying chemical composition. For example, on a percent of ash-free dry weight basis, *Juncus roemerianus* shoots contain more crude fiber but less total carbohydrate than its rhizomes.

A comprehensive comparison of species is hindered by the lack of uniformity in the plant parts and individual chemical constituents analyzed. In addition, a wide range of values are evident for chemical composition within many species. Use of differing analytical methods as well as sampling timing and techniques may account for some of the variation. For example, significant zonal differences in the chemical composition of *Juncus roemerianus* growing in a tidal marsh were reported (Kruczynski *et al.*, 1978). Ash, crude fiber, protein and lipid content of rhizomes varied among the lower, upper and higher regions of the marsh. Environmental conditions such as nutrient status also affects the data. Finally, much of the chemical information arises from ecological studies which are often concerned primarily with, for instance, the energetics of an environment. Such investigations generally have different objectives than a study which evaluates chemical composition for purposes of developing commercial uses. The lack of data for secondary chemical constituents, e.g. oils, phenolics, etc., in emergent aquatic plants is evidence of this difference in objective. A chemical which is considered inconsequential to many ecological or botanical research efforts may be very important as a commercial product.

It is recognized that information regarding the chemical content of a plant species is not by itself adequate for determining commercial feasibility. Assessing the viability of a potential product, whether it is fuel, fiber, industrial chemical, etc., requires consideration of the productivity, on a land unit basis, of the plant involved. This defines the amount of raw chemical available for processing. In addition, the availability and cost of the same or similar products from alternative sources must be assessed and compared to the proposed system.

Carbohydrate Composition

The total carbohydrate content of the selected emergent aquatic species varies greatly among plant parts within a species. The highest carbohydrate content is generally present in the underground portions of the plant, e.g. the rhizomes of *Typha latifolia* or *Juncus roemerianus*. However, the shoots of *Spartina patens* reportedly contain up to 64 percent (of dry weight) carbohydrate (Udell *et al*., 1969).

The cellulose content of above-ground portions of the species in Table 6 ranges from 24 to 58 percent of the dry weight. Like simple sugars, cellulose, a polymeric carbohydrate, can potentially be converted to alcohol fuels. However, because cellulose is somewhat resistant to microbial degradation, it must be hydrolyzed prior to conversion. Investigations of *Typha* as a cellulosic substrate (Ladisch and Dyck, 1979) demonstrated 50 percent conversion to fermentable sugars. The study pointed out that, as with other cellulosic residues, a pretreatment requirement unique to the substrate is necessary in order to obtain quantitative sugar yields. Emergent aquatic species especially high in cellulose, e.g., *Phragmites communis* and *Arundo donax*, have also been used in the manufacture of paper and other cellulosic derivatives (de la Cruz, 1978; Perdue, 1958).

Crude Protein Content

The leaves of certain emergent aquatic species reportedly contain relatively large amounts of protein (Boyd, 1968). These species, then, might potentially be used as a high protein roughage or supplement in human and non-ruminant animal diets. Although most of the species listed in Table 6 contain less than 15 percent foliar crude protein, the vegetative portions of _Justicia americana_ and _Phalaris arundinacea_ were found to contain over 20 percent (Boyd, 1968; Heath _et al._, 1973). These values would, of course, be expected to vary with soil nitrogen content. In addition, the crude protein measurement may be misleading as a portion of the nitrogen present in many aquatic plants is non-protein. For instance, a 1969 protein analysis of _Justicia americana_ resulted in a value of 10.19 percent of dry weight. The true protein value, i.e., the sum of amino acids, however, was 6.0 percent of dry weight, or 58 percent of the crude protein measured (Boyd, 1969).

One drawback to the production of emergent aquatic species for protein purposes includes the necessity of harvesting in May or June for high protein yields, since protein content declines as plants mature (Boyd, 1969). This time period may not, however, coincide with the optimum time for harvesting biomass for energy purposes.

Crude Lipid Content

According to Table 6, the emergent aquatic species are relatively low in crude lipid content, ranging from 0.2 to 4 percent of dry weight. The seeds of _Typha_ sp., however, reportedly contain up to 18 percent oil, approximately 70 percent of which is linoleic acid, potentially useful as a drying or edible oil (Marsh and Reed, 1956). Regardless, the yield required to supply viable amounts of seed may hinder commercialization of this product. An estimated 226,800 metric tons of cattail spikes would be necessary to provide 90,700 metric tons of seeds, for production of 15,300 metric tons of oil, and 75,200 metric tons of extracted meal. Further, linoleic acid production would require harvesting methods and equipment which would separate the spike inflorescence from the remainder of the plant.

TABLE 6. CHEMICAL COMPOSITION OF EMERGENT AQUATIC SPECIES

Species	Carbohydrate (% of dry weight) Cellulose	Sugar	Starch	Total	Crude Fiber	Lignin	Crude Protein† (% of dry weight)	Crude Lipid‖ (% of dry weight)	Ash (% of dry weight)	References
Arundo donax L.	40.1-								2.5-7.4	148
culms	58.0					9.4-24.4				
fresh aerial portion					37.5		7.6	1.3	9.2	136
Butomus umbellatus L.										
Carex spp.					31.0		9.7	2.4	7.1	136
Carex rostrata Stokes										
shoots									5.7-6.3	86
Cyperus esculentus L										
C. papyrus L.										
Distichlis spicata (L.) Greene										
shoots				51.2*			10.9*	2.02*		51
shoots				48.0	32.2-34.9		9.6	1.7	5.5	173
shoots (live and dead)				55.2*	31.1*		4.8*	1.4*	7.4	101
fresh aerial portion					29.8		6.9	1.7	9.3	136
Eleocharis dulcis (Burmf.f.) Trin.										
corm				19.0	0.8		1.4	0.2	1.1	89
non-pared corm				14.6	0.6		1.1	0.2	0.8	89
Juncus spp.										
fresh aerial portion					31.5		10.9	1.9	7.1	136
Juncus effusus L.										
(J.polyanthemus Buchenau)									3.65-9.98	86
roots									3.52-4.66	86
shoots										
Juncus roemerianus Scheele										
shoots (live)				50.7-51.9*	35.9-38.0*		5.7-6.4*	1.6-2.1*	3.4-5.0	101
rhizome				57.8-61.8*	25.5-29.5*		3.9-5.9*	1.3-1.9*	6.1-8.3	101
Justicia americana (L.) Vahl										
shoots and leaves	25.9						22.9	3.40	17.4	26
shoots and roots	24.56						10.19	3.68		27

TABLE 6. (Continued)

Species	Carbohydrate (% of dry weight)									
	Cellulose	Sugar	Starch	Total	Crude Fiber	Lignin	Crude Protein[†] (% of dry weight)	Crude Lipid[Π] (% of dry weight)	Ash (% of dry weight)	References
Paspalam spp.										
fresh aerial portion					33.4		6.9	1.7	12.9	136
P. vaginatum Swartz										
Phalaris arundinacea L.										
vegetative							7.0-25.0			82
hay	25-32					3-4			6.0-8.0	82
fresh aerial portion					22.0		17.2	4.4	10.0	136
Phragmites communis Trin. [P. Australis (Cav) Trin. ex Steud]										
shoots (throughout season)		1.7-8.6	1.2-11.4	6.2-13.9						40
fresh aerial portion					31.9		10.6	2.1	14.6	136
Saccharum spontaneum L.										
Scirpus acutus Muhl										
Scirpus americanus Pers.										
shoots (mature plant)				39.81*	25.45		11.67*	2.10*	6.77	52
Scirpus fluviatilis (Torr.) Gray										
Scirpus validus Vahl										
Scirpus robustus Pursh.										
Sparganium erectum L										
Sparganium eurycarpum Englem										
Spartina alterniflora Loisel										
shoots: short				46.1	17.9		12.4	2.3	20.6	173
medium				56.8	17.2		14.9	2.9	7.9	173
tall				63.9	9.2		14.4	1.6	11.0	173
shoots (live and dead)				48.4-52.5*	31.7-33.5*		5.0-6.4*	1.7-2.0*	8.6-13.4*	101
Spartina cynosuroides (L.) Roth										
shoots (mature plant)				53.05*	31.78		5.33*	1.26*		52

TABLE 6. (Continued)

Species	Carbohydrate (% of dry weight)									
	Cellulose	Sugar	Starch	Total	Crude Fiber	Lignin	Crude Protein[†] (% of dry weight)	Crude Lipid[Π] (% of dry weight)	Ash (% of dry weight)	References
<u>Spartina</u> <u>patens</u> (Ait) Muhl										
shoots				63.9	16.9		10.0	1.5	7.4	173
fresh aerial portion					33.3		5.0	2.4	8.5	173
<u>Typha</u> <u>augustifolia</u> L.										
hay					33.9		6.4	1.9	9.0	136
<u>Typha</u> <u>latifolia</u> L.										
shoots	33.2						10.3	3.9	6.9	26
defibered rootstock flour				79.09-81.41			7.22-7.75	0.65-4.91	2.48-2.84	129
<u>Zizania</u> <u>palustris</u> L.										
whole grain				75.2			12.9	1.0	1.4	166
ground				74.0			10.9	0.8	1.3	166
<u>Zea</u> <u>mays</u> L										
aerial portion w/o ears w/o husks					33.4		6.8	1.3	7.3	136
grain			76.3		2.4		10.9	4.7	1.6	136
<u>Helianthus</u> <u>annuus</u> L										
aerial portion					29.3		9.2	2.4	12.2	136
seed					31.0		17.9	27.7	3.3	136

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[*] % of ash-free dry weight

[†] crude protein = N x 6.25

[Π] crude lipid = ether extractable material

Inorganic Content

Utilization of residual N, P, and K resulting from biomass processing as soil amendments has been suggested as a means of decreasing the high monetary and energy cost of fertilizers manufactured from fossil fuels (Klass, 1980). The feasibility of this suggestion depends on several factors, including the amount of N, P, and K present in the plant under various management systems, the amounts of each element which could reasonably be reclaimed from processing, transportation distance, reapplication methods, and the age of the plant. N, P, and K levels in *Carex rostrata* were high in overwintering tissues and in newly emerged shoots but declined as the shoots aged (Bernard and Hankinson, 1979). N, P, and K composition of several emergent aquatic species is provided in Table 7. Again, corn and sunflower measurements are included for use in comparison.

The percent ash content of biomass has bearing on energy value as inorganic materials remain as residue after processing, and, therefore, do not contribute positively to the energy content of plant material. The selected species listed in Table 6 range from 0.8 to 17.4 percent ash (of dry weight).

