THE ESTABLISHMENT, DROUGHT TOLERANCE, AND WEED SUPPRESSION POTENTIAL OF MULTISPECIES SOD

by

Jennifer Grace Stark

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APPROVAL

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Jennifer Grace Stark

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Dr. Lisa J. Rew

Approved for the Department of Land Resources and Environmental Sciences

Dr. Bruce D. Maxwell

Approved for the Division of Graduate Education

Dr. Carl A. Fox

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ABSTRACT

Re-seeding is a frequently used technique to revegetate disturbed areas, but often leaves bare ground prone to weed invasion. Mixtures of drought tolerant or native species in sod could be used as an alternative to seed to provide rapid establishment of desirable plant communities that may potentially reduce weed emergence, survival, and productivity. Additionally, the reinforcement material required to aid transport of multispecies sod could further contribute to weed suppression and sod establishment.

The objective of this study was to evaluate the weed suppression and establishment potential of multispecies sod. Three experiments were each subject to a water regime ranging from 2.54 cm of water/week to natural precipitation, and repeated over two/three years.

In the first two experiments (A and B) *Brassica napus* (canola) was used as a surrogate weed species and sown either below the multispecies sod to represent weed seed bank, or above the multispecies sod to represent weed seed rain. In experiment A, *B. napus* was sown at six densities; while in experiment B reinforcement materials (nylon netting control, coconut-straw, jute, excelsior) were added below the sod and *B. napus* was sown at one density. *B. napus* suppression by multispecies sod, with or without reinforcement material, was evaluated by recording seedling emergence, survival and above-ground biomass.

Multispecies sod, especially combined with reinforcement material, suppressed a large proportion of seedling emergence. The seedlings that did establish produced less vegetative and seed biomass as water decreased. In the second season of both experiments no seedlings survived to maturity. The establishment success of the multispecies sod was evaluated through repeated measures of percent sod cover over two/three years. The results suggested that the multispecies sod was able to establish and persist under natural precipitation.

The third experiment evaluated the ability of multispecies sod to suppress *Cirsium arvense* (Canada thistle) vegetative propagules in two different habitat types, bare ground or multispecies sod, under high and low water treatments. More *C. arvense* shoots emerged in the bare ground, suggesting that multispecies sod could act as a buffer zone and reduce the vegetative spread of perennial weeds if used as a revegetation strategy.

CHAPTER 1

LITERATURE REVIEW

Ecological Theories on Plant Community Dynamics

A plant community is an assembly of plant species and their population(s) that exist within an area. There are various definitions of a plant community, however, depending on the audience. Crawley (1997) defined a plant community from a practical standpoint of an ecologist as "all the plants occupying an area which an ecologist has circumscribed for the purpose of study". This implies that a plant community can only be as large as is realistic to study. Gurevitch et al. (2002) defined a plant community as a subset of a community of other organisms, including decomposers, herbivores, pollinators, diseases, etc., that co-exist in both time and space and interact with one another either indirectly or directly to affect a plant population's dynamics. In addition to the community of other organisms, biotic factors such as: phenology, physiology, plasticity, propagule abundance, inter- and intraspecific interaction, and facilitation, as well as abiotic factors such as: physical disturbance, climate, topography, and soil variation, can further define a plant community by creating boundaries for a specific plant species existence.

Watt (1947) suggested that a plant community can be expressed from two main points of view: from a classification and diagnosis standpoint, as well as from the point of view that the plant community as a whole is a working mechanism. Taxonomists describe a particular species distribution or ecological attributes from morphological features which do not always account for genetic or phenotypic variation; all of which could be important to describing

ecological differences and relevance between plant individuals, populations, or entire biological communities (Harper, 1982). While ultimately individual plants make up a large part of a plant community, individual plant description, species description, as well as entire community description including spatial relationships, soil biota and other environmental factors, each provide insight indicative of a specific plant community's dynamics.

Two American ecologists with contradicting viewpoints, F. Clements and H.A. Gleason, were among the first to conceptualize plant community structure and dynamics in the early 20th century. Clements found a plant community to be in general a dynamic equilibrium composed of mutually interdependent species that acted as a highly organized superorganism, meaning it went through the stages of birth, development, growth, and death, and functioned for the benefit of the entire community (Gurevitch, 2002). Furthermore, Clements viewed succession, and thus plant community dynamics, as predictable and orderly. His view on succession was based on existing vegetation and what he defined as the six stages of predictable trajectory: nudation, migration, establishment, competition, reaction, and stabilization at a 'climax' community (Crawley, 1997). To Clements primary succession was generally a soil forming process, beginning with no existing plant propagules and relying mainly on species immigration from other areas. Secondary succession consisted of little change in the soil and was less reliant on species immigration (Crawley, 1997). Clements found that the strength, frequency, and complexity of ecological interactions increased as succession progressed (Crawley, 1997). H.A Gleason's ideology conflicted with Clements's theory in that he saw plant communities from more of an individualistic and less of a

predictable point of view. Although he did not dispute that particular species assemblages did exist, Gleason found community structure to be a result of continuous causes, mostly the interaction between environmental factors, independent plants or species, and chance (Gurevitch et al., 2002). Gleason rejected the idea that a plant community was a superorganism, suggesting instead that it was a coincidence (Crawley, 1997). Gleason believed that there were too many random elements such as disturbances, environmental conditions, and land history, to define a clear trajectory of succession. Instead he stated that the random elements could lead to different end-points and not to a particular climax vegetation as predicted by Clements (Crawley, 1997). Gleason thought that determining factors of plant community assemblage acted independently over time and space (Gurevitch et al., 2002).

Current ideas tend to be a combination of these and other theories that have developed over the decades, and lie somewhere in the middle of Clements and Gleason (Gurevitch et al., 2002). Presently there is broad agreement that species distribution is individualistic and that the composition of a community undergoes change along an environmental gradient (Clausen et al., 1947; Gurevitch, 1992; Linhart & Grant, 1996; Bradshaw, 1997; Gurevitch et al., 2002; Bowman et al., 2008). However, the importance of how biotic, abiotic, and chance events pertain to plant community assembly is still heavily disputed (Gurevitch et al., 2002).

Two conflicting theories concerning plant community structure are the niche assembly theory and the more contemporary neutral theory. The niche assembly theory

describes plant communities as groups of interacting species whose composition, or relative representation, is based on each species' functional role or ecological niche that create "assembly rules" (Hubbell, 2001). Although originally defined by Grinnell (1917) and then by Elton (1927), Gause (1934) introduced the main component of the niche assembly theory, competition among species, in his competitive exclusion principle which suggested that if two species are similar in that they have identical needs for the same limited resource, they will not be able to coexist together and one species will eventually exclude the other. In 1957, Hutchinson's niche "hypervolume" furthered Gause's principle to include not only limiting resources, but different species tolerance for physical environmental variables (Hubbell, 2005). He broke the niche concept into two scenarios: fundamental and realized niches. The fundamental niche encompasses the limiting values of all ecological conditions under which a species may potentially occur. The realized niche is often smaller than the fundamental niche, reflecting where a species may actually occur in the presence of interspecific competition (Hutchinson, 1957). In Hutchinson's theory, species coexist in interactive equilibrium and diverse communities are a result of different species niche requirements and niche differentiation within a habitat (Hutchinson, 1957). The niche assembly theory implies that plant communities are predictable and can be manipulated to create desirable outcomes.

The neutral theory, proposed by Hubbell in 2001, describes plant communities as non-equilibrium assemblages that are open and subject to chance, random dispersal, and random stochastic processes. The neutral theory assumes that natural selection is acting on

individuals due to varying environmental conditions instead of on whole species, and thus all individuals are equal in their probability of existing or going extinct. The root of the neutral theory is that there is such wide variability between individuals and between environmental conditions that it is hard to generalize on the species level and to use species traits as predictive tools.

Even though the neutral theory contradicts the niche assembly theory, both can be useful in describing a plant community. The neutral theory can work as a backdrop for the niche assembly theory. It can be a place to start when initially examining a plant community to determine how it originated and its overall relative community composition. For example, the theory of island biogeography was introduced by MacArthur and Wilson (1967) as an explanation of how islands initially became populated. The neutral theory is the basis of the theory of island biogeography, stating that all species have an equal probability of either immigrating to the island from the mainland, or going extinct (Hubbell, 2001). The neutral theory can also be used to help validate community dynamics that are not predictable. However, the niche assembly theory can be a useful tool to help further explain certain plant community dynamics that do not appear to be neutral as communities evolve. The basis of the niche assembly theory is that plant species progress toward a resource allocation pattern to increase their chance of survival. Species must therefore evolve ecological differences to coexist in nature (Gause, 1934) and survive in a plant community on an island, or anywhere else.

While the main ecological theories on plant community dynamics and structure are all different, the important issue is that plant communities are complex systems that can not

fully be explained or predicted (Watt, 1947; Crawley, 1997); however, there are general principles and processes that can be observed and understood.

Intraspecific vs. Interspecific Interference

It is widely accepted that interference, the effect that a plant's presence has on its neighboring plants, is important. This interaction can be in the form of competition, mutualism, commensalism, parasitism, etc. Individual plants interfere with one another, especially in resource consumption (Kira et al., 1953; Koyama & Kira, 1956; Shinozaki & Kira, 1956; Yoda et al., 1963; Firbank & Watkinson, 1990). Plants proximity to one another can cause interference for space as a function of their spatial arrangement or density. Plants generally either share or compete for space within themselves (e.g. light competition between leaves), between neighbors of same species (intraspecific interference), or between neighbors of different species (interspecific interference).

Intraspecific interference describes how plants interact in monocultures. Kira et al. (1953) determined that at high densities intraspecific interference had three major competitive effects. First, there is a reduction in the mean size, or total plant weight, of surviving plants. This is most likely because each plant has a limited uptake of resources due to competition and sharing the same space. Secondly, as density increases the probability of surviving decreases. This is referred to as density dependent mortality or self-thinning. Thirdly, the population size and structure is altered at high densities. While it has been found that individual plant weight of the same species has a normal distribution at the seedling stage, this distribution often becomes skewed as a population grows at high density, with a

couple of large individuals and numerous small ones (Kira et al., 1953; Koyama & Kira, 1956; Firbank & Watkinson, 1990).

The same competitive effects are assumed with interspecific interference; however, because different species have different growth patterns and resource requirements, interact with one another differently, and respond differently to various environmental conditions, the interference is more complex (Firbank & Watkinson, 1990). For example, relative emergence time can affect interspecific competition in that larger plants generally have more access to shared resources. The plants that emerge first generally grow bigger faster, hindering the growth of smaller seedlings. Weihe and Neely (1998) conducted a replacement series experiment in a greenhouse with *Typha latifolia* (cattail) and *Lythrum salicaria* L. (purple loosestrife) and found that *T. latifolia* per-plant biomass was much higher when grown in monoculture, than when grown in a mixture with *L. salicaria* at the same density. *L. salicaria* on the other hand had a lower per-plant biomass when in monoculture, than when grown in a mixture with *T. latifolia*. When species are grown in communities with other species they adapt differently, with spatially and temporally varying patterns of reproduction and growth depending on the different combinations of species present, resources available, and environmental factors (Pyke & Archer, 1991). In natural systems different species that can coexist with one another without competition can in fact stabilize a community and its ecosystem processes making it less susceptible to invasion (Tilman et al., 1996).

Plant Competition for Water and Light

All plants generally require the same resources: water, sunlight, mineral nutrients, and carbon-dioxide (Vance & Nevai, 2007), but in different ratios. Specific plant species'

physical attributes and resource requirements, as well as many physical and biological environmental traits such as soil quality, nutrient availability, climate, physical disturbance, dispersal ability, inter- and intraspecific interaction, competition, mutualism, seed predation, herbivory, and disease determine the presence, abundance, and number of species present in a given location. Given these biotic and abiotic variables, most studies have found that change in competitor abundance does not impact an individual plant as directly as to what degree supply and demand limit resource (mainly water, sunlight, and nutrients) availability and promote competition (Tilman, 1982; Casper & Jackson, 1997; Davis et al., 1998; Davis et al., 2000).

Water makes up about 85-90% of a plant's growing tissues, as well as 5-15% of its seed mass (Grace, 1997). Water also serves as a solvent for minerals and organic sugars that are carried by the xylem and phloem respectively for plant growth and survival. Most plants cope with low water levels through physiological responses such as osmotic adjustment, stomata regulation, anatomical modifications (reduced leaf area, increased leaf thickness, pubescence, increased root: shoot ratio, deep rooting) and overall growth reduction (Pessarakli, 1999). A plant's response to water stress differs greatly between species influencing the ecological range of where each species can exist.

Even though a plant's response to water is species dependent, there is a general trend of decreased productivity and increased competition when water is a limited resource (Davis et al., 1998; Asay et al., 2001; Villagra & Cavagnaro, 2006). For example, a field study in Utah on the response of tall fescue cultivars to an irrigation gradient found a significant decrease in productivity (dry matter yield) at decreased water levels when nutrient levels

were maintained with supplemental fertilizer (Asay et al., 2001). Similarly in Argentina, the seedling growth of two noxious shrubs, *Prosopis argentina* (Algarobilla mesquite) and *Prosopis alpataco* (Alpantaco mesquite), both declined at decreased water levels when subject to the same water stress gradient (Villagra & Cavagnaro, 2006). In a field study in Minnesota, Davis et al. (1998) also found that herbaceous vegetation biomass decreased with decreasing water input, suggesting that water has the potential to increase plant productivity.

