Revegetation Using Native Plant Materials

Guidelines for Industrial Development Sites

September 2003
R&R/03-3

Native species should be used where the revegetation goal is to re-establish a native plant community

Operators of industrial developments on specified land are required to conserve and reclaim disturbances and obtain reclamation certificates. Conservation includes planning and management that protects the essential physical, chemical and biological characteristics of the environment. Reclamation requires the re-establishment of plant species that are compatible with the intended land use. This Fact Sheet gives guidance regarding the use of native plant materials for revegetation.

BACKGROUND

A native plant is defined as a species occurring within its historic range or in an extension of that range bounded by the dispersal potential of the plant and under the condition that the extension of that range is not known to be related to human activities.

Native species are recognized for their ecological function and intrinsic values as part of the natural forest, grassland, montane and wetland ecosystems, and should be conserved. Native plant material is used where the revegetation goal is to re-establish a native plant community, and there are insufficient native plant propagules in the soil or adjacent vegetation to accomplish this.

The use of native species should be consistent with local and/or regional land use plans/objectives and with existing or surrounding vegetation. The publication, *Native Plant Revegetation Guidelines for Alberta,* (Native Plant Working Group, 2001) should be consulted for more information.

GUIDELINES

Planning Revegetation Projects

Some native plant communities (e.g., rough fescue prairie) are very difficult to re-establish. It is very important to avoid disturbance to native plant communities whenever possible. If avoidance is not possible, then minimal disturbance techniques should be employed. Reduction of the area disturbed, use of special equipment and techniques and careful timing of construction can reduce impacts.

The goal of native revegetation is to establish a self-sustaining plant community that is compatible with surrounding land use. Achieving compatibility means meeting one or more of the following objectives consistent with the agreed upon post-disturbance land use: erosion control, provision of livestock forage, wildlife habitat, reforestation, traditional use, control of problem plant species (e.g., weeds, invasive plants), maintenance of biodiversity and aesthetics.

Sites and the surrounding area must be evaluated prior to disturbance to determine the most appropriate revegetation strategy. Species composition and plant community condition need to be recorded.

Rare and sensitive plants and plant communities should be identified and mitigation planned. The Alberta Natural Heritage Information Centre (ANHIC) has a database that tracks rare plants, animals, native plant communities and landscapes. Project managers must consult this database (780 427-5209).

The salvage of existing native plant materials and topsoil is a priority and needs to be considered in the planning stages. This is particularly important for native plant species for which seed is generally unavailable or for species that do not establish readily from seed.

Alberta Environment

Guidelines for Industrial Development Sites

Native species should be selected based on their consistency and compatibility with pre-disturbance plant communities within the Natural Sub-region

Plant Material Selection
The revegetation goals of the project must be identified prior to deciding what types of native plant material to use, and how and where to use them. The revegetation plan should address short, medium and long-term goals within the context of the agreed upon end land use.

Guidelines For Native Plant Selection

- Native species should be selected based on their consistency and compatibility with pre-disturbance plant communities within the Natural Sub-region.
- Lists of native trees, shrubs, grasses and forbs suited to various climates, soil types, and moisture regimes can be found in the publication, *A Guide to Using Native Plants on Disturbed Lands* (Gerling et al., 1996).
- Native species should be selected on the basis of known performance.
- Only seed species that will not come back naturally from the soil seedbank. For example, wetland areas do not require seeding as these already have a large seedbank of native species.
- The use of early successional species or native plant species that can survive in altered conditions can be considered in areas where late successional species may be difficult to establish.

Guidelines For Selecting Plant Material For Erosion Control

- Use a native or non-native cover crop (annual, biennial, short-lived perennial) for early erosion control. Cover crops germinate and establish much more quickly than native species but do not persist in the community. It is important to seed the cover crop very lightly (1/10 of agricultural rate for cereal crops) or mow it so that it won't compete too much with native species for light and water.
- Seed or plant native species into the stubble of the annual crop or leave for natural recovery from the seed bank.
- Choose native species that have a range of heights/growth forms and rooting depths/patterns for maximum erosion protection.
- Use erosion control products (e.g., coir matting) and methods (e.g., water bars, diversion berms) in combination with seeding on erosion prone slopes.

Guidelines For Selecting Plant Material For Maintaining Biodiversity

- Use a range of native plant materials (e.g., multiple species, varieties and/or age classes).
- Use different seed mixes and varying seeding rates. Using the same prescription everywhere results in too much uniformity. Keep careful records of what is done and where.
- Salvage the seedbank for replacement and plant materials such as seed or sod (that might otherwise not be available). For example, on sandy prairie soils where rangeland is in good to excellent condition, it is not necessary to seed needle and thread grass because it will come back from the seed bank.
- If one of the goals is to maintain biodiversity by encouraging movement of plants from offsite (e.g., on prairie):
  - Keep the proportion of very competitive, short-lived species like slender wheatgrass low
  - Lower the proportion of rhizomatous species (e.g., northern, western and streambank wheatgrass) as these species spread readily

Guidelines For Selecting Plant Material For Sites Returned To Forest Cover

- Plant native or non-native cover crops for erosion and weed control the first year.
- Plant tree/shrub seedlings into stubble.
- Establish a grass cover only if the site has an erosion problem because perennial grass species can out-compete trees.

Alberta Environment

Guidelines for Industrial Development Sites

It is important that native plant material used in revegetation is suitable in terms of performance, purity and potential germination

Guidelines For Selecting Plant Material For Use By Domestic Livestock

- Choose plant materials that match the surrounding pasture (so that use of the revegetated area can occur at the same time of the year).
- Do not include native plants in the mix that are known to be toxic to livestock.
- The success of revegetating grazed areas can only be assured by protecting the site from use by animals in the first year (or until the plants are well established). The grazing rotation can often be changed so that the pasture where the disturbance is located is rested.

Guidelines For Selecting Plant Material For Creation Of Wildlife Habitat

- Use a holistic approach to revegation to provide food and habitat for various animal species.
- Use native plant materials that fulfill the life-cycle requirements of key wildlife species.
- Use species that are similar to offsite.
- Plant species in patterns that simulate offsite conditions.

Guidelines For Selecting Plant Material To Compete With Weeds Or Problem Plants

Sources are either close by or there are large volumes of undesirable seeds in the seedbank.

- Use a cover crop the first year (or longer) to compete with weeds and allow for weed control. If weeds still come up prolifically, mow and remove the excess prior to seed set (if growth of desirable plants is being inhibited).
- Seed native species that are known to be more competitive (e.g., wheatgrasses).
- Designing a seed mix with species that have differing growth forms (including roots) enables plants to occupy niches that would otherwise be occupied with weeds, and make more efficient use of resources (light, water). Healthy, desirable plants compete better with weeds.

Seed Sources

It is very important to ensure that native plant material used in revegetation projects is suitable in terms of performance, purity and potential for germination.

- Use the Decision Making Chart for Sourcing Native Plant Material on page nine of the Native Plant Revegetation Guidelines for Alberta (Native Plant Working Group, 2001).
- The Alberta Native Plant Council has a listing of available native plant materials on their website, www.anpc.ab.ca.
- Always ask for preferred species first (no demand means no supply). When preferred species are unavailable, be prepared with alternate choices or to alter the revegetation plan.
- Use scientific names when ordering seed.
- Make sure that the genetic source of the seed is from a similar region, otherwise performance can be an issue.
- Tree seed, seedlings and propagules use must be consistent with the *Management and Conservation Standards for Forest Tree Genetic Resources in Alberta* (Alberta Sustainable Resource Development - Lands and Forest Division, 2003). A seed lot registration number must be provided prior to use on public land.
- Ask the seed supplier for a Seed Analysis Certificate for each seed lot prior to mixing; check certificates for any weed species or other species of concern (e.g., invasive species like crested wheatgrass), timothy or smooth brome. This certificate indicates the germination potential of the seed which can vary widely and affects seeding rates.
- Order early (i.e., January) for availability.

Alberta Environment

Guidelines for Industrial Development Sites

Replacing topsoil, relieving compaction, controlling persistent weeds, creating microsites and preparing a firm seedbed are critical steps in preparing a site for revegetation

Site Preparation

Site preparation is one of the most important factors in determining the success of revegetation projects. Inadequate preparation is one of the most common reason for seeding failure.

- Topsoil and subsoil must be conserved and replaced. Newly constructed landforms require topsoil and subsoil suitable for the type of vegetation chosen.
- Any compaction that could inhibit root growth must be eliminated prior to seedbed preparation.
- Controlling persistent weeds/problem plants is crucial for revegetation success. Several years of control may be required to draw down the seedbank of undesirable species.
- Creating microsites using equipment that produces ridges and hollows (e.g., Kinsella Accuroller, Hodder Gouger) can enhance diversity and plant survival.
- Preparing a firm seedbed when drill seeding enhances germination by ensuring good soil to seed contact and regulating seeding depth.
- The use of nitrogen fertilizer is not recommended for most native revegetation projects. Fertilizer tends to promote weed growth and can slow down succession.

Seeding and Planting

The chosen seeding or planting method varies according to project goals, end land use, previous experience and specific requirements of the species being used.

- Drill seeding is usually preferred over broadcast seeding because it uses less seed and places it in direct contact with the soil.
- A special drill (e.g., Truax, John Deere Rangeland) is usually required. All seeders must be calibrated for each mix (several times a day) to ensure efficient delivery of seed.
- Broadcast seeding is used in areas where access for drill seeders is poor. Broadcasting is also used for small seeded species and those that require light to germinate (e.g., June grass). Two to three times the amount of seed needed for drill seeding has to be used. Sites should be harrowed or rolled afterwards to ensure good soil to seed contact.

Seeding or Planting Rates

Because native species differ so much in germination, establishment, growth habit and competitive interactions, it is recommended that an experienced revegetation specialist be consulted to design seed mixes.

- Seeding or planting rates should aim to meet project objectives.
- The target number of plants per square metre has to be decided.
- Reforestation guidelines recommend stems per hectare measurement as a guide to how many trees to place in a specific area. For other projects, the following target plant densities (following establishment) are recommended:
  - Grasses: 10 to 15 plants/m^2
  - Forbs: 5 to 10 plants/m^2
  - Shrubs: 1 to 2 plants/m^2
  - Trees: 1 to 2 metres apart
- For seeding, calculations are made to determine how many pure live seeds (PLS) should be planted per square metre. Adjustments are made according to the relative ability of the species to germinate, establish and spread.
- Grass seeding rates of 300 seeds/m^2 are adequate for erosion control on most sites. More seed is not always better. If plants are too crowded, they do not develop robust shoot and root systems that are important for erosion control.
- If erosion is a concern, it is better to use effective erosion control products in combination with revegetation.

Guidelines for Industrial Development Sites

Revegetation is successful when the site is protected from erosion and plant composition and productivity meet end land use goals.

- On sites where ingress of native species from the surrounding plant community is desired, total seeding rates should be less than 300 seeds/m^2. Since seed size is extremely variable, kg/ha varies according to the species used. Rates lower than 8 kg/ha are hard to run through a seed drill unless a carrier is used.
- Where competition from weeds or problem plants is a concern, increasing seeding rates of native species above normal rates can be beneficial.
- More information about calculating seeding rates and about the germination and establishment of various native species can be found in the publication, *Establishing Native Plant Communities* (Smreciu et al., 2003).

Management of Revegetated Areas
Effective management of established native stands is required to ensure that the vegetation is sustainable.

- Restricted weeds must be eliminated and noxious weeds and invasive problem plants controlled. Care has to be taken to use methods that are compatible with the survival of desirable native plants in the stand.
- Non-persistent annual weeds (e.g., stinkweed, flixweed, Russian thistle) should only be controlled if they are inhibiting the growth of desirable native plants. Mowing and removal of excess material is the best approach. These weeds usually disappear from the stand in three to four years.
- Protection from grazing or browsing is advisable during the establishment period. Controlled grazing may help to eliminate unwanted plants.
- Grazing, mowing or prescribed burning of the revegetated area may be necessary to retain plant vigour and diversity and to reduce the risk of wildfire by maintaining safe fuel loads.

Assessing Success
The establishment of a desired native plant community can be a lengthy process.

Landscape level assessments that should be made include erosion prevention and compatibility of the revegetated area with surrounding areas or agreed upon end land use. Revegetated areas should be checked several times in the first season and yearly thereafter.

Revegetation is considered successful if:

- Landforms are stable and there is no evidence of progressive erosion.
- There are sufficient numbers of plants, cover (live and litter) to ensure protection of the site from future erosion.
- The revegetated area can be used in the same manner and in conjunction with adjacent lands.
- The species growing on the site demonstrate that the existing or proposed end land use(s) can be sustained.
- Restricted or noxious weeds as designated in the *Weed Control Act* (or by the local municipality) are no more abundant than on controls.
- Eventually, vegetation productivity is equivalent or better than that of vegetation surrounding the disturbed area.
- Vegetation on the site is growing along expected successional trends.

There are key times that detailed assessments should be made to ensure that plant growth is sustainable:

- 3 to 6 weeks following seeding (density count to check seeding success; check health of shoots/roots).
- The end of the first growing season (density count; health).
- The end of the establishment period. This varies tremendously by species (e.g., one year for grasses; several years for many shrubs or trees). A density and/or cover assessment is carried out depending on the plant species. This assures that target plant densities have been met (e.g., 10 plants/m^2 for grasses). Health of plants above and below ground is also checked.

- For communities that take a longer time to develop (e.g., forests, droughty prairie sites) or on drastically disturbed landscapes (e.g., mine sites), assessment is required until the plant community is considered to be sustainable.
- For some disturbance types, reclamation criteria have been developed (e.g., wellsites, pipelines, borrow pits). For natural recovery sites, guidance for assessment is provided in C&R/IL/02-3, as amended. The new Range Health Assessment may also be helpful for well-established plant communities.
- Good record keeping of every step in a revegetation program can help manage a specific site; determine necessary mitigation and assist with planning for future disturbances. The interpretation of successful revegetation is closely tied to the specific revegetation goal(s) for the site.

USEFUL RESOURCES

Adams, B. W., G. Ehlert, C. Stone, M. Alexander, D. Lawrence, M. Willoughby, D. Moisey, C. Hincz, and A. Bogen. *Range Health Assessment for Grassland, Forest and Tame Pasture*. Public Lands Division, Alberta Sustainable Resource Development. Pub. No. T/044. 106 pp.

Alberta Agriculture, Food and Rural Development. 2000. *Purity of Native Seed used for Revegetation of Natural Landscapes*. Public Lands Update IND 2000-2. 4 pp.

Alberta Energy and Utilities Board. Informational Letter 2002-1: *Principles for Minimizing Surface Disturbance in Native Prairie and Parkland Areas*. http://www.eub.gov.ab.ca/bbs/requirements/ils/ils/il2002-01.htm

Alberta Environment. 2003. *Sites Reclaimed Using Natural Recovery Methods: Guidance on Site Assessment*, R&R/03-6. 8 pp.