TABLE 7. NITROGEN (N), PHOSPHORUS (P), AND POTASSIUM (K) COMPOSITION OF EMERGENT AQUATIC SPECIES

Species	% of Dry Matter			References
	N	P	K	
Arundo donax L. fresh aerial portion	1.12	0.11	2.55	136
Carex rostrata Stokes shoot	1.6 - 1.9	0.14 - 0.29		86
Distichlis spicata (L.) Greene				101
shoot		0.02*		
Eleocharis dulcis (Burmf. .f.) Trin.				89
pared corm		6.5		
non-pared corm		5.0		
Juncus effusus L.				86
root	0.7 - 0.8	0.1 - 0.3		
shoot	1.0 - 1.9	0.1 - 0.3		
Phalaris arundinacea L. fresh aerial portion	2.7	0.33	3.64	136
Phragmites communis Trin. fresh aerial portion	1.7	0.06		136
Zea mays aerial portion w/o ears w/o husk	1.1	0.10	1.64	136
Helianthus annuus L. seeds	2.9	0.56	0.71	136

*percent of ash-free dry weight

AGRONOMIC CONSIDERATIONS

A key factor in the development of efficient and economic biomass systems is the optimization of agronomic practices which facilitate production of large quantities of raw material per unit area at low unit cost. As will become evident, with the exception of rice production, the methods employed in the cultivation of most currently commercialized emergent aquatic species are very labor intensive. It is possible that certain features of mechanized rice production and manually cultivated emergents may, with appropriate modification, be applied to biomass energy systems. Evaluation of applicability will, however, require decisions regarding the value of harvesting underground biomass, the use of natural versus artificially engineered stands, availability of water and irrigation facilities, etc.

Brief descriptions of agronomic practices associated with *Eleocharis dulcis* (water chestnut), *Ipomoea aquatica* (water spinach), *Zizania palustris* (wild rice), and *Oryza sativa* (rice) are presented to give perspective to the level of research and development necessary to make emergent aquatic systems commercially feasible on a large scale. Mechanized harvesting methods, collection, densification, transportation, and storage of biomass production are then addressed. Finally, the roles of propagule availability and crop improvement in the development of managed emergent aquatic systems are considered.

Current Emergent Aquatic Systems

Eleocharis dulcis

Eleocharis dulcis (water chestnut), a crop of southeast China, is often grown in rotation with other aquatic plants such as rice and lotus (Hodge, 1956; NAS, 1976). It is a paddy crop, requiring relatively extensive pre- and early season (late March to early April) land preparation prior to planting. After plowing and harrowing, the land is fertilized. In China the source of this preplant fertilizer, as well as that applied throughout the remainder of the season, includes peanut cake, lime, plant ash, and various organic manures. A section approximately 10 percent of the total field is set aside as a nursery. The water chestnut corms are planted 2.5 cm apart in this area. The planting density is approximately 2.2 kg corms/m^2 of land. The nursery is kept moist but not innundated. When the seedlings are about 2.5 cm in height they are transplanted to rows 7.5 cm apart and fertilized again. When 19 cm tall, the seedlings are planted permanently in a field, spaced 0.4 to 0.7 m apart. The field is then flooded for the remainder of the season. The corms are harvested after the plants have been killed by frost, generally in late summer or early fall. Depending upon the variety of water chestnut, harvesting proceeds prior to, or after, the water is drained from the field. Both methods employ manual labor for removing the corms from the ground.

Ipomoea aquatica

Ipomoea aquatica (water spinach) is grown under two distinct management systems, dryland and wetland (Edie and Ho, 1969; NAS, 1976). The dryland system is employed when other crops occupy fields used for wetland cultivation. In this case, the water spinach crop is grown in raised beds, between which are irrigated ditches. The seed is either sown into the beds or germinated in a nursery. In the latter case, the emerged seedlings are transplanted to beds. The final stand consists of plants spaced 12 cm apart.

In the dryland system young plants require water supplied either by hand or by maintaining adequate water levels in the irrigation channel. Water spinach requires heavy fertilizer applications. In Hong Kong, organic manures serve as fertilizer, avoiding high priced sources such as peanut cake, etc. Approximately 3,100 kg/ha of night soil is applied every 2 to 3 days after the plants are past the seedling stage.

Under favorable fertilization and moisture requirements, weeds may flourish. Dryland systems generally require hand weeding in order to decrease the competition with water spinach.

The growth cycle of water spinach generally lasts 50 to 60 days. Plants are then harvested manually. Some varieties allow multiple harvests when lateral growth is encouraged by cutting the shoots above ground level.

Wetland cultivation of water spinach is more common than the dryland method. Since the seeds do not germinate well in water, they are usually planted in a dry section of the field. Six weeks later cuttings from these seedlings are transplanted at 40 cm spacing in a field which has been flooded to a depth of 3 to 5 cm and trampled in order to create a muddy substrate favorable to swift rooting. Water is added to the field slowly. When the crop has become established the water level is maintained at 15 to 20 cm. Throughout the growth period fertilizer is applied in a manner similar to that in dryland cultivation. The water flow through the field may be ceased for a half day upon application in order to enhance penetration of the fertilizer. Approximately 10 weeks after initial sowing the first harvest is taken, manually as in the dryland system. Subsequent harvests follow every 7 to 10 days throughout the summer.

Zizania palustris

Zizania palustris (wild rice) is an annual grass which generally reseeds itself year after year (Steeves, 1952; NAS, 1976). Upon maturation in the fall the seeds drop into the water and overwinter in the muddy substrate. The seeds then germinate in the spring, mid-May in Minnesota, a month earlier farther south. The seeds exhibit a limited amount of dormancy, as a stand which is destroyed prior to producing its own seed one year may regenerate the following year. Wild rice flowers in mid-July when its stalks are a few inches above the water level. In early September the seed is harvested. Both manual and mechanical methods have been employed. Although mechanical harvesters may require that the crop be reseeded for future production, they offer advantages of time and efficiency over manual harvesting. Regardless of whether the gathering of seed is mechanized or via manual labor, maximizing yields of wild rice requires multiple trips over a stand, as the grain in the panicle infloresence does not all mature simultaneously. This is a major setback to widespread incorporation into conventional agriculture, requiring excesses of time and expense.

Establishment of new stands demands attention to the specific storage requirements of the wild rice grain. The seed does not stand prolonged drying, and therefore must be kept moist from harvest until sowing. These requirements can be avoided to some extent by reseeding in the fall.

Oryza sativa

Of the four crops discussed, Oryza sativa (rice) is by far the most developed. It is widely grown throughout the world and has been adapted to both mechanical and labor intensive systems. An important commercial crop, much is known about its fertility requirements, pest problems, etc.

Rice production in the United States is highly mechanized (Martin et al., 1976). In the fall, winter, or spring, the land is plowed 10-15 cm deep, and a firm surface layer is achieved. Rice is sown via airplane or ground broadcasting or with a grain drill, between April and early June depending on the geographic region. Optimum planting density is approximately 90 kg seed/ha, depending on the method of seeding. Drilling generally requires 100-110 kg/ha, aerial broadcasting 140-180 kg/ha.

Land not previously in rice is generally drilled in order to encourage weed control. The seed is placed 2.5-5.0 cm within the soil. Alternatively, rice may be broadcast into the water directly. The seeds, often imbibed with water containing chemical disease deterrents, sink through the water to the muddy substrate. Germination occurs at the relatively low oxygen levels provided the seed upon broadcasting. However, if the seed is drilled into the ground, water coverage reduces O_2 to levels insufficient for germination. Drilled fields are, therefore, generally periodically irrigated and drained until the crop is established, usually in about 30 days. At this time the land is flooded to a depth of 2.5-5.0 cm. As the plants increase in height, the water depth is also increased, up to a maximum of 10-15 cm, the level maintained for 2 to 3 additional months.

The field generally remains flooded until harvest with the exception of temporary drainage for pest control or fertilization purposes. Final drainage occurs 10 to 15 days prior to crop maturity, at which time the grain is harvested with self-propelled combines.

In general nitrogen is the nutrient in most limited supply for rice growth. Deficiencies are corrected through addition of ammonium sulfate or phosphate, anhydrous or liquid ammonia, urea and cyanamide. Nitrogen in the form of nitrate is relatively unavailable to submerged soils due to reduction to nitrite in anaerobic conditions. Nitrates are also readily leached from soils, a problem which is controlled to some extent by tightly packed soils with little pore space. Nitrate fertilizers are generally less effective than ammonium fertilizers.

Fertilization prior to planting may consist of broadcast application and incorporation into soil via harrowing. During the growing season nitrogen fertilizer may be applied as top dressing at which time field drainage facilitates penetration into the soil. Coarse soils which allow nitrate to leach may require a split application of fertilizer. Foliar application of urea is another alternative. Injection or "knifing" of anhydrous ammonia into the root zone area of the plant has also been used (Luh, 1980).

Weeds are generally controlled with suitable chemical herbicides. In addition, seeding rice directly in water aids weed control by submersing undesirable plants. Unwanted blue-green algae growths may be suppressed upon addition of copper sulfate or other amendments to the water.

Rice, as most highly cultivated crops, suffers from various pests, including diseases, insects, and animals. Some disease infestations are deterred by submergence. Others are encouraged by high moisture conditions and control may require seed treatments and use of resistant and short season varieties. Periodic field drainage also rids of various disease pests. Insects may be contained via chemical insecticides and by destroying habitats in which the insects hibernate.

In the Orient, rice production is very labor intensive. The paddy system employed is similar to that of the other crops discussed, although chemical pesticides and fertilizers are used more frequently. Seed may be sown directly or seedlings transplanted from a nursery, and the land may be permanently flooded, or irrigated at intervals. Rice cultivation in some Asian countries employs a novel biological fertilizer source. Of China's rice fields, 1.3 million ha are planted with *Azolla*, a fern in symbiotic association with the blue-green algae *Anabaena azollae*. This algae, which lives in *Azolla* leaf cavities, produces nitrogen which can be used by a rice crop growing alongside it. China's 1.3 million ha of *Azolla* reportedly provide the equivalent of 90,700 metric tons of nitrogen fertilizer worth over $50 million annually (Clark, 1980; Lumpkin and Plucknett, 1980).

Mechanized Harvesting, Collection, Densification, and Transportation of Biomass

When considering the biological and economic viability of any integrated system developed to produce biomass energy, key concerns include the areas of harvesting, densification (and/or dewatering), transportation, and storage. Despite the biological potential of emergent aquatic plant species, these systems will suffer serious drawbacks without further developments in mechanization. As highlighted in previous sections, with the exception of rice, all emergent aquatic plant production systems have been characterized by labor intensiveness. In the United States, labor intensive agriculture systems are limited to high value, low volume products. Therefore, emergent aquatic systems must mechanize to become commercially viable. Amphibious machines have been available for reed harvesting since the 1950's. In fact, modern amphibious harvesters are used regularly for winter cutting of large areas in northern Jutland (Denmark), at the Newsiedler Lake in Austria and Hungary, in the Danube delta (Rumania), the Euphrates-Tigris reed marshes (Iraq), and elsewhere (Björk and Graneli, 1978). However, the harvesters currently used may differ significantly in purpose from those required for emergent aquatic plant energy systems. For example, current harvesters, like those developed by Seiga®, are designed to harvest the reed stems and to avoid damaging the rhizomes and new shoots. In this analysis, it has of yet not been determined if the starch-rich rhizomes should be harvested along with the stems. It is recognized that: (1) emergent aquatic plants tend to regrow from rhizomes much more effectively than from seeding (Pratt, et al., 1980); (2) rhizome harvesting may be very energy-intensive, much moreso than other commercial root crops like sugarbeet or potato; and (3) among emergent aquatic plant species, the rhizomes tend to contain the highest quantities of starch and may be among the more desirable plant parts as feedstock for conversion to useful energy products. Further energy balance and economic analyses will determine whether and/or how these below-ground parts will be utilized.

At this stage of development, conceptualization of harvesting methods which may be used for emergent aquatic energy systems is impeded by many unanswered questions such as the possibility of harvesting rhizomes, draining the field prior to harvest, etc.