Light is another potentially limiting resource. Plant interactions for light can be either facilitative or competitive depending on the species and specific environmental conditions (Pugnaire & Luque, 2001). There are some cases where larger plants are thought to have an advantage in light uptake because they shade smaller plants (Casper & Jackson, 1997). Yet the protection of a small plant by a larger plant can be beneficial in a harsh environment (Holmgren et al., 1997). Franco and Nobel (1989) conducted an experiment in the Sonoran desert with seedlings of the cactus *Ferocactus acanthodes* (compass barrel cactus). They found that 71% of *F. acanthodes* seedlings were found in association with nurse plants, consisting almost entirely of the bunchgrass *Hilaria rigida* (big galleta), whereas 29% of the seedlings were found in unsheltered conditions. In comparing the two habitats, sheltered and unsheltered, Franco and Nobel (1989) found that seedling establishment was facilitated by the nurse plants by reducing soil surface temperatures, providing shelter, and increasing nitrogen levels. However, the reduction in photosynthetically active radiation due to shading caused a decrease in seedling net CO_2 uptake. This combined with competition for water greatly reduced seedling growth and vigor. This reduction in growth and vigor has the

potential to weaken the competitive ability of the seedling species and could imply overall population reduction. In all studies the intensity of competition and success of the plants depended on the supply and demand of limiting resources.

The resource competition theory (R* Principle) developed by David Tilman (1977, 1982) helps to explain how species interact in competition for resources. R* is the required resource level for a species to maintain an equilibrium density, meaning the species reproduction and death rates are equal based on resource (R*) supply and consumption rates being equal. When a resource falls below a specific species R* value, that species population will decline. Therefore, the species with the lowest R* value will eventually displace other species who have a higher R* value for the same resource because the lowest R* value means that species can tolerate the lowest levels of resources and still maintain an equilibrium population. The theory suggests that two species that are limited by different resources can coexist in the same habitat, and that different amounts of resources lead to dominance by different species based on the species' R* value.

Seed Germination and Seedling Emergence

The Effect of Light: Plant recruitment into a system occurs through seed or vegetative propagules. Requirements differ between species, but frequently disturbance, hence light, can play one of the more critical roles in germination and seedling emergence. Benvenuti (1995) reported that at soil depths greater than 4 mm very little light (<0.001%) is transmitted through any type of soil. Seeds are generally exposed to light through disturbance that either moves the seed to a location that receives light, or removes an obstruction that was

limiting light penetration. Such disturbances can include cultivation, mowing, fire, wind, digging, footprints, and herbivory. In field studies, the presence of light when soil is cultivated is thought to promote weed seed germination (Wesson & Wareing, 1969; Chachalis & Reddy, 2000). Wesson and Wareing (1969) concluded that a 90 second flash of light was sufficient exposure to induce germination of all the weed seeds within a field.

The Effect of Established Plant Communities: Established plant communities may inhibit seedling emergence because of decreased light at the soil surface, as well as competition for resources (Wesson & Wareing, 1969; Turnbull et al., 2000). Established plant communities may also act as a physical barrier due to dense aboveground biomass. Wesson and Wareing (1969) demonstrated that when cultivation disturbed the soil in a pasture there was a flush of dicotyledonous weed seedlings that germinated within the grass but were not able to establish. Furthermore, a review of seed sowing experiments into natural or semi-natural plant communities by Turnbull et al. (2000), examined 27 studies with over 90 different species and found a consistent trend: population size increased with seed addition in newly plowed and early to mid-successional fields, and changed very little in arid and mesic grasslands that had been unplowed for > 30 years. They concluded that seed growth was more likely to succeed when bare ground was present. Twenty of 29 papers found a significant interaction between seed addition treatments and disturbed ground, with higher seedling recruitment in disturbed areas than in more established undisturbed plant communities (Turnbull et al., 2000).

Furthermore, Jutila and Grace (2002) examined mature indigenous grassland sod for natural seedling emergence under five treatments: cut (litter remained), hayed (litter

removed), burned, removal of plants, and a control, over a four and a half month season in a greenhouse study. Their results indicated that seedling emergence was least in the control and cut plots (probably because the seed was cut before maturity so the seed source was removed), and increased from hayed, burned, to plant removal treatments (Jutila & Grace, 2002). This again suggested that established plant communities, in this case indigenous grassland sod, can inhibit seedling emergence.

The Effect of Plant Litter: Plant litter directly and indirectly affects the physical and chemical environment within a plant community. When litter decomposes both nutrients and phytotoxic substances are directly released into the soil. Furthermore, changes in litter quality and quantity affect soil micro- and macrofauna, particularly the decomposers, which indirectly alters nutrient availability and the soil chemical environment (Wardle, 2002). Plant litter intercepts light, potentially shading seeds and seedlings, but it can also regulate soil temperatures, create a physical barrier hindering seed emergence, prevent seeds from contacting the soil, create a water vapor barrier, and may even alter soil water availability by retaining moisture from rainfall (Facelli & Pickett, 1991).

Litter either helps to increase or decrease the water availability required by all seeds and plants (Facelli & Pickett, 1991) depending on the environment. Litter can also reduce raindrop impact and thus soil disaggregation (Dyksterhuis & Schmutz, 1947). In ungrazed grasslands litter can directly reduce evaporation and increase infiltration in the soil (Larson & Whitman, 1942). Litter can also indirectly reduce evaporation by buffering soil temperatures. Weaver and Rowland (1952) found that plots without litter lost 64-75% more soil water content than plots with litter when exposed to sun and wind in their open prairie

environment. Litter is thought to increase soil water availability, especially in deserts and grasslands (Weaver & Rowland, 1952; Evans & Young, 1970), and may even aid with the establishment of some species.

Weaver and Rowland (1952) also observed that litter retained and evaporated up to one-third of water received from a day's rain before it was able to reach the plants. The net effect of litter on plant water may therefore depend on the water retention ability of the litter, as well as on the rainfall intensity (Facelli & Pickett, 1991). More water is often retained in litter after a light rainfall compared to after a heavy rainfall (Walsh & Voigt, 1977). Furthermore, during a heavy rainfall litter can increase surface run-off, or overland flow, because of the dense mat it can sometimes form (Facelli & Pickett, 1991). The species present in the litter, as well as their initial hydrological condition (wet or dry) before a rain event, can cause patchiness in the amount of soil water subsequently available (Facelli & Pickett, 1991) to live plants as well as to seeds ready to germinate.

Finally, the presence of litter can also act as a physical barrier inhibiting light and impeding seeds from coming in contact with the soil (Facelli & Pickett, 1991). Weaver and Rowland (1952) found that a dense mat of litter could reduce total radiation by 95-99%. This can affect the germination and seedling emergence of plant species that require light (Sydes & Grime, 1981). The physical barrier may also impede seedling emergence (Facelli & Pickett, 1991). If the seeds are held in litter and are not in contact with soil their germination may either be delayed or unsuccessful (Facelli & Pickett, 1991). For example Fowler (1986) found that most seedlings of *Aristida longiseta* (red threeawn) died when they germinated within litter because their roots were not able to penetrate the soil. Furthermore, Hamrick and

Lee (1987) found that in a greenhouse study the seedlings of *Carduus nutans* L. (nodding plumeless thistle) that germinated under a thick litter layer of plant stems, grass, and leaf fragments, had a higher mortality rate than seedlings growing under less or no litter. The seedlings growing under the litter had larger hypocotyls than seedlings without litter, demonstrating that the energy used to penetrate the litter mat most likely caused mortality (Hamrick & Lee, 1987). Bosy and Reader (1995) placed seeds that had already germinated beneath *Poa pratensis* (Kentucky bluegrass) litter in a greenhouse and found that emergence was reduced by 95-100% in comparison to the no-litter control. While litter has generally been found to reduce seed emergence, the size and shape of the seeds, as well as the structure and thickness of the litter mat may be mainly responsible for determining a seed's germination and emergence success (Facelli & Pickett, 1991). Small seeds have less storage and may not have the energy required to penetrate a litter mat (Facelli & Pickett, 1991). Even large seeds, with more storage, if confined beneath litter in a wet and shady environment without light to aid germination can lose vigor (Sydes & Grime, 1981), have an increased risk of being attacked by herbivores, and an increased susceptibility to disease (Facelli & Pickett, 1991).

Invasion by Weeds

Competition for resources such as water, light, and nutrients not only affects how plants interact, but can play a large role in habitat invasion by weeds. It is estimated that the impact of invasive species is only second to habitat destruction in causing loss of biodiversity globally (Groves, 2001). The United States, Australia, Canada, South America, European

countries, and other countries around the world have documented thousands of weed species (Vitousek et al., 1996). When weeds expand beyond their natural range they have the potential to impact an entire ecosystem causing ecological, economic, and social consequences (Vitousek et al., 1996; Davis et al., 2000; Pimental et al., 2000). It is estimated that the United States spends almost $25 billion dollars a year on environmental damage caused by weed plants alone (Pimental et al., 2004).

Weeds compete with native species for resources, can alter the gene pool of native flora by interbreeding with native plants (Lee and Hovorka, 2003), and can alter environmental processes. For example, the introduction of *Bromus tectorum* (downy brome/cheat grass) to the Colorado Plateau (USA) decreased the stability of the ecosystem by not only increasing the C:N ratio of the litter so that there was less nitrogen available for microbial activity, but also by increasing litter abundance. Consequently fire frequency has increased in some areas where *B. tectorum* has been introduced (Evans et al., 2001) from once every 60-100 years to once every 3-5 years (Pimental et al., 2000).

The success of invasions by weeds into indigenous ecosystems is linked to the suitability of the native habitat and the resources available, as well as to propagule pressure and specific plant traits (Davis et al., 2000). Parendes and Jones (2000) state that invasion occurs when biological, physical, and/or environmental "barriers" are removed that previously inhibited a plant species from existing at a site. For example, dispersal limitation can be a biological barrier, obstacles (such as oceans or mountains) that affect dispersal pathways can be a physical barrier, and unsuitable light that inhibits germination could be an environmental barrier (Parendes & Jones, 2000). When one of these barriers is removed the

habitat conditions are changed in such a way that different species may find more opportunity to exist (Dukes & Mooney, 2004).

Role of Disturbance

Disturbance "decreases competition and increases the probability of invasion" (Vila & Weiner, 2004). Disturbance can facilitate weed invasion and establishment (Grime, 1979; Hobbs & Huenneke, 1992; Parendes & Jones, 2000) by altering existing habitat and creating new conditions that may favor certain species. Disturbance is caused by both natural and anthropogenic things including fire, flooding, freeze-thaw, fallen trees or rocks, wind, digging, cultivation, trampling, trails, and roads. Because disturbed areas are heterogeneous (Peterson & Pickett, 1990), a specific plant species' phenological, morphological, and physiological traits, as well as that species' ability to resist the disturbance and competition from other species, help to determine the probability that a species will inhabit a newly disturbed area (Crawley, 1997). Three important characteristics of disturbance are spatial extent, frequency, and intensity (Crawley, 1997).

Spatial extent is the size of the disturbance, or the size of the microsite that is available for the plants to become established in. Size can play an important role in many aspects of developing plant communities because it defines the space, and therefore the resources available to plants. Frequency determines how often the disturbance will occur, and thus can contribute to many things such as microsite availability, plant succession, and species present. Finally, the intensity of the disturbance helps to determine to what severity a microsite is disturbed. The "intermediate disturbance hypothesis" suggests that a species diversity is high when an area is subject to moderate disturbance levels (Hobbs &

Huenneke, 1992), although the timing and type of disturbance that occurs will affect different plant species and different microsites uniquely.

Roadsides

Roadsides are often disturbed and consequently create ideal microsites for weed invasion (Tyser et al., 1998). Typical roadside characteristics (such as culverts and ditches, air turbulence, habitats of disturbed soil and vegetation) and the traffic associated with them (mostly in dirt attached to vehicles) contribute to the dispersal of weeds (Forman & Alexander, 1998). Once weeds have established along road corridors they are propagules for future invasion (Parendes & Jones, 2000) permitting weeds to spread not only along road corridors, but into surrounding ecosystems potentially creating an even larger ecological problem.

Parendes and Jones (2000) found that in the H.J. Andrews Experimental Forest in Oregon, weeds were almost entirely restricted to corridor areas that had been disturbed: mainly roadsides, recent clear cuts, and streams. Furthermore, Tyser and Worley (1992) found that weed richness declined with distance from primary and secondary roads in Glacier National Park, Montana, USA, suggesting that roads, and the disturbance associated with them, are habitats where weeds flourish (Tyser & Worley, 1992; Rew et al., 2005). There are over 12 million acres of highway corridors in the United States (Harper-Lore & Wilson, 2000) and this number is increasingly growing. The 2000 census states that in the past decade in the USA, the west was the most rapidly growing region, averaging a 19.7% population increase compared to the national average of 13.2% (WTI, 2003). Growth in low density land use areas such as the west generally requires an increase in roads to access

everyday commodities to which people are accustomed (WTI, 2003). Residential and commercial development leads to an increase in road construction, which requires more roadside revegetation and maintenance, and thus potentially more new sites susceptible to invasion by weeds.

Revegetation

When a natural landscape is disturbed, regardless of whether it was anthropogenically (e.g. construction of new roads) or by natural processes (e.g. fire), weeds are often a problem and need to be reduced. Revegetation is a common technique to re-establish plant communities and provide direct competition with the unwanted weeds. Revegetation projects generally offer unique challenges including large areas of concern, minimal watering capabilities, severely compacted nutrient poor soils, and potentially steep slopes that are very susceptible to erosion (Landis et al., 2005). Historically, revegetation has commonly been accomplished by broadcast, drill, imprinting, and hydroseeding methods. While these methods have proven successful and can be cost effective at lower angle slopes (Warren & Ostler, 2002), steep slopes continue to present a revegetation challenge simply because the seed has the potential to wash away. Studies have shown that increasing vegetation can reduce erosion considerably (Sutherland et al., 1998; Grace, 2002).