Alberta Environment. 2003. *Problem Introduced Forages on Prairie and Parkland Reclamation Sites: Guidance for Non-cultivated Land*, R&R/03-5. 3 pp. http://www3.gov.ab.ca/env/protenf/landrec/

Alberta Sustainable Resource Development - Lands and Forest Division. 2003. *Management and Conservation Standards for Forest Tree Genetic Resources in Alberta*.

Allen, L. 2002. *Alberta Natural History Information Centre Preliminary Plant Community Tracking List*. Alberta Community Development. 51 pp.

Gerling, H.S. 2000. *Control Options for Downy Brome on Prairie Reclamation Sites*. Public Lands Division, Alberta Agriculture, Food and Rural Development. 4 pp.

Gerling, H.S., M.G. Willoughby, A. Schoepf, K.E. Tannas and C.A. Tannas. 1996. *A Guide toUsing Native Plants on Disturbed Lands*. Alberta Agriculture, Food and Rural Development and Alberta Environmental Protection. 247 pp. (Available from Alberta Agriculture 1-800-292-5697).

Johnson, J. D. and E.M. Lefebvre. 2000. *Rare Vascular Plants of Alberta*. Natural Resources Canada, Canadian Forest Service, Northern Forest Centre. Edmonton, Alberta.

Lancaster, J. 2000. *Alberta Native Plant Council Guidelines for Rare Plant Surveys*. http://www.anpc.ab.ca/downloads.htm

Native Plant Working Group. 2001. *Native Plant Revegetation Guidelines for Alberta*. H. Sinton (ed). Alberta Agriculture, Food and Rural Development and Alberta Environment. 58 pp. www.agric.gov.ab.ca/publands/nprg/

Native Prairie Guidelines Working Group. 2002. *Petroleum Industry Activity in Native Prairie and Parkland Areas: Guidelines for Minimizing Surface Disturbance* (Calgary: Alberta Energy and Utilities Board), 36 p. Available from Alberta Energy and Utilities Board, Information Services, Main Floor, 540 - 5 Avenue SW, Calgary, Alberta T2P 3G4.

Restoring Our Native Prairie Heritage. Video script. Alberta Agriculture, Food and Rural Development.

Sinton, H. M. 2001. *Prairie Oil and Gas: A Lighter Footprint*. Alberta Environment. ISBN 0-7785-1711-X. 67 pp. www.gov.ab.ca/env/protenf/publications

Smreciu, A., Sinton, H., Walker, D. and J. Bietz. 2003. *Establishing Native Plant Communities*. Alberta Agriculture, Food and Rural Development, Alberta Environment and Alberta Sustainable Resource Development (Available from Alberta Agriculture 1-800-292-5697).

Western Rangeland Consultants Inc. 2000. *The Transplantation of a Rare Native Grassland Ecosystem Adjacent to Highway 43, Near Grande Prairie, Alberta. Volume 3, Final Report*. Report prepared for Civil Projects Branch, Alberta Transportation, Edmonton, AB. 43 pp.

CONTACTS

The following can be reached toll free by calling 310-0000 and then dialing the number shown below.

For public lands:
Alberta Sustainable Resource Development
Public Lands Branch,
3rd Floor, 9915 - 108 Street,
EDMONTON, Alberta T5K 2G8.
Phone: (780) 427-3570
Fax: (780) 422-4251
e-mail: reclaim.account@gov.ab.ca

For all other lands:
Alberta Environment,
Science and Standards Branch,
4th Floor, 9820-106 Street,
EDMONTON, Alberta T5K 2J6
Phone: (780) 944-0313
Fax: (780) 422-4192
e-mail: land.management@gov.ab.ca

Seeding Rangeland

Tommy G. Welch, Barron S. Rector and James S. Alderson*

Soil and water conservation, high quality forage production for livestock and wildlife, revegetation of deteriorated rangeland and old cropland and obtaining a sustainable level of forage production are management goals which keep landowners and researchers investigating new and old plant materials for range seeding. Although production on some land may be improved by grazing management alone, most land requires grazing management, brush and weed control and/or seeding to restore production potential. This publication has been prepared to serve as a guide for seeding Texas rangelands.

The most common objective of rangeland seeding is to alter vegetation composition. This usually is done because of a need for more or higher quality forage. Occasionally a better seasonal balance of forage supply is needed. Other objectives met by altering vegetation composition through rangeland seeding include soil stabilization, improved water infiltration, improved vegetation ground cover for reduced water runoff, return to a prairie-like vegetation and improved wildlife habitats.

WHEN TO SEED

Since seeding rangeland is expensive and the risk of failure is always present, carefully consider seeding or allowing natural revegetation. When the management objective is to improve range condition, evaluate the quantity and distribution of current desirable plants. If desirable plants make up less than 10 to 15 percent of the vegetation, seeding probably is necessary. If desirable plants are uniformly distributed and make up more than 10 to 15 percent of the vegetation, use grazing management to improve range condition.

Often, however, another management decision dictates the necessity for seeding. For example, seeding usually is necessary following a brush control method, such as rootplowing, that destroys the existing turf. Also, when a better seasonal balance of forage supply is desired, seeding usually is required because the species needed to extend the period of green forage are not present. These plants often are introduced species and are seeded in pure stands.

In addition, seeding usually is the most effective way to establish desirable vegetation on abandoned cropland, since natural revegetation processes may take 50 to 100 years on land barren from farming. On other bare areas, such as newly constructed dams and newly laid pipelines, seeding to establish a plant cover often is necessary to prevent wind and water erosion.

WHERE TO SEED

Seed only those sites having sufficient potential to insure reasonable chances of success. First, survey the area to determine if there is a mixture of range sites or if one predominates; then, decide whether the sites are suitable for seeding. If the area is a mixture of sites, expend the most effort on ones with the best chance for success. Select seeding sites so the area can be incorporated into the overall ranch management.

Sites with sufficient soil depth for adequate root development and water storage or sites that can be modified mechanically to accomplish a greater effective soil depth usually are suitable. However, avoid barren, rocky sites, which have greater temperature extremes at the soil surface and are more droughty than sites with soil and litter on the surface. Low soil moisture and wide temperature extremes can kill plant seedlings.

Although the amount of precipitation received on an area cannot be controlled, select sites that receive runoff water, thereby increasing the amount of moisture available. However, do not disturb steep, potentially erosive areas.

* Respectively, Associate Department Head and Extension Program Leader for Rangeland Ecology and Management, Texas Agricultural Extension Service, College Station; Associate Professor and Extension Range Specialist, Texas Agricultural Extension Service, College Station; Plant Materials Specialist, Soil Conservation Service, Temple.

WHAT TO SEED

Plants selected for seeding depend on management objectives. For example, plants to improve range condition are different from those selected to stabilize a disturbed area or to extend the grazing season. However, regardless of management objective, select only species of plants that are adapted to the soil, climate and topography of the area to be seeded. If possible, choose plants that: (1) establish easily, (2) are palatable to animals that will graze the seeded area, (3) are relatively productive, (4) withstand invasion by undesirable plants, (5) withstand moderate grazing, (6) prevent erosion under moderate grazing and (7) are available at a moderate price.

Usually, plants best adapted to an area are native ones growing in the area, so it is important to determine the original source of seeds of native species. When available, use certified named varieties. Generally, seed of native species should originate from local sources or from within 200 miles north or south and 100 miles east or west of the area to be seeded. Recommended species and varieties for the various resource areas and soil groups are shown in Table 1. Consult local Soil Conservation Service personnel for information on seeding specific range sites, because some species are adapted to only certain range sites within a resource area.

Often, mixtures of native and/or introduced species are seeded on rangeland, partly as an attempt to simulate natural conditions. Using a mixture is helpful because all areas have variations in soil, moisture and slope, and each species in the mixture is adapted better than other species to certain site characteristics. For instance, variation in rooting habits of species in the mixture allows for more efficient use of moisture and nutrients from the various soil depths. Also, the mixture usually extends the grazing season because each species varies slightly in its period of lush growth and dormancy. Finally, a mixture provides a varied diet that often is more desirable to animals.

Under certain conditions, a pure stand of a single species is more desirable. Species low in palatability and needing special management, or species requiring intensive management, should be planted alone. In addition, many introduced species are easier to manage when planted in a pure stand.

Use seed of known quality. Know the germination and purity of the seed, since seeding rates are based on pure live seed.

HOW TO SEED

Seedbed Preparation

An ideal seedbed is firm below seeding depth, free from live, resident plant competition and has moderate amounts of mulch or plant residue on the soil surface. A major purpose of seedbed preparation is to reduce existing plant competition.

Plowing is the most common method of preparing a seedbed. A variety of plowing methods is available. The method selected depends on the type of vegetation to be controlled and the level of financial resources available. On abandoned cropland use a moldboard, offset disk or one-way. On a brush infested area, consider rootplowing.

Herbicides also may be used to control existing vegetation. After applying the herbicide, drill seeds of desired plants directly into the dead vegetative cover. Although this method of seedbed preparation seldom is used, it offers possibilities where wind erosion occurs.

In areas where wind or excessive heat is a problem, protect clean-tilled soil with a crop or dead litter crop. Sorghums, small grains and other cool season annual grasses make an excellent dead litter mulch. To prevent seed production in sorghum, plant it late in the growing season or harvest it, leaving the stubble for mulch. Small grains also may be used as a cover crop. After establishing the cover crop, drill or broadcast seeds of desired species into the stubble or mulch.

In some areas seedbeds have been successfully prepared by burning. For example, prescribed burning may reduce competition from certain perennial plants, allowing subsequently seeded species to establish more easily. Following a wildfire, seeding may be necessary to restore the area's productivity.

On abandoned cropland, an ideal seedbed may be prepared without undue expense, but on rangeland, the ideal seedbed is a goal seldom attained because expenses exceed expected returns. Even though preparing an ideal seedbed may not be economically feasible, prepare the best seedbed that available resources allow. On some brush-infested rangeland, rootplowing, followed by roller chopping, raking or chaining, is an acceptable method of seedbed preparation. Roller chopping usually is conducted before seeding. On potentially productive sites the expense of rootplowing, raking and plowing with an offset disk may be justified. In addition, smooth seedbeds allow for harvesting seed, and the income from seed sales could pay for seedbed preparation costs.

Timing

Choosing the correct time to seed is very important. Try to seed at the beginning of a period that will provide the best growing conditions (favorable temperatures and good soil moisture). In most cases, achieve the greatest success by seeding just before the season of expected high rainfall. Most parts of Texas receive significant rainfall in early to mid-spring; in those areas, warm season plants may be seeded successfully during late winter to early spring. The Trans-Pecos region usually receives its precipitation during mid to late summer, so seeding in midsum-

mer may be best. In the more southern areas of the state where a rainfall peak occurs in the fall, seeding in late summer or early fall may allow seedlings time to become established before the winter season. In terms of temperature, many cool season plants may be seeded either in the spring or early fall, though late summer or fall normally is best because young seedlings may not tolerate hot, dry summers. On the other hand, warm season plants grow best if seeded in the spring.

Seeding Methods

The two most common methods of seeding rangeland are drill and broadcast. Drill methods place the seed in the soil; broadcast methods place the seed on the soil's surface.

Drilling is a superior method because the drill places the seed in the soil, thus improving the probability of seedling establishment. Use drills on old fields and on areas where a smooth seedbed has been prepared. A good drill has the following:

- Double disk opener to provide a trench with minimum soil movement.
- Depth bands for proper depth control.
- Packing mechanism to place seed more firmly in contact with soil.
- Seed boxes with agitators to keep seed mixed and prevent fluffy seed from lodging in box, separate boxes for large and small seed, divided or partitioned boxes to keep seed feeding to individual metering devices and a good metering device to control the amount of seed to be planted.

Since most drills are not sturdy enough to be used on rough rangeland, broadcast seeding often is used instead. However, broadcast seeding has limitations because seed are poorly covered with soil and stand establishment often is slower.

Broadcast the seed by aerial or ground application. Ground application includes broadcasting by hand, rotary spreader, with airstream or exhaust or seeder boxes of the fertilizer-spreader type. Aerial application is popular because it is faster. Aircraft must be equipped with a spreader and a positive, power-driven seed metering device.

Broadcast seeding seldom is effective without some soil disturbance before the seeding operation. Be sure to distribute seed uniformly. Small, slick seed lend themselves to broadcast seeding much better than fluffy seed, since small seed are easier to broadcast and are covered by natural sloughing of the soil.

Broadcast seeding is more successful if the seed are broadcast on loose, rough soil, where natural sloughing and settling will cover the seed, or when seeding is followed by harrowing, chaining or cultipacking. If the seedbed consists of large clods of soil, seed may be buried too deeply.

Seeding Rate

The quantity of seed to apply per acre depends upon the species, method of seeding and potential site productivity. Seeding rates usually are based on pounds of pure live seed (PLS) per acre. PLS is the percentage of the bulk seed material that is live seed. This is determined by multiplying percentage germination by percentage purity of the lot of seed. When hard seed are involved, PLS = (percent germination + percent hard seed) x percent purity.

Recommended seeding rates usually call for 20 live seed per square foot. The number of seed per pound varies with species. Table 1 gives the number of seed per pound and recommended seeding rates for species used in Texas.

Seeding Depth

Optimum seeding depth is roughly proportional to seed size. Since smaller seeds have a smaller quantity of stored energy, do not seed them as deeply as larger seed. As a rule, plant seed at a depth four to seven times the diameter of the seed. When using a mixture of small and large seed, determine the planting depth by the diameter of smallest seed. In most rangeland seedings, plant the seed about 1/4 to 1/2 inch deep but not deeper than 3/4 inch. Plantings can be deeper in light, sandy soils than in heavier, clay soils.

MANAGEMENT AFTER SEEDING

Protect a newly seeded area from grazing until plants are established. Some species establish sooner than others, but in general, plants should be well-rooted before grazing to prevent pulling up the seedlings. Length of deferment from grazing varies. In exceptionally good growing conditions, deferment through one growing season may be sufficient. During periods of harsh growing conditions, however, 2 or 3 years of deferment may be necessary. Grazing during dormant periods may help improve the stand by scattering and trampling seed into the soil. After plants are established, practice good grazing management to maintain the seeded stand.

Because seeded areas usually receive some type of soil disturbance, weeds or weedy species often become abundant during the growing season following seeding. Weed control measures such as mowing, shredding or use of herbicides may be necessary during the first growing season to allow seeded species to become established. Most grass seedlings can tolerate a herbicide application after the seedlings have reached the fourth leaf stage.

Table 1. Seed characteristics, seeding rates and adaptations of species used for seeding Texas rangeland.