Current emergent aquatic plant harvesting systems are designed to be used in winter, preferably on the ice of frozen bottom. To avoid rhizome damage, the ground pressure of the big, tubeless rubber tires of the amphibious harvester varies from 40 g/m^2 (empty vehicle) to 100 g/m^2 (two-ton load). Most machines are combinations of harvesters and transporters and have a load capacity of 30 m^3 (Bjork and Graneli, 1978). Of the many critical areas which will greatly affect the commercial viability of emergent aquatic systems, the logistics of harvesting equipment, techniques, and timing will be among those which must be resolved. Bjork and Graneli (1978) have hypothesized harvest costs of about $50 per ton in Sweden. This would not be cost-effective by any means in the United States. To be competitive, much further work is needed.

In addition, harvesting the plant material in winter may or may not be the best system, depending on the needs of a given situation, e.g., what fuel or chemical products are desired, whether the climate provides a freezing period, when the conversion facility can best use the material, etc.

A major problem associated with aquatic plant utilization, in general, has been the alleged high water content of the plant material. This is too broad a generalization and, in fact, may be a myth when considering emergent aquatic species. Although the dry matter content of floating aquatics, e.g., Eichhornia crassipes, ranges from 5 to 15 percent, the value ranges from 10 to 40 percent for emergent aquatics. This range is the equivalent to the dry matter content of terrestrial forages.

Few data have been reported on densification, transportation, and storage of emergent aquatic species. In Sweden, experiments are underway in which harvested stems of the common reed are transported to a mobile mill for grinding into powder. The powder is transported and stored according to procedures for flour products (Björk and Granéli, 1978; Granéli, 1980).

In the United States, commercial hauling of emergent aquatics would appear as an important cost component where biomass production areas are separated from the processing plants. Intuition suggests that bulk density of the harvested material and haul distances are important variables when commercial transportation is required. Baling of the harvested material may increase the dentisty; however, it is apparent that the potential savings in transportation costs from densifying harvested emergent aquatics must be balanced against the in-field costs associated with each type of collection, i.e., chopping, baling, field cubing, etc. Whether or not harvested emergent aquatic biomass could be sun-dried to an 80 percent dry matter level in the United States must be answered on a site-specific basis. Actual dry matter content of the biomass will depend greatly on weather conditions such as temperature, solar insolation, rainfall, snow, etc.

Crop Improvement

A crop improvement program would enhance efforts toward the development of managed systems of emergent aquatic species by providing plants which possess the features most desirable for site specific optimum growth. As an example, biomass quantity might be increased by improving the seasonal adaptation of a plant, or the plant's tolerance to adverse environmental factors, pests and diseases. Several widely employed tools are available for crop improvement purposes, including hybridization, polyploid development, and selection.

Hybridization potential is, in part, a function of reproductive morphology. If a plant produces perfect flowers, the male and female parts in close proximity, it may well be predominately self-fertilized. The progeny from such a plant, then, in general exhibit the phenotypic characteristics expressed by the parent plant. On the other hand, if a plant bears imperfect flowers on the same plant, it is monoecious. This condition often favors cross-fertilization. The extreme case, finally, is a dioecious plant, which possesses unisexual flowers on different plants. In this case, cross-fertilization predominates.

The ease with which hybridization and, thus, heterosis or hybrid vigor is achieved is affected greatly by these reproductive features. A case in point contrasts the hybridization potential of corn (*Zea mays*) versus soybeans (*Glycine max*). Corn is a monoecious plant, the staminate flowers composing the tassel, the pistillate flowers the corn silk. Hybridization, as has long been demonstrated, is manipulated by eliminating the viable male pollen from one parent via, for instance, emasculation or cytoplasmic sterility, and allowing pollen from a genetically different corn plant to fertilize it. The soybean plant, on the other hand, possesses relatively small, perfect flowers, the male and female organs in close association. Cross fertilization has been attempted using cytoplasmic sterility and techniques which involve alteration of floral morphology, e.g. "designing" a flower in which one of the two sexual parts is underdeveloped, thus deterring self-pollination. These efforts, though promising, have not yet met the widespread success of corn hybridization.

As can be seen from Table 1, several of the selected emergent aquatic species are monoecious or dioecious. In addition, at least one genus, *Spartina*, possesses members which produces proterogynous flowers, which may result in outbreeding despite possession of perfect flowers.

The development of polyploids, i.e., plants which possess multiple genomes per cell nucleus, may also offer potential for improvement of certain emergent aquatic species. Polyploids, which can be achieved naturally or, as is more often the case, through application of the chemical colchicine, are sometimes larger and more vigorous than their diploid counterparts. Triploid aspen trees, for instance, possess larger leaves, pollen grains and stomatal cells than the corresponding diploid aspen (Srb *et al*., 1965). Many commercial crops, e.g., wheat, cotton and tobacco, are polyploids. Emergent aquatic species show particular promise for polyploidy as most may be vegetatively propagated, and, thus, circumvent one major drawback to the multiplication of nuclear genomes, the development of infertile progeny.

Screening plant genotypes for specific desirable traits is still another way a crop may be improved. For instance, Epstein _et al_ (1980) are presently selecting for salt tolerance in barley, wheat, and tomatoes with the purpose of developing plants adaptable to saline environments. A similar program for this trait or some other favorable feature could be applied to emergent aquatic species. Comprehensive assessment of the genetic variability within the species, both cultivated and wild, would enhance these efforts.

Hybridization, polyploid development, and selection are important to plant improvement. In addition to these more conventional avenues, other contemporary methods such as induced mutation, tissue culture, and recombinant DNA techniques also deserve attention in a crop development program.

Propagule Availability

Most of the selected emergent aquatic species are undeveloped in terms of crop production. Propagule availability, then, becomes an important factor in the selection of species for use in managed systems. If a plant species is not commercially available propagation may require harvesting natural stands using hand labor. Gathering propagules in this manner is complicated by several factors including the need to obtain seeds or vegetative material in large quantities and of sufficient viability to provide an adequate crop stand. In addition, removing propagules may damage the donor habitat. Finally, the propagules must be properly stored and then transported to the managed site.

Twelve of the 27 emergent aquatic species in Table 1 are described in _Hortus Third_, a dictionary of cultivated plant species, indicating commercial availability to some extent. Table 8 provides a list of these species, along with their horticultural uses according to _Hortus_.

TABLE 8. SEVERAL CULTIVATED EMERGENT AQUATIC SPECIES AND THEIR HORTICULTURAL USES (Bailey and Bailey, 1976).

Species	Horticultural Use
Arundo donax L.	erosion control; stems are source of musical instruments
Butomus umbellatus L.	ornamentals for pool or pond margins, aquaria
Cyperus esculentus L.	edible tubers cooked or roasted, or made into flour
Cyperus papyrus L.	paper making in ancient times, now primarily an ornamental plant
Eleocharis dulcis (Burmf .f.) Trin.	edible corms
Juncus effusus L.	weaving
Phalaris arundinacea L.	ornamental*
Phragmites communis Trin.	lattice work
Sparganium erectum L.	ornamental
Sparganium eurycarpum Engelm	ornamental
Typha augustifolia L.	leaves - basketry; floss - kapok substitute; ornamental
Typha latifolia L.	same as T. augustifolia
Zizania palustris L.	human, wildlife food

*P. arundinacea is also grown as a forage

Several marsh transplants are reportedly available from commercial sources at costs ranging from $0.14 to $0.75 per plant. (Waterways Experiment Station, Vicksburg, Miss., 1978). Seeds of some emergent aquatic species are also available from various governmental and private sources.

ECOLOGICAL CONSIDERATIONS

The possible ecological effects of emergent aquatic plant cultivation depend on physical, chemical, hydrological, and biological parameters unique to the particular ecosystem under consideration. Freshwater ponds, swamps, and marshes, rivers, open coastal salt marshes, estuarine and embayed marshes represent dynamic systems which could be utilized for the cultivation of emergent aquatics. Many unique interrelated and often interdependent factors and processes govern the stability of each of these ecosystems.

Water Quality

Cultivation of emergent aquatic plants may have either beneficial or deleterious effects on water quality, depending largely on the trophic status of the ecosystem. In many instances, the addition of large quantities of anthropogenically derived inorganic nutrients to wetland and aquatic ecosystems has led to pollution and accelerated eutrophication. When inputs of N, P, and other nutrients exceed limiting levels, proliferation of bacterial, algal, and aquatic plant growth can lead to a deterioration of water quality, and, further, to a decline in the recreational and commercial value of the wetland ecosystem. On the other hand, since plants absorb nutrients efficiently, cultivation and harvesting of emergent aquatics could provide a method for removal of excess nutrients from eutrophic natural waters and effluents. Stewart (1970) has reported successful restoration of nutrient balances in eutrophic water and industrial effluents by water hyacinth (*Eichhornia crassipes*) and bulrush (*Juncus lacustris*) respectively. In the extreme case of nutrient limiting conditions, however, cultivation of emergent aquatics could deplete available nutrients to the point of reducing phytoplankton primary productivity and ultimately productivity at higher trophic levels. Based on productivity and plant nutrient compositions, the nutrient removal potential of various emergent aquatic species is presented in Table 9.

Marsh development of cultivated emergents may also tend to minimize summer algal blooms in lakes which receive drainage from marshes. This is due to the fact that, in some systems, summer algal blooms are dependent on receipt of nutrients from the watershed. Marsh development on tributaries to such lakes would result in nutrient storage in plant tissues rather than release during this period of algal bloom.

In eutrophic waters populated by nuisance vegetation, herbicide control is often utilized. Such management procedures can result in increased biological and chemical oxygen demands, fish kills, and invasion by additional nuisance species. Replacement of nuisance angiosperms with desirable emergent aquatics might diminish the need for such drastic chemical control measures.

In undisturbed aquatic ecosystems, the cultural changes involved in cultivation would be superimposed on currently evolving or existing steady-state conditions. Since the level of metabolism in aquatic ecosystems is strongly dependent on nutrient and energy input, the addition of dissolved substances via fertilization and inputs of particulate organic matter during harvesting will periodically disrupt or degrade steady-state conditions in the system. Disruption of the tight nutrient cycles associated with undisturbed oligotrophic ecosystems will result in an acceleration of natural succession processes. The impact on nutrient relations within the system will vary according to the extent and intensity of disturbance.

Habitat Disruption and Development

Aquatic wetlands provide food, water, and cover for species of both commercial and recreational value. Cultivation of aquatic crops will result in habitat disruption and displacement, in addition to habitat development. The net negative or positive effects of cultivation will depend on the function and relative resource value of the existing and developed habitats, as well as on the degree of alteration of the location's

TABLE 9. NUTRIENT REMOVAL POTENTIALS OF EMERGENT AQUATIC SPECIES

Species	Location	Composition (% Dry Wt.)		Crop Content kg/ha		Reference
		N	P	N	P	
Typha latifolia	Minnesota	1.5	0.18	688	82	167
Cyperus papyrus	Tropics	1.5	0.15	1122	112	167
Phragmites communis	Rumania	1.5	0.15	437	44	167
Justicia americana	USA	2.02	0.12	496	29	27
Juncus effusus	S.E. USA	1.14	0.13	213	24	33

biological structure. Ecosystems considered for cultivation include a wide variety of habitats, and each habitat will respond differently to the same treatment. Habitats likely to be most susceptible to disturbance are those which depend on the presence of one particular species for their integrity (Lung *et al*., 1978). Prior to cultivation, the functional role of existing habitats must be evaluated on an individual basis, and their relative resource values assessed.

