Production of Cattail (Typha spp.) Biomass in Minnesota, USA

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ABSTRACT

Typha spp. are being considered for bio-energy crops in Minnesota because of their high productivity in northern latitudes, starchy rhizome system, and ability to utilize the state's 3.4 million hectares of wetlands. Standing crop yields up to 22.4 Mg ha\(^{-1}\) of leaves and 30.9 Mg ha\(^{-1}\) of rhizomes have been observed for Typha spp. This review article characterizes Typha in terms of biomass and nutrient accumulation patterns, evapotranspiration rates, pest problems, and fuel characteristics. Problems of establishing stands of Typha from seed, seedlings or rhizomes are identified; management practices needed to maximize productivity while minimizing system inputs are examined. Finally, multiple use opportunities, land availability, harvesting equipment requirements, and overall economics are assessed. At present, annual harvesting of leaves appears favored because of sustainable yields, minimal nutrient requirements, effective weed control, and low harvesting costs while sacrificing only 13-17% of the average annual yield from a combined leaf and rhizome harvest. Annual leaf harvests were found to have a potential return on investment of 18%. If the price differential between cellulosic leaf biomass and starchy rhizome biomass becomes high enough, a combined leaf and rhizome harvest may be preferable in the future.

Key words: Typha, biomass, energy, productivity, nutrient, evapotranspiration, economics.

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INTRODUCTION

The State of Minnesota, located in north central United States, is an energy importing state with no indigenous fossil fuel reserves. The demand for biomass-derived fiber fuels has grown substantially in the past decade and is expected to continue to grow in coming decades. With growing demand, currently exploited sources such as forest product wastes and crop residues may need to be supplemented with inexpensive biomass grown expressly for fuel use (bio-energy crops). Wetland plants have been under consideration as potential bio-energy crops in Minnesota since 1973 because of their high productivity, interesting chemical composition, and the fact that they already grow naturally on a substantial portion of the state's 3.5 million hectares of wet marginal lands.1

Early screening for potential wetland bio-energy crops was conducted through literature reviews and natural stand surveys to identify productive species which are adapted to wetland habitats and occur naturally in monoculture or in mixed stands with species of similar harvesting requirements.2,3 Eight potential species were identified and subjected to yield trials and nutrient requirement studies. The species included three cattails (Typha latifolia L., Typha angustifolia L., Typha × glauca Godr.), common reed (Phragmites australis (Cav.) Trin. ex Steudel), sedge (Carex atherodes Spreng.), bulrush (Scirpus fluviatilis (Torr.) Gray), bur reed (Sparganium eurycarpum Engelm.) and cordgrass (Spartina pectinata Link).4 Of the eight native wetland plants selected and tested, cattails (Typha spp.) appear to be the most promising candidates for a wetland bio-energy system in Minnesota. This conclusion is based on the results of the yield and nutrient studies as well as other criteria, such as adaptability to site conditions, resistance to pest problems, and harvesting requirements. Additionally, a substantial amount of research has been done on Typha spp., which should result in a shorter timetable for commercial development than for other wetland species.

Evaluation of the commercial potential of wetland plants as an energy source depends on an understanding of the trade-offs between productivity and production costs. Research supported by the Bio-Energy Coordinating Office at the University of Minnesota has sought to identify, test, and evaluate potential production practices to better understand these trade-offs. Ultimately, information gained from this project could be used to develop a bio-energy production system that maximizes output while minimizing inputs, resulting in a renewable energy resource that is economically competitive. This report reviews the information compiled on this system since 1974. All weights presented are on a dry weight basis.
CHARACTERISTICS OF *TYPHA* SPECIES

Several species of cattails are native to Minnesota, and differences between them must be considered in the selection of a species for a particular site. *Typha latifolia* (broadleaf cattail), *Typha angustifolia* (narrow leaf cattail), and *Typha × glauca* (a hybrid of the other two species), all occur naturally in Minnesota and are potential bio-energy crops. These species all have aboveground leaves, an interconnected belowground rhizome system, and an easily recognizable inflorescence (Fig. 1). Traits which may vary between species, and thus affect species selection, include yield potential, tolerance to various site conditions, nutrient uptake patterns, evapotranspiration rates, resistance to insect and animal pests, and characteristics as a fuel.

**Productivity**

Natural stand surveys and field trials have provided baseline numbers on potential productivity of *Typha* spp. Mean above- and belowground yields were compiled from reports for stands of the two native cattail species and their hybrid (Table 1). Strict comparisons of these yields cannot be made since many variables, such as age of stand, planting

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**Fig. 1.** General growth characteristics of perennial *Typha* species showing aboveground leaves, a flowering shoot, and the belowground interconnected rhizome system.
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### TABLE 1
Comparison of Standing Crop for *Typha* spp. from Natural and Cultivated Stands