Name	Variety[1]	Seeds per lb	Seeding rate[2] lb PLS per acre		Ratings of adaptation[3]						Native (N) or Introduced (I)	[4]	Regional adaptation[5]																			[6]
					Tolerance			Soil																									
			Normal rows (40 in)	Drill (20 in or less) or broadcast	Drought	Cold	Salt	Sandy	Loam	Clay		Season of growth	Coast Saline Prairie	Coast Prairie	East Texas Timberlands	Claypan Area	Blackland Prairie	East Cross Timbers	West Cross Timbers	Grand Prairie	North Central Prairies	Central Basin	Edwards Plateau	Northern Rio Grande Plain	Western Rio Grande Plain	Central Rio Grande Plain	Lower Rio Grande Valley	Rolling Plains	High Plains	Trans-Pecos	Minimum rainfall (inches)
Alkali sacaton (*Sporobolus airoides*)	Saltalk	1,750,000	0.4	1.0	2	1	1	3	2	1	N	W										X	X	X	X	X	X	X	10
	Salado				2	1	1	3	2	1	N	W				X			X							X	X		10
					1	1	1	3	2	1	N	W						X					X	X	X	X		X	10
Angleton bluestem (*Dichanthium aristatum*)		500,000	0.4	1.0	2	3	2	3	3	1	I	W		X															30
Big bluestem[7] (*Andropogon gerardii*)		130,000	2.0	6.0	2	1	2	2	1	2	N	W	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	25
Black grama (*Bouteloua eriopoda*)	Nogal	1,335,000	0.5	1.5	1	2	3	1	1	3	N	W																X	X	10
Blue grama (*Bouteloua gracilis*)	Lovington	711,000 (spikelet)	0.5	1.5	1	1	2	2	1	1	N	W															X	X	X	10
	Hachita				1	1	2	2	1	1	N	W															X	X	X	10
					1	1	2	2	1	1	N	W															X	X	X	10
Blue panicgrass (*Panicum antidotale*)		657,000	0.8	2.0	2	3	2	2	1	1	I	W									X	X	X	X	X	X	X	X	X	20
Boer lovegrass (*Eragrostis chloromelas*)	Catalina	2,922,000	0.8	1.5	1	2	2	1	1	1	I	W																X	X	10
					1	2	2	1	1	1	I	W																X	X	10
Buffelgrass (*Cenchrus ciliare*)	Common	225,000 bur or 867,000 grain	1.0	2.0	1	3	3	2	1	2	I	W											X	X	X	X				16
	Higgins[8]		0.5	1.5	1	3	3	2	1	2	I	W											X	X	X	X				16
	Nueces				1	3	3	2	1	2	I	W											X	X	X	X				16
	Llano				1	3	3	2	1	2	I	W											X	X	X	X				16
Buffalograss (*Buchloe dactyloides*)	Texoka	42,000 bur or 275,000 grain	5.0	16.0	1	1	2	3	1	1	N	W					X	X	X	X	X	X	X				X	X		15
			---	3.0	1	1	2	3	1	1	N	W					X	X	X	X	X	X	X				X	X		15
California cottontop (*Digitaria californica*)		1,092,000	0.4	1.2	2	2	2	2	1	2	N	W									X		X	X	X	X	X	X	X	15
Caucasian bluestem (*Bothriochloa caucasica*)		860,000	0.5	1.2	2	2	2	2	1	1	I	W				X	X	X	X	X	X	X	X				X	X		18
Common reed[9] (*Phragmites australis*)	Shoreline	Rhizomes 12 to 18 in long	1 to 1 1/2 rhizomes per foot of row		3	1	2	1	1	1	N	W	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	30
Eastern gamagrass (*Tripsacum dactyloides*)	Pete	7,200	10.0	20.0	1	1	3	2	1	1	N	W	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	20
	luka	7,500	8.0	15.0	1	1	3	2	1	1	N	W		X	X	X	X	X	X	X		X	X	X	X	X	X	X		20
		5,500-7,500	8.0	15.0	1	1	3	2	1	1	N	W		X	X	X	X	X	X	X		X	X	X	X	X	X	X		20
Engelmanndaisy (*Engelmannia pinnatifida*)	Eldorado	58,500	5.0	15.0	1	1	3	2	1	3	N	C				X	X	X	X	X	X	X	X		X	X	X	X		16
Gordo bluestem (*Dichanthium aristatum*)		500,000	0.5	1.2	2	2	2	3	2	1	I	W		X			X						X		X	X			25

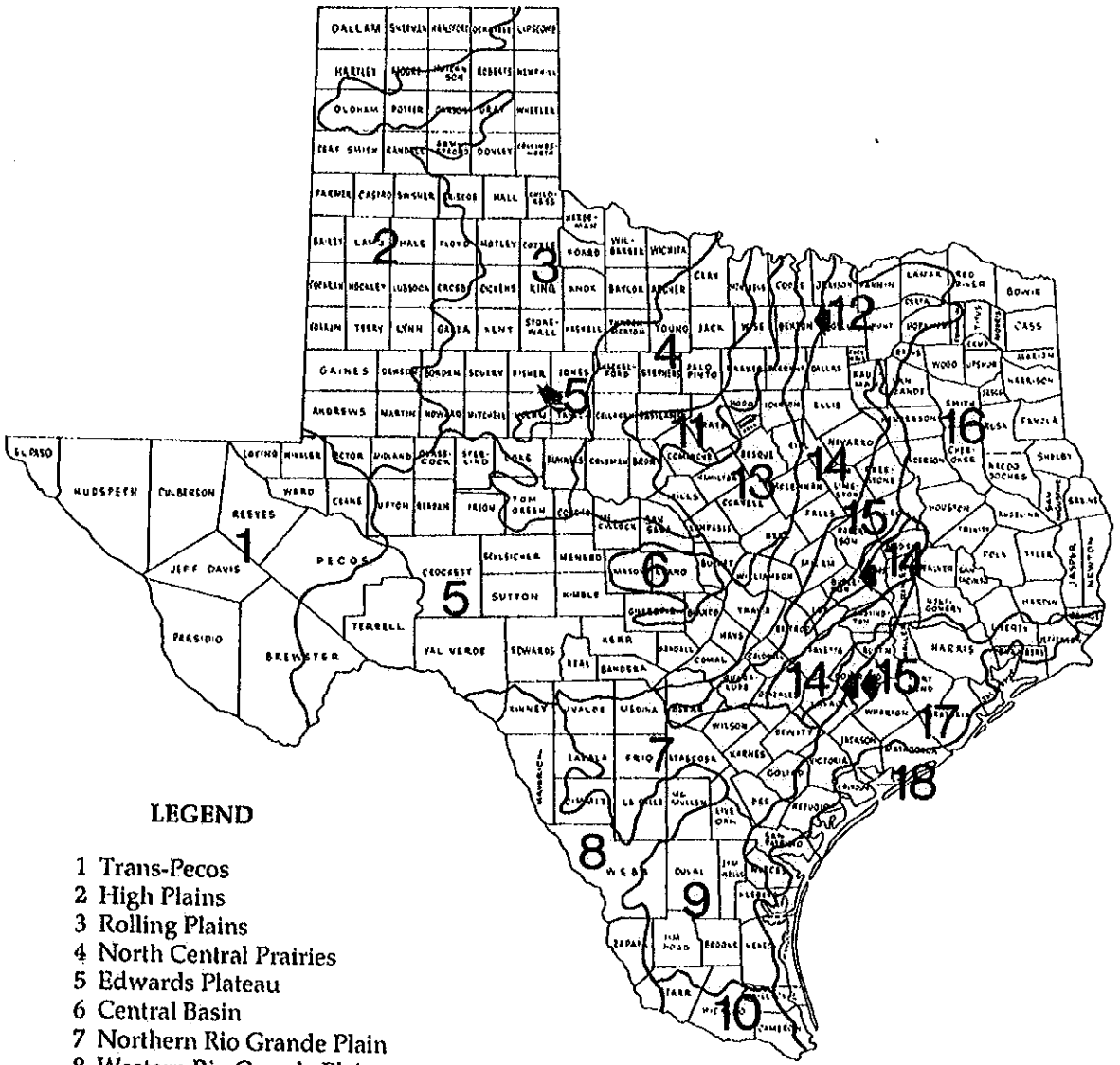
Green sprangletop (*Leptochloa dubia*)	Van Horn	538,000	0.7	1.7	1	1	2	1	1	2	N	W						X	X	X	X	X	X	X	X	X	X	X	X	X	10
		538,000			1	1	2	1	1	2	N	W						X	X	X	X	X	X	X	X	X	X	X	X	X	10
Illinois bundleflower (*Desmanthus illinoensis*)	Sabine	64,000	4.5	13.5	1	1	3	2	1	1	N	W		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		16
Indiangrass[7] (*Sorghastrum nutans*)		170,000	1.5	4.5	3	1	2	1	1	2	N	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		16
	Cheyenne				3	1	2	1	1	2	N	W						X	X	X	X							X	X		16
	Lometa				3	1	2	1	1	2	N	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			22
King Ranch bluestem (*Bothriochloa ischaemum* var. *songarica*)		835,000	0.5	1.2	1	1	2	3	1	1	I	W		X		X	X	X	X	X	X	X	X	X	X	X	X	X			20
Kleberg bluestem (*Dichanthium annulatum*)		800,000	0.5	1.2	1	2	2	2	1	1	I	W		X		X	X			X		X	X	X	X	X	X				20
Kleingrass (*Panicum coloratum*)	Selection 75[6]	500,000	0.5	1.5	2	3	2	2	1	1	I	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		20
	Verde	450,000	0.6	1.7	2	3	2	2	1	1	I	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		20
Lehmann lovegrass (*Eragrostis lehmanniana*) (*E. lehmanniana* x *E. trichophora*)	Cochise	4,245,000	0.5	1.5	1	3	2	1	1	2	I	W											X	X	X	X	X		X	X	10
					1	3	2	1	1	2	I	W											X	X	X	X	X		X	X	10
Little bluestem (*Schizachyrium scoparium*)		255,000	1.2	3.4	2	1	3	1	1	1	N	W		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	20
	Pastura				2	1	3	1	1	1	N	W																	X		16
	Cimarron				2	1	3	1	1	1	N	W																X	X		16
Maximilian sunflower (*Helianthus maximiliana*)	Aztec	320,000	---	0.25-1.0[10]	2	1	3	1	1	1	N	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		18
Medio bluestem (*Dichanthium aristatum*)		500,000	0.4	1.0	2	3	2	3	3	1	I	W	X				X							X	X	X	X				25
Old World bluestem (*Dichanthium* spp - *Bothriochloa* spp blend)	T-587	854,000	0.5	1.2	1	2	2	2	1	1	I	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	14
Plains bristlegrass (*Setaria leucopila*)		293,000	1.0	3.0	1	1	2	1	1	1	N	W				X					X	X	X	X	X	X	X	X	X	X	12
Rhodesgrass (*Chloris gayana*)	Bell	1,405,000 (spikelet)	0.4	1.0	2	3	1	2	1	1	I	W	X	X										X	X	X	X				20
Sand bluestem (*Andropogon gerardii* var. *paucipilus*)		125,000	2.0	6.0	2	1	3	1	2	3	N	W						X	X	X	X							X	X		18
	Woodward				2	1	3	1	2	3	N	W						X	X	X	X							X	X		18
	Elida				2	1	3	1	2	3	N	W																X	X		14
Sand dropseed (*Sporobolus cryptandrus*)		1,750,000	0.4	1.0	1	1	3	1	2	3	N	W	X	X	X	X	X	X	X	X	X	X	X		X						10

[1]Named varieties are adapted to regions checked. If a named variety is not listed, seed used should have a local origin or be from within 200 miles north or south and 100 miles east or west of site to be seeded. This is particularly important for widely adapted species.
[2]PLS = pure live seed = (percent germination + hard seed) x percent purity.
[3]Symbols for adaptation: 1 = good; 2 = fair; 3 = poor.
[4]Symbols: W = warm season; C = cool season.
[5]Land resource areas are shown in Figure 1. Consult local Soil Conservation Service personnel for information for seeding specific range sites because some species are adapted to only part of a resource area and/or to only certain range sites within a resource area.
[6]Extra moisture from runoff may substitute for rainfall. Figure 2 shows the average annual precipitation in Texas.
[7]These tallgrass species occur in resource areas listed. However, seed only on sites with high soil moisture potential such as bottomland range sites in the lower rainfall areas of the state.
[8]Higgins is better adapted to clay soil than other varieties. Nueces and Llano are more cold tolerant than Common and Higgins.
[9]Common reed is used at waterline on farm ponds and watershed dams for stabilization. When used at waterline, use anywhere in the state regardless of quantity of rainfall.
[10]Low rate for range seedings. High rate for wildlife block seedings.

Table 1. Seed characteristics, seeding rates and adaptations of species used for seeding Texas rangeland (concluded).

Name	Variety[1]	Seeds per lb	Seeding rate[2] lb PLS per acre		Ratings of adaptation[3]						4		Regional adaptation[5]																			6
					Tolerance			Soil																									
			Normal rows (40 in)	Drill (20 in or less) or broadcast	Drought	Cold	Salt	Sandy	Loam	Clay	Native (N) or Introduced (I)	Season of growth	Coast Saline Prairie	Coast Prairie	East Texas Timberlands	Claypan Area	Blackland Prairie	East Cross Timbers	West Cross Timbers	Grand Prairie	North Central Prairies	Central Basin	Edwards Plateau	Northern Rio Grande Plain	Western Rio Grande Plain	Central Rio Grande Plain	Lower Rio Grande Valley	Rolling Plains	High Plains	Trans-Pecos	Minimum rainfall (inches)
Sand lovegrass (*Eragrostis trichodes*)	Mason	1,300,000	0.5	1.5	1	1	3	1	2	3	N	W						X	X	X	X							X	X		18
		2,000,000			1	2	3	1	2	3	N	W						X	X	X	X	X	X	X	X			X	X		18
Sideoats grama (*Bouteloua curtipendula*)	Haskell	143,000 (spikelet)	1.5	4.5	2	1	2	2	1	1	N	W				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	14
	Premier				2	1	2	2	1	1	N	W			X													X	X		14
	El Reno				2	1	2	2	1	1	N	W																X	X	X	14
	Niner				2	1	2	2	1	1	N	W						X	X	X	X							X	X		14
	Vaughn				2	1	2	2	1	1	N	W																X	X	X	14
	Uvalde				2	1	2	2	1	1	N	W																	X		14
					2	1	2	2	1	1	N	W									X	X	X	X							18
Sorghum almum (*Sorghum almum*)		90,000	---	2.0 15.0[11]	2	2	2	2	1	1	I	W		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	18
Switchgrass[7] (*Panicum virgatum*)		389,000	1.2	3.5	2	1	2	1	1	1	N	W		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	20
	Alamo	427,365	0.8	2.0	2	1	2	1	1	1	N	W		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	25
	Blackwell	389,000	1.2	3.5	2	1	2	1	1	2	N	W					X	X	X	X	X							X	X		20
	Caddo	389,000	1.2	3.5	2	1	2	1	1	2	N	W					X	X	X	X	X							X	X		20
	Grenville	389,000	1.2	3.5	2	1	2	1	1	2	N	W																X	X		20
	Kanlow[12]	389,000	1.2	3.5	3	1	2	1	1	1	N	W					X	X	X	X	X							X	X		25
Weeping lovegrass (*Eragrostis curvula*)		1,500,000	0.5	1.5	2	2	2	1	1	1	I	W			X	X	X	X	X	X	X			X				X	X		16
	Ermelo				2	2	2	1	1	1	I	W			X	X	X	X	X	X	X			X				X	X		16
	Morpa				2	2	2	1	1	1	I	W			X	X	X	X	X	X	X			X				X	X		16
	Renner				2	2	2	1	1	1	I	W			X	X	X	X	X	X	X			X				X	X		16
Western wheatgrass (*Agropyron smithii*)		110,000	2.4	7.0	2	1	1	3	1	1	N	C																X	X		16
	Amba				2	1	1	3	1	1	N	C																	X		16
	Barton				2	1	1	3	1	1	N	C																	X		16
Wilman lovegrass (*Eragrostis superba*)	Palar	1,103,000	0.5	1.5	1	3	2	1	1	2	I	W									X	X	X	X	X					X	10
Yellow bluestem (*Bothriochloa ischaemum* var. *ischaemum*)	Plains	830,000	0.6	1.8	2	1	2	2	1	2	I	W			X	X	X	X	X	X	X							X	X		18
	Ganada				2	1	2	2	1	2	I	W																X	X	X	10
	WW Spar				2	1	2	2	1	2	I	W			X	X	X	X	X	X	X							X	X		18
	WW Iron-master[13]				2	1	2	2	1	2	I	W			X	X	X	X	X	X	X								X	X	18

[11] Low rate is for seeding with rangeland mixture
[12] Adapted to lowlands receiving extra moisture from rainfall
[13] Use only if iron is deficient in the soil



LEGEND

1 Trans-Pecos
2 High Plains
3 Rolling Plains
4 North Central Prairies
5 Edwards Plateau
6 Central Basin
7 Northern Rio Grande Plain
8 Western Rio Grande Plain
9 Central Rio Grande Plain
10 Lower Rio Grande Valley
11 West Cross Timbers
12 East Cross Timbers
13 Grand Prairie
14 Blackland Prairie
15 Claypan Area
16 East Texas Timberlands
17 Coast Prairie
18 Coast Saline Prairies

Figure 1. Land resource areas.