While many factors contribute to successful erosion control, including soil type, slope, and precipitation events; plant density, biomass, and cover considerably influence the success of vegetation at controlling water and soil sediment runoff (Thurow et al., 1986; Ludwig et al., 2004). Vegetation plays a significant role in decreasing sediment

loss (Thurow et al., 1986; Prosser & Dietrich, 1995; Ghidey & Alberts, 1997; Ludwig et al., 2005) by reducing soil particle detachment and transport as a result of enhancing the development of soil structure and infiltration with roots and organic matter (Caltrans, 2004). In addition, aboveground biomass acts as a barrier to actively transported sediment by slowing and diverting overland flow (Thurow et al., 1986) and trapping wind- and water-borne litter and sediments (Thurow et al., 1986; Grace, 2002; Ludwig et al., 2004). Ludwig et al. (2005) proposed that vegetation and erosion control is a positive feedback system containing both hydrological and ecological processes: vegetation obstructs the overland runoff, increasing retained water, which increases plant growth, and enables the vegetation to be more effective in obstructing the overland runoff. At high water levels the nature of the feedback can change so that if the area becomes saturated, thus anaerobic for too long, it may result in a negative feedback due to plant mortality (Ludwig et al., 2005).

Common Revegetation Techniques

In general, revegetating a landscape with seed is one of the most economical ways to cover large disturbed areas (Montalvo et al., 2002; Robichaud et al., 2006). A downfall to using seed for revegetation is that it is often slow to establish (Beard & Green, 1994) leaving bare ground prone to erosion and invasion by weeds.

There is no revegetation technique suitable for every environment. Revegetation techniques commonly used on level slopes include: broadcast, imprinting, and drill seeding methods. Revegetation techniques commonly used on steep slopes include hydroseeding, erosion control mats, and contour grass strips.

Seed Selection

The first step to any revegetation technique is the choice of species. The use of indigenous species is becoming more popular in revegetation practices (Harper-Lore & Wilson, 2000). Provided the site has not been too drastically disturbed, indigenous plants can be better adapted to localized conditions, require minimal maintenance, help blend an area into the surrounding natural landscape (Landis et al., 2005), contribute to flora and fauna habitat connectivity (Ries et al., 2001), and create self-sustaining ecosystems. Furthermore, Landis et al. (2005) found that revegetating with indigenous species may help to minimize the chance of weed species establishment on roadsides.

Non-indigenous species, such as species sown for pasture grass, were once commonly used for roadside revegetation (Tyser et al., 1998) but have been proven relatively susceptible to environmental stress and can even interfere with indigenous flora establishment (Wilson, 1989; Beyers, 2004). It is generally thought that a non-indigenous species' most desirable trait is increased aboveground biomass, and while some studies have found this true, others have also found that indigenous species may produce more initial biomass more quickly than non-indigenous species (Bugg et al., 1997; Pinaya et al., 2000). Furthermore, indigenous regional materials can be more successful at establishing and persisting than commercially produced materials because they are adapted to the local environment (Petersen et al., 2004). Such species will likely endure extreme local climate conditions, such as short growing seasons and abrupt influxes in cold temperatures (Petersen et al., 2004). For example, Peterson et al. (2004) found indigenous commercially produced seed to produce higher vegetative density the first growing season

compared to regionally collected indigenous seed of the same species. However, by the second and continually throughout the third and fourth growing seasons, the regional seed produced higher vegetative density than the commercial seed.

Successful establishment from seed is more common in early successional, more open habitats than in grassland communities (Turnbull et al., 2000). This emphasizes the importance of using long term desirable species when seeding new sites because it is easier to establish new plants in disturbed ecosystems than in established vegetative communities (Turnbull et al., 2000). From a plant competition and invasion standpoint, non-indigenous perennial or annual grasses sown for increased initial ground cover have in general shown to displace indigenous species (Beyers, 2004).

Revegetating Level Slopes

Revegetation techniques commonly used on level slopes include: broadcast, imprinting, and drill seeding. Dry broadcast seeding places seeds directly on the soil surface, imprinting pushes seeds slightly below the soil surface, and drill seeding slices the seeds into the soil burying them typically around 10-12 mm deep (Montalvo et al., 2002). Seeds on the soil surface are more vulnerable to desiccation and predation (Montalvo et al., 2002; Holland et al., 2008). Imprinting and drilling protects seeds from desiccation and predation, but depending on the seed size may place the seeds either too deep or too shallow for optimal emergence.

Short and long term studies have found broadcast seeding to be as effective as drill seeding (Newman & Redente, 2001) especially if the broadcast seeding rate is twice the drill seeding rate (Doerr et al., 1983; Wilson et al., 2004). In addition, Bakker et al. (2003) found

plant survivorship of the same species to be consistently higher in broadcast compared to drill seeded plots. The difference in results between these studies highlights the need to consider specific site and species characteristics when comparing seeding methods, although generalizations can lend some insight.

Broadcast seeding is the least expensive technique and can create a natural look initially, unlike drill seeding where the seeded rows can remain visible for quite some time (Caltrans, 2004). Caltrans (2004) also found that while drill seeding and imprinting were successful, the large machinery required to implement these techniques was not practical on steep slopes or in small areas.

Revegetating Steep Slopes

Revegetation techniques commonly used on steep slopes include hydroseeding, erosion control mats, and contour grass strips.

Hydroseeding: Hydroseeding is a common method for seeding slopes, especially those greater than 2.5:1 (horizonal:verticle) (Montalvo et al., 2002) but it is also one of the more expensive (Stott, 2007). Montalvo et al. (2002) determined that seed size affected the vegetative success of hydroseeding. Small seeded species had higher emergence and survival success than large-seeded species (Montalvo et al., 2002). This could be a result of optimal planting depth differences as seeding success is highest when seeds are planted two-times as deep as their size, and hydroseeding places seeds in a matrix on the surface of the soil (Montalvo et al., 2002). However, because the seeds are closer to the surface in a hydroseed slurry they are more susceptible to predation and desiccation (Montalvo et al., 2002, Holland

et al., 2008).

An experiment at Bryce Canyon National Park in Utah comparing seeded nylon-netted excelsior erosion control mat, seeded un-netted excelsior mat, and woodchip hydroseed mulch, found hydroseeding to be just as effective at producing vegetation as the other treatments (Petersen et al., 2004). Furthermore, Caltrans (2004) found that hydroseeded plots had good germination, but after two years provided less vegetative cover than plots that had been drill seeded. The most effective seeding method is therefore a decision based on specific revegetation objectives, including species' characteristics, site specifications, and available budget.

Erosion Control Mats: Erosion control mats are another steep slope revegetation technique. Some erosion control mats contribute to plant biomass by aiding with water retention and buffering soil temperatures (Sutherland et al., 1998). Many erosion control mats are biodegradable and so they provide only temporary erosion control depending on the degradability of their fiber composition. Long-term slope sustainability is thus a synergism between erosion control mats and plant growth (Sutherland et al., 1998). While there are a lot of studies confirming that erosion control mats reduce erosion, fewer studies compare the effect of the different available materials on increasing plant biomass or reducing weed establishment.

Erosion control mats can be made of many different materials including jute, straw, coconut, excelsior wood products, synthetic materials such as woven polymers and nylon netting, as well as combinations of these materials. By contributing to surface cover, erosion control mats help with dissipating and absorbing raindrop energy, preventing soil particle

detachment (Krenitsky et al., 1998). However, erosion control mats alone may not be as effective at reducing erosion as erosion mats in combination with established vegetation (Krenitsky et al., 1998; Grace, 2002). Grace et al. (2002) found excelsior mat sown with grass species to reduce sediment yield by more than 70% and runoff yield by 50% compared to bare and seeded plots without erosion mat (Grace, 2002). However, over the four-year study period soil loss from all vegetative treatments, with and without erosion mats, declined considerably, suggesting that established vegetation is critical to erosion control (Grace, 2002).

In a study of *Lolium* (ryegrass) yields grown with six erosion materials, Sutherland et al. (1998) found jute and P300 (polypropylene fiber matrix between two nets) to be the only erosion mats that showed no significant difference in vegetative biomass or soil moisture content compared to bare control plots. In this experiment wheat-straw and excelsior increased vegetative biomass and soil moisture content considerably (Sutherland et al., 1998) concurring with Grace et al. (1998) who also found excelsior mat sown with grass to have significantly more ground cover than grasses sown without erosion mat. These studies suggest that certain erosion control mats, particularly excelsior, contribute to soil moisture, resulting in increased vegetative biomass production (Sutherland et al., 1998).

Contour Grass Strips: Contour grass strips are bands of species-specific grass, sown or laid as sod strips along the contour of a slope to help slow the velocity of runoff, reducing sediment transport (Boubakari & Morgan, 1999). Contour grass strips operate effectively when they pool water on the upward slope encouraging sediment deposition. Both field

studies and greenhouse simulated rainfall studies have quantified water runoff and soil sediment loss. Melville and Morgan (2001) simulated a rainfall intensity of 40 mm h^{-1} for 45 minutes collecting both runoff and sediment removal. The sediment discharge and total water runoff decreased on plots with *P. pratensis* and *Festuca ovina* (sheep fescue) contour grass strips compared to bare plots. This suggested that contour grass barriers can reduce soil loss (Melville & Morgan, 2001). Similarly, Le Bissonnais et al. (2004) simulated rainfall at an intensity of 66mm h^{-1} for one hour and found that their fescue contour grass strips also reduced sediment and nutrient runoff loss.

While evidence suggests that contour grass strips are effective at reducing sediment loss and water runoff, the effectiveness is dependent on numerous factors including soil type, slope, precipitation, grass barrier width, and grass composition, including species, density, age, height, and management (Lakew & Morgan, 1996; Le Bissonnais et al., 2004). Furthermore, contour grass strips may not be very effective at suppressing weeds because they do not revegetate an entire area. Strips of bare ground are left between the contours of vegetation that may be susceptible to weed invasion.

Sod

Using sod in a revegetation strategy may help to eliminate some of the constraints caused by seeded revegetation, particularly the bare ground that is susceptible to erosion and weed invasion. Sod provides a mat of more mature plants with established roots that are ready to anchor to the soil, and may act as a physical barrier suppressing weeds present at a site.

Sod is an expensive revegetation technique because of the time and resources involved in its production. Because of the expense, it is likely a revegetation technique for priority sites such as steep slopes and areas with high weed pressure. The instant vegetative plant community sod provides could have an immediate effect on reducing soil erosion because it increases surface roughness and acts as a protective soil cover obstructing direct soil impact (e.g. from precipitation). The aboveground vegetation associated with sod could also slow and divert overland flow (Thurow et al., 1986), as well as trap water and wind born sediments (Thurow et al., 1986; Grace, 2002; Ludwig et al., 2004). Once the sod roots have anchored to the soil, like established plant communities, they could aid soil structure development and increase water infiltration (Thurow et al., 1986).

The thatch associated with sod is a combination of alive plants and dead litter. This mat of plants and litter may not only contribute to reducing erosion (Grace, 2002), but may also help to suppress weed seeds from germinating by inhibiting light (Sydes & Grime, 1981; Vazquezyanes et al., 1990) and impeding seed contact with the soil (Facelli & Pickett, 1991). Furthermore, because sod is composed of mature plants, it is likely to directly compete with weed species as well as produce additional plant litter rapidly compared to newly seeded vegetation, contributing to these processes even more.

The non-indigenous species *P. pratensis*, sown as a monoculture of various cultivars, is the most common species used for residential and commercial revegetation. While this sod is widely produced and thus readily available, it also typically requires a lot of water: equivalent to 2.54 cm of water a week (Christians, 2004).

Supplemental Irrigation

Revegetation areas are generally too large to irrigate with any consistency, so it is impractical to think that a large revegetated area will receive supplemental irrigation. It is estimated that over 271 million hectares of the earth's surface relies on supplemental irrigation, particularly for crop production (Grace, 1997). This is a lot of water, particularly as the world's population rises, increasing the demand for fresh water as global climate change continues to create uncertainties (Gleick, 1993). Fresh water resources are also irregularly divided. Some regions have excess water, while others are extremely short on water. As these trends continue, there is growing interest in water conservation (Schaller, 1993; Tengberg et al., 1998; Rosegrant & Cline, 2003; Reeve et al., 2004). Experiments examining plant response over a water gradient lend insight into how much supplemental irrigation truly is necessary. A goal of my study was to determine whether a multispecies sod was capable of establishing without supplemental irrigation, and in doing so, suppress both seed and vegetative weed propagules.

Multispecies Sod

With the growing interest in both water conservation (Schaller, 1993; Tengberg et al., 1998; Rosegrant & Cline, 2003; Reeve et al., 2004) and revegetating with indigenous plant species (Harper-Lore (Bugg et al., 1997; Harper-Lore & Wilson, 2000; Pinaya et al., 2000), using a sod composed of multiple species, as opposed to *P. pratensis*, has the potential to be a useful revegetation technique. Multiple species help to stabilize a plant community and its ecosystem processes (Tilman et al., 1996), making it less prone to environmental variation

(Gurevitch, 1992) and potentially less susceptible to invasions (Macarthur, 1970; MacArthur, 1972; Tilman, 1997).

The problem associated with multispecies sod is that its tensile strength is potentially less than sod comprised of only rhizomatous species, like *P. pratensis*. The reason for this is that many indigenous grass species have a bunch grass form and thus reproduce primarily by seed, rather than both vegetatively and from seed. It is therefore often necessary for reinforcement material to be used to aid transportion of the multispecies sod from the turf farm to the project site. This reinforcement material has the potential to serve additional purposes such as weed suppression, soil stability, addition of organic matter, and reduction in evapotransporation, all of which are relevant to revegetation concerns. Research shows that erosion control mat can reduce sediment lost particularly if it is combined with rooted vegetation (Grace et al., 1998). Biodegradable erosion control mat composed of materials such as recycled wood, straw, jute, etc., may also contribute nutrient content to the soil as it decomposes, as well as aid with water retention. Erosion control mat may therefore be a good reinforcement material option to aid multispecies sod transport.

Primary Objectives of Research

The primary objectives of this research were to evaluate the establishment, drought tolerance, and weed suppression capabilities of multispecies sod for application with any revegetation strategy requiring rapid vegetation cover. Three experiments were conducted to examine the ability of multispecies sod to establish with minimal supplemental irrigation, as well as to act as a physical barrier to reduce the spread of weed species into adjacent indigenous natural ecosystems.