<table>
<thead>
<tr>
<th>Species</th>
<th>Source</th>
<th>Standing crop (dry Mg ha$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Above-ground</td>
<td>Below-ground</td>
</tr>
<tr>
<td><em>T. latifolia</em></td>
<td>Natural Stands —</td>
<td>4.3–14.8</td>
<td>4.9–9.2</td>
</tr>
<tr>
<td></td>
<td>North Central USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cultivated Stands* —</td>
<td>4.7–8.2</td>
<td>4.4–5.4</td>
</tr>
<tr>
<td></td>
<td>Minnesota, USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>T. angustifolia</em></td>
<td>Natural Stands —</td>
<td>12.3–21.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>North Central USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cultivated Stands* —</td>
<td>2.2–13.9</td>
<td>6.6–25.3</td>
</tr>
<tr>
<td></td>
<td>Minnesota, USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>T. × glauca</em></td>
<td>Natural Stands —</td>
<td>6.7–22.4</td>
<td>10.1–30.9</td>
</tr>
<tr>
<td></td>
<td>North Central USA</td>
<td></td>
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<tr>
<td></td>
<td>Cultivated Stands* —</td>
<td>5.7–8.1</td>
<td>6.9–9.2</td>
</tr>
<tr>
<td></td>
<td>Minnesota, USA</td>
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</tbody>
</table>

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*2–5 year old planted stands ≥ 0.2 ha in size.

density, soil fertility and pH, are inherent in the mean values given. However, the data from both natural stands and field trials suggest that *T. angustifolia* and the hybrid have a higher yield potential than *T. latifolia* in the north central United States.

In field trials designed to compare the yields of *Typha* species under identical growing conditions, one study found higher yields for *T. × glauca* (14.8 Mg ha$^{-1}$ of total biomass) than for *T. angustifolia* (11.7 Mg ha$^{-1}$ of total biomass). A second trial found that *T. angustifolia* produced nearly twice as much shoot biomass (8.1 Mg ha$^{-1}$) as *T. latifolia* (4.7 Mg ha$^{-1}$) under identical field conditions. These two studies agree with data of others (Table 1) which indicate that *T. angustifolia* and *T. × glauca* are generally more productive than *T. latifolia*.

In addition to yield considerations, patterns of biomass distribution in the plant over the growing season are important for determining harvest times and composition of biomass end product. Patterns of *Typha* leaf and rhizome biomass production and partitioning in a managed field trial showed that during the establishment season, growth is in a lag phase during the first 8 weeks after planting (Fig. 2). Peak dry matter production occurs during the next 4-week period, when nearly half of the season’s net biomass production takes place. From early September through the end of the growing season, total biomass production
Fig. 2. Variation in leaf, rhizome, and total dry weight from pooled data of *Typha latifolia*, *T. angustifolia*, and *T. × glauca* over the course of two growing seasons and two winters. Sampling interval equals 28 days. (Randomized complete block design; regression analysis showed no difference between species at $\alpha = 0.01$.)

continues to increase, although all of this increase occurs in the below-ground rhizome system.

Different patterns of biomass production and partitioning occur during the second season, although the general shape of the growth curves is similar. The duration of the lag phase in the second year is several weeks shorter than in the establishment season, probably due to the biomass reserves in the rhizomes which are mobilized for leaf growth. The period of rapid growth following the lag phase is longer in the second season, lasting around eight weeks. Approximately two-thirds of the net seasonal biomass production occurs in the 8-week period between 7 July and 2 September (Fig. 2). In September and October, total biomass production slowed as it had in the first season, with only 10% of the total seasonal biomass being produced during these two months. Partitioning of biomass again shifts from leaves to rhizomes during this time, although not as completely as it did in the establishment season.

Net seasonal production, defined as standing crop at the end of the growing season minus standing crop at the beginning of the growing season, more than doubles for leaf biomass in the second year, while net seasonal rhizome biomass production is nearly identical in the two years (Fig. 2). Over winter, the standing crop of *Typha* rhizomes declines 25% during the first winter and a nearly identical 28% during the second winter (Fig. 2). These growth curves, which are typical of many perennial plants, are important for understanding the consequences of various
management techniques which can disrupt normal accumulation and partitioning of biomass important to the sustainability of biomass yields. Understanding the curves also may provide opportunities for selecting the chemical composition of the biomass end product, since the rhizome biomass varies between 11 and 41% starch and sugars, depending on the time of year.\textsuperscript{3}

**Nutrient requirements**

Seasonal patterns of nutrient uptake in *Typha* spp. have been characterized\textsuperscript{4,19} using randomized designs in fertilized field trials to identify ways in which management practices can be altered to reduce the need for expensive fertilization. Patterns of uptake of nitrogen, phosphorus, and potassium, and partitioning of these nutrients between *Typha* leaves and rhizomes (Fig. 3) over the course of two growing seasons and two winters, showed that during the establishment season, patterns of nutrient uptake and partitioning closely paralleled patterns of biomass production (Fig. 2). A lag phase of approximately 8 weeks is followed by a 4-week period of rapid nutrient accrual, when 50% of the net seasonal uptake of nitrogen, phosphorus, and potassium occurs. Nutrient uptake continues at a slower rate in September and October, just as biomass production does, with less than a third of the season’s total nitrogen, phosphorus, and potassium taken up during this 8-week interval.

Partitioning of nutrients between leaves and rhizomes also follows a pattern similar to biomass production, with nutrients shifting from the rhizomes to the leaves during the lag and linear growth phases, and shifting to the rhizomes again during the fall. By the last sampling date, over two-thirds of the season’s nitrogen, phosphorus, and potassium accumulation was found in the rhizomes. It appears that translocation of these nutrients occurs, since the net increase of nutrients in the rhizomes in the fall greatly exceeded total plant uptake.