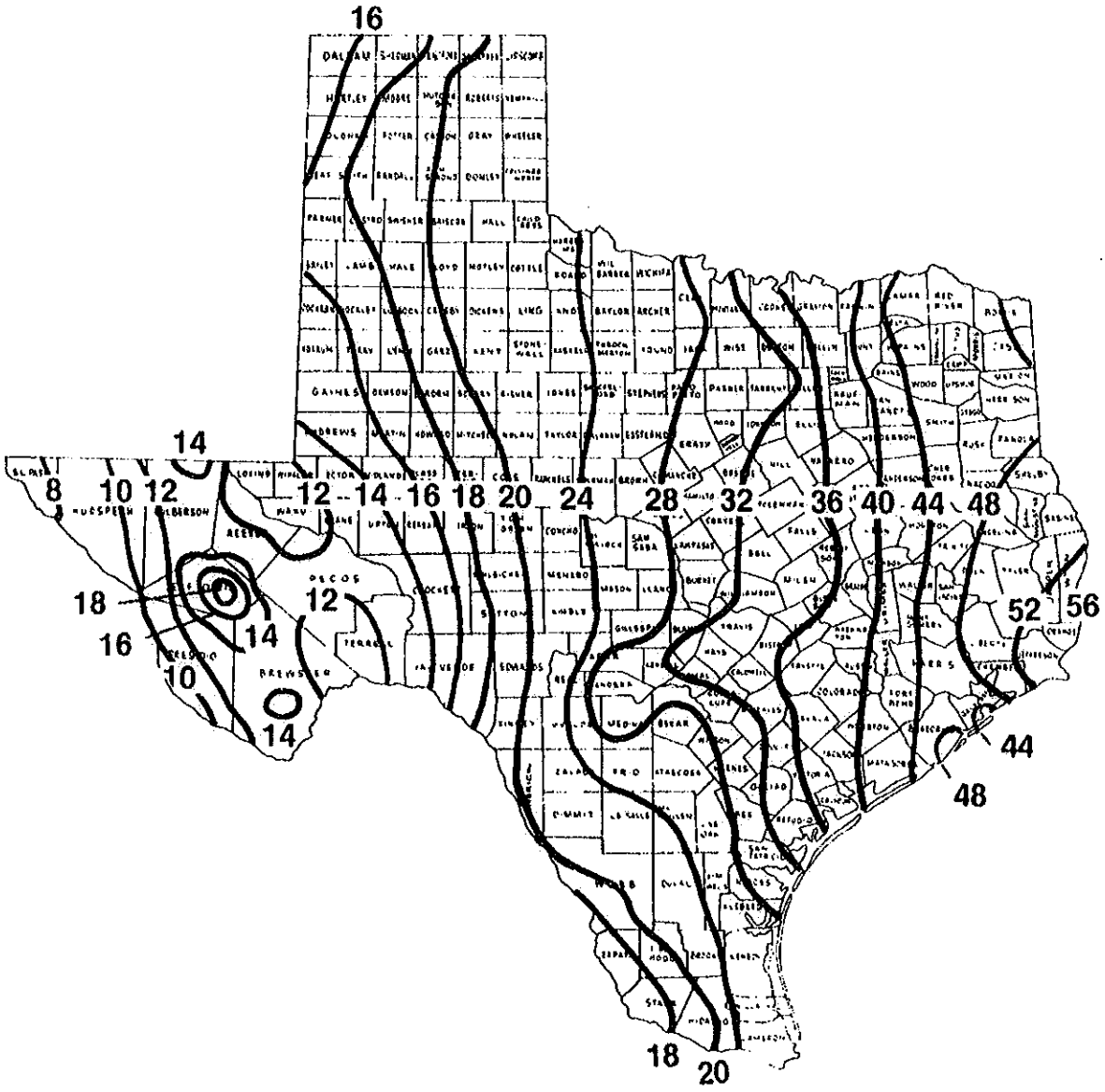


Figure 2. Mean annual total precipitation in Texas.

USDA ARS United States Department Of Agriculture
Agricultural Research Service

Pacific West Riverside, CA US Salinity Laboratory

Halophyte DataBase

Salt-Tolerant Plants & Their Uses

USDA ARS by N.P. Yensen

This searchable database is provided as a cooperative effort between the USDA-ARS U.S. Salinity Laboratory and NyPa International.
Information contained within the database has been provided by Dr. Nicholas Yensen.

Choose GENUS query

Choose FAMILY query

Choose SPECIES query

Alkali grass

(Note: The two following queries may take some time)

Habitat: Go

Geography: Go

Information Help

Built today: 17-SEP-08 PST

Halophyte Book @ NyPa

USDA-ARS U.S. Salinity Laboratory *Riverside, California*

http://www.ussl.ars.usda.gov/pls/caliche/halophyte.query

USDA ARS United States Department Of Agriculture Agricultural Research Service

Pacific West Riverside, CA US Salinity Laboratory

ARS Home | About ARS | Help | Contact Us | En Español

Halophyte DataBase

Salt - Tolerant Plants & Their Uses

by N.P. Yensen

This searchable database is provided as a cooperative effort between the USDA-ARS U.S. Salinity Laboratory and NyPa International. Information contained within the database has been provided by Dr. Nicholas Yensen.

New Search Record 1 of 1

Family: POACEAE

Sub Family:

Genus: Puccinellia

Species: ciliata

Authority: Bor.

Common Name: Alkali grass (English; USA), Puccinellia (Latin; Australia)

Salt Tolerance: It is considered to have salt tolerance and will tolerate salinities up to that of ocean water (46 dS/m), but in trials in Tucson, Arizona productivity dropped rapidly after about 10 dS/m. The growth curve over salinity forms an 'S' shape, suggesting that is a salt-tolerant plant rather than a true halophyte even though it will survive very high salinities. (Aronson 1989:69; Herrmann 1994b; N.P. Yensen per. obs.)

Habitat: It is a hydrohalophyte and occurs in wet saline areas or areas with a shallow water table and 350 mm of precipitation or more. (Aronson 1989:69; Herrmann 1994b)

Geographic Distribution: It is native to the Irano-Turanian region and has been introduced into Australia. (Aronson 1989:69)

Description: GRASS, perennial; LEAVES long and narrow. (Aronson 1989:69)

Uses and Notes: It has C3 photosynthesis and grows best from autumn to spring. It is waterlogging tolerant. Plant in early Fall (late winter to early spring is also possible) into cultivated soil with ridges or a rough texture. Sow seeds (6-10 Kg/ha) on surface without harrowing; light rolling may be beneficial. It is an excellent stock feed and is superior to tall wheat grass. At 3-4 dS/m it will produce 2-3 tons of dry matter per hectare per annum. With fertilizer and good management it can produce as much as 8 tons. The applicaton of 100-150 kg/ha of phosphate may be applied at planting with 20-50 units (40-100 Kg urea) of nirtogen in late winter to boost growth. Grazing may be allowed 18 months after seeding. It will withstand heavy grazing but every second or third year it shoul be allowed to go to seed. (Aronson 1989:69; Herrmann 1994b)

New Search Record 1 of 1

(Note: The two following queries may take some time)

Journal of Applied Ecology 2002
39, 402–415

Germination and establishment of halophytes on brine-affected soils

CAROLYN HOWES KEIFFER* and IRWIN A. UNGAR†

**Department of Botany, Miami University, Middletown, OH 45042, USA; and †Department of Environmental and Plant Biology, Ohio University, Athens, OH 45701, USA*

Summary

1. Contamination of soils with oilfield brines is a significant environmental problem in many oil-production areas. This study tested the feasibility of using different salt-accumulating halophyte species to remediate brine-contaminated soils at a site in south-eastern Ohio, USA, and tested whether planting season affected the germination, yield and sodium uptake of selected species.

2. *Atriplex prostrata*, *Hordeum jubatum*, *Salicornia europaea*, *Spergularia marina* and *Suaeda calceoliformis* were sown in October 1992 (autumn sowing) and March 1993 (spring sowing). For *A. prostrata* and *Spergularia marina*, spring-sowing produced greater germination and survival, while *H. jubatum* exhibited greater germination and survival in autumn sowings. Germination and survival of *Salicornia europaea* and *Suaeda calceoliformis* were not significantly affected by sowing season, but *Salicornia europaea* germinated and survived poorly in both seasons.

3. Spring-sown *A. prostrata* and *Suaeda calceoliformis* and autumn-sown *H. jubatum* and *Spergularia marina* produced the greatest yields.

4. High soil conductivities negatively affected the survival and yield of spring-sown *A. prostrata*, *H. jubatum* and *Spergularia marina*, but did not significantly affect autumn sowings.

5. Root biomass allocation was greater in autumn-sown *H. jubatum*, *Spergularia marina* and *Suaeda calceoliformis*. We hypothesized that autumn-sown seeds of these species have earlier root development that facilitates avoidance of extreme salinity and moisture fluctuations found at the soil surface.

6. All species accumulated higher amounts of Na^+ and Cl^- than other ions. Autumn-sown *A. prostrata* and *Suaeda calceoliformis* accumulated significantly more Na^+ than when spring-sown. Ash content (a measure of accumulated inorganic matter) ranged from 15% to 35% in the various plant tissues. *Hordeum jubatum* had significantly more Na^+ in its roots than in its shoots, making it less suitable for site remediation than *A. prostrata* or *Suaeda calceoliformis*.

7. With the exception of *Salicornia europaea*, all species reduced soil salinity significantly compared with paired control plots, ranging from 4% in *H. jubatum* to 17% in *A. prostrata*. Leaching following precipitation resulted in a 44% reduction in Na^+ from control plots over a 4-year period. However, there was a 59% reduction in Na^+ from plots vegetated with halophytes over the same period.

8. The results indicate that establishment of salt-accumulating halophytes on salt-affected sites can sufficiently remediate the soil to the point where it can be returned to agricultural productivity or where native plants can invade and become established. The phytoremediation process can be facilitated by tailoring plant selection to site conditions, using inputs of fertilizer and water to enhance the growth of the halophytes, and by harvesting the plants on a regular basis.

Key-words: *Atriplex*, *Hordeum*, pytoremediation, *Salicornia*, saline soils, *Spergularia*, *Suaeda*.

Journal of Applied Ecology (2002) **39**, 402–415

© 2002 British Ecological Society

Correspondence: Carolyn Howes Keiffer, Department of Botany, Miami University, Middletown, OH 45042, USA (fax +513 727 3450; e-mail keiffech@muohio.edu).

Introduction

Soil salinization is an increasing problem world-wide. An estimated 3·8 billion acres (1·5 billion hectares) of land are salt-affected, with a third to a half of all irrigated land suffering from reduced production due to excessive salts (Szabolcs 1976, 1994; Choukr-Allah 1996). Soil salinization may result from salt-water intrusion, run-off from salt used during road de-icing, and a build-up of inorganic ions in irrigated regions. Contamination of soils with oilfield brines is also a significant environmental problem in many oil-production areas (Merrill, Lang & Doll 1990). Soils are frequently contaminated with brine because of pipeline breaks, surface spills at wellheads or battery sites and surface and underground movement from buried reserve or disposal pits. Oil-production reports indicated that approximately nine barrels of salt water are produced for every single barrel of crude oil in many parts of the USA (Burnitt & Adams 1963). Brine salts are predominately chlorides (90% or more NaCl) with an electrical conductivity of about 200 dSm^{-1}, which is nearly four times the concentration of sea water (McMillion 1965; Kinghorn 1983).

Most plant species are killed on contact with brine and, unless reclaimed, 'brine spill' sites may remain unvegetated due to persistent high soil salinity and extensive soil erosion (Murphy *et al.* 1988). High concentrations of sodium in brine-contaminated soils may cause the eventual deterioration of soil structure (Hoffman & Shannon 1986). When the amount of absorbed sodium exceeds 10% of the total cation exchange capacity (CEC), soil mineral particles tend to disperse and hydraulic conductivity decreases. Low permeability becomes a problem when the rate of soil water infiltration is reduced to the point where plants are not adequately supplied with water (Hoffman & Shannon 1986). Excess sodium may also cause a salt crust to form on the surface of the soil, which may persist for decades in low rainfall areas. In addition to Na^+ and Cl^-, other ions contained in the brine solution, such as Ca^{2+}, Mg^{2+}, K^+ and SO_4^{2-}, can be phytotoxic if concentrations are above levels that plants can tolerate, even though most of these elements are essential for plant growth (Munn & Stewart 1989). Soils are considered to be salinized when a soil saturation extract has an electrical conductivity (EC) value of 4 mS cm^{-1} or greater (Treshow 1970). Effects of soil salinity on sensitive species are reported to be negligible below 2 mS cm^{-1}, but only very salt-tolerant species remain productive above 15 mS cm^{-1} (Rozema *et al.* 1995).

Revegetation and remediation of brine-contaminated soils therefore pose a number of challenges. Auchmoody (1989) concluded that forest sites damaged by brine spills could regenerate rapidly without mitigation treatment provided that brine sources can be removed and there is abundant precipitation to flush the soil. However, many of the leading oil-producing regions are located in semi-arid regions where rainfall at < 25 cm $year^{-1}$ is not sufficient to leach soils of excess salts. Preliminary studies suggest that a soil saturated with brine would need at least a 100-fold dilution with fresh water to bring the levels of salts down to levels permitting satisfactory plant growth (Munn & Stewart 1989). Leaching soils with $CaCl_2$ solutions will efficiently replace Na^+ from the cation exchange sites on clay and remove the soluble Na^+ from the root zone (Hettinger 1982; Merrill, Lang & Doll 1990). Unfortunately, this process is not practical or cost-effective in arid areas where fresh water is unavailable.