Coastal Wetlands

Cultivation of emergent aquatics in vegetated tidelands could have both positive and negative ecological consequences. Coastal salt marshes and wetlands are among the most productive natural systems known (Teal and Teal, 1969). They are essential to the storage and transfer of nutrients from upland sources to coastal waters, and they provide nutrients for both detrital and grazing food chains.

Creation of additional vegetated tidelands could serve to stabilize estuarine shorelines, prevent erosion, remove toxic substances and excess nutrients from estuarine waters, reduce sedimentation in navigation channels and shellfish beds, reduce the severity of flooding, and create habitats (Clark, 1974). In coastal regions, emergent species such as *Spartina* spp. provide trapping surfaces for oil spills and serve to strain such contaminants from tidal waters.

As a result of multiple pressures for use of the coastal zone for industrial and commercial development, recreation, food production, etc., many wetland ecosystems continue to experience intrusion. Cultivation of emergent aquatics could contribute to the preservation of wetlands valued for their unique ecological structure. Cultivation might also promote reclamation and marsh development on dredge spoils. Artificial marshes have been established on dredge spoils in several fresh and salt water locations throughout the United States by the U.S. Army Corps of Engineers. In south San Francisco Bay, for example, a *Spartina foliosa* marsh was successfully established on confined dredge material within two years of construction (Morris *et al*., 1978). In North Carolina, artificially established salt marshes on dredge spoils have resulted in stabilization and in the reduction of expenses involved in repeated dredging. Both dry matter production and appearance resembled that of the natural marsh after two years, although there were considerable differences in the abundance and production of macroinvertebrates between the two systems (Packard and Stiverson, 1976; Woodhouse *et al*., 1974).

Improper management of emergent plant cultivation in coastal regions can have serious consequences. In southern New Jersey, salt hay farmers have diked over 4,000 hectares of tidelands and wetlands in order to stabilize water flow (Clark, 1974). Dike construction obstructed both nutrient flow to the estuary and fish passage to the marsh. Clark (1974) reported that restoration of the area to normal marsh would provide breeding ground for 20,000 clapper rails and wintering grounds for 10,000 black ducks. With proper management, cultivation of coastal and inland marshes and wetlands is likely to be compatible with migratory pathways for birds (Ketchum, 1972). Pesticide usage, however, must be sufficiently low to preclude potential biomagnification.

Since salt marshes are well known for their production of biting flies and mosquitos, cultivation of marsh plants could promote the use of mosquito ditching and insect control methods, which could induce deleterious ecological effects.

Poor management and frequent cropping of existing *Spartina* marshlands could have serious and widespread ecological effects, although such effects are not likely to be readily observable within a short time frame. *Spartina* dominates vegetated tidelands in major coastal regions of the world. *Spartina* forms the basis of both detrital and grazing food chains in these ecosystems, and its production is essential to the integrity of the system. Estuarine marshes provide food and cover for a large diversity of species. They support the egg, larval, and juvenile stages of commercially valuable shellfish and finfish, including penaid shrimp, oysters, clams, and mussels. Populations of crabs and other invertebrates move in and out of the marshes, using them as feeding grounds (Ketchum, 1972). About one-half of the vegetation produced within these tidal marshes is exported into the estuaries to support an array of species. Sykes (1968) has reported that in some areas of the world, 90 percent or more of the commercial fish catch consists of estuarine dependent species. According to

Niering (1972), 227 million kg of the 360 million kg of fishery products landed in New England in 1960 were directly dependent on tidal marshes, and these marshes are dependent on Spartina production.

Teal (1962) detailed trophic level production in Georgia salt marsh ecosystems dominated by Spartina. In this ecosystem, the community consists of organisms which derive their energy directly from living Spartina and algal detritus. Cropping of Spartina would decrease food availability to insects (e.g. Orchelium, Prokelisia) which in turn support spiders, wrens, and sparrows. A decrease in Spartina detrital production as a result of biomass removal would impact numerous detritovores important to the marsh economy. These include deposit feeders such as fiddler crabs, Littorina, and obligochaetes, as well as suspension feeders such as Modiolus and Manayunkia. These detritovorous organisms provide a food source for higher trophic level organisms, including raccoons, rails, and mud crabs.

Processing and Conversion

Processing of harvested emergent aquatic plants could have several ecological consequences. Removal of vast quantities of biomass by underwater mowing machines will increase turbidity and displace habitats. This will be greatly enhanced if roots or rhizomes are harvested. Once settling of particulates has occurred, phytoplankton growth may be stimulated by the increased depth to which light can penetrate.

Construction and maintenance of roads to the collection sites is likely to increase erosion and disrupt normal nutrient flow at the aquatic-terrestrial interface. This effect is likely to impact tidal wetlands to the greatest extent.

Potential environmental consequences likely to occur during biomass conversion include the production of large quantities of effluents characterized by high biological and chemical oxygen demands. In conversion to ethanol, particulate air pollution from boilers to power the distillery may also pose a problem. Gasification might also result in air pollution problems as a result of raw product gas leaks. Potential air pollutants include ammonia, hydrogen sulfide, hydrogen cyanide, and polynuclear aromatic compounds (OTA, 1980).

ECONOMIC CONSIDERATIONS

As has been discussed earlier, very little technical research has been conducted on emergent aquatic plants expressly for biomass production. Informational constraints to evaluation of emergent aquatic species are even more severe when considering the potential economics of emergent aquatic biomass systems. With few exceptions, published economics on emergent aquatics refer to systems of soil stabilization, recreation management, etc. (see, for example, Smith, 1979). Such systems, operated on a limited scale (and usually by various governmental agencies), do not have a profit-making objective and, therefore, few obvious attempts have been made to reduce costs from a large-scale commercial perspective.

Those attempts that have been made to document the economics of large-scale biomass operations using emergent aquatic plants either are based outside the U.S. or are hypothetical in nature. Nonetheless, the efforts by Bjork and Graneli, de la Cruz, Ladisch and Dyck, Midwest Research Institute, NAS, and others are useful starting points for major research efforts designed to properly evaluate the potential of emergent aquatics as a viable biomass resource.

This section of the report has the overall objective of establishing a framework for future economic evaluation of emergent aquatic biomass systems. Within this context, several topics will be covered:

- Prior research efforts
- Production costs for candidate species
- End product potential
- Commercial development and potential competition
- Future research opportunities.

Due to the paucity of information regarding economics of commercial emergent aquatic systems, in many cases the discussion that follows provides a generalized evaluative mechanism (or set of guidelines) for future research efforts.

Prior Research Efforts

Phragmites communis

Bjork and Graneli (1978) have investigated biomass potential of the common reed grass, Phragmites communis in the Swedish lowlands. Included within their investigation was a brief analysis of estimated costs of delivered powdered fuel from Phragmites. Harvesting of the wet common reed (above-ground) was estimated to be about $50 per metric ton (1978) dollars). [Bjork and Graneli do not indicate the moisture content of the material.] Costs for drying, grinding to a powder and one hundred kilometers of transport was estimated at $10 per metric ton (again in 1978 dollars).* Given a total delivered cost of $60 per metric ton, Bjork and Graneli then compare the Phragmites cost to a consumer price of $125 per cubic meter of heating oil. If the energy content of the Phragmites powder is 50 percent of that of one cubic meter of heating oil, then the net price of the powdered fuel and heating oil would be approximately equivalent (at about $3.50 per million Btu's in 1978 dollars). Bjork and Graneli admit some optimism as their estimates do not include the production costs up to harvesting. On the other hand, Bjork and Graneli imply that harvesting costs could be lower if machinery were optimized (Bjork and Graneli, 1978).

De la Cruz, (1978) has investigated Phragmites in Romania. The reeds are a cellulosic feedstock for the production of paper pulp. The hydrolyzed Phragmites material is blended in a 3:2 ratio with wood pulp, the pulp offering tear strength and density characteristics. The resulting fabricated paper apparently exhibits adequate properties for commercial sale. The yield of Phragmites averages 5 metric tons per hectare (assume near dry). Although rotation is practiced in some areas, no fertilizer is used and no cultivation is practiced. The

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*Bjork and Graneli state that harvesting in Sweden normally would take place during the winter months when the reed would be in a very dry state. As such, drying would not be required.

reeds are harvested with cutter and bundling machinery mounted on boats or high-flotation wheels. Harvesting begins in November after the plants have shed their leaves and extends through February or March. De la Cruz reports that the bundled reeds are loaded manually onto vehicles for transport to the pulp plant. The pulp plant pays $85 per ton for the raw material. De la Cruz suggests that the $85 per ton price is somewhat high and suggests the probability of a government subsidized system. Also, the system operates principally to provide employment rather than from identification of a profit-making opportunity.

Arundo donax

Midwest Research Institute (MRI) (1979) has constructed hypothetical investment and operating costs for a giant reed (Arundo donax) biomass production system in the southern parts of the United States.

Over a 20-year stand lifetime, MRI estimated an average yield of 16.1 field dry (11 percent moisture) metric tons per hectare with four years to a mature stand. Fertilizer costs were estimated at $7 per field dry metric ton, or $111 per hectare per year. Harvesting costs are estimated to be $14 per field dry metric ton, or $255 per hectare per year. Irrigation, land, transportation, management, and other charges totalled about $28 per field dry metric ton. On a delivered dry basis, and after deduction of 5 percent for various losses, the costs totalled about $63 per metric ton. This is equivalent to approximately $4 per million Btu's. Based on preliminary estimates, MRI concludes by indicating that Arundo appears to be a viable candidate for the warm, humid climates of the Southeast, and the semi-arid Southwest. MRI suggests no specific end use for the Arundo plant material, although it is implied that the fiber would be used as a cellulosic substrate.

Other Research

The above reviews of information relating to the economics of emergent aquatic systems only are illustrative and are not intended to provide a complete survey of the literature. Other authors imply economic relationships within their work (see especially Smith, 1979; Marsh and Reed, 1956; Koegel, Et, Al., 1978; and NAS, 1975).

Production Costs for Candidate Species

The six candidate species (see following candidate selections) represent extreme diversity in terms of cultural, harvesting, transport, and processing requirements. This diversity influences production costs and, therefore, the ability to exploit the potential of emergent aquatics as a biomass resource. Also, the diversity implies that a "standardized" production system probably will be impossible to obtain, nor would a standardized production system necessarily be desirable.

Nonetheless, several comments can be made regarding the likely production costs of emergent aquatic plants relative to the prior research efforts noted above. Also, while the development of meaningful production budgets for the six candidate species is impossible at this time, it may be valuable to establish target costs for the future development of emergent aquatic systems. One means of establishing targets is to provide production inputs among the various major activities (e.g., planting, crop management, harvesting, transportation, etc.) and select parts of existing agricultural systems as being analogous to the aquatic emergents.* In this manner, a composite production cost is derived.

The analogous crop selections are noted in Table 10 and discussed below.

Planting and Crop Management

All six candidates species are rhizomatous, and all flower to varying degrees. Managed stands, then, presumably could be established

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* In addition to the danger of selecting an inappropriate analogous crop, this approach can also stifle the imaginative development of new and more efficient systems.