Nutrient uptake and partitioning patterns in the second season (Fig. 3) were slightly different than those seen in the first season. The *Typha* plants began the season with more than half of the second season’s peak nutrient content stored in the rhizomes, whereas less than 5% had been present in the planting stock in the first season. The lag phase of nutrient uptake is generally shorter in the second season and the period of maximum nutrient uptake lasts 8 weeks rather than 4 as it had in the first year, with three-fourths of the season’s total nitrogen, phosphorus, and potassium accumulating during that time. The final 12 weeks of the season accounted for only 10–16% of the nitrogen, phosphorus, and potassium uptake for the second season.
Fig. 3. Nitrogen, phosphorus and potassium uptake patterns in managed stands of *Typha latifolia*, *T. angustifolia* and *T. × glauca* over the course of two growing seasons and two winters. Sampling interval equals 28 days. (Randomized complete block design; regression analysis showed no difference between species at \( \alpha = 0.01 \).)
Information on nutrient storage in *Typha* rhizomes over the course of two winters (Fig. 3) showed approximately 10% of the nitrogen stored in the rhizomes was lost over winter in both years. For phosphorus, about 25% is lost during the winter. Potassium losses are more variable since potassium is subject to greater leaching than nitrogen or phosphorus; losses have been observed to vary from 10 to 30%.

**Water requirements**

Estimates of water use by *Typha* species are important for selecting biomass production sites and estimating potential irrigation costs. Although wetlands, with water tables at or near the soil surface, will be used for *Typha* bio-energy production, it is possible that irrigation will be required to maintain an equilibrium balance of water inputs to water losses. If irrigation is required, sites will need to be located near streams or other water bodies, dikes will need to be constructed, and annual irrigation costs will be incurred. The irrigation requirements and water control methods will also be important determinants of management and harvesting equipment requirements.

Evapotranspiration amounts (105–150 cm year\(^{-1}\)) previously reported in the literature\(^{20,21}\) for *Typha* spp. in Poland are approximately twice those for corn (*Zea mays*) and alfalfa (*Medicago* spp.) grown in Minnesota. These amounts form *Typha* also are one and a half to two times greater than annual precipitation in Minnesota. More recent studies of water loss by *Typha* species in Minnesota suggest that evapotranspiration rates under field conditions are only 40–60 cm year\(^{-1}\), although significant differences in evapotranspiration occur with variations in microclimate, water regime, and species.\(^{22}\)

Microclimate appears to have the most significant effect on water loss from, and irrigation requirements for, *Typha* paddies.\(^{22}\) A large contiguous stand of *Typha* uses 24–57% less water per unit of biomass produced than small, exposed research paddies in terrestrial environments. For example, a 0.2 ha cultivated stand of *T. angustifolia* was found to produce 1.9 g of leaf biomass per liter of water evaporated, whereas small (0.9 m diameter) research paddies produced only 0.8 g liter\(^{-1}\).

Species differences also result in significant variability in evapotranspiration. When water use efficiency is calculated, *T. latifolia* has been found to be slightly more efficient (0.88 g leaf biomass per liter evaporated) than *T. × glauca* (0.80 g liter\(^{-1}\)) or *T. angustifolia* (0.83 g liter\(^{-1}\)).\(^{22}\) Water regime is another factor causing differences in both productivity and water use efficiency, as discussed later.
Physiography

Another variable among cattail species is their tolerance to various site conditions. Although the optimum pH range for each species is not clearly defined, it appears that *T. angustifolia* is more tolerant of alkaline and saline environments than *T. latifolia*.\textsuperscript{23-28} Observations in Minnesota of *T. angustifolia* growing vigorously in pH 9 soil and *T. latifolia* growing in pH 5 peat soils support these reports, although productivity of *T. latifolia* does diminish when the pH drops below 6.5.\textsuperscript{29}

*T. angustifolia* is better suited to deeper water conditions (50–115 cm) than *T. latifolia* because of its taller leaves and larger rhizome storage system.\textsuperscript{30,31} Although *T. angustifolia* grows well in shallow water, *T. latifolia* can outcompete *T. angustifolia* in shallow water sites because of its greater leaf area and shade tolerance.\textsuperscript{30} *T. × glauca* is generally found in habitats intermediate between the two parent species. Soil pH and water depth, then, are two factors which might affect site selection, or, alternately, selection of a species for a particular site.

Herbivory

Insect and animal herbivory is another factor which appears to occur differentially among cattail species. *Bellura obliqua* is a stem-boring moth whose larvae are found frequently on *T. latifolia*, but rarely on *T. angustifolia*.\textsuperscript{32-34} This moth is the most destructive and common insect pest found on cattails in Minnesota, and has been shown to reduce total plant productivity by 45% in affected shoots,\textsuperscript{35} although only about 10% of shoots are affected. Muskrats can also significantly reduce the extent of wetland vegetation, including cattails.\textsuperscript{36} It has been reported that muskrat prefer *T. latifolia* and *T. × glauca* to *T. angustifolia*.\textsuperscript{24} Observations in a Minnesota field study support this finding.\textsuperscript{11} It is known that muskrats can have a major impact on cattail productivity in small stands if they are not controlled. Control measures should not be that difficult, however, and the value of pelts from harvest animals could contribute an additional economic benefit.