Several researchers have suggested that salt-accumulating halophytes could be used to revegetate and improve the quality of saline soils (Staples & Toenniessen 1984; Flowers 1986; Zhao 1991). Qadir *et al.* (1995) compared the reclamation efficiency of four halophyte species, *Sesbania aculeata*, *Leptochloa fusca*, *Eleusine coracana* and *Panicum colonum*, against traditional gypsum amendments. They determined that gypsum amendments and plantings of *Sesbania aculeata* resulted in equivalent reductions in the soil sodium content. *Sesbania aculeata* also produced good quality forage, reduced erosion and further soil degradation, and increased the soil nitrogen levels through biological nitrogen fixation (Qadir *et al.* 1995). Many genera of Chenopodiaceae, including *Atriplex*, *Salicornia* and *Suaeda*, are extremely salt tolerant and have been studied for their potential use as forage and oilseed crops (Watson 1990; Glenn *et al.* 1991; Rozema *et al.* 1995). Studies with *Suaeda salsa* indicated that a density of 15 plants m^{-2} could potentially remove 3090–3860 kg of Na^+ ha^{-1} if the plants were harvested at the end of the growing season (Zhao 1991).

However, the relative tolerances of halophytic plant species to soil salinity vary, affecting their suitability for use in remediation of brine-contaminated soils. The likely success of reseeding of contaminated sites with seed of halophytic plant species, for example, depends strongly on germination responses under different levels of soil salinity. Many halophytes are subjected to osmotically induced seed dormancy, and their seeds either do not germinate or have reduced germination at salinities above 1·5% NaCl (approximately half-strength sea water) (Woodell 1985; Ungar 1991). Partial or incomplete inhibition may occur depending on species' tolerance limits relative to levels of soil salinity (Ungar 1978a, 1982). Germination responses of halophyte seeds to salinity are highly variable and species-specific (Ungar 1978a, 1982). Seeds typically germinate early in the spring or in a season with high precipitation, when soil salinity levels are reduced (Chapman 1974; McMahon & Ungar 1978). Such a pattern results in the establishment of seedlings prior to the period of highest salt stress. However, many halophytes, including all of the species in this study, have the potential to germinate at any time of the year if temperature and edaphic conditions are suitable (Woodell 1985; Ungar 1991). Badger & Ungar (1989) determined that germination of *Hordeum jubatum* seeds was inhibited in the

© 2002 British Ecological Society,

summer, when higher temperatures and increased evaporation reduced soil moisture and led to an increase in soil salinity that inhibited seed germination. However, field data comparing the germination of species at different times of year is generally limited.

The objectives of this study were: to compare the germination, survival and biomass accumulation of selected halophytic species when sown in the autumn or spring; to determine whether salinity and soil moisture affected survival and yield; and to determine if sodium accumulated in sufficient amounts in the above-ground plant portions for significant reduction in soil concentrations to occur. Any reduction in soil sodium concentrations due to leaching was measured in control plots over the 4-year period of the study.

Methods

STUDY SITE

The 2-ha study area was located in Athens County, Ohio (39°20′N and 81°57′W), USA, on Rome Township Road 229 near New England, Ohio (US Geological Survey 1961). The annual average precipitation for Athens, Ohio, in 1992 was approximately 101 cm, and the mean temperature was 7·8 °C (US Department of Commerce 1992). Ten-year averages from 1982 to 1992 for Athens County were 117 cm of precipitation and a mean temperature of 7·5 °C (US Department of Commerce 1992). The site has silty clay loam soils with moderate to good water drainage (US Department of Agriculture 1985). The site, a former pasture, was contaminated by a series of leaks from a brine collection tank from 1989 to 1990, when the leak was corrected. The majority of the site was unvegetated when it was first selected for this study in 1991. The soil was rototilled to a depth of 20 cm to give uniform conditions for the study species, which have rooting depths ranging from 6 to 18 cm. A 2-m high game fence was installed prior to planting in order to exclude deer and other herbivores from the site.

STUDY SPECIES

Five halophytic plant species were included in this study. Their selection was based on their life-history pattern, tolerance to salinity and seed availability.

Hordeum jubatum L. (Poaceae), the only grass species included in this study, is a short-lived perennial indigenous to western North America that has become naturalized in eastern North America (Badger & Ungar 1994). It is most prevalent on saline soils with a high water table and can be found along roadsides where salt is used as a de-icing agent in the winter. Typically, *H. jubatum* is restricted to areas that are only slightly saline (< 1% NaCl) and is a poor competitor with other species in the absence of salt (Badger & Ungar 1994).

Spergularia marina (L.) Griseb. (Caryophyllaceae) has a cosmopolitan distribution in moist, moderately saline, habitats (< 2% NaCl) (Ungar 1988). This species can occur as a short-lived perennial, biennial or annual depending upon edaphic conditions. *Spergularia marina* is a small plant (< 15 cm tall), and continuous flowering during the course of the growing season will lead to the production of many seed capsules, each containing approximately 50 seeds (Ungar 1988). Seeds may mature and germinate during the same growing season or may remain dormant in the soil (Ungar 1988).

Salicornia europaea L. (Chenopodiaceae) is an obligate halophyte with cosmopolitan distribution in coastal and continental saline habitats, usually occupying the zone of highest salinity up to 5% NaCl (Chapman 1960; Waisel 1972; Ungar 1979). *Salicornia europaea* is a succulent-stemmed annual, with most branches producing fruiting cymes that yield dimorphic seed types late in the autumn.

Atriplex prostrata Boucher ex DC (SYN: *Atriplex triangularis* Willd.) (Chenopodiaceae) is a herbaceous annual halophyte of cosmopolitan distribution in coastal and inland salt marshes (Osmond, Bjorkman & Anderson 1980). Its habitats vary in salinity from 0·003% to 3·6% total salts (Ungar 1991). *Atriplex prostrata* also produces a large quantity of dimorphic seeds late in the autumn.

Suaeda calceoliformis (Hook.) Moq. (SYN: *Suaeda depressa* (Pursh) Wats.) (Chenopodiaceae) is a succulent-leafed annual halophyte that occurs throughout the western half of North America (Ungar & Capilupo 1968; McNeill, Bassett & Crompton 1977). Two growth forms occur (erect and prostrate), with the more prostrate form occurring on soils with higher salinities up to 5% NaCl (Williams & Ungar 1972; Youngman & Heckathorn 1992).

SOURCE OF SEEDS

Seeds of *A. prostrata, H. jubatum, Salicornia europaea* and *Spergularia marina* were harvested from salt marsh plants in Rittman, Ohio, USA (40°57′30″ and 81°47′30″W) in October 1992. Seeds of *Suaeda calceoliformis* were collected from a salt marsh in the Quivira National Wildlife Refuge, Stafford County, Kansas, USA (38°20′52″ and 98°67′38″W) during the same time period. The fruits were air dried in the laboratory for 7 days and sieves were used to separate the seeds from the chaff. Mature and intact seeds (n = 1600) of each species were counted into 25 seed lots and placed into dry Gelman™ Petri dishes (Fisher Scientific, Pittsburgh, Pennsylvania, USA) and stored at 5 °C until planting. Seed viability testing was performed in distilled water for 30 days in a lighted Percival™ incubator (Percival Scientific Inc., Boone, Iowa, USA) maintained at 5/25 °C, 12-h thermoperiod (dark:light, 400–700 μm, 28 μmol m^{-2} s^{-1}), which has been determined previously to produce optimum germination for all study species (Ungar 1991). The seed germination potential was determined to be 96–98% for *A. prostrata* and *Suaeda calceoliformis*, 86% for *Spergularia marina*, 63% for *H. jubatum* and 53% for *Salicornia europaea* (Keiffer & Ungar 1995).

© 2002 British Ecological Society,

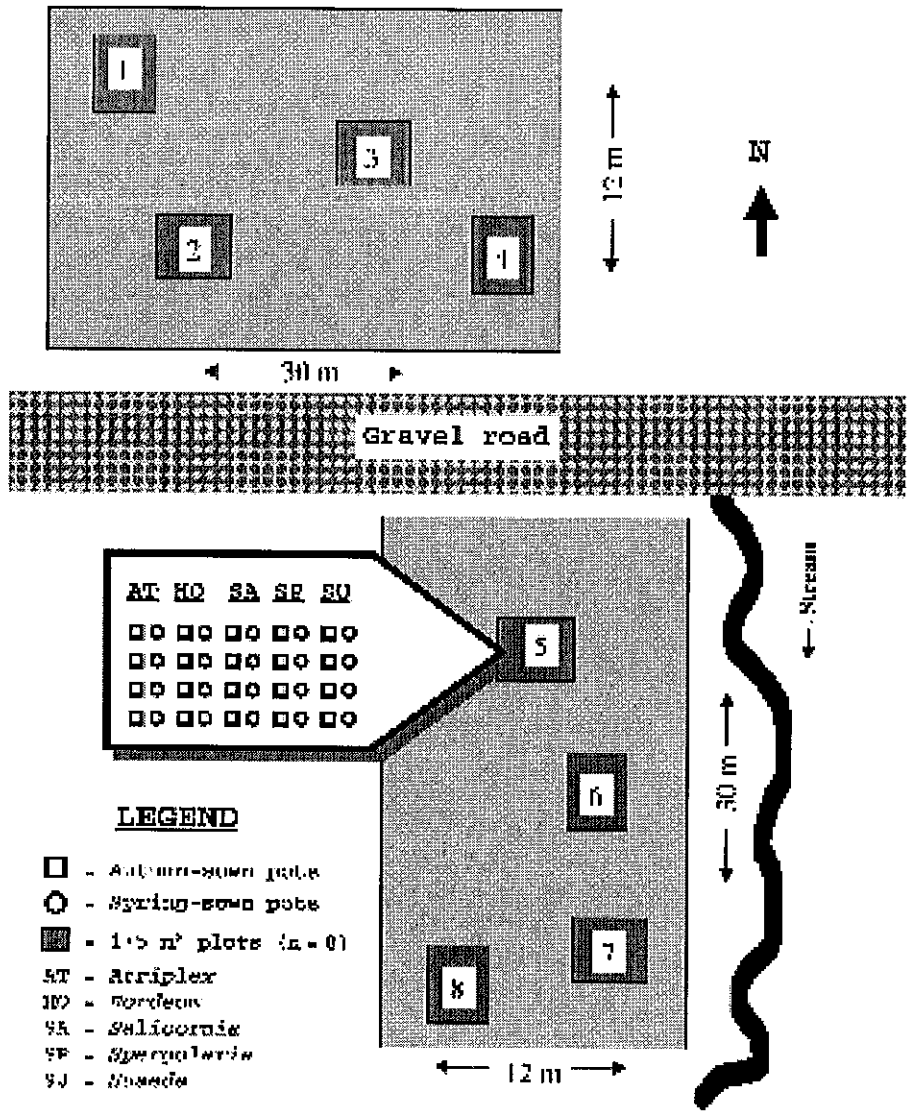


Fig. 1. Diagram of the study site in Athens County, Ohio, USA. The source of contamination, a brine storage tank, is located approximately 12 m west of plot 1. Autumn-sown seeds of each species were placed in square pot collars and spring-sown seeds were placed in round pot collars within each of the eight 1·5-m² plots.

FIELD METHODS

Eight 1·5-m² plots were selected at random within the fenced brine-contaminated site (Fig. 1). 'Pot collars' (the top 5 cm of plastic pots, area = 100 cm²) were inserted into the soil, and four replicate pot collars were used for each species in each of the eight plots. Orientation of plots and the location of pots within the plots were determined randomly. Samples were taken 100 cm deep with a 20-mm diameter soil corer (Oakfield Apparatus Company, Oakfield, WI) from within each pot prior to planting and at the time of harvest. Control plots were set up 100 cm away from each pot and soil samples were taken at the time of planting and then on a weekly basis from May to the end of August Twenty-five seeds of each species were sown randomly in each pot collar in October 1992 and in March 1993 (n = 800 seeds per treatment). Seedling emergence and survival were recorded at weekly intervals from January to the end of August 1993 by counting all seedlings within each pot.

PLANT ANALYSIS

Plants were harvested on 1 October, and the roots were rinsed gently with distilled water for 20 s to remove soil particles. The plants were then dried for 48 h in a forced draft oven at 60 °C. The dry mass was determined for each plant, and biomass allocation was determined by separating the plants into roots, stems, leaves and fruits. Stems and leaves were combined into a shoot group for *Salicornia europaea* and *H. jubatum*. In some cases, plant parts from the same treatment pot were combined in order to obtain a 1-g sample that was required for ion analysis. The dried plant parts were placed in porcelain crucibles and ashed in a muffle furnace for 24 h at 500 °C, to determine the percentage ash content of plant material. Ashed plant material

© 2002 British Ecological Society,

Table 1. Mean germination (%) ± SE for autumn- and spring-sown seeds of *Atriplex*, *Hordeum*, *Salicornia*, *Spergularia* and *Suaeda*. Probability values are based on one-way ANOVA results

Species	Mean germination (%) ± SE			
	Autumn	Spring	*F*	Probability
Atriplex	27·5 ± 6·8	40·8 ± 3·0	127·51	0·03
Hordeum	30·8 ± 10·2	15·1 ± 4·1	84·66	0·04
Salicornia	0·6 ± 0·9	2·0 ± 1·9	2·14	0·09
Spergularia	11·1 ± 4·6	27·4 ± 6·1	35·07	0·05
Suaeda	17·5 ± 8·3	16·6 ± 2·2	3·66	0·08

was dissolved in 20% sulphuric acid and diluted in distilled water for analysis. Chloride ion content was measured with a Beckman specific ion electrode. Data for Cl^- ions did not indicate any significant loss on ignition in the muffle furnace. Cation content of plant organs was analysed using a Varian model 20 atomic absorption spectrophotometer. The Na^+ and K^+ concentrations of plant tissues were assayed by flame emission, and Ca^{2+} and Mg^{2+} concentrations by atomic absorption spectrophotometry.

SOIL ANALYSIS

Soil moisture was determined gravimetrically from the soil samples collected weekly from the control plots. Oven-dried soil samples were sieved through a 2-mm sieve and the water-soluble cations were extracted from the soil by mixing 25 g of soil in 50 ml of distilled water (1 : 2, w/v) in a 250-ml plastic container. The samples were shaken at 150 r.p.m. on a platform shaker at room temperature for 2 h. The slurries were filtered through Whatman No. 2 filter paper (Fisher Scientific, Pittsburgh, Pennsylvania, USA). Soil conductivity (mS cm^{-1}) was determined for all soil extracts using a specific conductance meter (Radiometer Copenhagen CDM 83 Conductivity meter; Radiometer, Copenhagen, Denmark), and a Beckman ion-specific electrode (Beckman, Fullerton, Ca) was used to determine the Cl^- content. Cation content of the soil extracts was determined using the same methods as described for the plant material.