TABLE 10. PRODUCTION COSTS: ANALOGOUS BIOMASS FEEDSTOCKS FOR EMERGENT AQUATICS

Production Activity	Analogous Crop
Planting	Sugarcane/Wheat/Corn
Maintenance	Sugarcane/Corn
Harvesting	Sugar Beet/Corn
Drying and Densification	Corn/Sun Dried Corn Stover

through at least two basic patterns.* Using rhizomes as a means of stand establishment implies that the rhizomes would need to be laid in the seedbed in an appropriate pattern and covered (or buried) with soil. Assuming a relatively dry seedbed, i.e., not flooded, it appears that sugarcane planting practices may be analogous. If seeds can be used to establish stands, then conventional drilling, row planting, or aerial or ground broadcasting may be practiced. Wheat and rice are the more obvious selections for analogous crops.

With the exception of MRI's efforts on Arundo, most authors have ignored maintenance (planting to harvesting) aspects of emergent aquatic systems. It appears reasonable that intensive emergent aquatic production systems likely will require some fertilization, and weed and insect control. The amount of fertilizer required will depend upon the species, the soil and water environment, climate, and the desired yield. Similar factors would be considered for weed and insect control, In discussing Arundo, MRI states that "while the literature reports no problems with pests or disease, the limited experience in the United States does not as yet furnish assurance of such problems will not surface if it (Arundo) is extensively grown". (MRI, 1979). Likewise, virtually every commercial crop grown in the United States has required protection from weeds, insects and/or disease to remain a long term viable entity in its particular production region. The intensity (proportion of a particular crop grown per unit area of land) and the crop mix in the region also will be major determinants of the severity of pressure of weeds, insects, and disease. For comparative purposes, rice and corn will be used.

Harvesting

Harvesting has received the most attention in previous economic research of emergent aquatic systems. And, several machines have been

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* There is evidence of a tendency toward the replacement of sexual by vegetative reproduction among hydrophytes (Sculthorpe, 1971). Sexual reproduction might, however, be enhanced through appropriate breeding efforts.

developed for aquatic plant harvesting. Although the aquatic plant harvesters can improve the extreme labor intensivity problem, the machines are awkward and slow, and possess low capacity relative to, for example, grain combines.

One of the major questions regarding development of efficient harvesting machinery is the plant parts which should be harvested. The rhizomes of several of the candidate species are rich in carbohydrates. Harvesting of rhizomes, however, could be more difficult and energy intensive than even sugar beet or potato systems especially if harvesting is accomplished in standing water. Also, if stands are established via the rhizomes, their removal through harvesting would necessitate annual replanting.

Harvesting only the stems and/or seed heads may be more practical and less expensive but would leave a considerable (possibly a major) amount of below-ground storage photosynthate in the field. The below-ground starch, etc. has been "paid for" in the sense that the rhizomes already have received fertilizer and pesticides, used the land, and required some management time. At this stage it cannot be determined which plant parts should be harvested nor can other questions be answered regarding harvesting costs. As such, corn grain and sugar beet harvesting cost estimates are used to represent the great deal of potential variability.

Drying and Densification

Somewhat unexpectedly, it does not appear that the dry matter content of emergent aquatic species is comparable to the floating aquatics. Rather, the dry matter content of most emergent aquatics ranges from 10 to 40%, much like most terrestial forages. Depending upon the growth habitat, however, the well known problems of removing entrained water may be as severe as those of floating aquatics. In any case the relatively high dry matter content of the emergent aquatics represents a major advantage. Sun-drying also may be possible in some climates and at certain times of the year, but as has been found with other biomass candidates dewatering and/or drying may be required.

In addition to drying, densification reflects greatly on potential transportation costs of an emergent aquatic system. Bjork and Graneli (1978), and de la Cruz (1978) both reported a densification system reminiscent of shocking corn, that is, the bundling of reeds into a size manageable for manual loading onto transport trailers. Clearly this system is unacceptable for an intensive biomass system in the United States. Other means of densification have been developed (e.g., cubing, baling, grinding, etc.) which would appear to be much more cost effective.

In order to represent the extreme diversity in potential drying and densification systems, baling of sun-dried corn stover and conventional corn grain handling and drying were selected for comparison purposes.

Total Costs

It should be noted that the target cost totals presented in Table 11 do not include the fixed costs of land, operation overhead, labor, interest, or return to management. These costs are important, frequently representing over 50% of total production costs.

It is important to recognize that not all of the analogous crops used in the target cost analysis necessarily are economically competitive biomass feedstocks at this time. Therefore, if emergent aquatics are to be used effectively as sources of fuels and chemicals, their delivered costs may (but not necessarily) need to be lower than those stated in the target analysis. The target cost analysis also does not consider the returns for the grower's use of the land. In order for emergent aquatics to be grown for biomass purposes, growers must at least perceive that the returns per hectare from growing emergent aquatics on a specific land area will be greater than the current best alternative.

TABLE 11. ESTIMATED COSTS OF PRODUCTION FOR VARIOUS CULTURAL PRACTICES POTENTIALLY ANALOGOUS TO EMERGENT AQUATIC BIOMASS SYSTEMS, 1979 DOLLARS

Cultural Practice	Analogous Crop and Assumed Yield	Est. Cost/Unit/Year[b] (Rounded to Nearest Dollar)		Notes	Reference
	Tons/Ha. (Field Wt.)[a]	$/Ton	$/Ha.		
Planting	Sugarcane (56 net T/Ha.)	$10	$580	Include only seed cane, variable and fixed machinery costs, and labor for fallow plowing and planting.	42
	Corn Grain (8.5 T/Ha.)	9	80	Include only seed costs; and variable and fixed machinery costs associated with stalk shredding, discing, and planting.	21
	Wheat (3 T/Ha.)	23	70	Include only seed costs, and; variable and fixed machinery costs associated with plowing, discing, harrowing, and planting.	21
Crop Maintenance	Corn Grain (8.5 T/Ha.)	16	138	Include only costs of fertilizer, herbicide, and insecticide, and; variable and fixed machinery costs associated with the chemicals' application and cultivation.	21
	Sugarcane (56 net T/Ha.)	5	277	Include only costs of labor, fertilizer, herbicide, and insecticide, and variable and fixed machinery costs associated with the chemicals' application and cultivation.	42
Harvesting	Corn Grain (8.5 T/Ha.)	4	37	Include only costs of variable and fixed machinery costs associated with harvesting.	21
	Sugar Beet (47 T/Ha.)	4	199	Include only labor and variable and fixed machinery costs associated with harvesting and custom hauling.	69
Drying and Densification	Corn Grain (8.5 T/Ha.)	6	55	Include only variable and fixed costs of hauling and binning, augering, and drying.	21
	Sun-Dried Corn Stover (5.6 T/Ha. <u>dry</u> wt.)	42	234	Include all costs associated with harvesting, densifying into large round bales, and transporting material an average of 40 km.	109

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a) Except as noted, all yields assumed are expressed in field weights. Estimated dry weight contents for various crops, are: sugarcane 30%; corn grain 84%; wheat, 86%; sugar beets 30%.

b) Costs of production inflated or deflated to 1979 price levels as necessary.

End Products and Potential Competition

As was discussed earlier in the Chemical Considerations portion of this report, very little information is available in general relative to chemical composition of emergent aquatics. The information that is available refers principally to above-ground plant parts, and the analyses are environmentally oriented; citing at best only crude protein, crude lipid, ash, and total carbohydrate. Considerable research is needed at an early stage in development to determine chemical composition (by plant part) from an end-product commercial perspective. The potential of a particular crop then can be more adequately assessed. The overall assessment, however, must be made subject to the inherent productivity of the plant, the agricultural inputs invested in crop growth, and the perceived returns to the grower per area unit of land.

Emergent aquatics have been used commercially since ancient times. Various authors (see especially Morton, 1976; Reimold and Queen, 1974) have commented on the multitude of applied uses for emergent aquatics. Construction materials, energy, tools, weapons, foods, and medicinals are mentioned most frequently.

Future consideration of energy, chemicals, and other products from emergent aquatics should be centered around the concept presented in Figure 2. That is, there is an inverse relationship between price per unit and size of market. The products able to be derived from emergent aquatics should attempt to be marketed in the highest valued market possible given each market's competitive framework. Those products that fill niches in the higher value-smaller sized markets are better able to recapture the higher investment costs associated with early development of products from a new crop. This is due to the inherently greater margins associated with the higher value-smaller market size products. Also, although the high value/small market size segment of the continuum is harder to enter initially (due to patent positions, etc.) the ability to stay in such markets once entered is easier.

As can be seen from Figure 2, seeking markets in the high-value/small market size area removes emergent aquatic-derived products from direct competition with fossil fuels -- relatively speaking, a very low priced, low margin industry.

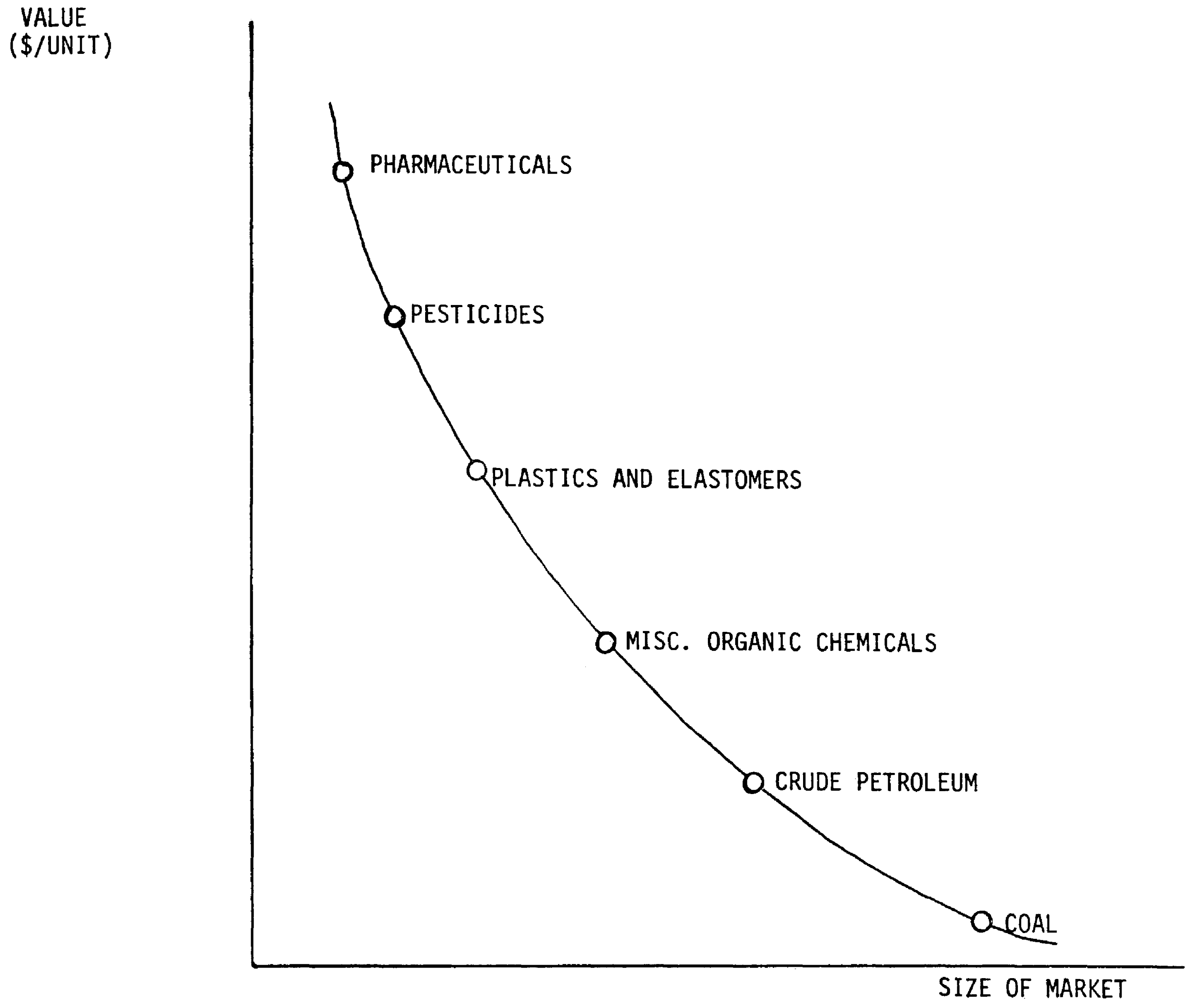

FIGURE 2. CONTINUUM HIERARCHY OF POTENTIAL END-PRODUCTS FROM EMERGENT AQUATICS.