Fuel characteristics

The chemical composition of *Typha* leaves and rhizomes varies significantly. Leaves are largely cellulosic in composition, while rhizomes in the fall consist of approximately 40% starch and sugars.\textsuperscript{3} The energy content of dry shoots ranges from approximately 17.6 to 18.9 MJ kg\textsuperscript{-1}, with no clear distinction between species.\textsuperscript{11} The rhizome energy content is
generally lower for all species, ranging from approximately 16.7 to 16.8 MJ kg\(^{-1}\). Ash content, which represents an undesirable by-product in any fuel conversion process, also does not appear to differ between species, with ash contents of shoot samples ranging from 3.7 to 6.8%.

**STAND ESTABLISHMENT**

Three possible methods have been examined for establishing *Typha* stands: seeding, transplanting seedlings, and transplanting portions of the rhizome system. Field experiments have demonstrated that each of these methods is technically feasible.\(^2\)\(^,\)\(^10\)\(^,\)\(^11\) Criteria for selecting the best method have been based on the goals of minimizing establishment costs and ensuring rapid, uniform stand establishment and development. Costs include those for labor, equipment, materials, and, if needed, storage of plant material and greenhouse space. Also, since establishment only occurs once for these perennial plants, the costs of productivity differences in the establishment season and subsequent years resulting from the choice of establishment method must be considered.

**Transplantation**

The principal advantages of establishing cattail stands by transplanting either seedlings or rhizome pieces are similar. A consistently high survival rate (generally 90–95% of transplants) results in uniform stands and rapid growth during the establishment season. Also, transplants are generally tolerant of mechanical handling and a range of moisture conditions from saturated soil to 15 cm of standing water. This tolerance allows the use of mechanical vegetable transplanters and permits early flooding of the field which minimizes competition from weed species. First season productivities of stands established by either rhizome or seedling transplant methods are generally high enough to warrant above-ground biomass harvest in the first year.

The principal disadvantages of transplanting either seedlings or rhizome pieces are also similar. Costs of materials, labor, and production space are high whether it is for harvesting and storing rhizome planting stock, or for growing seedlings. Given that an initial planting density of at least 10 seedlings or rhizomes per square meter appears to be necessary to achieve high productivities, 100,000 transplants would be required for a 1-ha field. This number of transplants would be expensive to obtain, since rhizomes must be harvested and processed before using and seedlings must be grown for 90 days in a greenhouse prior to plant-
ing. Transplantation is also relative expensive, slow and labor-intensive using current technology.

**Seeding**

With evidence that initial planting density is correlated with eventual stand productivity, seeding appears to be the preferred method of stand establishment. Cattail plants can produce 200,000 seeds per flowering head, and these are relatively simple to collect and process. Assuming 100% germination, a single inflorescence could theoretically provide enough seed to establish a stand approximately 0.4 ha in size with a density of 50 plants per square meter, although the seeding rates actually used in the field experiments were about 10 times this theoretical rate. Seeding also offers the advantage of being able to use inexpensive rapid application methods.

While seeding has several obvious advantages, it also has major problems associated with a lack of reliability as an establishment method, resulting from highly variable germination and seedling survival rates under a number of field conditions tested to date. The field establishment problems appear to result from the sensitivity of cattail seed germination and development to certain environmental factors. Optimum germination rates were demonstrated under the following conditions: high temperatures (29.5°C), reduced oxygen concentrations, and exposure to red light. This is consistent with observations in nature of dense cattail seedlings, occurring primarily in shallow water or mudflats resulting from marsh drawdowns. Thus, establishing cattail stands from seed may require mimicking the field conditions seen in natural marsh drawdown in order to meet the physiological requirements for seed germination and development.

In addition to these physiological constraints on field conditions for successful cattail seeding, there are also some technical constraints which have been encountered in past seeding attempts. Dry seeding requires very precise control of soil moisture: too little moisture inhibits cattail seed germination and stimulates weed growth; too much moisture (standing water) can cause a redistribution of the floating dry seeds, resulting in uneven stand establishment. With hydroseeding, germination may be induced prior to field application, giving the seedlings an advantage over weed competitors, but once applied, the seedlings must have a narrowly defined environment for continued growth in the month following application. Also, fertilizer application to the site prior to planting has been found to be inadvisable despite potential yield increases, since fertilization frequently results in extensive algal blooms.
which have been shown to shade and subsequently kill the young seedlings.

Taking into account technical and physiological limitations, it appears that germination and survival is superior in flooded paddies which are slowly drawn down to saturated conditions over the course of three weeks, than in paddies which have no standing water (Fig. 4). This is true whether or not the downy seed hairs are removed. Under flooded or saturated conditions, germination and survival is higher when the hairs are left intact. This difference is possibly explained by the observation that in both flooded and saturated paddies the hairs aid in keeping the tiny seed from being buried in the mud; the difference does not appear to be caused by seed being damaged during the hair removal process.