STATISTICAL ANALYSIS

Number Cruncher Statistical Software (NCSS) was used to perform a one-way ANOVA on the results of growth and ion content studies (Hintze 1991). An arcsine transformation was used for percentage data prior to analysis, and a $\log_{10}$ transformation was used to normalize some ion data in order to meet the assumptions of ANOVA. Post-hoc multiple comparison procedures (Duncan's and Fisher's LSD) were also used to identify differences between means. Survival data for each species were analysed with the Kolmorgorov–Smirnoff test to identify significant differences between planting times (Sokal & Rohlf 1995). Linear regression analysis was used to compare the relationships between soil moisture and conductivity, with survival and yield data (Jandel Scientific Software 1992). This analysis was followed by a bootstrapping procedure to refine the *P*-values (Simon 1992).

Results

GERMINATION AND SURVIVAL

Field-sown seeds had a much lower germination compared with those observed in the laboratory during the seed viability study. Germination and survival of autumn and spring treatments followed similar patterns within species (Table 1 and Fig. 2). Spring-sown *A. prostrata* and *Spergularia marina* had significantly ($P = 0·03$ and $P = 0·05$) greater germination and significantly ($P = 0·0006$ and $P = 0·0001$) greater survival than when sown in the autumn (Table 1 and Fig. 2). *Hordeum jubatum* had significantly ($P = 0·04$) greater germination and significantly ($P = 0·0001$) greater survival when sown in the autumn (Table 1 and Fig. 2). Germination (%) from autumn and spring sowings was not significantly ($P = 0·92$ and $P = 0·83$) different for *Salicornia europaea* and *Suaeda calceoliformis* (Table 1). Survival of *Suaeda calceoliformis* did not differ significantly between autumn and spring sowings (Fig. 2). *Salicornia europaea* sown in either season had poor survival: 4% and less than 1% survival for spring and autumn sowings, respectively (Fig. 2).

Soil moisture (percentage) remained high and conductivity readings remained relatively low, ranging from 12 ± 2·4 to 15 ± 1·8 mS cm^{-1} from March until late May 1993 (Fig. 3). The majority of observable germination from both plantings occurred during this period (Fig. 2). Low rainfall from May to mid-July caused a steady decrease in soil moisture that also resulted in an increase in soil conductivity (Fig. 3). Several days of rain in mid-July increased the soil moisture to 23 ± 4·3%, and reduced conductivity levels. Additional seed germination was observed the following week in spring-sown *A. prostrata* (Fig. 2). In the later half of the summer, soil moisture was lower and conductivity higher than earlier in the growing season (Fig. 3). Mortality of *H. jubatum* and *Suaeda calceoliformis* plants between July and August appeared to be the result of the combined effects of drought and salinity stress (Fig. 2).

© 2002 British Ecological Society,

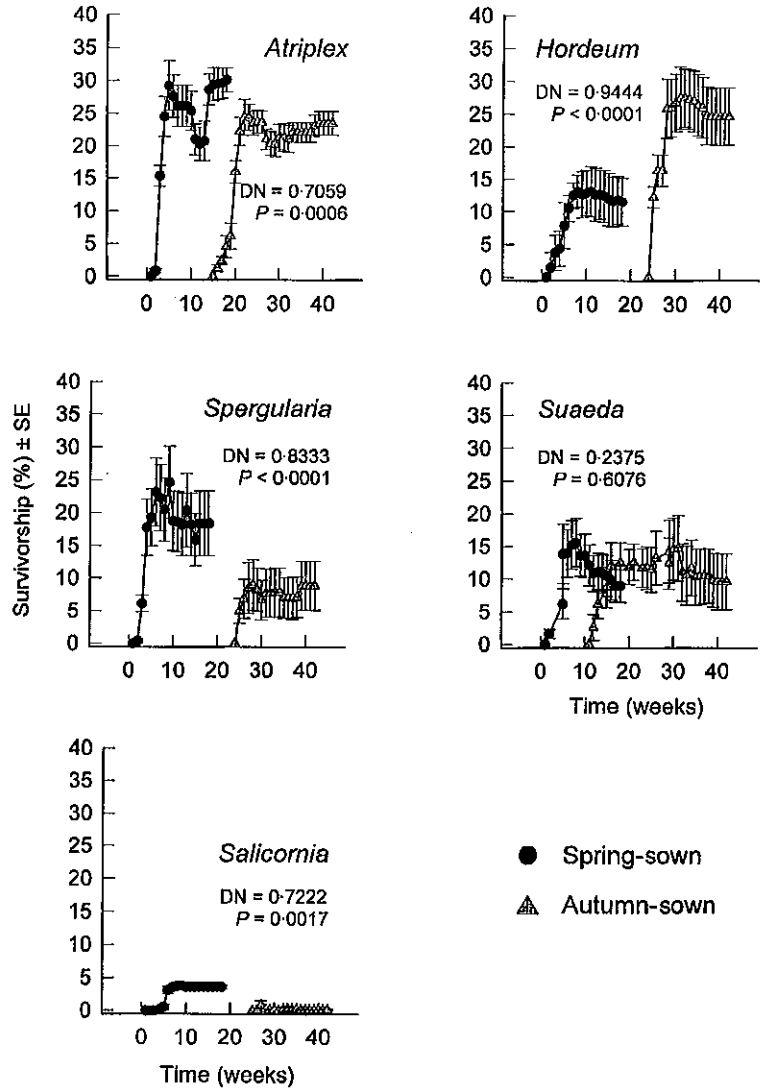


Fig. 2. Mean (n = 32) survivorship (± SE) for five study species at the brine spill site, Athens County, Ohio, USA. Survivorship percentage represents the number of seedlings surviving of the 100 seeds sown per plot. Circles represent spring-sown seeds; triangles represent autumn-sown seeds. Time 0 is 15 March, 1993.

Regression analyses comparing soil moisture and survival indicated a positive relationship for autumn-sown *H. jubatum*, spring-sown *Suaeda calceoliformis* and for *A. prostrata* and *Salicornia europaea* sown in either season (Table 2). Similar analyses comparing conductivity and survival indicated that conductivity did not significantly ($P > 0{\cdot}05$) influence the survival of autumn-sown species (Table 2). However, survival of spring-sown *A. prostrata*, *H. jubatum* and *Spergularia marina* was negatively correlated with increasing conductivity (Table 2).

YIELD

Atriplex prostrata and *Suaeda calceoliformis* yielded significantly ($P < 0{\cdot}0001$ and $P < 0{\cdot}01$) greater biomass when spring-sown than when sown in the autumn (Fig. 4). Conversely, *H. jubatum* and *Spergularia marina* had significantly ($P < 0{\cdot}01$ and $P < 0{\cdot}0001$) more biomass when autumn-sown. *Salicornia europaea* produced low yields regardless of sowing season. Regression analysis comparing biomass to soil moisture (percentage) indicated a highly significant ($P < 0{\cdot}001$) positive relationship (Table 3 and Fig. 4). Increased soil moisture (percentage) positively influenced yields for all autumn-sown species with the exception of *Spergularia marina* (Table 3). Increased soil conductivity negatively affected yields of spring-sown *A. prostrata*, *H. jubatum* and *Spergularia marina* (Table 3). However, conductivity did not significantly ($P > 0{\cdot}05$) influence the biomass of any of the species when autumn-sown, or *Salicornia europaea* and *Suaeda calceoliformis* sown in spring.

BIOMASS ALLOCATION

Salicornia europaea densities were too low to provide enough plants to determine biomass allocation.

© 2002 British Ecological Society,

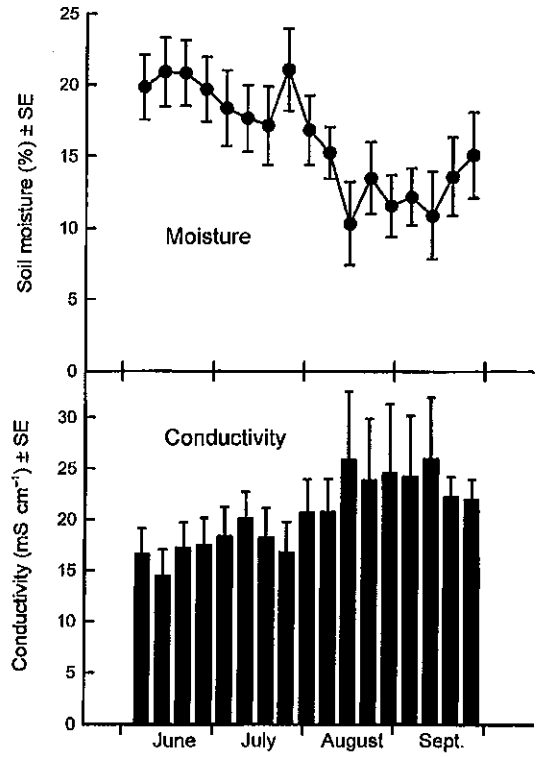


Fig. 3. Mean (n = 8) soil moisture (% H_2O 100 g^{-1} dry weight) and conductivity (± SE) for each week of the 1993 growing season at brine spill site, Athens County, Ohio, USA.

Autumn- and spring-sown *A. prostrata* had very similar allocation patterns (Fig. 5). Autumn-sown *H. jubatum* and *Spergularia marina* had significantly ($P < 0.01$) greater allocation to roots than spring-sown cohorts (Fig. 5). Autumn-sown *Suaeda calceoliformis* also exhibited a similar trend, but this was not significant ($P > 0.05$). Spring-sown *Suaeda calceoliformis* had significantly ($P < 0.01$) greater biomass and significantly ($P < 0.05$) greater allocation to fruit than autumn-sown plants (Fig. 2).

Table 2. Summary of regression analyses comparing edaphic effects (moisture and conductivity) on the survival (%) of spring- and autumn-sown *Atriplex*, *Hordeum*, *Salicornia*, *Spergularia* and *Suaeda*. Interactions with $P > 0.05$ were considered to be non-significant (NS)

	Soil parameter			
	Moisture (%)		Conductivity (mS cm^{-1})	
Species Survival (%)	Autumn	Spring	Autumn	Spring
Atriplex	$P < 0.01$ $R^2 = 0.59$	$P < 0.05$ $R^2 = 0.31$	NS	$P < 0.01$ $R^2 = 0.43$
Hordeum	$P < 0.01$ $R^2 = 0.36$	NS	NS	$P < 0.01$ $R^2 = 0.51$
Salicornia	$P < 0.001$ $R^2 = 0.68$	$P < 0.001$ $R^2 = 0.62$	NS	NS
Spergularia	NS	NS	NS	$P < 0.01$ $R^2 = 0.65$
Suaeda	NS	$P < 0.05$ $R^2 = 0.45$	NS	NS

ASH CONTENT

The ash content of the various plant parts followed a similar pattern within each species (Fig. 6). Autumn-sown *A. prostrata* had significantly ($P < 0.05$) greater amounts of ash in all plant parts than spring-sown plants. Both *A. prostrata* and *Suaeda calceoliformis* had higher ash content in the stems and leaves (35–38%) than in roots or fruits (33–35%) (Fig. 6). Spring-sown *H. jubatum* had significantly ($P < 0.05$) greater ash content in all plant parts compared with the autumn cohort. Ash content of *H. jubatum* roots ranged between 25% in the autumn planting to 30% in the spring cohort. *Hordeum jubatum* shoot and fruit tissues contained approximately half this amount of ash (Fig. 6). Spring-sown *Spergularia marina* had significantly ($P < 0.05$) greater ash content in leaves and

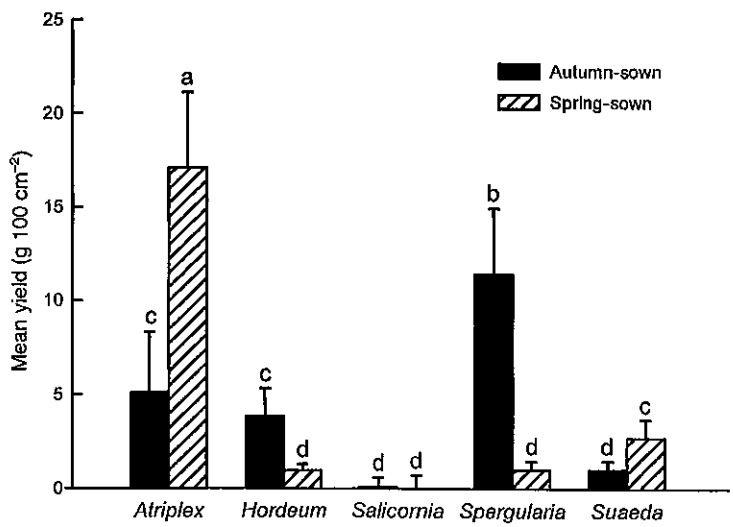


Fig. 4. Mean (n = 32) yield (g 100 cm^{-2}) (± SE) for five study species at a brine spill site in Athens County, Ohio, USA. Solid black bars represent the biomass at the time of harvest from autumn-sown seeds, and hatched bars represent the biomass of spring-sown seeds. Groups sharing the same letter are not significantly different (Duncan's multiple comparison test; $P < 0.05$).

© 2002 British Ecological Society,

Table 3. Summary of regression analyses comparing the effects of soil moisture and conductivity on the dry mass production (g 100 cm^{-2}) of spring- and autumn-sown *Atriplex*, *Hordeum*, *Salicornia*, *Spergularia* and *Suaeda*. Interactions with *P*-values > 0·05 were considered to be non-significant (NS)

	Soil parameter			
	Moisture (%)		Conductivity (mS cm^{-1})	
Species Yield (g 100 cm^{-2})	Autumn	Spring	Autumn	Spring
Atriplex	$P < 0.01$ $R^2 = 0.67$	$P < 0.05$ $R^2 = 0.45$	NS	$P < 0.01$ $R^2 = 0.64$
Hordeum	$P < 0.01$ $R^2 = 0.60$	NS	NS	$P < 0.01$ $R^2 = 0.59$
Salicornia	$P < 0.001$ $R^2 = 0.83$	$P < 0.001$ $R^2 = 0.74$	NS	NS
Spergularia	NS	NS	NS	$P < 0.01$ $R^2 = 0.54$
Suaeda	$P < 0.05$ $R^2 = 0.63$	NS	NS	NS

fruits than autumn-sown plants. *Spergularia marina* leaves contained 15–19% ash, while roots, stems and fruits contained 24–32% ash.

ION ANALYSIS

Sodium ion content for all species and plant parts was considerably greater than for any of the other cations (Fig. 7 and Table 4). Sodium concentrations in autumn- and spring-sown plants were significantly ($P > 0.05$) different for all of the species except *Spergularia marina* (Fig. 7). Autumn-sown *A. prostrata* and *Suaeda calceoliformis* had significantly ($P < 0.01$) greater concentrations of Na^+ in the various tissues than did those sown in the spring. The opposite was true for *H. jubatum*, with significantly higher Na^+ content in the tissues of spring-sown plants. The Na^+ content in roots of *H. jubatum* was approximately two times greater than the amount in shoots and fruits. *Spergularia marina* leaf tissue had a significantly ($P < 0.01$) greater amount of Na^+ in spring-sown plants than in autumn-sown ones. With the exception of *H. jubatum*, all species had significantly ($P < 0.001$) lower amounts of Na^+ in fruit tissue than in other plant parts (Fig. 7).