Multispecies Sod Species Used for Research

The multispecies sod used for the experiments was sown with three grasses native to Montana (Dorn, 1984) mixed by weight: 27% *Festuca idahoensis* (Idaho fescue), 22% *Elymus lanceolatus* (thickspike wheatgrass), 17% *Agropyron smithii* (western wheatgrass) and one naturalized species, 34% *Poa compressa* (Canada bluegrass). Because the sod was grown adjacent to other species at the sod farm two volunteer grasses, *P. pratensis* and *Festuca rubra* (red fescue) were observed in the sod on delivery. The following are descriptions of the native habitat of the species that were originally sown to create the multispecies sod:

Festuca idahoensis (Idaho fescue): A early summer blooming, C_3, densely tufted perennial grass that grows naturally at 274-4023 m elevation (FEIS, 2009) throughout western North America (Harrison, 2000). *F. idahoensis* is adapted to all soil textures with a pH range between 5.6-8.4, and has an average root depth of 35.5 cm (USDA, 2008). *F. idahoensis* consumes moisture moderately, requiring a minimum to maximum annual precipitation range from 30-51 cm, and 130 frost-free days to complete its life cycle (USDA, 2008). *F. idahoensis* is often found in open grasslands and open, dry forests. Some species commonly associated with *F. idahoensis* are *Agropyron spicatum* (bluebunch wheatgrass), *F. ovina*, *Muhlenbergia montana* (mountain muhly), *Artemisia* spp. (sagebrush), and *Pinus ponderosa* (ponderosa pine) (Harrison, 2000).

Elymus lanceolatus (syn. *Agropyron dasystachyum*) (thickspike wheatgrass): A early summer blooming, C_3, sod-forming perennial grass with deep rhizomes that grows naturally at 0-3350 m elevation (FEIS, 2009) throughout the northern Great Plains and Intermountain

regions of western North America (Sykes, 2000). *E. lanceolatus* grows best in medium to coarse textured soils with good drainage and a pH range between 6.6-8.4 (USDA, 2008). *E. lanceolatus* has an average root depth of 63 cm and is extremely drought tolerant, requiring a minimum to maximum annual precipitation range from 20-51 cm, and 90 frost-free days to complete its life cycle (USDA, 2008). *E. lanceolatus* is often found in mixed grass prairie. Some species commonly associated with *E. lanceolatus* are *Achnatherum hymenoides* (Indian ricegrass), *Sporobolus cryptandrus* (sand dropseed), *Artemisia tridentate* (big sagebrush), *Calamovilfa longifolia* (prairie sandreed), *A. spicatum, Festuca* spp. (fescue spp.), *Stipa* spp. (needlegrasses), *A. smithii*, *Koeleria cristata* (junegrass), and *Carex eleocharis* (thread-leaved sedge) (Horvath, 2000).

Agropyron smithii (syn. *Pascopyrum smithii*) (western wheatgrass): A mid-summer blooming, C_3, sod-forming perennial grass that grows naturally at 732-3049 m elevation (FEIS, 2009) throughout North America, with the exception of the southeast (USDA, 2008). *A. smithii* is adapted to fine and medium soil textures (USDA, 2008) and is usually displaced by *E. lanceolatus* in coarser soils (Sykes, 2000). However, *A. smithii* can tolerate poor drainage, saline soils, and a pH range between 4.5-9 (USDA, 2008). *A. smithii* has an average root depth of 51 cm and requires little soil moisture, with a minimum to maximum annual precipitation range from 25-51 cm, and 90 frost-free days to complete its life cycle (USDA, 2008). *A. smithii* is often found in mixed grass prairie and foothills (Sykes, 2000). Some species commonly associated with *A. smithii* are *Bouteloua gracilis* (blue grama), *Buchloe dactyloides* (buffalograss), *Stipa* spp., *A. spicatum*, *Festuca. hallii* (rough fescue), *F.*

idahoensis, *K. cristata*, and *Sarcobatus vermiculatus* (greasewood) (Sykes, 2000; USDA, 2008).

Poa compressa (Canada bluegrass): A mid-spring blooming, C_3, sod-forming perennial grass with extensive rhizomes (Sykes, S., 2000) that grows at 0-3659 m elevation (FEIS, 2009) throughout North America. *P. compressa* was introduced from Tasmania and New South Wales (Sykes, 2000) and is capable of growing in cooler climates under almost all conditions: clay to sand, low fertility to high fertility, acidic to alkaline, except it is shade intolerant (Sykes, 2000). *P. compressa* requires a minimum to maximum annual precipitation range from 30-114 cm, and 90 frost-free days to complete its life cycle (USDA, 2008). *P. compressa* is often found in disturbed sites within innumerable habitats (FEIS, 2009). Some species commonly associated with *P. compressa* include many grassland, prairie and forest species, such as *Agropyron* spp. (wheatgrass), *Deshampsia* spp. (hairgrass), *Artemesia* spp., *A. hymenoides*, and *Festuca* spp. (FEIS, 2008). *P. compressa* can have invasive characteristics and is listed in Connecticut as a banned invasive species (USDA, 2008).

CHAPTER TWO

THE ESTABLISHMENT AND ANNUAL WEED SUPPRESSION POTENTIAL OF MULTISPECIES SOD

Introduction

Weed invasions have the potential to impact entire ecosystems causing ecological, economic, and social consequences (Vitousek et al., 1996; Pimental et al., 2000; Davis et al., 2000). Weed species are generally strong competitors because typically their individual and population growth rates are high due to short life cycles and high reproductive capacities, as well as to their efficiency to utilize (Orians, 1986) and compete (Sumners & Archibold, 2007) for resources. Factors that influence the invasion of a new species into an environment include: species specific characteristics (Lonsdale, 1999), the environments' susceptibility to invasion (Lonsdale, 1999; Davis et al., 2000), resource availability (Davis et al., 2000), and propagule pressure (Tilman, 1997; Lonsdale, 1999; Jongejans et al., 2007).

Once present at a site, a species' population abundance is driven largely by seed dispersal, germination, establishment, and survival (Ellsworth et al., 2004; Benvenuti, 2007; Baker & Beck, 2008; McAlpine & Jesson, 2008). Seed banks also accumulate and store dormant seed of many species that have the potential to replace mature plants (Baker, 1989). The amount of time a seed remains viable in the seed bank varies from months to years to decades (Thompson et al., 1997) depending on the species and heterogeneous environmental characteristics such as predation, moisture, and oxygen (Richardson & Kluge, 2008). Reducing the abundance of weed species present in the seed bank is imperative to successfully managing these unwanted species (Ellsworth et al., 2004; Richardson & Kluge,

2008). For example, because annual weed species rely on seed production and dispersal to survive year after year, studies have found that when local weed seed rain is minimized, the abundance of annual weed seeds present in the local seed bank is greatly reduced (Schweizer & Zimdahl, 1984; Burnside et al., 1986; Cavers et al., 1995; Williams & Harvey, 2002) and thus the weed population declines.

Soil surface disturbance has been shown to promote successful seed bank and seed rain germination (Jutila & Grace, 2002; Ellsworth et al., 2004; Benvenuti, 2007; McAlpine & Jesson, 2008) by decreasing competition and altering existing habitats to create microsites or conditions that may favor the emergence and survival of different species. Disturbance is caused by factors including but not limited to fire, flooding, freeze-thaw, fallen trees or rocks, wind, digging, as well as anthropogenic activities including construction and land management activities. Land managers can reduce weed problems by minimizing disturbance (Renne & Tracy, 2007; Richardson & Kluge, 2008).

While many studies have looked at the effect of native ecosystem propagule pressure on weed establishment and productivity (Tilman, 1997; Blumenthal et al., 2005), few have looked specifically at the effect of weed propagule pressure on weed establishment success. Propagule pressure may have similar effects regardless of whether the species is invasive. One example is a study conducted by Sheley et al. (1997) that sowed two different densities of *Centaurea diffusa* (diffuse knapweed) into *Pseudoroegneria spicata* (bluebunch wheatgrass)/ *Stipa comata* (needle and thread) and *Agropyron cristatum* (crested wheatgrass) ungrazed grass communities in eastern Washington that were either subject to manual grass biomass defoliation or not. The results indicated that the higher *C. diffusa* seeding rate

produced more seedlings compared to the lower seeding rate in the *A. cristatum* community but not in the *P. spicata* and *S. comata* communities. Additionally, weed biomass increased in the defoliated grass communities compared to the non-defoliated grass communities likely due to decreased competition. Weed seedling establishment and productivity are therefore in general often limited by competition intensity and above- and belowground microsite availability (Jongejans et al., 2007; Renne & Tracy, 2007; McAlpine & Jesson, 2008). Another study, in a sandy uncultivated field in Minnesota, found that when weed seeds of twelve species were broadcast onto subplots of either bare, newly sown native prairie, or established prairie sown with additional native seed, weed biomass decreased significantly in both sown plots compared to the bare control (Blumenthal et al., 2005). The latter study suggests that increasing competition, through revegetating bare or disturbed areas, will likely decrease weed productivity.

Revegetating a landscape with seed is one of the most economical ways to cover large disturbed areas (Montalvo et al., 2002; Christians, 2004; Robichaud et al., 2006) such as those being reclaimed after resource extraction or roadside construction. Common revegetation techniques include broadcast, imprint, drill, and hydroseeding methods. However, seeded revegetation can be slow to establish (Beard & Green, 1994). Slow plant establishment creates available microsites prone to competition from other plants. Seedling establishment is therefore more common in open habitat or disturbed ecosystems than in productive established grassland communities (Turnball et al., 2000; Jutila and Grace, 2002). For example, Jutila and Grace (2002) conducted a greenhouse experiment using coastal tallgrass prairie sod and found that new seedling emergence was least in the control sod that

was left intact with no manipulation, increased throughout the hayed and burned treatments, and was highest in the sod that was subject to complete destruction by removing plants. Promoting competition through maintaining functionally diverse grassland communities may therefore have the potential to reduce weed establishment (Naeem et al., 2000; Tilman et al., 2006). Furthermore, revegetating with more established plants, like sod, as opposed to seed, may be a more effective revegetation strategy to minimize undesired seed germination.

Sod is composed of a mature plant community with a mat of established roots that are ready to anchor to the soil. Sod may have the potential to be even more competitive with seed bank and seed rain weed populations, as well as increase its' potential for successful establishment, if it is diversified by being composed of multiple species, as opposed to the commonly used monoculture of *Poa pratensis* (Kentucky bluegrass). It is known that diverse specie assemblages help to stabilize a community making it less prone to environmental variation (Gurevitch, 1992) and potentially less susceptible to invasion (MacArthur, 1970; MacArthur, 1972; Tilman, 1996). Furthermore, revegetating with multispecies sod adapted to a local climate may also contribute to plant community stability because localized and indigenous species may be better adapted to localized environmental stress, such as short growing seasons (Petersen et al., 2004) and limited water availability (Villagra & Cavagnaro, 2005; Zegada-Lizarazu et al., 2006), than non-localized and non-indigenous species.

Another advantage to multispecies sod is that *P. pratensis* sod generally requires a lot (2.54 cm/week) of water (Christians, 2004) consistently throughout the heat of the summer. While supplemental irrigation is often used to aid any sod establishment to help adhere the roots to the soil surface (Christians, 2004), revegetation areas are generally too large to

irrigate with any consistency. It is therefore recommended that all revegetation be conducted during periods of adequate moisture (Hardegree & Van Vactor, 2004; Bay & Sher, 2008). Experiments examining a multispecies sod over a water gradient would help determine the optimum range of moisture necessary for successful sod establishment and survival.

This experiment quantified the potential of a multispecies sod to suppress six different densities of annual weed seed invasion from either seed bank or seed rain. A second objective examined the potential of the multispecies sod to establish with minimal (e.g. natural) and varying levels of supplemental irrigation. The intention was to determine whether the use of multispecies sod as an alternative revegetation technique could directly reduce the emergence and survival of weed species by rapidly creating self-sustaining plant communities capable of establishing in semi-arid environments.

Methods

Study Site

The study was conducted at Montana State University's Montana Agricultural Experiment Station (MAES) Horticulture Farm (45.68 N, 111.05 W) in Bozeman, Montana, USA. The site was a level agricultural field, tilled fallow with no herbicide for weed management for two years prior to the experiment. The soil, defined by the hydrometer method, was clay loam (36% sand, 36% silt, 28% clay).

The 30-year average (1971-2000) annual precipitation in Bozeman is 49.00 cm, with the highest monthly averages occurring in April (4.75 cm), May (8.18 cm), June (7.26 cm), and September (5.00 cm) (Western Regional Climate Center, 2008). The annual precipitation during the three years of the experiment (40.75 cm, 44.21 cm, and 40.53 cm for 2006-2008

respectively) was below the 30-year average (Western Regional Climate Center, 2008). However, the cumulative off-season (October-May) precipitation that occurred each year of the experiment (27.86 cm, 33.38, and 27.87 cm for 2006-2008 respectively) was similar to the 30-year average (27.62 cm; Western Regional Climate Center, 2008), demonstrating that the summer months were where the deficit occurred.

The 30-year average (1971-2000) daily maximum and minimum temperatures for the summer months over which the experiment was conducted (June-September) were 25 °C and 8 °C respectively (calculated from Western Regional Climate Center, 2008). Growing degree days (GDD) throughout 2006 and 2007 were higher than the 116 year average (1892-2008); however, in general GDD throughout 2008 were lower than 2006 and 2007 and thus similar to the historical average. Furthermore, the GDD for July of 2007 (1074) was a lot higher than for July 2006 (979) and July 2008 (849). Table 2.1 displays these GDD as well as the monthly averages (1892-2008).

Table 2.1 Growing degree days (GDD) for the four summer months (June-September) and the cumulative off-season (October-May) during the experimental period (2006-2008), as well as the long term average (1892-2008). GDD were calculated by the Western Regional Climate Center. Calculations use a 5 ºC base temperature.