In summary, applying seed, with hairs intact, onto a flooded site and allowing the water level to drop slowly is apparently the best scenario for establishing a cattail stand from seed. This scenario mimics the establishment of new stands which occurs during natural marsh drawdowns, and has the advantage of offering improved weed control over constant saturated conditions.

A final consideration for stand establishment from seed is that of seed source. *Typha angustifolia* and *Typha latifolia* seed can be collected from large monospecific natural stands with reasonable certainty that the seeds are not hybrids. Seeds for *Typha × glauca* must be obtained by

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**Fig. 4.** Germination and survival percentages for *Typha latifolia* and *T. angustifolia* seed using four seeding methods. Methods were flooded versus saturated soil applications and seed hairs present (H) versus seed hairs absent (NH). (2 × 2 × 2 factorial design; 6 replicates per treatment. No significant difference between species; flooded versus saturated and H versus NH different at α = 0.01.)
crossing *T. latifolia* and *T. angustifolia*. While crossing is relatively easy to accomplish, there are currently no readily available sources of seed for *Typha × glauca*. There will be a need for commercial seed producers if *Typha × glauca* bio-energy systems are developed.

**STAND MANAGEMENT PRACTICES**

Following the initial establishment phase of the production process, management of *Typha* stands becomes an important factor in achieving high, sustained productivity. Management factors are also critical in determining the economic feasibility of a *Typha* bio-energy system. Fertilizer, irrigation, and pest control requirements can result in significant costs, as in comparable agricultural systems, and must be minimized wherever possible while maintaining adequate productivity levels.

**Fertilization**

In a natural system, nutrient recycling can greatly reduce the need for additional nutrient inputs. In a bio-energy production system, nutrients are removed from the system when the biomass is harvested. High, sustained yields require that these nutrients be replaced. This can be accomplished to varying degrees by natural biological and physical processes and by application of fertilizers. The actual amounts and types of nutrients which need to be replaced through fertilizer application will depend on how much is replaced by natural processes, and the overall nutrient requirements of *Typha* described previously.

In addition to gross levels of nutrients used for *Typha* production over the course of a growing season, seasonal patterns of uptake are of interest since applied nutrients can be lost from the system before being taken up by the plant, as is the case with nitrogen losses resulting from denitrification. Several measures can be taken to minimize fertilizer losses, such as selecting the proper form of fertilizer and controlling water levels to minimize leaching and aeration. Additionally, timing of fertilizer application to coincide with the time of maximum uptake by the plant appears to be a promising control measure.

Results addressing the questions of timing and method of nitrogen application showed end of season productivity was highest for the preplant and midseason soil injection treatments (Fig. 5). The high productivity of the preplant method was not expected since loss of nitrogen through denitrification was anticipated. Possibly, early season nitrogen availability allowed the plants in the preplant treatment to grow
faster than the plants in other treatments during the first two months of the growing season. Relative productivity for the preplant treatment was three times that of other treatments by the time of midseason nitrogen application. Despite this productivity advantage, preplant treatment is applicable only for rhizome and seedling planting; not seeding where algal blooms can be a problem, as previously discussed.

The surface-applied and foliar-applied treatments both resulted in lower productivities than the preplant and injected treatments. Both of these treatments would be superior application methods from a technical and cost standpoint since they could make use of existing agricultural equipment or aerial application methods. The injected method, by comparison, would require equipment modification or development.

The time of harvest is another factor which can affect nutrient loss from the system. Nutrients are mobilized from the aboveground plant tissue late in the growing season and transported to the rhizome system for storage over winter. By timing harvest to occur after nutrients have been translocated to the rhizomes, unnecessary nutrient removal can be avoided when leaf tissue is the desired biomass product. Harvesting dates and the type of biomass harvested will also be important for determining fertilizer requirements. This is a point worth considering in more detail, since there are several productivity–production cost trade-off
possibilities inherent in the nutrient uptake results. Possible harvesting scenarios for cattail which are discussed later include: (1) shoot biomass only, harvested annually, (2) shoot biomass only, harvested semiannually, and (3) shoot biomass harvested annually combined with rhizome biomass, harvested biennially. Each harvesting scenario will result in different productivity levels and require different levels of nutrient inputs.

The first harvesting scenario — annual, shoot biomass harvests — would result in the greatest conservation of nutrients. Forty per cent of the nitrogen, phosphorus, and potassium (kg ha\(^{-1}\) basis) found in the shoots (Fig. 3) in midseason is transferred to the belowground rhizome system by the end of the growing season. Approximately 75% of these nutrients are conserved in the rhizome system over winter and are then available the following spring for new growth. By harvesting shoots in October and November, the least amount of nutrients would be removed from the plant system compared with other harvesting scenarios, thus requiring the lowest amount of fertilization.

The second harvesting scenario — semiannual harvests of shoots only — is of interest because of the potential of increasing yields. This scenario is analogous to multiple harvests of crops like alfalfa (Medicago spp.). One of the disadvantages of multiple harvests of cattails is the large amount of nutrients that would be removed during the midseason harvest. The greatest amount of nitrogen, phosphorus, and potassium (kg ha\(^{-1}\) basis) in shoot biomass is found at midseason, prior to transfer of nutrients to the rhizome system (Fig. 3). By removing this nutrient-rich biomass at midseason and again at the end of the season, the amount of fertilizer required would be increased around twofold compared with the annual harvest.