The Cl^- content of plants was slightly higher than Na^+, and both were accumulated in concentrations 10–20 times higher than those found in the soil (Table 4). A fairly uniform pattern in Ca^{2+}, Mg^{2+} and K^+ was found in all tissues. Concentrations of Ca^{2+} and Mg^{2+} were 20–30 times higher than those found in the soil, and the K^+ concentration in tissue was approximately 500 times higher than the K^+ content of the soil (Tables 4 and 5). The Ca^{2+} concentrations were significantly ($P < 0.01$) higher than Mg^{2+} or K^+, and ranged from 60·2 to 80·4 meq 100 g^{-1} (Table 4). The Mg^{2+} concentrations ranged from 28·7 to 40 meq 100 g^{-1}, and K^+ content ranged from 15·8 to 25·6 meq 100 g^{-1} (Table 4). *Hordeum jubatum* shoot tissues from both plantings had lower K^+ concentrations than any of the other species regardless of sowing season. Ionic analysis of the soil from the root zone of the plants at the time of harvest indicated Na^+ and Cl^- concentrations were 10–15 times higher than those of Ca^{2+} or Mg^{2+}. The K^+ content was low, ranging from 0·03 to 0·5 meq 100 g^{-1} (Table 5).

SOIL SODIUM REDUCTION

Soil collected in October 1991 at the initial inspection of the brine spill site had a Na^+ content of approximately 42 meq 100 g^{-1} (Fig. 8). Soil samples taken a year later in October 1992 from eight control plots and the plots scheduled for autumn sowing indicated similar Na^+ concentrations ($P > 0.05$). However, the Na^+ content had decreased approximately 12% from the previous year. Presumably, this difference was due to leaching by precipitation because the site was still

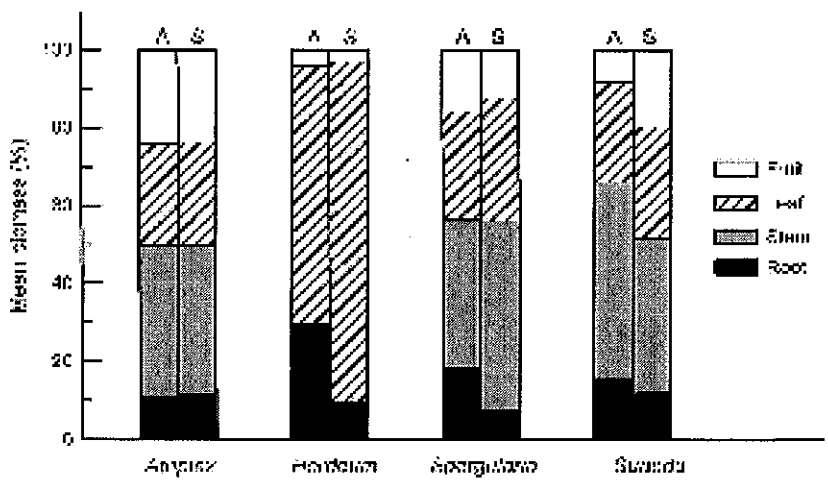


Fig. 5. Mean ($n = 90$) biomass allocation (± SE) for four species sown in the autumn (A) and spring (S) at the brine spill site, Athens County, Ohio, USA. Roots are represented by black bars, stems by grey bars, leaves by hatched bars, and fruit by open bars. *Hordeum* stems and leaves were combined into a shoot group.

© 2002 British Ecological Society,

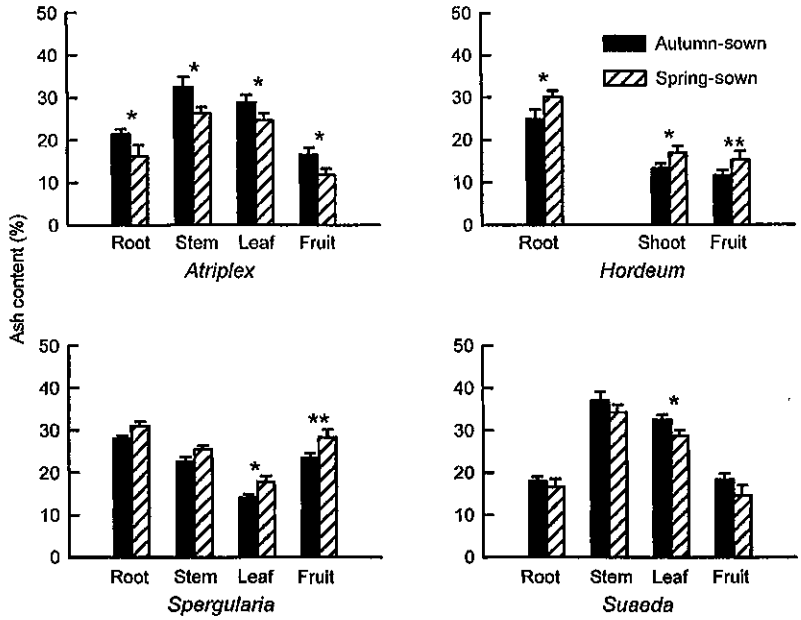


Fig. 6. Mean (± SE) ash content (%) in root, stem, leaf and fruit tissue of four species sown in the autumn (black bars) and spring (hatched bars) at the brine spill site, Athens County, Ohio, USA. *Hordeum* stems and leaves were combined into a shoot group. Significant differences in ash content between autumn and spring sowings are indicated by *, ** and ***, which correspond to probability values of $P < 0{\cdot}05$, $P < 0{\cdot}01$ and $P < 0{\cdot}0001$, respectively (ANOVA).

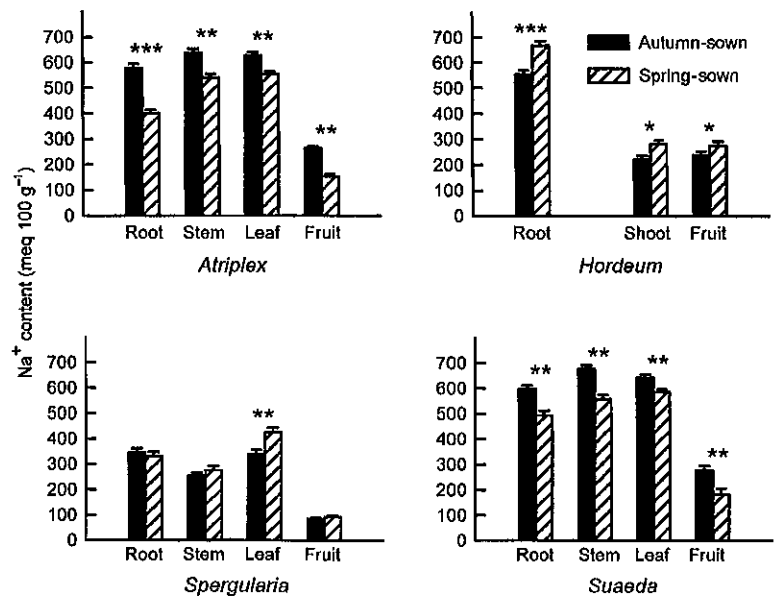


Fig. 7. Mean (± SE) Na^+ content in root, stem, leaf and fruit tissue of four species sown in the autumn (black bars) and spring (hatched bars) at a brine spill site, Athens County, Ohio, USA. *Hordeum* stems and leaves were combined into a shoot group. Significant differences in Na^+ content between autumn and spring sowings are indicated by *, ** and ***, which correspond to probability values of $P < 0{\cdot}05$, $P < 0{\cdot}01$ and $P < 0{\cdot}0001$, respectively.

unvegetated. Soil samples taken in March 1993 from eight control plots and from the plots scheduled for spring sowing indicated similar levels of Na^+ content ($P > 0{\cdot}05$) (Fig. 8). Soil samples taken at a depth of approximately 10 cm from the root zone of the plants at the time of harvest in October 1993 had a significantly ($P < 0{\cdot}05$) lower Na^+ content the control plots. Similar data were collected in March 1994 and October 1994 from the root zones of 'volunteer' *A. prostrata*, *Spergularia marina* and *Suaeda calceoliformis*. Soil analysed in October 1994 had a significantly ($P < 0{\cdot}01$) lower amount of Na^+ (19 meq 100 g^{-1}) in comparison with the control plots (24 meq 100 g^{-1}). Overall reduction of Na^+ from October 1991 to October 1994 was determined to be 59% in halophyte plots and 44% in control plots (Fig. 8).

© 2002 British Ecological Society,

Table 4. Mean concentration of ions (meq 100 g^{-1} tissue ± SE) in roots, stems, leaves and fruits harvested from autumn- and spring-sown *Atriplex*, *Hordeum*, *Spergularia* and *Suaeda*. Stems and leaves were combined into a shoot group for *Hordeum*

	Atriplex		*Hordeum*		*Spergularia*		*Suaeda*	
Tissue/ion	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring
Roots								
Calcium	71·8 ± 0·6	65·7 ± 0·2	67·5 ± 0·4	61·2 ± 0·7	66·9 ± 0·6	64·3 ± 0·2	66·8 ± 0·1	64·2 ± 0·7
Chloride	599 ± 8·5	422 ± 6·7	574 ± 9·2	690 ± 8·7	368 ± 6·4	356 ± 7·8	594 ± 8·4	550 ± 7·3
Magnesium	35·2 ± 0·4	31·3 ± 0·3	36·2 ± 0·7	34·8 ± 0·5	34·9 ± 0·4	31·3 ± 0·4	37·3 ± 0·2	35·2 ± 0·3
Potassium	24·9 ± 0·7	22·6 ± 0·7	15·8 ± 0·5	17·2 ± 0·2	17·3 ± 0·5	18·2 ± 0·9	18·6 ± 0·8	16·4 ± 0·7
Stems								
Calcium	75·8 ± 0·3	72·1 ± 0·4	74·2 ± 0·9	73·2 ± 0·6	63·4 ± 0·8	68·3 ± 0·6	80·4 ± 0·4	77·5 ± 0·1
Chloride	682 ± 9·6	574 ± 8·4	246 ± 6·4	301 ± 7·3	267 ± 6·7	279 ± 4·9	701 ± 9·6	579 ± 8·5
Magnesium	40·5 ± 0·8	38·9 ± 0·7	33·2 ± 0·3	31·2 ± 0·2	36·7 ± 0·3	38·9 ± 0·1	36·1 ± 0·6	34·2 ± 0·3
Potassium	25·3 ± 0·1	22·6 ± 0·5	18·3 ± 0·6	17·6 ± 0·7	22·1 ± 0·5	25·7 ± 0·5	23·4 ± 0·2	19·7 ± 0·8
Leaves								
Calcium	68·1 ± 0·2	62·7 ± 0·1	–	–	75·8 ± 0·7	78·4 ± 0·2	75·6 ± 0·9	72·1 ± 0·4
Chloride	645 ± 9·1	591 ± 7·4	346 ± 7·2	402 ± 6·3	659 ± 8·4	603 ± 8·9		
Magnesium	40·1 ± 0·7	37·6 ± 0·9	–	–	39·6 ± 0·5	40·2 ± 0·5	40·1 ± 0·2	39·5 ± 0·9
Potassium	23·6 ± 0·4	21·2 ± 0·7	–	–	20·1 ± 0·9	25·4 ± 0·6	24·3 ± 0·5	21·7 ± 0·2
Fruits								
Calcium	60·4 ± 0·6	63·2 ± 0·9	68·4 ± 0·7	79·5 ± 0·4	60·2 ± 0·4	64·9 ± 0·3	65·8 ± 0·7	61·4 ± 0·3
Chloride	266 ± 6·8	148 ± 7·3	256 ± 6·3	2 89 ± 7·4	95 ± 5·9	102 ± 6·4	326 ± 9·1	217 ± 6·7
Magnesium	36·3 ± 0·1	37·8 ± 0·2	28·7 ± 0·4	35·4 ± 0·1	33·7 ± 0·9	34·5 ± 0·4	33·2 ± 0·3	31·1 ± 0·2
Potassium	18·1 ± 0·5	16·2 ± 0·1	16·4 ± 0·3	21·2 ± 0·5	17·6 ± 0·5	18·2 ± 0·8	25·6 ± 0·4	20·2 ± 0·7

Table 5. Mean concentration of ions (meq 100 g^{-1} soil ± SE) from soil obtained in October from the root zones of *Atriplex*, *Hordeum*, *Spergularia* and *Suaeda*

Ion	*Atriplex*	*Hordeum*	*Spergularia*	*Suaeda*
Sodium	28·6 ± 1·0	32·9 ± 1·1	31·8 ± 1·3	29·6 ± 1·3
Chloride	36·8 ± 2·1	33·2 ± 1·8	34·0 ± 2·1	31·2 ± 1·2
Calcium	1·4 ± 0·01	2·1 ± 0·03	2·5 ± 0·05	2·4 ± 0·04
Magnesium	2·2 ± 0·06	2·1 ± 0·03	2·6 ± 0·08	1·9 ± 0·06
Potassium	0·04 ± 0·01	0·03 ± 0·01	0·04 ± 0·01	0·05 ± 0·01

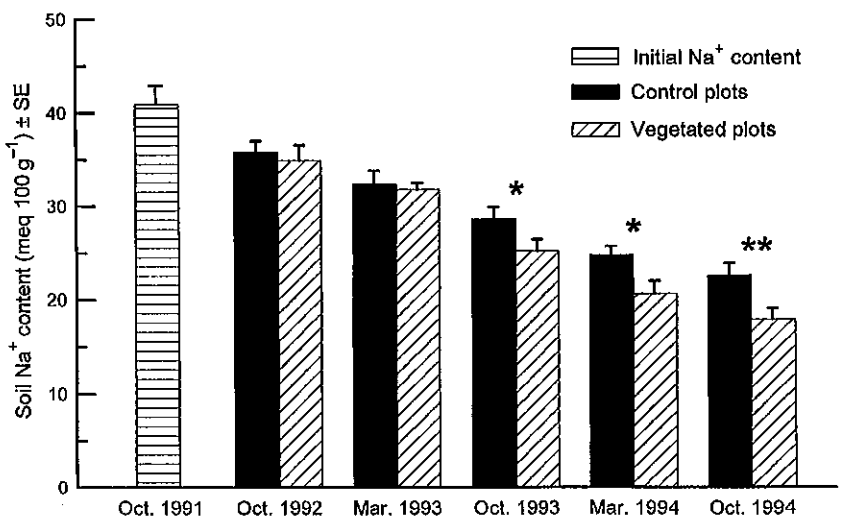


Fig. 8. Mean (n = 8) Na^+ content (± SE) of soil from control and vegetated plots at the brine spill site in Athens County, Ohio, USA. October 1991 data were collected at initial inspection of site. Data from 1994 vegetated plots were taken from the root zones of 'volunteer' *Atriplex*, *Spergularia* and *Suaeda*. Significant differences in Na^+ content between autumn and spring sowings are indicated by * and **, which correspond to probability values of $P < 0·05$ and $P < 0·01$ (t-test).