Source: Adapted from W.J. Sheppard and E.S. Lipinsky, "Can Sucrose Compete With Hydrocarbons as a Chemical Feedstock", ACS Symposium Series #41, Sucrochemistry (J. Hickson, ed.), 1977.

SELECTION OF CANDIDATE SPECIES

Six out of the 26 emergent aquatic species described have been chosen as those which offer the greatest potential for incorporation into managed biomass systems. Thumbnail sketches highlighting several important characteristics of each species are provided on pages 64 through 69.

The criteria for selection of the six emergent aquatic species for future development were not extremely rigorous because of a number of important gaps in the data base. However, a number of key factors were noted in the selection process. Each species stands on its own in terms of one or more significant considerations, e.g., growth habitat, genetic diversity, productivity, chemical composition, etc. The detailed attributes of each of the six is addressed in previous chapters and in the thumbnail sketches and, therefore, will not be reiterated. As a group, however, several important points deserve emphasis. Collectively, the six species represent:

- a wide range of climatic adaptability
- salt sensitive, intermediately salt tolerant, and halophytic plants
- indigenous and introduced species
- C_3 and C_4 photosynthetic pathways, along with the associated physiological characteristics
- upright, erect growth (a large effective leaf area)
- high productivity in natural stands which are often monospecific
- high proportion of constituents useful for fuel and fiber.

The flexibility inherent within the group will greatly facilitate their incorporation into managed systems, allowing exploitation of specific sites essentially wherever they become available in the United States.

At this point, is is difficult to determine precisely what end products from the six selected species appear most feasible. Careful economic analyses are required prior to this decision. These economic analyses are, in turn, dependent upon comprehensive chemical and agronomic investigations which, for the most part, have not been adequately pursued. However, because it has been established that emergent aquatic species exhibit a dry matter composition similar to terrestrial forages, analogous fuel products can be considered. These products include:

- heat and electricity via combustion
- methanol via gasification
- oil, char, gas via pyrolysis
- ethanol via fermentation.

The key point in the selection of potential end products is the flexibility inherent within emergent aquatics. This flexibility is not found in, for instance, many floating aquatics and marine organisms. It is important to stress that chemical and fiber products may also play integral roles in biomass systems. As has been mentioned previously, additional analyses are required prior to identifying and assessing these products. (See Economic Considerations.)

Thumbnail Sketches of Six Selected Emergent Aquatic Species

Arundo donax L.

Botanical Description:

- common names--giant reed, carrizo, bamboo reed
- classification--monocot, family Poaceae
- growth habitat--along irrigation ditches, on sand bars and levees, occasionally in marshes
- culm erect, 2-8 m, often in large clumps
- herbaceous perennial
- rhizomatous
- flowers perfect, in panicle
- varieties recognized

Physiological Characteristics:

- photosynthesis - probably C_3
- rate of net aboveground production (t dry matter ha^{-1} yr^{-1}) - 12 to 38
- percent dry weight aboveground biomass -43

Chemical Composition: (percent of dry weight)

- culms

cellulose	40.1 to 58.0
lignin	9.4 to 24.4
ash	2.5 to 7.4

- fresh aerial portion

crude fiber	37.5
crude protein	7.6
crude lipid	1.3
ash	9.2

Cyperus papyrus L.

Botanical Description:

- common names--papyrus, paper plant, Biblical bulrush
- classification--monocot, family Cyperaceae
- growth habitat--banks and shores, in quietly flowing water up to 0.9 m deep
- culms erect, thick, woody, 1.2 to 4.6 m
- herbaceous perennial
- rhizomatous
- flowers perfect, in umbel

Physiological Characteristics:

- C_4 photosynthesis
- rate of CO_2 assimilation (mg dm^{-2} hr^{-1}) - 26
- crop growth rate (g m^{-2} d^{-1}) - 50
- rate of net aboveground production (t dry matter $ha^{-1}yr^{-1}$) - 30 to 50
- percent aboveground:belowground biomass - 78:22

Phragmites communis Trin.

Botanical Description:

- common names - common reed, carrizo
- classification - monocot, family Poaceae
- growth habitat - fresh to alkaline marshes, pond margins, ditches, along shores of lakes and streams
- culms erect, 1.5 to 6 m
- herbaceous perennial
- rhizomatous, stoloniferous
- flowers staminate or perfect, in panicle

Physiological Characteristics:

- C_3 photosynthesis
- rate of CO_2 assimilation (mg dm^{-2} hr^{-1}) - 15 to 30
- crop growth rate (g m^{-2} d^{-1}) 25 to 48
- rate of net production (t dry matter $ha^{-1}yr^{-1}$) aboveground - 15 to 35; belowground - 1 to 14
- percent dry weight aboveground biomass - 25 to 46
- percent aboveground:belowground biomass - 17:83

Chemical Composition: (percent of dry weight)

- fresh aerial portion:
  crude fiber 31.9
  crude protein (N x 6.25) - 10.6
  crude lipid (ether extract) - 2.1
  ash - 14.6

Saccharum spontaneum L.

Botanical Description:

- common names--wild sugarcane
- classification--monocot, family Poaceae
- growth habitat--along river banks
- culms tufted and small; 35 cm high, to erect forms 8 m tall
- herbaceous perennial
- rhizomatous
- flowers perfect in tassel

Physiological Description:

- C_4 photosynthesis
- rate of CO_2 assimilation (mg $dm^{-2}h^{-1}$) - 50 to 60
- crop growth rate (g m^{-2} d^{-1}) - 18 to 37
- rate of net aboveground production (t dry matter $ha^{-1}yr^{-1}$) - 15 to 40
- percent dry weight aboveground biomass - 15 to 30 percent
- percent aboveground:belowground biomass - 80 to 90:10-20

Spartina alterniflora Loisel

Botanical Description:

- common names--saltwater cordgrass
- classification--monocot, family Poaceae
- growth habitat--shallow water, salt marshes along seacoast
- culms erect, 0.1 to 2.5 m tall
- herbaceous perennial
- rhizomatous, but flaccid
- flowers perfect in spike, may be proterogynous

Physiological Characteristics:

- C_4 photosynthesis
- crop growth rate (g $m^{-2}d^{-1}$) 5 to 10
- rate of net production (t dry matter $ha^{-1}yr^{-1}$) aboveground - 5 to 22; belowground 1 to 8

Chemical Composition:

- shoots (percent of dry weight)

	crude fiber	crude protein	crude lipid	ash
short	46.1	12.4	2.3	20.6
medium	56.8	14.9	2.9	7.9
tall	63.9	14.4	1.6	11.0

Typha latifolia L.

Botanical Description:

- common names--common cattail, cossack asparagus, nailrod, broadleaved cattail
- classification--monocot, family Typhaceae
- growth habitat--shallow bays, sloughs, marshes, springs
- stem erect, 1-3 m
- herbaceous perennial
- rhizomatous
- monoecious
- imperfect flowers in dense, terminal spike, lower flowers pistillate, upper staminate

Physiological Description:

- C_3 photosynthesis
- rate of CO_2 assimilation (mg dm^{-2} h^{-1}) - 22 to 34
- crop growth rate (g $m^{-2}d^{-1}$) - 25 to 48
- rate of net production (t dry matter ha^{-1} yr^{-1}) aboveground - 11 to 33; belowground - 14 to 26
- percent dry weight aboveground biomass - 23 to 31
- percent aboveground:belowground biomass - 30 to 50:50 to 70

Chemical Composition: (percent of dry weight)

- defibered rootstock flour

total carbohydrate	- 79.09 to 81.41
crude protein	- 7.22 to 7.75
crude lipid	- 0.65 to 4.91
ash	- 2.48 to 2.84

- shoots

cellulose	33.2
crude protein	10.3
crude lipid	3.9
ash	6.9

Level of Development of Systems Components

Figures 3 and 4 depict the development level of several managed system components for the six selected emergent aquatic species. The 18 components address botanical, physiological, chemical, agronomic, economic, and ecological considerations, reflecting findings contained within the report and, as well, additional information obtained from literature and experience not necessarily referred to directly in the report.

Any approach to identifying undeveloped or less developed systems components is admittedly not without subjectivity on the part of the investigators. However, recognizing inherent constraints, it is felt that this treatment allows a fair and critical judgment as to the relative status of the species and components of managed systems, therefore identifying areas which require further research.

The format surveys the research needs of managed system development from several different perspectives. Evaluating each of the six species individually illustrates:

- the general level of development of a species, and
- the development level of the individual components within a species.

Considering all six of the species together illustrates:

- the general level of development of the six species combined
- the general development level of the individual components
- the differences among species in terms of general development level and individual components.

This flexible analysis allows a comprehensive evaluation of options for future research.