The final harvesting scenario — annual, aboveground shoot harvests combined with biennial rhizome harvests — has the potential of increased yields over the other two scenarios and would also result in a higher quality biomass product since rhizomes have been shown to contain 40% fermentable starches and sugars in the fall.\(^3\) Again, one of the disadvantages of this scenario is increased nutrient removal and higher fertilization costs. By removing the rhizomes, the overwintering nutrient storage system of the cattail plant would be lost. Although a study has not yet been done to determine the amount of additional fertilizer that would be required compared with an annual aboveground harvest, it could be estimated from data in Fig. 3 that twice the amount of fertilizer would be needed.

Based on the above results, it appears that an annual shoot biomass harvest would require the lowest levels of fertilization. The effect of
these harvesting scenarios on sustainable total annual productivity is currently being investigated.

Irrigation

In addition to estimates of seasonal water use by *Typha* spp. described earlier, studies have been conducted to determine if water use could be reduced by using different water management scenarios, including: (1) flooding throughout the season, (2) maintenance of a saturated soil only, and (3) a midseason drawdown of water similar to the system of wild rice (*Zizania palustris* L.). In examining these options, it is necessary to analyze the trade-offs between irrigation, productivity, and other factors such as weed competition and harvest conditions.

On average, for all *Typha* species, constantly flooded paddies use approximately 5% more water through evapotranspiration and transpiration than saturated paddies, which in turn use more water than midseason drawdown paddies. Since water use is, in part, a function of productivity, biomass dry weights need to be divided by evapotranspiration rates to determine water use efficiency. When this is done, the constantly flooded paddies have a higher water use efficiency (0.89 g leaf biomass per liter evapotranspired) than saturated (0.80 g liter\(^{-1}\)) or drawdown (0.83 g liter\(^{-1}\)) paddies. The saturated and drawdown management options have a detrimental effect on leaf productivity which lowers their water use efficiency.

A flooded water management system appears superior to the other systems studied in terms of water use efficiency. However, a drawback of a constantly flooded field is that wet field conditions for harvesting in the fall will require specialized high flotation equipment instead of the conventional farm equipment which would probably be suitable if a midseason drawdown occurred. A drawdown just prior to harvest is of limited use since organic soils encountered in most sites drain slowly because of their high water-holding capacity.

Pest control

Pests of concern in managed *Typha* stands include weeds, insects, disease and herbivores. Although natural and small cultivated *Typha* stands are occasionally susceptible to infestations of phytophagous insects and herbivores, it seems unlikely that insect pests would have much effect on productivity. Control measures would probably be unnecessary. Diseases have not been observed in natural or managed stands of cattail in Minnesota and do not appear to represent a threat in the future. Since
diseases have not been observed under natural monoculture conditions where their potential incidence is highest, disease control should also be unneeded.

Problems with competition from weed species have been encountered in most field trials. The problem is most severe during stand establishment when it is aggravated by fluctuating water levels, newly cultivated soils, and the small size of cattail seedlings. So long as the stand is successfully established at a uniform density greater than five plants per square meter, weeds do not pose a problem in subsequent years if flooded field conditions are maintained during the early growing season. Although several studies have been conducted to evaluate potential chemical control methods for weeds during the establishment season, it should be emphasized that proper site preparation methods and early flooding will preclude the need for chemical controls. A precultivation treatment with a non-selective herbicide, such as glyphosate, is recommended to eliminate perennial weeds which may be present.

Perennial grasses, such as reed canarygrass (Phalaris arundinacea L.), are the predominant weed control problem. Amitrol-TM (3-amino-s-triazole) was reported to be non-effective against cattails at a rate of 11.2 kg ha\(^{-1}\) when applied early in the season. In field trials, however, all Typha was heavily damaged at rates of 2.2–11.2 kg ha\(^{-1}\), with damage to \(T. \text{latifolia}\) being particularly severe. Roundup\textsuperscript{TM} (glyphosate) and Poast\textsuperscript{TM} (BASF Wyandotte Corp. BAS-90520H), at rates of 2.3, 4.7 and 7.0 liter ha\(^{-1}\) and 1.2, 2.3 and 3.5 liter ha\(^{-1}\), respectively, were effective against the perennial grasses, but caused little or no damage to either Typha species at any application rate. In subsequent greenhouse studies, glyphosate was found to damage small seedlings, indicating that the time of application, probably related to translocation patterns, is important. Water level also appears to affect the sensitivity of Typha to these herbicides.

In summary, further research is needed to determine what factors would influence the chemical control of the weed species and damage to Typha under the particular growing conditions required. At this point, weed control by cultural practice, such as early flooding and maintaining sufficient water depth during the establishment of the stand, would probably be safer and more effective.