GGD	June	July	August	September	Cumulative (October-May)
Average	**552**	**812**	**771**	**460**	**791**
2006	692	979	783	493	996
2007	663	1074	846	519	1061
2008	540	849	834	466	770

Multispecies Sod

The multispecies sod used for the experiment was sown with three grasses native to Montana (Dorn, 1984) mixed by weight: 27% *Festuca idahoensis* (Idaho fescue), 22% *Elymus lanceolatus* (thickspike wheatgrass), 17% *Agropyron smithii* (western wheatgrass) and one naturalized species, 34% *Poa compressa* (Canada bluegrass). The sod was purchased from Bitterroot Turf Farm (Bitterroot, MT), where it had been cultivated for three years prior to acquisition for the experiments. Their sod management included watering 2.54 cm a week, mowing to 3.8 cm height twice a week (April-September), fertilizing three times a year (March, June, and September) with 25-10-10 fertilizer at 1,496 l/ha, and controlling broadleaf weeds as needed with 1.81 kg of Triplet (8.16% MCPP-p, 2.77% Dicamba dimethylamine salt, and 30.6% 2,4-dichlorophenoxy acetic acid) at 5.84 ai/l/ha. Two volunteer grasses, *P. pratensis* and *Festuca rubra* (red fescue) were observed in the sod on delivery. These two species were being grown in different sod mixtures adjacent to the multispecies sod at the turf farm.

Experimental Design

The experiment was of split-split plot design blocked throughout with a water regime. Seed bank or seed rain were the main split. These plots were further split by sown weed density. Two experiments (A_1 and A_2) were performed, displaced in start date by one year. A_1 was conducted during 2006 through 2008. A_1 was replicated in an adjacent plot (A_2) during 2007 through 2008. This design enabled replication in both space and time so that two years of first season (2006 (A_1) + 2007(A_2)) data and two years of second season (2007(A_1) + 2008(A_2)) data were collected and compared within and between years. Species

composition of the multispecies sod in A_1 also continued to be monitored a third season (2008) for additional information. During the first season, seed bank or seed rain sown treatments were replicated four times in A_1 and six times in A_2 within each of five rows that were spaced at incremental distances away from the line source irrigation (blocks) to create a water regime (Figure 2.1). Replicates were increased the second season of A_1 and with the installation of A_2 to increase the detection of differences between treatments. All multispecies sod plots were watered 15 minutes per day for five days (total applied $\bar{x}$ = 3.84 cm, stdev=1.59 cm in A_1; $\bar{x}$ = 5.31 cm, stdev=1.30 cm in A_2) following installation to mimic the ideal time to revegetate during high seasonal precipitation (Hardegree & Van Vactor, 2004; Bay & Sher, 2008).

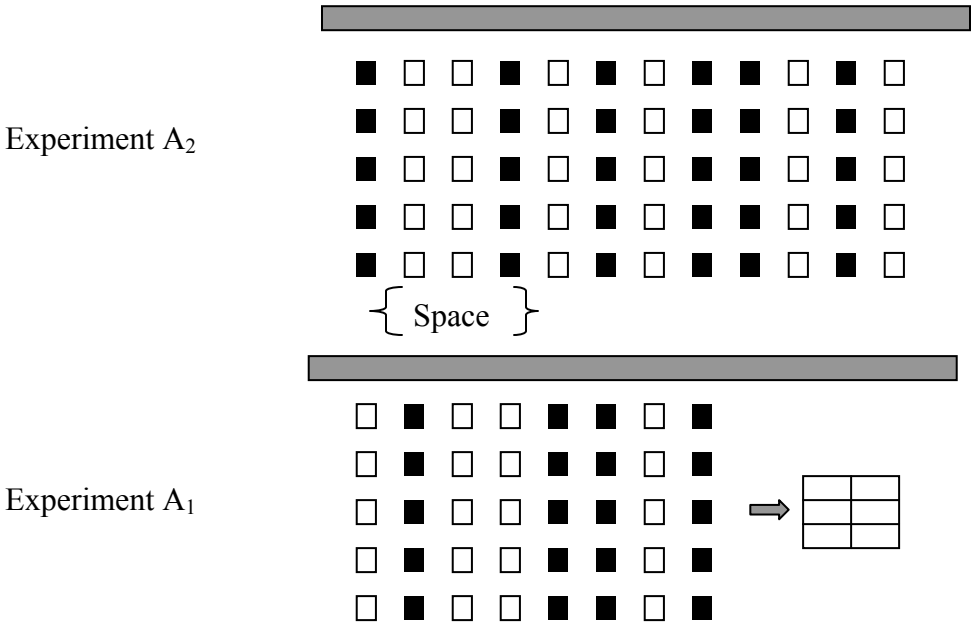


Figure 2.1 Field layout of experiments A_1 and A_2. Seed bank or seed rain were the main split, with each plot split further (inlay) by six randomized sown weed densities (0, 25, 50, 100, 500, 1000 per 0.21 m^2). Symbols represent each main plot (■ seed bank plots, □ seed rain plots). Gray lines represent line source irrigation. Space (30 m) between experiments to avoid mixing water applications.

The objective of the watering regime was for the plots receiving the highest water to obtain the equivalent of 2.54 cm of water a week, which is a typical watering rate for *P. pratensis* sod (Christians, 2004), and for the plots receiving the lowest water to obtain only natural precipitation with no supplemental water. The remaining three rows of plots received a continuum between these extremes. Plots were irrigated three times per week (Monday, Wednesday, and Friday) from June through September (Table 2.2). If natural precipitation occurred between scheduled irrigation times the amount of precipitation was recorded and the irrigation volume modified appropriately.

The amount of moisture contacting the surface was recorded in A_1 in 2006 by ten fence post rain gauges placed at ground level in each of the five rows at the northern and southern ends of the experiment. To determine if water was being applied evenly across the field, in 2007 and 2008 the rain gauges continued to be monitored as well as catch-cans that were strategically placed throughout both A_1 and A_2. The catch cans revealed that the water was being applied evenly in A_1, but that there was variation in A_2 with more water applied to the north end of the field compared to the south end of the field. Because of this variation the collected water cross the field was used in analysis.

Table 2.2 Exact dates supplemental irrigation was applied. *The delay in 2008 was due to technical problems with the pump.

Year	Dates
2006	June 5 – September 15
2007	June 5 – September 15
2008*	June 16 – September 19

The line source irrigation system provided a similar range of water application over the seasons (June-September) in all three years of A_1; however, application varied between years in A_2 with more water applied throughout the entire water regime in 2007 compared to 2008 (Table 2.3). This created a difference in cumulative water collected in A_1 compared to A_2 of each year. In 2007, A_2 received more water in the low water regime and slightly less water in the high water regime compared to A_1. In 2008, A_2 received less water in the low water regime and less water in the high water regime compared to A_1. Variation throughout experiments and years was due to environmental factors such as wind during water application, evapo-transpiration from warm temperatures, and yearly natural precipitation differences.

Table 2.3. Range of cumulative water (June-September) collected for both A_1 and A_2 each year the experiments were conducted. Includes both irrigation and natural precipitation.

Experiment A_1	Range of Collected Cumulative Water (cm) from Low to High
2006	8.71 – 41.12
2007	9.78 – 41.30
2008	8.78 – 42.02
Experiment A_2	
2007	13.83 – 40.20
2008	5.98 – 32.69

The sod was laid in 2006 (A_1) and 2007 (A_2) in 1.88 m x 1.08 m plots, with 0.21 m^2 subplots. *Brassica napus* (canola) was used as a surrogate weed species to represent common annual non-indigenous invasive plant species in the Brassicaceae family. *B. napus* seed

viability was determined by placing petri dishes (10 cm^2) with blotter paper containing twenty seeds each, in an incubator at 23 ºC under twelve hours of light/dark for seven days. Seeds were kept consistently moist. There were five replicates per germination trail and the trial was repeated for each of the three years, 2006-2008, that *B. napus* seed was sown in the field experiment to standardize the number of viable sown seeds accordingly.

During the first season six densities of *B. napus* (0, 25, 50, 100, 500, 1000; equivalent to 0, 119, 238, 476, 2380, 4760 per 1.0 m^2 respectively) were sown per 0.21 m^2 subplot either below the multispecies sod to represent weed seed bank, or above the multispecies sod to represent weed seed rain. During the second season of A_1 and A_2, the same six densities were sown only as seed rain onto the existing sod. The same seed rain plots were used in both seasons, plus two additional plots in A_1 (originally seed bank plots laid in 2006), to provide six seed rain replications in A_1 and A_2 in the second season.

B. napus sowing date was adjusted to allow for the yearly differences in GDD. Plots were sprayed in May of their second (A_1 and A_2) and third (A_1) season with 2.72 kg of 2-4D Low Volatile 6 (2,4-dichlorophenoxy acetic acid) at 2.34 ai/l/ha to create plots free of volunteer weeds before beginning second season seeding and data collection.

Weed Suppression: Annual weed suppression was evaluated by assessing *B. napus* seedling emergence and survival in each multispecies sod subplot throughout the water regime. Seedlings sown as either seed bank or seed rain were counted twice a week during the first month of the growing season, followed by once a week until harvest. It was evident with the first flush of germination that the 500 and 1000 sown densities were too crowded to

count accurately. Each week these plants were removed and counted thus capturing only emergence trends.

B. napus productivity was recorded for the plants that survived the season that were sown in the 25, 50, and 100 density treatments. No plants emerged in the control (0 density sown treatement). All plants were harvested when seed was mature. Seed pods were seperated from the vegetative biomass and each dried in an oven at 49 °C for five days. Dry weight was recorded.

Four (A_1) and six (A_2) 0.21 m^2 randomized bare ground control plots per experiment were set up adjacent to multispecies sod plots. Volunteer weeds were counted in both the sod and bare soil control. Species were identified and relative abundance recorded mid-season each year.

Multispecies Sod Establishment: Repeated measures of percent cover of each species and whether each species was actively photosynthesizing or senescing/dormant were taken in September of each growing season for each control (0 density sown per 0.21 m^2) multispecies sod subplot. Changes in plant community composition with treatment and time were documented using species richness and species diversity/evenness metrics. Species richness was defined as the number of species present in each multispecies sod subplot. Species diversity incorporated species richness, as well as the relative abundance or evenness of the different species distributions. The Simpsons Diversity Index ($Diversity=1/(s\sum i=1)pi^2$) was used to calculate species diversity where "pi" is the proportion of individuals of the i^{th} species in a community. The index is bound between 0-1, where 1 indicates an even distribution of species, and 0 indicates complete dominance by one species.

Species richness and diversity were calculated incorporating all the species present in each subplot. This included the originally sown sod species (*F. idahoensis*, *E. lanceolatus*, *A. smithii*, *P. compressa*), volunteer sod species (*P. pratensis* and *F. rubra*), unidentified senescing/dormant sod and unidentified newly photosynthesizing seedlings and ramets as two separate entities, as well as each volunteer weed species.

At the conclusion of the experiment (2008 after 3 seasons for A_1, 2007 after 2 seasons for A_2) above-ground sod biomass (0.10 m^2) was harvested from each control subplot and dried in an oven at 49 °C for five days. The dry weight was recorded by species.

Statistical Analysis

Analyses were conducted using R statistical software (www.R-project.org, 2007). Data were analyzed using general linear regression in either the quasi or Gaussian family (see Appendix A for models). Various normality tests (density plots, boxplots, normal probability plots, correlation plots, and the R package Nortest) on the raw data and residuals showed generally non-normal data.

B. napus proportional emergence and survival were analyzed bound between 0-1 using general linear regression. This was performed in R using using the quasi family with a logit link function. Proportional emergence was calculated by the total number of plants emerged 21 days after sowing, when emergence had leveled off, divided by the number of seeds sown. Proportional survival was calculated as the number of plants harvested divided by the emerged number of plants per subplot. Dry weights of the vegetative and seed biomass were analyzed using general linear regression assuming a Gaussian distribution. The independent variables for all analyses were: experiment (A_1 and A_2), cumulative water (cm)

collected throughout the water regime in each experiment during each experimental period (June-September) of each year, whether *B. napus* was sown as seed bank or seed rain, *B. napus* sown density, time since sod was transplanted (first year the sod was installed, or second or third year when it may be more established), and the number of *B. napus* plants harvested (biomass responses only).

To determine the establishment success of the multispecies sod the relative abundance of: volunteer weed species, senescing/dormant sod, and *P. compressa* and *P. pratensis* (the dominant species), as well as species richness, species diversity, and the multispecies sods' final biomass were all analyzed either bound between 0-1 using general linear regression in the quasi family with a logit link function or using general linear regression assuming a Gaussian distribution. The independent variables for all analyses were: experiment (A_1 and A_2), time since sod was transplanted (first year the sod was installed, or second or third year when it may be more established), and cumulative water (cm) collected in each experiment during each experimental period (June-September) of each year.

Results and Discussion

Weed Suppression

Seed Bank and Seed Rain Weed Emergence: During the first season of both A_1 and A_2, the proportional emergence of *B. napus* sown was greatly reduced in all treatments compared to the 100% germination rates observed in the laboratory. Intact vegetation and litter from the sod likely limited both the seed bank and seed rain emergence due to the

physical barrier that reduced light, moisture, with seed rain soil contact (Barrett, 1931; Weaver & Rowland, 1952; Sydes & Grime, 1981; Hamrick & Lee, 1987; Facelli & Pickett, 1991; Jensen, 1998; Ellsworth et al., 2004; Blumenthal et al., 2005), as well as increased competition for resources with mature plants (Wesson & Wareing, 1969; Turnball et al., 2000; Jutila & Grace, 2002; Blumenthal et al., 2005; Kruk et al., 2006). These results are consistent with other studies. For example, Barrett (1931) found oak seedling germination was reduced under forest litter in a natural setting. The seedlings that did emerge were etiolated or so elongated that they were more vulnerable to mechanical damage. Furthermore, Hamrick and Lee (1987) found that *Carduus nutans* L. (nodding plumeless thistle) seedlings that emerged from under a thick litter layer of plant stems, grass, and leaf fragments in a greenhouse study had a high mortality rate because of the energy it took to penetrate the litter mat. Overall, the reduction in both seed bank and seed rain *B. napus* proportional emergence suggested that the multispecies sod suppressed the emergence of the surrogate weed.