A brief discussion of the format will aid effective use of the analysis. On the abscissa are listed the considerations, e.g., botanical, physiological, etc, and within these are related components. The range of

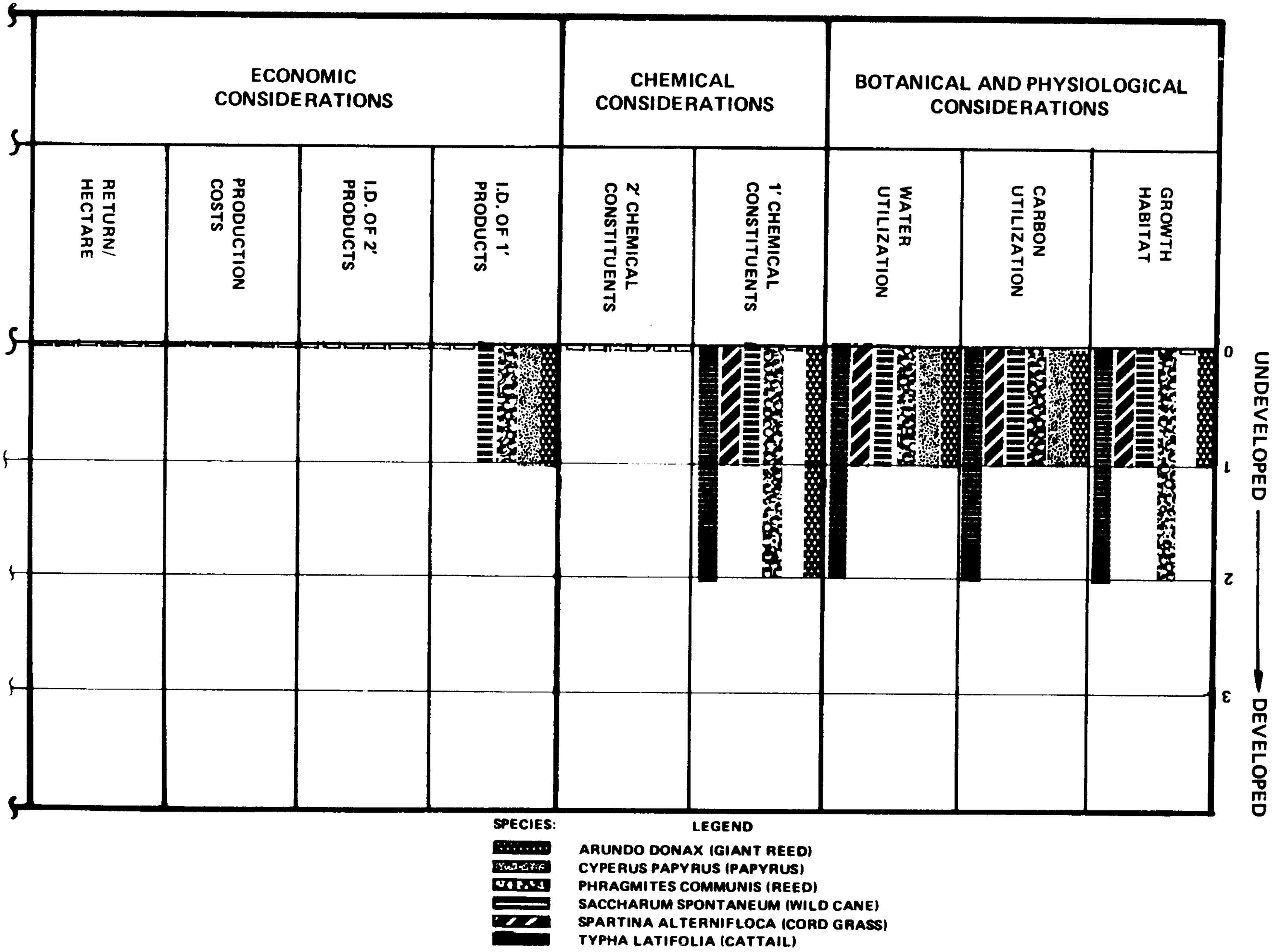

FIGURE 3. DEVELOPMENT LEVELS OF SYSTEMS COMPONENTS (Botanical and Physiological, Chemical and Economic Considerations)

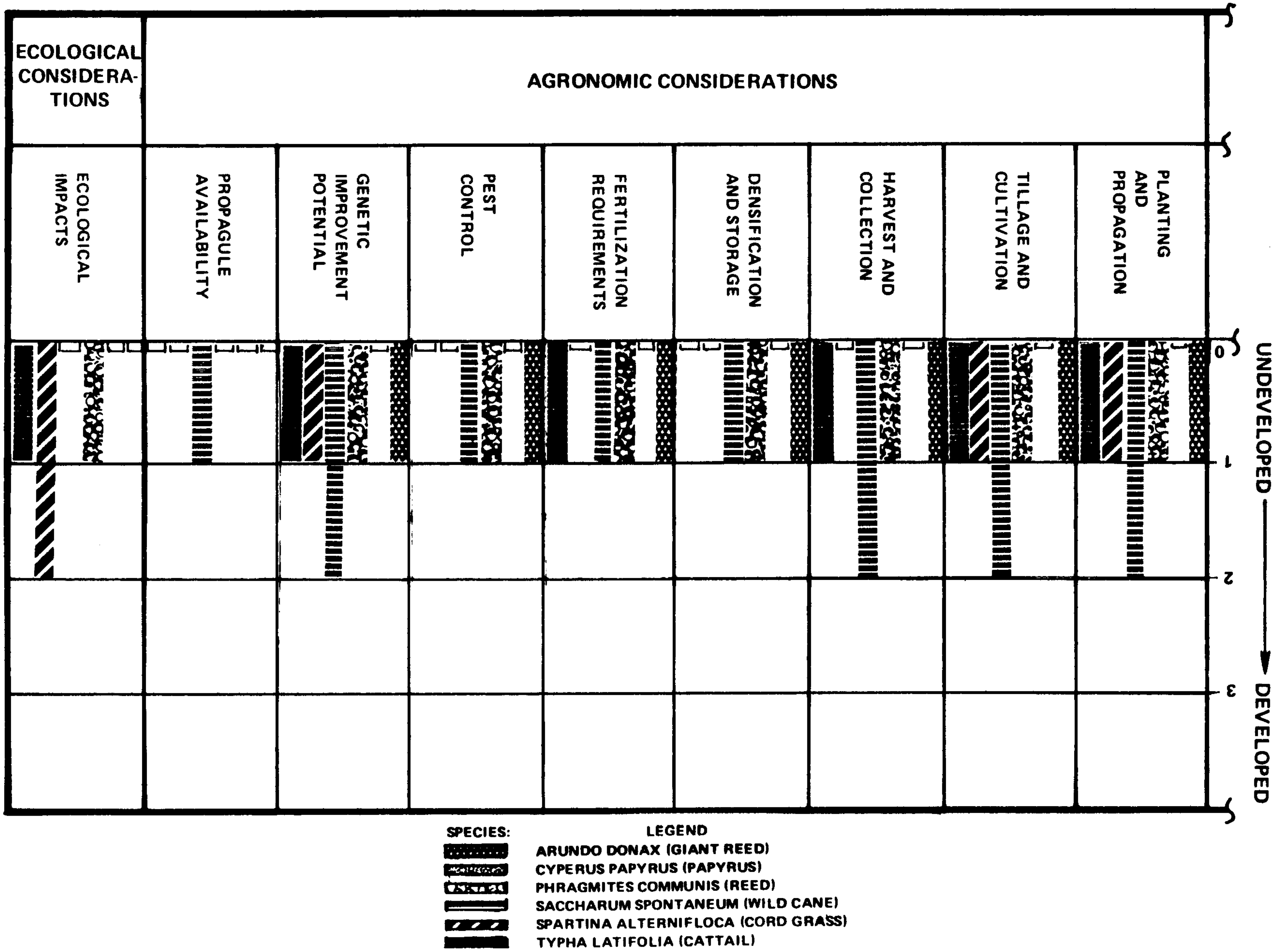

FIGURE 4. DEVELOPMENT LEVELS OF SYSTEMS COMPONENTS (Agronomic and Ecological Considerations)

development, from undeveloped (0) to most developed (3), is on the ordinate. The "0", "1", "2", and "3" designations are treated as discreet levels defined in the following manner:

0 little or no literature, little or no on-going research, or little or no analogy to existing developed system
1 some literature, on-going research and analogy to existing developed system
2 moderate to good amount of literature, on-going research and analogy to existing developed system
3 extensive literature, on-going research; currently an existing developed system.

It should be kept in mind that this evaluation is geared toward the development of _economically feasible_, _optimally managed_ systems of emergent aquatic species for _biomass energy_ purposes. In other words, a developed harvesting mechanism may be useful for the removal of aboveground biomass for weed eradication; however, if belowground biomass possesses chemical components desirable for the fuel production needed to make a biomass energy system economically sound, development of a suitable harvesting mechanism becomes necessary. As further illustration, planting mechanisms developed in terms of revegetation and stabilization of coastlines may be very undeveloped in terms of use in intensively managed biomass energy systems. Finally, although a species' natural growth conditions are extensively covered in botanical literature, the conditions necessary for optimum growth may not coincide precisely with those found in nature. There are many considerations such as those which temper the labeling of a system component "developed".

In order to further elucidate the rating criteria, an example of each of the levels (0, 1, 2, 3) in terms of the development of economical, optimally managed biomass energy systems will hopefully provide perspective.

Cyperus papyrus is rated "0" for planting and propagation. Even though this is the species reportedly used for papermaking in Biblical times, very little, if any, useful information is available regarding how it might _best_ be propagated and planted in a managed system.

Certain alternatives can be suggested but no firm conclusion can be reached. *Arundo donax*, *Phragmites communis*, *Spartina alterniflora*, and *Typha latifolia* are given "1" ratings for planting and propagation development. The first two species are currently in commercial production, *A. donax* for musical reeds, *P. communis* for pulp. (*P. communis* for energy purposes is in the experimental stages.) *S. alterniflora* is currently utilized for seacoast stabilization. Obviously, then, propagation is occurring in some form, generally vegetatively. However, whether the methods currently employed are economical, optimally managed, etc., has not been addressed. Furthermore, the use of these species for biomass energy sheds a different light on the situation. If rhizomes are removed to be used as energy feedstock, will vegetative propagation still be feasible? Is seed propagation more viable? If so, what are the storage and germination requirements of the seed? These questions, among others, require careful consideration. *T. latifolia* is not regarded as commercialized and, therefore, widely propagated. However, it qualifies for a "1" rating due to literature and ongoing research specifically regarding propagation in terms of both rhizome and seed.

Saccharum spontaneum is rated as "2" for planting and propagation. In the case of this species an analogy can be made with the presently cultivated sugar crop *S. officinarum*. In addition, *S. spontaneum* has been propagated for use in breeding programs for *S. officinarum*. However, planting and propagation is not truly "developed" until *S. spontaneum* has been applied to managed systems in its own right for the purpose of producing an energy feedstock.

None of the species has been given a "3" rating for planting and propagation. The mechanisms of planting and propagation are not currently available for application to managed systems, i.e., they are not developed. In contrast, the planting and propagation of corn is well understood and would be considered a developed component of a biomass energy system.

Evaluating the reasons behind the ratings for the 18 components within each species would be helpful but very lengthy. The above example, however, serves as a background for decision making.

The development levels graphically illustrated by the figures can also be numerically interpreted. For instance, the average ratings for all components within one species may be compared to the maximum possible (3 = developed), or to the average ratings for another species. Similarly, the ratings for each component may be averaged and compared. Such averaging may be somewhat misleading, as some components may interact or be of unequal weight or importance. However, noting these drawbacks, useful comparisons can be made. The average ratings for each of the six species and 18 components are provided in Tables 12 and 13.

TABLE 12. NUMERICAL COMPARISON OF DEVELOPMENT LEVEL OF THE SIX SELECTED SPECIES

Species	Average Level of Development* (all components combined)
Arundo donax (giant reed)	0.7
Cyperus papyrus (papyrus)	0.1
Phragmites communis (reed)	0.8
Saccharum spontaneum (wildcane)	0.9
Spartina alterniflora (cordgrass)	0.5
Typha latifolia (cattail)	0.8

*0 (undeveloped) to 3 (developed)

TABLE 13. NUMERICAL COMPARISON OF DEVELOPMENT LEVEL OF SYSTEMS COMPONENTS

System Component	Average Level of Development* (Six Species Combined)
Optimum Growth Habitat	1.2
Carbon Utilization	1.2
Water Utilization	1.2
Primary Chemical Constituents	1.3
Secondary Chemical Constituents	0
Planting and Propagation	1.0
Tillage and Cultivation	1.0
Harvest and Collection	0.8
Densification and Storage	0.5
Fertilizer Requirements	0.7
Pest Control	0.5
Propagule Availability	1.0
1ʹ Products	0.7
2ʹ Products	0
Production Costs	0
Return/Hectare	0
Ecological Impact	0.7

*0 (Undeveloped) to 3 (Developed)

RESEARCH OPPORTUNITIES

The goal of the Aquatic Species Program is to develop, demonstrate, and commercialize aquatic biomass energy systems for maximum contribution to U.S. energy demands. This goal will be accomplished if the following criteria can be met:

- Produce aquatic biomass at high and cost-competitive yields.
- Harvest aquatic biomass efficiently and inexpensively.
- Process aquatic biomass to by-products and feedstocks appropriate for the manufacture of fuels and/or petro-chemical substitutes.
- Convert processed aquatic biomass feedstocks to fuels and/or petro-chemical substitutes.