Harvesting

Harvesting can affect the long-term productivity of Typha stands in a number of ways.\(^4\) Harvesting can affect nutrient storage in perennial plant tissue, depending on the time of harvest and the type of biomass
(leaf, rhizome, or both) harvested. Harvesting also can alter rhizome carbohydrate storage needed for early season growth and stand vigor. If a portion of the belowground rhizome system is harvested, time may be required for the stand to fill in and become productive again. Finally, harvesting may affect overwinter survival or early spring growth by removing the leaf litter which normally shades and insulates unharvested stands.

Previous studies determined yield values for *Typha* spp. based on measurements taken in natural stands and in first-, second- and third-year cultivated paddies. However, sustainable productivity levels with repeated biomass harvesting were not evaluated. Recently, a study was undertaken to evaluate the effect of various harvesting scenarios on sustained *Typha* productivity. The three harvesting scenarios under consideration were: (1) harvest of aboveground leaf biomass annually in the fall, (2) harvest of aboveground leaf biomass semiannually in mid-summer and fall, and (3) harvest of aboveground leaf biomass annually in the fall coupled with harvest of belowground rhizomes biennially in the fall.

A summary of mean results for the 3 years (Fig. 6) uses 1984, the year in which treatments were applied, as the base year for evaluating the sustainability of harvesting scenarios. The biomass yield (Fig. 6) is the harvestable yield under the three scenarios and not, necessarily, total productivity. In the case of the combined leaf and rhizome harvest, the

![Graph](image_url)

**Fig. 6.** The effect of harvest method over time on harvestable yields of *Typha × glauca* (*harvestable yield refers to: (1) Typha leaf biomass greater than 15 cm above the ground, and (2) 50% of Typha rhizome biomass for the harvest treatments. It refers to 100% of the biomass for the control treatments.*22)
results are only applicable to a situation in which 50% of the rhizomes are harvested. A larger percentage rhizome harvest would possibly increase harvestable rhizome yield, but might reduce overall harvestable yield, since stand regeneration would presumably take a longer period of time.

Conclusions from this study and one other study investigating annual leaf harvest only, are that annual harvest of *Typha* leaf biomass results in no stand damage and appears to actually enhance productivity by allowing more rapid stand emergence in the spring. Semiannual harvesting of *Typha* leaf biomass in northern latitudes, on the other hand, both damages the stand and requires high nutrient inputs, eliminating a semiannual harvest as a viable management option. Finally, annual harvests of *Typha* leaf biomass combined with biennial rhizome harvests (50% removal) result in sustainable, but fluctuating, yields which are only 15–20% higher than yields for the annual harvest scenario.

**COMMERCIALIZATION**

The work to date on *Typha* biomass production has focused largely on developing the information base needed to domesticate this wild plant species. Commercialization will depend on the economics of the system as a whole. Many economic factors are beyond the control of potential commercial producers, but certain factors can be manipulated to enhance *Typha* bio-energy’s economic advantage. In addition to identifying efficient management techniques discussed previously, these factors include taking advantage of multiple use opportunities, selecting appropriate wetlands, and minimizing equipment capital and operating costs.

**Multiple use opportunities**

In Minnesota, multiple use opportunities are present in the form of peatland reclamation, wastewater treatment, wildlife management and watershed flood control. The use of *Typha* for peatland reclamation following mining has been studied in northern Minnesota where the supply of, and interest in, peat as an energy resource is highest. Providing that some organic matter is left following mining, *Typha latifolia* and *Typha x glauca* have been shown to grow successfully on simulated mined peatland. The peatlands studied were a reed-sedge peat with a depth of approximately 2 m and a pH of 5·0. The advantages of the *Typha* reclamation method versus other agricultural methods are that extensive drainage is not required, nitrogen and organic soil losses are
minimized by maintaining an anaerobic environment, and the biomass harvested is similar in fuel composition to the previously harvested peat. The major disadvantage appears to be poor equipment operating conditions resulting from the low density and integrity of disturbed peat soils.

Wastewater treatment is another multiple use situation particularly appropriate to *Typha* biomass production. There has been considerable interest in the possible use of wetland ecosystems to improve the quality of wastewater.\(^{46-48}\) Much of the interest has focused on the potential of wetlands to reduce levels of nitrogen and phosphorus in secondarily treated effluent. Evidence suggests that the nitrogen removal capacity of wetlands is high, owing primarily to favorable conditions for denitrification. If biomass harvesting were added to these systems, the potential for removal of other nutrients, as well as nitrogen, increases dramatically. Studies have been conducted in Minnesota at a metropolitan wastewater treatment facility\(^{49}\) and at a sugar beet processing plant.\(^{50}\) The high loading rates of a large metropolitan facility appear to limit the effectiveness of *Typha* wetlands, although the potential for smaller cities appears high. The study using industrial wastewater is still underway, but appears to provide a system capable of removing phosphorus and other nutrients, while producing good biomass yields with no additional fertilization.

An interesting, but as yet unstudied, multiple use situation appears to exist in natural wetlands used for waterfowl and watershed management. *Typha* spp. tend to become weeds in these situations, requiring constant, and generally unsuccessful, control. By developing a rotational harvesting system, habitat could be maintained at the desired 50% open water and the biomass harvested could be used to cover the costs of control.