Total proportional emergence was different ($P<0.001$) between experiments therefore each experiment was analyzed separately. More plants emerged in the first year in A_2 compared to A_1 which could have been caused by the slight increase in June temperatures in 2007 versus 2006, as well as other general and biological variation. In A_1 more ($P<0.001$) *B. napus* emerged from seed rain compared to seed bank (Figure 2.2). Within the seed bank plots no further significance from the water regime ($P=0.164$) or sown density ($P=0.286$) was found. In the seed rain treatment of A_1 there was a significant ($P=0.008$) interaction between the water regime and the time since sod was transplanted (Figure 2.2 ii & iii). This interaction was due to a slight decrease in emergence

in the middle water regime in the first year seed rain treatments, compared to a slight increase in emergence throughout the water regime in the second year seed rain treatments. While water contributed to a large degree of variability in each year of A_1, there was a clear trend in all sown densities under all water levels that more seed rain sown *B. napus* emerged the first season the year the sod was laid, compared to the second season when the sod was more established. Additionally, in the seed rain treatment of A_1, sown density also significantly ($P=0.009$) interacted with time since the sod was transplanted (Figure 2.2). This interaction was significant ($P=0.007$) in the seed rain treatment of A_2 as well and is due to different patterns of emergence in the six different densities sown in each experiment each year, with again more *B. napus* emergence the first season the year the sod was laid, compared to the second season when the sod was more established (Figure 2.3). Furthermore, in A_2 there was a significant interaction ($P<0.001$) between seed bank or seed rain sown *B. napus* treatment and sown density (Figure 2.3). In A_2 seed bank sown *B. napus* emergence decreased with increased sown densities, whereas seed rain sown *B. napus* proportional emergence remained similar at all sown densities in both seasons. In A_2 there was also an increase ($P<0.001$) in emergence with increased cumulative water in the seed rain sown plots, but no significant ($P=0.192$) water regime effect was found in the seed bank sown plots (Figure 2.3).

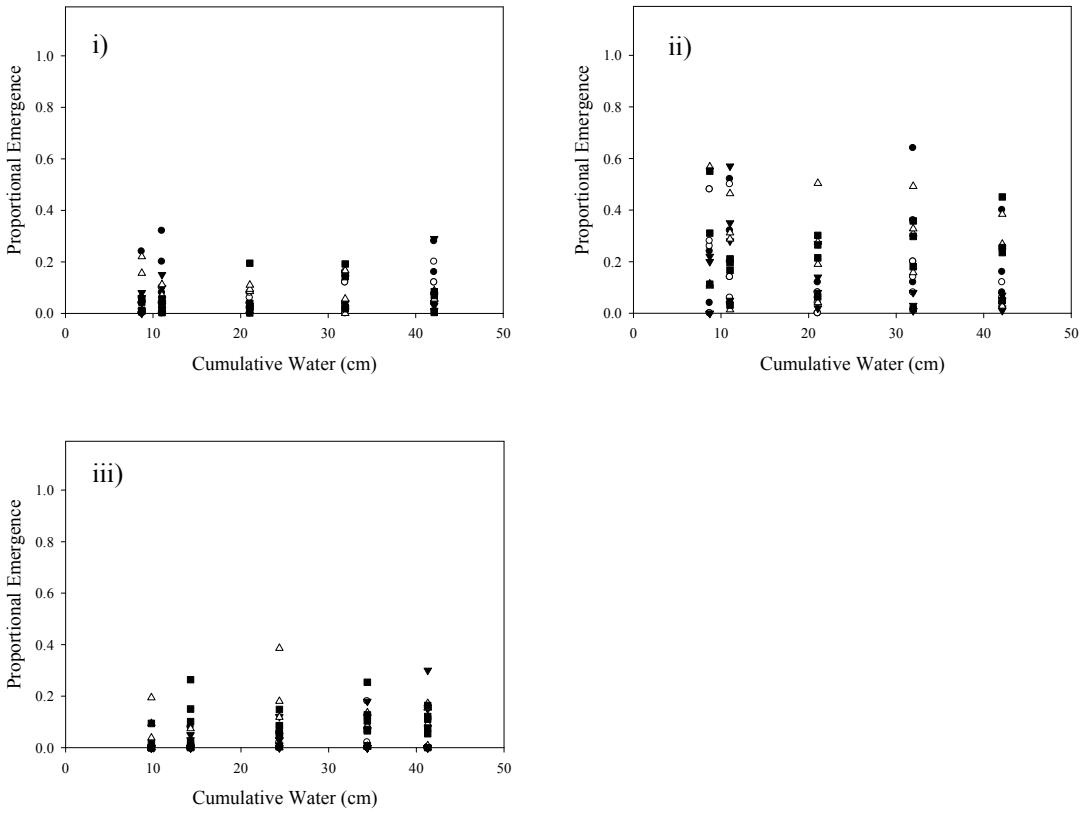
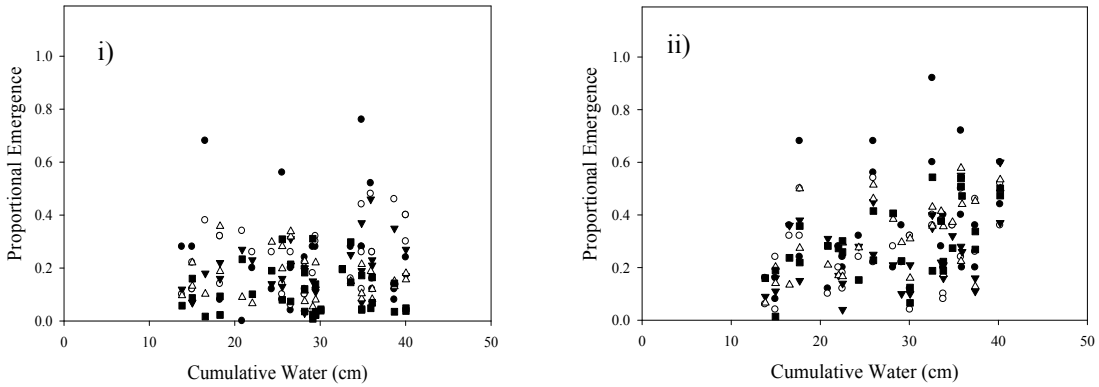


Figure 2.2. Proportional emergence of sown *B. napus* in A_1: i) seed bank, ii) seed rain the first season the sod was laid, iii) seed rain the second season when the sod was more established. There was a significant difference between seed bank and seed rain emergence in the first season ($P<0.001$). No further significance was found in the seed bank treatment. In the seed rain treatment there were significant interactions between sown density and time since the sod was transplanted ($P=0.009$), as well as between the water regime and time since the sod was transplanted ($P=0.008$). Symbols represent *B. napus* sown density per 0.21 m^2 (● 25 seeds, ○ 50 seeds, ▼ 100 seeds, Δ 500 seeds, ■ 1000 seeds).



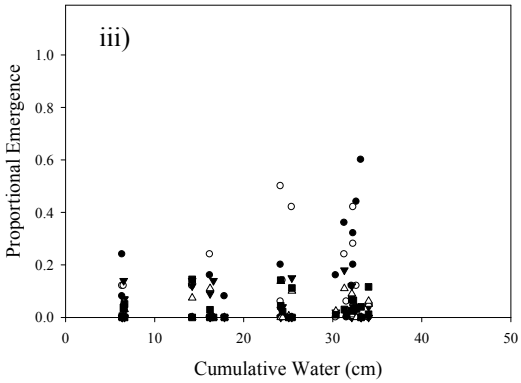


Figure 2.3. Proportional emergence of sown *B. napus* in A_2: i) seed bank, ii) seed rain the first season the sod was laid, iii) seed rain the second season when the sod was more established. There was a significant interaction between seed bank/seed rain treatment and sown density ($P<0.001$), as well as between sown density and time since the sod was transplanted ($P=0.004$). The water regime was significant ($P<0.001$) in the seed rain, but not in the seed bank ($P=0.192$) treatment. Symbols represent *B. napus* sown density per 0.21 m^2 (● 25 seeds, ○ 50 seeds, ▼ 100 seeds, Δ 500 seeds, ■ 1000 seeds). X-axis displays spatial variability in the water regime across the field.

It could be expected that sowing density (a propagule pressure component) (Kolar & Lodge, 2001; Lockwood et al., 2005) would have a strong effect on the ability of a species to emerge and become established. The lack of a consistent trend in our results, as well as in other studies, suggests that the response to propagule pressure is not always clear. For example, Davies (2008) found that in a sagebrush-bunchgrass steppe of southeastern Oregon there was an increase ($P<0.001$) in *Taeniatherum caput-medusae* (medusahead) emergence and establishment with increased rates of seed introduction into established plant communities; whereas along a highway right-of-way in Mississippi, Holly and Ervin (2007) found no evidence that propagule density affected *Imperata cylindrical* (Japanese blood grass) seedling emergence even in bare soil where competition from other plants was not an

issue. A review of seed sowing experiments into natural or semi-natural plant communities, by Turnball et al. (2000), examined twenty-seven studies with over ninety different species and found a consistent trend: seed addition increased population size significantly in newly plowed and early/mid-successional fields, but changed very little in arid and mesic grasslands that have been unplowed for > 30 years. The lack of a consistent sown density effect on *B. napus* emergence may therefore likely be influenced by competition from the more established plant community of the multispecies sod, as well as to some degree a certain amount of random chance (Hubbell, 2001).

Overall the results from A_1 and A_2 indicate that the multispecies sod was capable of reducing weed emergence from both seed rain and seed bank the first year it was installed under all water levels. Furthermore, in the second year the more established sod was even more resistant to seed rain weed invasion.

Volunteer Weed Emergence: The volunteer weeds that emerged in both the bare ground control and control multispecies sod subplots included: *Bromus inermis* (smooth brome), *Bromus tectorum* (cheatgrass) *Bromus anomalous* (nodding brome), *Agropyron repens* (quackgrass), *Amaranthus retroflexus* (redroot pigweed), *Erodium cicutarium* (stork's-bill), *Lamium amplexicaule* (henbit), *Cirsium arvense* (Canada thistle), *Malva rotundifolia* (round-leaved mallow), *Phleum pratense* (timothy), *Trifolium repens* (white clover), and *Taraxacum officinale* (dandelion). Although the variance is better understood, due to increased replicates, in the control multispecies sod subplots compared to the bare ground control, time since the sod was transplanted had a significant ($P<0.001$) effect on the

relative abundance of volunteer weeds. The first year the sod was laid the relative abundance of volunteer weeds, calculated from percent cover measurements, was higher (P=0.019) in A_2 ($\bar{x}$=0.18, stdev=0.29) compared to A_1 ($\bar{x}$=0.07 , stdev=0.11). There was no difference (P=0.381) in the relative abundance of volunteer weeds between the bare ground control and the control multispecies sod subplots, nor in the water regime (P=0.531). In the second year no effect was found between experiments (P=0.239) nor in the water regime (P=0.834); however, the relative abundance of volunteer weeds was higher (P<0.001) in the bare ground control plots ($\bar{x}$ = 0.063, stdev=0.036) compared to the multispecies sod plots ($\bar{x}$=0.004, stdev=0.023) (Figure 2.4). This suggests that, similar to the *B. napus* emergence results, the more established multispecies sod was effective at suppressing these weeds.

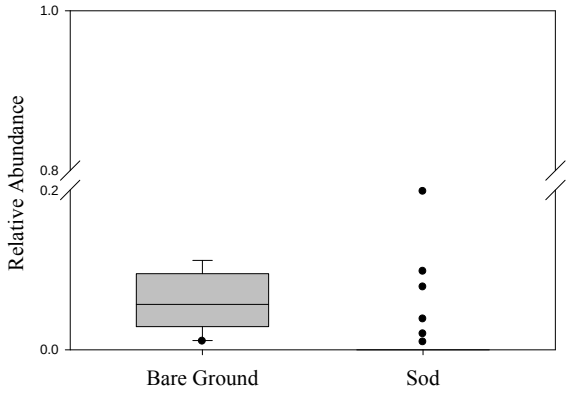


Figure 2.4. Relative abundance (0.21 m^{-2}) of emerged volunteer weeds in the bare ground and multispecies sod plots during the second year of both A_1 and A_2 (P<0.001). Each box captures 50% of the data. The dark line represents the median with whiskers extending to the minimum and maximum values within 95% of the data. Circles represent outliers.

Seed Bank and Seed Rain Weed Survival and Productivity: The proportional survival of emerged *B. napus* seedlings at the end of the growing season was not significantly

different (P=0.321) for seed bank or seed rain plots in the first year of both experiments A_1 and A_2. However, survival was affected by the water regime (P<0.001), with increased survival with increased cumulative water. In the second year no emerged *B. napus* plants survived until harvest in either A_1 or A_2, suggesting that the more established sod has the potential to out-compete weeds. These results are consistent with the hypothesis that competition with mature plants, thus a reduction in available resources, can reduce weed invasion (Wesson & Wareing, 1969; Jutila & Grace, 2002; Blumenthal et al., 2005; Kruk et al., 2006).