© 2002 British Ecological Society,

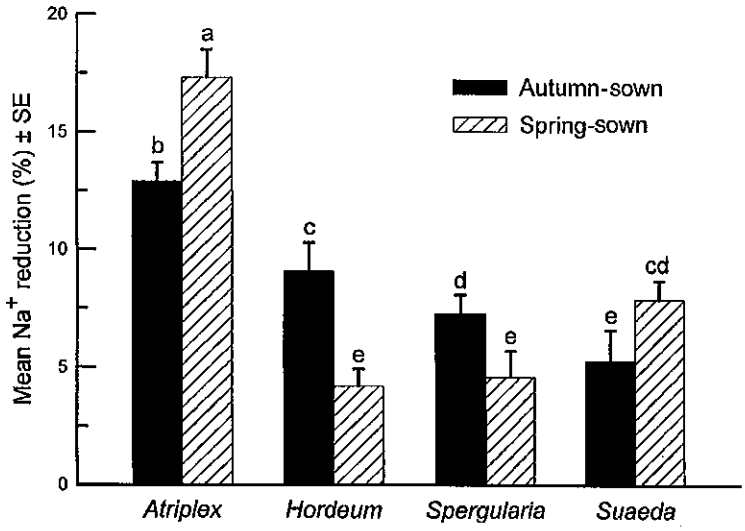


Fig. 9. Mean (n = 32) reduction (± SE) in sodium content of the soil from the root zone of four species when compared with paired control plots at a brine spill site in Athens County, Ohio, USA. Solid black bars represent the reduction associated with autumn-sown seeds and hatched bars represents the reduction associated with spring-sown seeds. Groups sharing the same letter are not significantly different (Duncan's multiple comparison test; $P < 0{\cdot}05$).

All autumn- and spring-sowings reduced soil Na^+ content compared with the paired control plots (Fig. 9). *Atriplex prostrata* plots had the greatest reduction of Na^+, the spring sowing resulted in a 17% reduction and the autumn sowing led to a 12% reduction (Fig. 9). Autumn-sown *H. jubatum* and *Spergularia marina* plots resulted in reduction of Na^+ from the soil ranging from 7% to 12% greater than in unvegetated control plots. Spring-sown *H. jubatum* and *Spergularia marina* and autumn-sown *Suaeda calceoliformis* resulted in a 4–5% reduction of Na^+ from the soil compared with the unvegetated control plots (Fig. 9).

Discussion

All species had much lower germination under field conditions than in viability tests in the laboratory using distilled water. Reduced germination was probably related to temperature and moisture fluctuations at the soil surface, rather than the toxic effects of the salt, because the salinity and soil moisture at this site were well within the tolerance limits of the five species (Ungar 1991). It is possible that some of the seeds were lost from the pots because of heavy wind, rain or predation by birds and insects. The majority of seeds were established early in the spring when the soil salinity level was reduced. However, spring-sown *A. prostrata* had additional germination occurring in mid-July following heavy rainfall. These results support previous work by Woodell (1985) and Ungar (1991), which indicated that many halophytes have osmotically induced dormancy that permits germination at any time of the year under favourable temperature and edaphic conditions.

The species differed in the extent to which seed germination, seedling survival and plant yield were influenced by season of sowing. The results for *H. jubatum*, which showed better germination, seedling survival and plant yield if sown in the autumn, are consistent with those of Badger & Ungar (1989), who found high germination in *H. jubatum* under cool temperatures, with inhibition of germination at higher temperatures.

In general, the performance of the species in the study was consistent with their observed autecology. *Hordeum jubatum* and *Spergularia marina* both often germinate in autumn and overwinter as seedlings, and both performed best in this study when sown in the autumn. *Atriplex prostrata* and *Suaeda calceoliformis*, on the other hand, normally germinate in the spring and performed best in this study when spring-sown.

Regression analyses indicated that increased soil conductivity had a negative effect on the survival and yield of spring-sown *A. prostrata*, *H. jubatum* and *Spergularia marina*. However, conductivity did not affect the performance of spring-sown *Salicornia europaea* or *Suaeda calceoliformis*, the two most salt-tolerant species in this study. Soil conductivity was also found to have no influence over the survival and yield of any of the species when they were sown in the autumn. Surface soils in saline habitats often have much higher salinities than in the subsoil, and shallow rooted seedlings may be subjected to additional environmental stress (Ungar 1978a). We hypothesize that the autumn-sown seed had earlier root development and avoided the extreme salinity/moisture fluctuations found at the soil surface, which is supported by the observed greater root biomass allocation in autumn-sown *H. jubatum*, *Spergularia marina* and *Suaeda calceoliformis*. Soil moisture was determined to be the key factor influencing the germination, survival and yield of *Salicornia europaea*. This species performed very poorly whether

© 2002 British Ecological Society,

sown in spring or autumn, and establishment on brine soils without additional inputs of water seems unlikely.

As a method of regulating internal water potentials, many species in the Chenopodiaceae accumulate large amounts of Na^+ and Cl^- when the external salinity is high (Albert 1975; Tiku 1975; Ungar 1978b; Flowers 1986). The majority of the plants had ash contents ranging from 20% to 35% of total biomass, which was closely related to the amount of NaCl accumulated by the plants at this site.

In most saline environments, including this Ohio brine spill site, external Na^+ and Cl^- concentrations far exceed those of Ca^{2+}, K^+ and Mg^{2+} (Table 5). Soil concentrations of K^+, Mg^{2+} and Ca^{2+} were low compared with Na^+, but K^+ was accumulated by the plants in a much greater ratio than Na^+. Correlations have been found between Na^+ content in plants and in the soils in which they grow (Hansen & Weber 1975; Tiku 1975). Rozema, Buizer & Fabritius (1978) and Ungar (1978b) found that an increase in external NaCl concentrations resulted in a decrease of K^+ and an increase of Na^+ concentration within *Glaux maritima* and *Salicornia europaea* plants.

Efficient ion partitioning is necessary for survival and reproduction of plants under salinity stress. All of the species, with the exception of *H. jubatum*, had reduced accumulation of Na^+ in the fruit. This indicates that plants can control the amount of Na^+ and Cl^- transported to seeds, as these elements are maintained at lower concentrations in the seeds than in shoots. In this manner, halophytic plants avoid injury from ionic and osmotic stress during the period of embryonic development. Other researchers have determined that reproductive structures have reduced ion content in comparison with shoots and roots (Khan, Weber & Hess 1985; Jeschke & Wolf 1988; Ungar 1991). For remediation purposes, plants with the greatest concentration of ions in their shoots would be the most desirable because of the ease in harvesting the above-ground portion of the plant on a regular basis.

Halophytic grasses reportedly differ from dicotyledonous halophytes in their mechanisms and degree of salt tolerance, and many species are characterized as sodium excluders that use organic solutes for osmotic adjustment (Glenn 1987). The results from this experiment confirm that *H. jubatum* sequesters Na^+ in different organs than the dicotyledon species. The Na^+ content in *H. jubatum* roots was approximately two times greater than the amounts found in fruits and shoots.

Hordeum jubatum and *A. prostrata* have been reported to transport K^+ and Ca^{2+} selectively to young parts of its shoot, while retaining NaCl in its older tissues (Greenway 1962a,b; Jeschke & Stelter 1983). However, all plant tissues from the Ohio brine spill site were low in K^+ and the resulting ion imbalance may have reduced plant yields (Adam 1990; Ayala & O'Leary 1995). Plant yield was negatively correlated with the Na^+ concentrations in plant tissues.

All species, with the exception of *Salicornia europaea*, significantly reduced soil salinity when compared with the paired control plots. *Atriplex prostrata* plots had the greatest Na^+ reduction; the spring-sown plants led to a 17% reduction and the autumn-sown plants resulted in a 12% reduction. Autumn-sown *Hordeum jubatum* plots had a 9% reduction, but it is important to note that *H. jubatum* accumulated a large amount of Na^+ in roots. Although the roots were harvested for analysis during this experiment, only above-ground structures will typically be harvested from contaminated sites during remediation. Other researchers have found similar net reductions of Na^+ from the soil. Watson (1990) determined that several *Atriplex* species accumulated significant amounts of Na^+ from the soil, and *Suaeda salsa* plants were found to reduce the sodium content by 4·5% following a 120-day growing period (Zhao 1991). Pakistan field trials of four halophyte species indicated that the plants produced a significant decrease in electrical conductivity ranging from 12·5% to 40·6% following a 135-day growing period (Qadir *et al.* 1995).

Spergularia marina also reduced soil salinity, but because of its small size we believe this plant would be better used for revegetating saline areas than for remediating them. *Spergularia marina* plants have continuous flowering and seed production from May to November, which might eliminate the need to reseed the site each year.

Precipitation resulted in leaching of 44% of Na^+ from the soil in control plots from 1991 to 1994. These data corroborate the findings of Auchmoody (1989) from high rainfall areas. Unfortunately, many of the most salinized soils of the world are found in arid regions, where leaching would not play a significant role in the reduction of sodium from the soil. Vegetated plots had a 59% net reduction of Na^+ from the soil compared with initial sodium levels in 1991. Additional use of irrigation and soil amendments such as gypsum, organic material and fertilizers would increase plant establishment and yield (DeJong 1982). Increased productivity would result in greater amounts of sodium being accumulated each year and more efficient remediation of the area. Qadir *et al.* (1995) found that the reclamation of four halophyte species was proportional to their biomass production capacity.

In order to facilitate soil bioremediation the plants must be harvested or removed from the site. In many cases, the harvested plants can be processed to yield multiple products for food, feed, fodder and fibre, as well as phytochemicals for industrial use. For example, *Salicornia* can be eaten as a gourmet salad garnish, and some species have seeds that can produce a high-quality cooking oil. It has also been tested as animal fodder because the *Salicornia* meal (parts of the seed that are left after oil extraction) contains *c.* 40% protein that is about the same as soybean meal (Glenn *et al.* 1991).

The global demand for food and raw materials produced by agriculture makes the further study and optimal utilization of soil resources of the earth imperative

© 2002 British Ecological Society,

Murphy, E.C., Kehew, A., Groenewold, G. & Beal, W. (1988) Leachate generated by an oil-and-gas brine pond site in North Dakota. *Ground Water*, **4**, 31–38.

Osmond, C.B., Bjorkman, O. & Anderson, D.J. (1980) *Physiological Processes in Plant Ecology*. Springer-Verlag, New York, NY.

Qadir, M., Ahmad, N., Qureshi, R.H. & Ilyas, M. (1995) Role of salt tolerant plants to reduce salinization and sodification. *Biology of Salt Tolerant Plants* (eds M. A. Khan & I. A. Ungar), pp. 371–379. University of Karachi, Pakistan.

Rozema, J., Buizer, D.A.G. & Fabritius, H.E. (1978) Population dynamics of *Glaux maritima* and ecophysiological adaptations to salinity and inundation. *Oikos*, **30**, 539–548.

Rozema, J., DeCae, R., Niazi, B., Abdullah, Z., Zaheer, H., Ahmad, R., Linders, H. & Broekmann, R. (1995) Salt tolerant crops, halophytes and crop cultivation in salt affected arable land. *Biology of Salt Tolerant Plants* (eds M. A. Khan & I. A. Ungar), pp. 380–387. University of Karachi, Karachi, Pakistan.

Simon, J.L. (1992) *Resampling: The New Statistics*. Resampling Stats Inc., Arlington, VA.

Sokal, R.R. & Rohlf, F.J. (1995) *Biometry: The Principals and Practice of Statistics in Biological Research*, 3rd edn. W.H. Freeman, New York, NY.

Staples, R.C. & Toenniessen, G.H. (1984) *Salinity Tolerance in Plants: Strategies for Crop Improvement*. John Wiley and Sons, New York, Tucson, NY.

Szabolcs, I. (1976) Present and potential salt affected soils, prognosis of salinity and alkalinity. *Soils Bulletin*, **31**, 9–13.

Szabolcs, I. (1994) Soils and salinization. *Handbook of Plant and Crop Stress* (ed. M. Pessarakli), pp. 3–21. University of Arizona, Tucson, AZ.

Tiku, B.L. (1975) Ecophysiological aspects of halophyte zonation in saline sloughs. *Plant Soil*, **43**, 355–369.

Treshow, M. (1970) *Environment and Plant Response*. McGraw-Hill Book Co., New York, NY.

Ungar, I.A. (1978a) Halophyte seed germination. *Botanical Review*, **44**, 233–264.

Ungar, I.A. (1978b) The effects of salinity and hormonal treatments on growth and ion uptake of *Salicornia europaea*. *French Botanical Society, Actualités Botaniques*, **125**, 95–104.

Ungar, I.A. (1979) Seed bank investigations with soils from an inland salt pan. *Bulletin of the Ecological Society of America*, **60**, 134.

Ungar, I.A. (1982) Germination ecology of halophytes. *Contributions to the Ecology of Halophytes* (eds D. N. Sen & K. S. Rajpurohit), pp. 143–154. Junk, The Hague, the Netherlands.

Ungar, I.A. (1988) A significant seed bank for *Spergularia marina* (Caryophyllaceae). *Ohio Journal of Science*, **88**, 200–202.

Ungar, I.A. (1991) *Ecophysiology of Vascular Halophytes*. CRC Press, Boca Raton, FL.

Ungar, I.A. & Capilupo, F. (1968) An ecological life history study of *Suaeda depressa* (Pursh) Wats. *Advancing the Frontiers of Plant Science*, **23**, 137–158.

US Department of Agriculture (1985) *Soil Survey of Athens County, Ohio*. Soil Conservation Service, Government Printing Office, Washington, DC.

US Department of Commerce (1992) *Climatological Data Annual Summary of Ohio*, Vol. 97. National Oceanic and Atmospheric Administration, Asheville, NC.

US Geological Survey (1961) *Athens Quadrangle, Ohio–Athens County Topographic Map*. US Government, Washington, DC.

Waisel, Y. (1972) *Biology of Halophytes*. Academic Press, New York, NY.

Watson, M.C. (1990) *Atriplex* species as irrigated forage crops. *Agriculture, Ecosystems and Environment*, **32**, 107–118.

Williams, M.D. & Ungar, I.A. (1972) The effect of environmental parameters on the germination, growth, and development of *Suaeda depressa* (Pursh) Wats. *American Journal of Botany*, **59**, 912–918.

Woodell, S.R.J. (1985) Salinity and seed germination patterns in coastal plants. *Vegetatio*, **61**, 223–230.

Youngman, A.L. & Heckathorn, S.A. (1992) Effect of salinity on water relations of two growth forms of *Suaeda calceoliformis*. *Functional Ecology*, **6**, 686–692.

Zhao, Ke-Fu (1991) Desalinization of saline soils by *Suaeda salsa*. *Plant and Soil*, **135**, 303–305.

Received 12 March 2001; final copy received 30 January 2002

© 2002 British Ecological Society,