**Available land base**

Selection of appropriate land for *Typha* biomass production is also an important economic consideration. Studies have attempted to identify land use conflicts and economic limitations which affect the land base available for bio-energy production using *Typha*.\(^{1,51}\) Land use conflicts considered include commercial forestry, expansion agriculture, mining, recreation, wildlife and unique natural areas; economic limitations considered include productivity, water access, road access, access to agriculture and management unit size. Several models were then developed which took into account various combinations of land use conflicts and economic limitations, ranging from no constraints to maximum constraints.

For three Minnesota counties studied, the maximum constraint model was found to reduce available wetlands by 80–97% from that in the no-
constraint model. Constraints in a farm development model, relying on the expansion of existing farms into adjacent wetlands, reduced available wetlands by 28–64%. Finally, a commercial development model requiring at least 450 contiguous hectares reduced available wetlands by 81–91%. The range of values results from the different characteristics of the three counties studied. These results point to the importance of public policy decisions which have the potential of encouraging or discouraging bio-energy commercialization. To encourage commercial developments, improvements in the infrastructure of roads and water access would significantly increase the land base available. Zoning, environmental regulations, and tax structure can also be used to both encourage commercialization and protect the citizens at large.

Harvesting equipment

Harvesting options for cattail plants are limited by field conditions and plant characteristics. Field conditions range from organic soils with bulk densities as low as 0·14 g cm$^{-3}$ to mineral soils with densities around 1·6 g cm$^{-3}$. Depending on irrigation practices, soil type, weather and the ability to control water level, soil moisture will generally vary between 50 and 90% of the total wet weight. Because of this, and the destruction of soil/rhizome integrity accompanying rhizome harvesting, equipment traction and flotation are critical considerations in harvester design.

*Typha* leaf biomass harvest has been attempted using experimental harvesters and conventional farm equipment. Experimental harvesters have used a modified flail harvester running in reverse rotation to cut, chop and throw *Typha* leaves. The harvester was attached to an amphibious transport vehicle (Seiga Co.) and was operated in conditions ranging from moist soils to soils covered with approximately 10 cm of water. Generally, this experimental harvester works satisfactorily, producing leaf material in pieces ranging in size up to 20 cm in length, and predominantly 10–15 cm in length. However, depending upon the stiffness of the soil support structure for the stalks, the front bar on the flail head sometimes bends the stalk forwards before being encountered by the flail knives. This results in the stalks not springing back sufficiently to establish a 'low' cut or low stubble after initially being cut. Unrecoverable crop losses have ranged from 2 to 11% of the net harvested yield. Moisture content, leaning of stalks, wind direction, stalk rigidity, stalk support and stalk density, are only a few of the factors which influence the loss level.

The second approach of using conventional farm equipment has worked successfully when field conditions are fairly dry or frozen. A
managed *Typha angustifolia* stand growing on a mineral soil was harvested using an unmodified haybine and round baler attached to a medium-size tractor. Another test used a conventional forage chopper. If the water level can be controlled, or if the harvest can wait for frozen conditions, the use of conventional equipment offers the opportunity to begin utilizing *Typha* biomass immediately.

Rhizome harvesting is a significantly more difficult problem than leaf harvesting. Rhizomes grow parallel to the soil surface with lengths ranging from 2 to 61 cm with a diameter of 1-2 cm. The rhizomes and associated shoot bases lie 0-30 cm below the soil surface and have a moisture content of approximately 90% of total wet weight.

One approach for harvesting rhizomes has been to modify a potato harvester. Using a simple blade and conveyor, this system has been able to remove rhizome/soil strips from a *Typha* stand for delivery to a separation device. One separation device which works well is a rotary tumbler with a water rinse. Although both stages have been shown to work, problems are encountered when considering integration of the stages. The blade harvester requires a high draft force to propel it through the soil; dry conditions provide the support and traction necessary for this draft force. The rotary tumbler, on the other hand, requires a readily available water source, such as a flooded field, to operate. The conflicting requirements of the two harvest stages are unresolved at this point. Other systems have been considered for rhizome harvesting. These include vibrating screens, modified pea combines, and modified oyster harvesters. A floating platform with submerged bars for uprooting cattails has been tried with some success in southeastern USA.

With total sustained biomass productivity for combined leaf and rhizome harvests only 15–20% higher than leaf harvests, as discussed earlier, it is doubtful whether any advantage is gained from the added equipment and operating expense involved with rhizome harvests. Additionally, the loss of soil integrity accompanying a rhizome harvest may preclude the use of conventional forage harvesting equipment, thus increasing the cost of leaf harvests. At this time, with no significant added demand for the sugar-rich rhizomes, the combined harvest does not appear to be commercially viable.

**Economics**

With what is currently known about *Typha* biomass production, local economics, and existing tax structures, the economics of *Typha* appear neither exceptionally dismal nor exceptionally bright. A recent study incorporating all phases and expenses of a theoretical 1450 ha *Typha*
bio-energy plantation, producing 13 Mg ha\(^{-1}\) of leaf biomass annually, found a return on investment of 18% compared with 12% for a *Populus* bio-energy plantation of the same size and yield. This return would not reward the current risks involved in commercialization, but shows that if energy prices climb again or if further research identifies a means of improving the efficiency of production, a *Typha* system has a great deal of promise — especially in northern latitudes with short growing seasons.

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