When water is a limiting resource there is a general trend of decreased productivity (Davis et al., 1998; Asay et al., 2001; Petersen et al., 2004; Villagra & Cavagnaro, 2005). In both experiments there was a consistent trend of increased *B. napus* vegetative biomass with increased water (P=0.038 in A_1; P<0.001 in A_2) and increased number of harvested plants (P<0.001 in A_1; P=0.012 in A_2); however, there was a difference (P<0.001) between experiments because more plants emerged and survived until harvest in A_2 compared to A_1 therefore each experiment was analyzed separately. In A_1 there was a significant (P=0.023) interaction between the water regime and whether *B. napus* was sown as seed bank or seed rain. Vegetative biomass was similar between seed bank and seed rain sown *B. napus* in the low water regime, but in the high water regime seed bank *B. napus* produced more vegetative biomass than seed rain *B. napus* (Figure 2.5 i & ii). In A_1 there was also a significant (P=0.001) interaction between the water regime and *B. napus* sown density, with an increase in vegetative biomass as the water regime increased in all densities except the midrange density (50 seeds/0.21 m^2). *B. napus* vegetative biomass at this density increased with

cumulative water and then slightly decreased at the highest water level (Figure 2.5 i & ii) in both seed bank and seed rain sown plots. In A_2 *B. napus* sown as seed bank or seed rain (P=0.415) at different densities (P=0.559) had no significant effect on the vegetative biomass; however, similar to A_1, vegetative biomass increased with increased water (P<0.001, Figure 2.5 iii) as well as with increased number of harvested plants (P=0.012, Figure 2.5 iv).

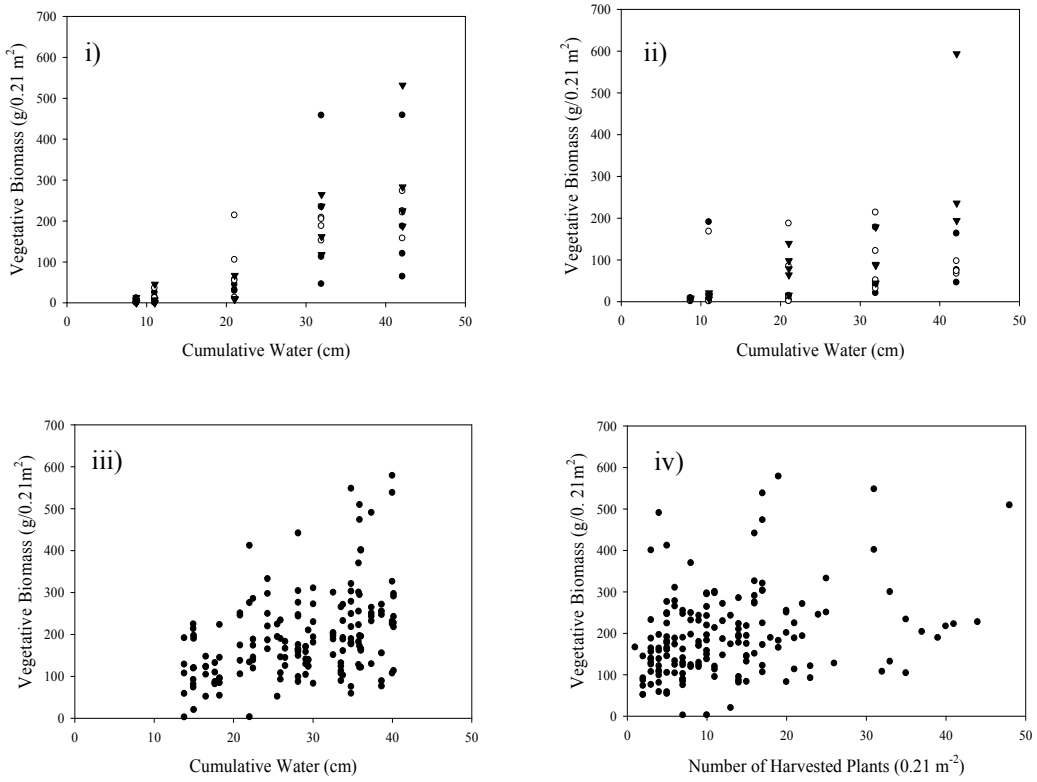


Figure 2.5. Vegetative productivity of seed bank and seed rain sown *B. napus*: i) A_1 seed bank by sown density and cumulative water, ii) A_1 seed rain by sown density and cumulative water, iii) A_2 seed bank and seed rain by cumulative water (P<0.001), iv) A_2 seed bank and seed rain by number of harvested *B. napus* plants (P=0.012). There were significant interactions in A_1 between the water regime and whether *B. napus* was sown as seed bank or seed rain (P=0.023), as well as between the water regime and *B. napus* sown density (P=0.001). Symbols represent *B. napus* sown density per 0.21 m^2 (● 25 seeds, ○ 50 seeds, ▼ 100 seeds) and apply to i and ii only. No difference between seed bank and seed rain (P=0.415) or sown density (P=0.559) was found in A_2 therefore these results are combined. Cumulative water x-axis displays spatial variability in the water regime across the field.

B. napus seed biomass followed a similar trend to the vegetative biomass, increasing with increased water (P<0.001; Figure 2.6 i) and number of harvested plants (P=0.006; Figure 2.6 ii). No further significance was found in whether *B. napus* was sown as seed bank or seed rain (P=0.380), experiment (P=0.153), nor sown density (0.711).

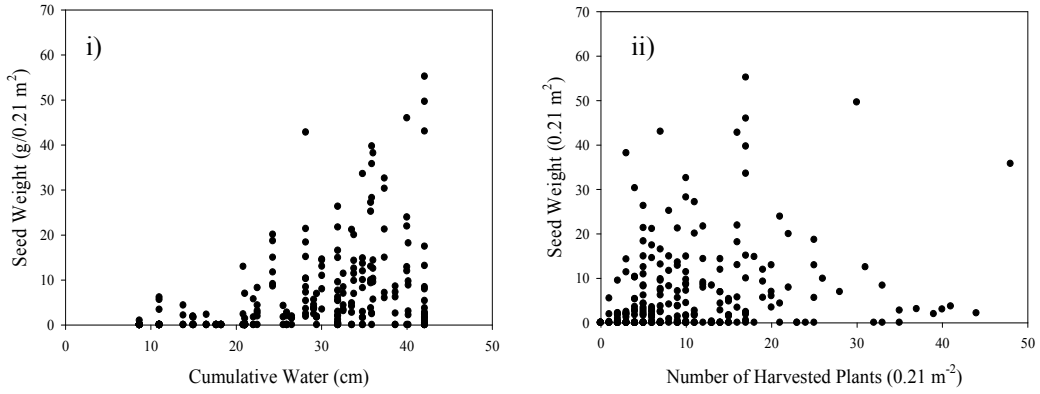


Figure 2.6. Seed productivity from seed rain and seed bank sown *B. napus* in both experiments A_1 and A_2: i) seed weight by cumulative water (P<0.001), ii) seed weight by number of harvested *B. napus* plants (P=0.006). No significant difference was observed between seed bank and seed rain so the results are combined. Cumulative water x-axis displays spatial variability in the water regime across the field.

Water requirements for plants differ between species generally influencing the ecological range where they can exist. Coping with water stress is species dependent, with some species better adapted than others (Villagra & Cavagnaro, 2005; Zegada-Lizarazu et al., 2006). *B. napus* is a widely cultivated crop and other studies have found that *B. napus* productivity increased with increased water input (Pannu et al., 1992; Narang et al., 1993; Mathur & Wattal, 1996; Banuelos et al., 2002; Sarkar et al., 2007). Experiments A_1 and A_2 therefore demonstrate a basic principle: annual weed productivity has the potential to be

reduced by decreased water input. Decreased productivity can decrease weed seed rain, which in turn will reduce weed seed bank and overall reduce future invasions (Witkowski & Wilson, 2001; Williams & Harvey, 2002; Blumenthal et al., 2005; Davis, 2008; Richardson & Kluge, 2008).

The reduction in *B. napus* productivity was especially apparent the second year of both experiments where no emerged seedlings survived to harvest. This reduction in biomass productivity is again likely a result of competition with the more established multispecies sod plant communtiy (Sheley et al., 1997; Blumenthal et al., 2005; Davies, 2008), suggesting that revegetating with multispecies sod could significantly reduce weed invasions.

Overall Multispecies Sod Establishment

Multispecies Sod Biomass: In both experiments at the conclusion of the study the dry weight of the multispecies sod biomass increased ($P<0.001$) as the water regime increased (Figure 2.7). There was no difference between experiments ($P=0.184$) despite the fact that A_1 had been installed for three years and A_2 had only been installed for two years. This again agrees with the general theory that adequate soil moisture contributes to plant establishment and productivity (Davis et al., 1998; Asay et al., 2001; Petersen et al., 2004; Villagra & Cavagnaro, 2005).

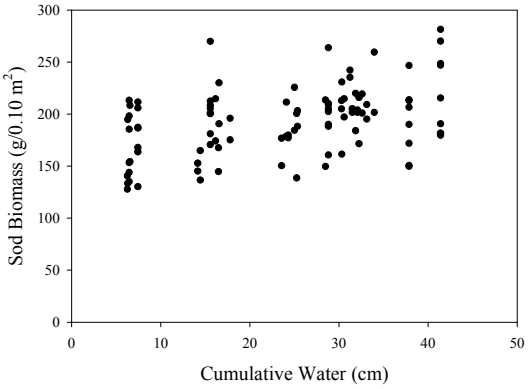
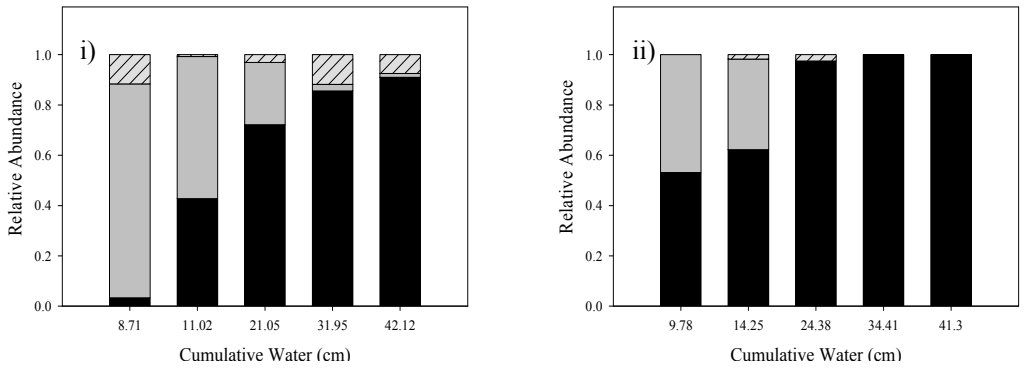


Figure 2.7. Multispecies sod biomass at the conclusion of the study (2008 after 3 years in A_1; 2007 after 2 years in A_2).

Relative Abundance of Senescing/Dormant Sod: The proportion of senescing/dormant sod measured in September of every year was different between experiments ($P<0.001$). However, in each experiment there was a significant interaction between the water regime and the time since the sod was transplanted ($P<0.001$ in A_1, $P<0.001$ in A_2), with a consistent trend of more photosynthesizing sod in the high water regime compared to the low water regime and a decrease in the relative abundance of senescing/dormant sod throughout the entire water regime over time (Figure 2.8 for A_1 as an example). Overall, the results suggest that the multispecies sod was able to establish and persist at all water levels, including the plots that received natural precipitation.



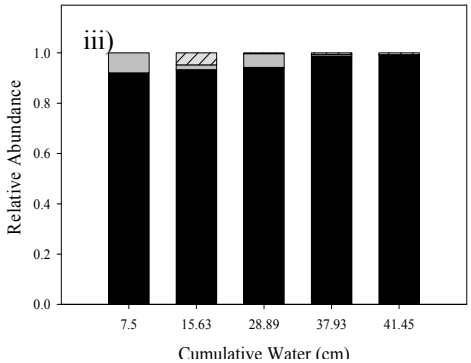


Figure 2.8. Mean relative abundance (0.21 m^{-2}) of photosynthesizing sod (black), senescing/dormant sod (light gray), and volunteer weeds (striped) in A_1: i) September 2006, ii) September 2007, iii) September 2008.

Species Richness and Diversity: Species richness (P=0.009 in A_1; P=0.004 in A_2) in each experiment and species diversity (P=0.004) in both experiments had significant interactions between water and the time since the sod was transplanted due to different patterns throughout the water regime over time. For example, in A_1 species richness decreased from year 1 to year 2 with no evident water regime pattern, and then increased in year 3 as the water regime increased. However, overall, in all seasons of all experiments averaged throughout each high and natural precipitation water regimes, the maximum mean species richness and diversity were low, ($\bar{x}$=3.3, stdev=0.89 for species richness; $\bar{x}$=0.3, stdev=0.18 for species diversity) (Table 2.4), suggesting that the multispecies sod was dominated by the two naturalized rhizomatous species *P. compressa* and *P. pratensis* (Figure 2.9). Dominant species have been shown to crowd out less dominant species causing a decline in species density and richness (Gurevitch, 1992). This decline is often observed after fertilizer has been applied (Stevens & Carson, 1999). Prior to arriving at MAES, the multispecies sod was subject to intense management for three (A_1) and four (A_2) years. The

decline in species richness and diversity from what was originally sown (27% *F. idahoensis*; 22% *E. lanceolatus*; 17% *A. smithii*; and 34% *P. compressa* mixed by weight) was apparent.

Table 2.4. Multispecies sod mean (0.21 m^{-2}) species richness in each experiment (A_1 and A_2) and mean species diversity in both experiments combined (year 3 A_1 only) per time since the sod was transplanted. Calculations for high water and natural precipitation averaged throughout each water regime. Standard deviations in parentheses.