Based on our review of the available literature pertaining to the development of the emergent aquatic biomass resources, research opportunities needed for successful implementation of this program have been identified. The following research opportunities are also integral to the development of a planning program which will be able to address a "go, no-go" decision on emergent aquatic plants in a rapid, cost-effective manner.

Development of Baseline Yield Data For Managed Systems

The great majority of data collected regarding productivity of emergent aquatic plant communities has been based on addressing objectives from a botanical and/or ecological perspective. Therefore, a limited amount of information quantifying responses of emergent aquatic species under managed systems has been accessed. If the goal is to produce high and cost-competitive yields from emergent aquatic plant systems, these systems must then be managed as are other agricultural resources.

Future studies on emergent aquatic species must determine to what extent environmental factors, e.g. solar insolation, temperature, precipitation, and cultural factors, including planting method and fertility level, affect productivity. Based on this information, managed emergent aquatic systems can be implemented with the goals of producing a reliable, high yield of biomass with the cheapest unit-cost possible. In addition, this original baseline cropping information is necessary to perform the required economic analyses which determine potential commercial viability of any agricultural venture. The more accurate and precise the production information, the more accurate and precise will be the economic projections.

Improvement in Agronomic Efficiency Through Mechanization

As highlighted in the Agronomic Considerations chapter, the majority of commercial emergent aquatic systems are highly labor intensive, from seeding and/or transplanting through harvest operations. In conventional agricultural systems in the United States, such labor intensive systems are not possible due to limited access to labor and high labor costs.

Since emergent aquatic systems for fuel and fiber are "new" conceptually, much work is necessary for defining equipment needs. Particularly, the logistics of planting, tillage, and harvest of large operations must be delineated. As a further development, once needs have been identified, research will be needed to "engineer" equipment which is both energy efficient and cost-effective.

Logistics of Utilization of Belowground Biomass

Data presented in the Physiological Considerations indicate that many of the emergent aquatic species translocate much of their fixed carbon to belowground organs (rhizomes) to be stored as starch. For example, *Typha latifolia* may produce up to 70 percent of its total biomass in its belowground organs and, in some instances, 70-80 percent of the rhizomes may be composed of starch. The question then arises as whether (if possible) to harvest the rhizomes or to selectively remove only the above ground material, leaving the rhizomes to reproduce the next crop. The recovery of the starch in the rhizomes will have a great effect on the economic viability of the emergent aquatic system. Therefore, if the rhizomes are to be harvested, logistics must be developed which are energy-efficient, environmentally safe, and cost-effective. If these requirements cannot be achieved, possibly a breeding program which selects for maximum production of above ground biomass, should be implemented.

Genetic Improvement

Optimum production of the various emergent aquatics should be promoted through exploiting the species genetically. The Crop Improvement discussion suggests several means of genetic manipulation including the use of breeding, selection, and polyploid development, among others. The high returns which come as a result of a concerted effort towards genetic improvement of a plant are well documented by the development of many crops, including Saccharum spp., or sugarcane. Taking advantage of the variability of the genus, the natural polyploidy of several species, interspecific hybridization, and selection has resulted in substantial increases in disease resistance, vigor, hardiness, and, therefore, yield. Similar improvement might also be achieved with other emergent aquatic species. This would require efforts in several areas. Initial activities should focus on assessing inter- and intraspecific variability. Germplasm representing this variability should then be collected for use in actual breeding and selection measures.

Site Selection

The growth habitats and geographic distribution of emergent aquatics were described in Tables 1 and 2, respectively. The wide range of the species should be used to their greatest advantage in site selection for managed systems. Many natural habitats presently accommodate these species, e.g. marshland, seacoasts, etc. Under management these locations are likely to exhibit enhanced productivity. However in addition to these existing environments it is important to consider the development of artificial habitats where appropriate. For instance managed systems might be incorporated into industries with aquatic components such as waste effluent disposal. Stands of emergent aquatics could reduce pollutive loads; simultaneously, the harvested biomass could provide fuel, and, perhaps, additional relevant products. A comprehensive examination of these applications should be actively pursued.

Secondary Plant Metabolites

An inadequate amount of information regarding secondary plant constituents in emergent aquatic species is available in the literature. Attention needs to be directed toward this end, as commercialization of these chemicals contributes to the development of hybrid production systems, i.e., systems in which a number of coproducts are manufactured. This integrated-product concept promotes efficient use of biomass and provides adaptability to market fluctuation (Lipinsky, 1978). In addition, producing chemicals from biomass has been proposed as a means of reducing current dependence on petroleum feedstocks as a source of chemicals. Because native biomass is relatively oxygenated, production of oxygenated chemicals from biomass offers possible energy as well as economic savings relative to the current practice of manufacturing these compounds from reduced hydrocarbon feedstocks (Budiansky, 1980)

Propagule Availability

Developing managed systems of plant species which have not been cultivated on a widespread basis requires assessment of propagule availability. Initially seeds or other generative material are necessary for experimental purposes such as field and growth-chamber studies, breeding research, etc. Additionally, for purposes of commercial-scale production, a feasible means of producing, transporting and storing viable propagules in an economically sound fashion must be developed.

Plant Chemistry and Energy Products

The wide range of values for chemical composition, lack of complete information for many of the plants, and the absence of information pertaining to belowground material indicate the need for various chemical analyses of emergent aquatic species. In terms of energy production, however, composition alone is not adequate for accurately predicting potential levels of fuel generation. Chemical engineering aspects of fuel production from each of the biomass feedstocks must also be addressed.

As was mentioned briefly in the Chemical Considerations Section, saccharification of *Typha* cellulose required unique experimental conditions (Ladisch and Dyck, 1976). In addition, hydrolysis of Typha root starch has reportedly met with some difficulty (Line, 1980). The dense micelles which contain the starch were found to be somewhat resistant to the conventional hydrolytic processes applied to potato and grain starch. Further, yields of ethanol resulting from fermentation were much lower than expected, due perhaps to organic or inorganic constituents detected in the root which adversely affect the yeast. It may be necessary, therefore, to investigate each of the emergent aquatic species in terms of the specific conditions necessary for conversion to a fuel product.

Economics

Economics virtually is an untouched area in emergent aquatic biomass evaluations to-date. Future work in the emergent aquatic area should be approached from the outset, in a multidisciplinary systems framework, economics acting as the sounding board for technological ideas. Economics also can provide direct guidance to technical efforts. For example, early determination of chemical composition of emergent aquatic plants will allow the economics staff to determine potential markets, necessary cost targets and existing competition. Economics also will aid in dictating which plant parts to harvest, thereby aiding breeding efforts, machinery development, etc. Actual field trials with commercial growers conducted by a combined economic and technical staff will allow early determination of grower acceptance, needed cultural practices, costs of production, yield potential, and logistic concerns.

GLOSSARY

adventitious - developing in an irregular manner, e.g., stems from roots

adventive - an introduced plant which has not been established or naturalized with certainty

alkaline - associated with an alkali, a soluble mineral salt of some arid soils

annual - a plant which completes its life cycle in one year or less

anthropogenic - relating to man's impact on nature

argillaceous - growing in a clayey substrate

brackish - water containing intermediate levels of dissolved salts

calcareous - containing excess available calcium

corm - enlarged, bulblike stem, often underground

cosmopolitan - found in a widespread geographical location

culm - the stem of grasses and sedges

cyme - a broad, flat-topped inflorescence possessing a single terminal flower which opens before the lateral flowers

detritovores - organisms which consume non-living organic matter

detritus - particulate organic matter derived from decomposition of dead organisms

dioecious - a plant which has pistillate and staminate flowers occurring on different plants

dredge spoil - rock and earth removed by dredging operations

edaphic - pertaining to soil conditions

embayed - a sheltered or partially enclosed bay

emergent - raised above the water surface

estuarine - relating to regions where coastal streams enter the sea

eutrophication - process by which water bodies are enriched in dissolved nutrients and organic matter

endemic - restricted to a particular geographic region form - a category used to describe sporadic variations within a species, e.g., a white petaled flower occurring within a normally purple petaled species

genome - a chromosome set

grain - the fruit of members of the Poaceae family

habit - the growth form or general bodily appearance of a plant

habitat - the environment in which a plant grows

halophyte - in general, a plant of saline or alkaline substrates; may be restricted to plants which survive in a concentration of NaCl greater than 0.5 percent

involucre - the condition in which a group of bracts subtend or enclose an inflorescence

marcescent - withering but attached

marsh - a region of wet or periodically wet land usually characterized by grasses, cattails, etc.

moniliform - cylindrical with contractions at intervals

monoecious - a plant which has pistillate and staminate flowers occurring in different locations on the same plant

morphology - the structure of the vegetative and reproductive features of an organism

naturalized - a plant with foreign origin, which thrives as if native

obligochaetes - a class of worm-like organisms

oligotrophic - deep water bodies with low nutrient levels and low primary productivity

outcrossing - mating with another individual

paludal - marshlike

panicle - a compound inflorescence in which the axis is branched at least once.

perennial - a plant which lives for more than two years

pistillate - plants or structures bearing female and not male parts

prostrate - lying horizontally e.g., stems or leaves proterogynous - a flower having the stigma ripe for pollen prior to the maturity of the anthers of the same flower

rhizome - a horizontal, underground stem

saline - pertaining to salt

slough - a sluggish channel; a muddy place

spike - an inflorescence with a single axis and sessile flowers

staminate - plants or structures bearing male and not female parts

stolon - a horizontal stem rooting at the nodes

submergent - not rising above the surface of the water

terete - cylindrical or tapering

trophic - nourishment; trophic level refers to one of the hierarchal strata of the food web

tuber - an enlarged, fleshy underground stem

umbel - an inflorescence consisting of a few to many flowers on pedicels of equal length, arising from a common stalk

variety - subdivisions of species; a major variation within a species

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16. Abstract (Limit: 200 words) A review was conducted of the available literature pertaining to the following aspects of emergent aquatic biomass: identification of prospective emergent plant species for management; evaluation of prospects for genetic manipulation; evaluation of biological and environmental tolerances; examination of current production technologies; determination of availability of seeds and/or other propagules, and projections for probable end-uses and products. Species identified as potential candidates for production in biomass systems include *Arundo donax*, *Cyperus papyrus*, *Phragmites communis*, *Saccharum spontaneum*, *Spartina alterniflora*, and *Typha latifolia*. If these species are to be viable condidates in biomass systems, a number of research areas must be further investigated. Points such as development of baseline yield data for managed systems, harvesting conceptualization, genetic (crop) improvement, and identification of secondary plant products require refinement. However, the potential pay-off for developing emergent aquatic systems will be significant if development is successful.

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