	A_1 Mean Species Richness	A_2 Mean Species Richness	Mean Species Diversity
Year 1			
High Water	2.6 (1.30)	2.2 (0.83)	0.3 (0.21)
Natural Precipitation	2.3 (0.71)	2.3 (1.16)	0.2 (0.18)
Year 2			
High Water	2.5 (0.53)	3.2 (1.27)	0.3 (0.18)
Natural Precipitation	1.8 (1.16)	2.0 (0.58)	0.1 (0.18)
Year 3			
High Water	3.3 (0.89)	NA	0.3 (0.17)
Natural Precipitation	1.9 (0.83)	NA	0.1 (0.17)

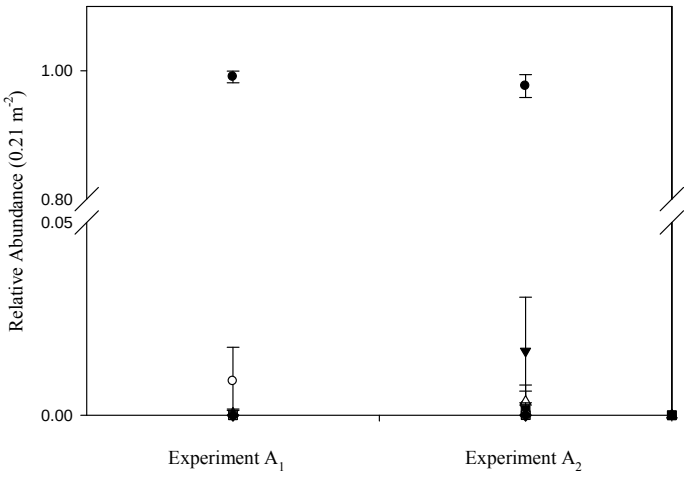


Figure 2.9. Relative abundance of species present in the sod when it arrived at MAES. Symbols represent each species (● *P. compressa*, ○ *P. pratensis*, ▼ *F. idahoensis*, Δ *E. lanceolatus*, ■ *A. smithii*, □ *F. rubra*, + volunteer weeds, ◊ senescing/dormant sod, ▲ unidentified mix) with standard error bars. "Unidentified mix" refers to species that were unidentifiable due to new seedling or ramet growth. Personal observation would suggest that most of these unidentified species were either *P. compressa* or *P. pratensis*.

Relative Abundance of *P. compressa* and *P. pratensis*: The relative abundance of *P. compressa* had a significant ($P<0.001$) interaction between water and time since the sod was transplanted. During the first year of both experiments *P. compressa* increased as the water regime increased. In the second year of both experiments there was no apparent pattern between the relative abundance of *P. compressa* and the water regime, and in the third year (A_1 only) *P. compressa* decreased with increasing cumulative water. The relative abundance of *P. pratensis*, on the other hand, increased with increasing cumulative water ($P=0.002$) in all years of both experiments (Figure 2.10). Time since the sod was transplanted was marginally significant ($P=0.050$) for the relative abundance of *P. pratensis*; however, when each year was analyzed separately the same trend of increased *P. pratensis* as the water regime increased was apparent. Even though a plant community's response to irrigation is species dependent (Depuit, 1984; Newman & Redente, 2001), adequate soil moisture is one of the factors that contributed to the increase in productivity and establishment of *P. pratensis* and *P. compressa.* Furthermore, the rhizomatous habit of *P. compressa* and *P. pratensis* potentially helped these species be better competitors (Ba et al., 2008) because they can reproduce both vegetatively and from seed, compared to many of desired indigenous and naturalized grass species that have a bunch grass form and generally reproduce primarily by seed.

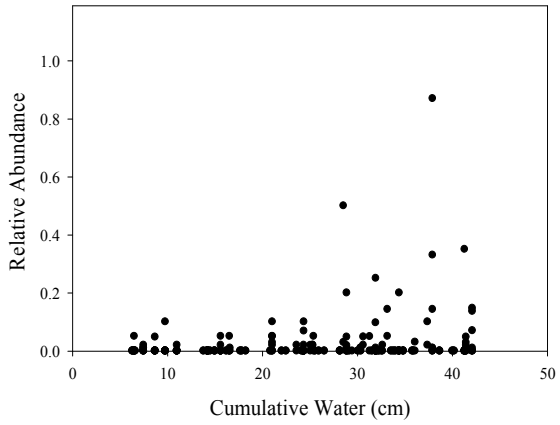


Figure 2.10. *P. pratensis* relative abundance (0.21 m^{-2}) in all years of both experiments along the cu,ulative water gradient (P=0.002).

The use of indigenous species is becoming increasingly common in revegetation (HarperLore, 1996). Provided the site has not been too drastically disturbed, indigenous plants could be better adapted to localized conditions, require minimal maintenance, contribute to flora and habitat connectivity (Ries et al., 2001), and help blend an area back into the surrounding natural landscape (Landis et al., 2005). The concept of a multispecies sod containing indigenous and naturalized species, compared to the typical monoculture of *P. pratensis*, may therefore be important to plant community dynamics that relate to ecological processes such as community stability, evolution, competition, productivity, and niche structure (McIntosh, 1967).

Nonetheless, the effect of species diversity on plant invasion (Levine & D'Antonio, 1999) is inconsistent. While some studies suggest that increased diversity increases a plant community's susceptibility to invasion (Stohlgren et al., 2002; Stohlgren et al., 2003; Crall et al., 2006; Floyd et al., 2006), others suggest that a diverse plant community is less susceptible to invasions (MacArthur, 1972; Tilman, 1997). What may be more important in

the long term is that diverse plant communities, such as multispecies sod, in general are less prone to environmental variation (Gurevitch, 1992).

This experiment, as well as other studies suggest that initial species selection for revegetation projects, as well as initial cultural practices, will influence the long term development of a plant community over time (Newman & Redente, 2001). Newman and Rendente (2001) examined a revegetated site over 20 years and found that originally sown species were still apparent. Furthermore, they found that non-indigenous seed mixtures created lower species richness than indigenous seed mixtures because the non-indigenous species were often better competitors (Newman & Redente, 2001). This was apparent in A_1 and A_2 by the dominance of *P. compressa* and *P. pratensis*.

Conclusion

These experiments demonstrate that multispecies sod can reduce both seed bank and seed rain weed emergence and survival because it rapidly provides established vegetative cover under natural preciptiation conditions the first year the sod is laid. The additional reduction in the surrogate weed's emergence and productivity the second year suggests that multispecies sod could be a useful revegetation technique that is very effective at suppressing weeds. Furthermore, the results emphasize that species selection for multispecies sod and cultural practices should reflect the goals and objectives of the revegetation site, especially if a priority is a true diversified plant community.

CHAPTER 3

THE ESTABLISHMENT AND ANNUAL WEED SUPPRESSION POTENTIAL OF MULTISPECIES SOD IN COMBINATION WITH FOUR REINFORCEMENT MATERIALS

Introduction

As the human population continues to grow the fragmentation of natural habitat and the consumption of natural resources is becoming more prevalent. Anthropogenic disturbance can facilitate weed invasion and establishment (Grime, 1979; Hobbs & Huenneke, 1992; Bosy & Reader, 1995; Parendes & Jones, 2000) by altering existing habitat and creating new conditions that may favor certain species. It is estimated that the impact of invasive species may be second only to habitat destruction in causing loss of biodiversity globally (Groves, 2001). When weed species encroach beyond their natural range they have the potential to impact entire ecosystems causing ecological, economic, and social consequences (Vitousek et al., 1996; Pimental et al., 1999; Davis et al., 2000). The success of invasions by weeds into ecosystems is linked to the suitability of the habitat, the resources available (Davis et al., 2000), species traits (Lonsdale, 1999), and propagule pressure (Lonsdale, 1999; Jongejans et al., 2007). Plant competition can increase when the amount of unused resources increases (Bertness & Callaway, 1994; Davis et al., 2000). Therefore, in areas where rehabilitation practices are required after disturbance the importance of revegetating with multiple species should be considered. Because species are adapted to different conditions, diverse communities combined with heterogeneous environmental

variation in both space and time, make it more likely that at least one species will thrive in any given year (Gurevitch, 1992). While different land use objectives define specific revegetation goals, there tends to be a general focus on rapid vegetation establishment to increase short term site and long term ecological stability (Newman & Redente, 2001).

Non-indigenous species seed mixtures are often used in revegetation projects because they are relatively cheap, easy to obtain commercially, and typically consist of species that provide rapid ground cover to compete with undesired plant species as well as bind soil in place (Beyers, 2004; Landis et al., 2005; Matesanz et al., 2006). More recently the demand for indigenous and localized seed has developed, particularly for road and other revegetation projects that are adjacent to native wildland habitats (Richards et al., 1998; Montalvo et al., 2002; Petersen et al., 2004). In general, revegetating a landscape with seed is one of the most economical ways to cover large disturbed areas (Montalvo et al., 2002; Christians, 2004; Robichaud et al., 2006).

Many studies have compared the success of different seeding methods, including broadcast, imprinting, drill, and hydroseeding. Dry broadcast seeding places seeds directly on the soil surface. Imprinting pushes seeds slightly below the soil surface. A third method, drill seeding implants the seeds into the soil in rows, burying them typically 10-12 mm deep (Montalvo et al., 2002). Finally, hydroseeding places seeds on the soil surface embedded in a wet hydromulch slurry that averages 0.5-10 mm thick (Montalvo et al., 2002) so the seeds may never come in direct contact with the soil. Seeds on the soil surface are more vulnerable to desiccation and predation (Montalvo et al., 2002; Holland et al., 2008). Imprinting and

drilling protects seeds from desiccation and predation, but depending on the seed size may place the seeds either too deep or too shallow for optimal emergence. Broadcast seeding tends to be the least expensive technique, but because plant establishment is slow the area can be susceptible to weeds (Beard & Green, 1994). Most results imply that revegetation success, regardless of the seeding methods, is site and species specific (Fattorini, 2001; Montalvo et al., 2002; Fernandez-Abascal et al., 2003; Taylor & McDaniel, 2004).

A revegetated site can be susceptible to erosion and invasion by less desirable plants due to slow vegetation establishment with all seeding methods. Using multispecies sod in a revegetation strategy, instead of seed, may help to eliminate these constraints. Sod provides a mat of established roots ready to anchor to the soil. The sod mat may also act as a physical barrier, suppressing weeds present at a site. Common turfgrass sod is usually grown with rhizomatous species, e.g. *Poa pratensis* (Kentucky bluegrass), that produce a strong bonded sod. With the growing interest in indigenous and localized seed mixtures it is necessary to consider the life-form of the grasses in the area of interest. For example, in drier environments many of the indigenous grass species have a bunch grass form and generally reproduce primarily by seed. Thus sod created from bunch grass species, or a mix of bunch and rhizomatous species, does not necessarily have as high of a tensile strength as a *P. pratensis* sod (Stott, 2007). It is therefore often necessary for a reinforcement material to be used to transport indigenous or multispecies sod from its origin to the target site (Christians, 2004).

Reinforcement materials have the potential to serve additional purposes such as physical weed suppression, soil stability, soil water availability, addition of organic matter,

reduction in evapo-transpiration, and soil cooling and light inhibiting effects that may delay seed germination (Cotts et al., 1991; Sutherland et al., 1998; Petersen et al., 2004). Erosion control mats could make suitable multispecies sod reinforcement materials because they have been shown to help increase soil moisture for plant establishment (Muzzi et al., 1997; Grace et al., 1998; Sutherland et al., 1998; Petersen et al., 2004). Erosion mats are primarily produced to control erosion. They can be made of different materials including: jute, straw, coconut, excelsior wood, synthetic materials such as woven polymers and nylon netting, as well as combinations of all these materials. Most erosion control mats are biodegradable and provide temporary erosion control depending on the degradability of their fiber composition. Vegetation also decreases erosion (Thurow et al., 1986; Grace, 2002) through interception, infiltration and an increase in surface cover. The long-term stability of a revegetated slope is therefore a synergism between erosion control mat and established plant growth (Sutherland et al., 1998).

Achieving good vegetation establishment and survival is related to the conditions under which the site is revegetated. Supplemental irrigation is often used to aid sod establishment, helping to adhere the roots to the soil surface (Christians, 2004) as well as to subsequently maintain the sod's plant population. As many revegetation areas cover too large an area to add supplemental water, it is of interest to understand the establishment success of multispecies sod under different water regimes.

The objectives of this research focused on the evaluation of annual weed suppression and establishment capabilities of multispecies sod in combination with four different

reinforcement/erosion mat (hereafter stated as reinforcement) materials under a water regime. The three stated hypotheses were that: 1) multispecies sod in combination with reinforcement materials, is capable of suppressing seed bank and seed rain weed invasion, 2) water rate will affect multispecies sod establishment, and 3) reinforcement materials will contribute to the establishment success of multispecies sod.

Methods

Water Absorption Capacity of Reinforcement Materials (Laboratory Study)

A water absorption capacity experiment to evaluate different reinforcement materials was conducted in the laboratory. The procedure (Figure 3.1) followed the standardized methods stated by the Erosion Control Technology Council (ECTC, 2008). Four square (20.32 cm x 20.32 cm) replicates of each of the reinforcement materials were individually weighed on a square (22.86 cm x 22.86 cm) tared No. 19 galvanized wire screen. Another screen of the same size was placed on top of the reinforcement material to help preserve the integrity of the material and to avoid loss of the materials' components. The reinforcement material, sandwiched between the two screens, was then placed 6.35 cm deep in a pan of 21 ± 2 °C water for 24 hours. After soaking, the material and screens were placed horizontally above the water on wire supports and allowed to drip-drain for 10 minutes. Each material was then placed in a tared pan and weighed. The amount of water held by the material was calculated by subtracting the weight of the dry material from the weight of the wet material. The water absorption capacity was reported as the water held by the material divided by the weight of the original dry material, averaged over the four replicates.

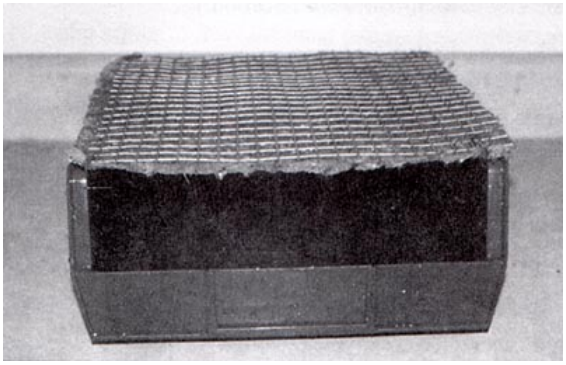


Figure 3.1. Picture demonstrating the procedure for the reinforcement materials water absorption capacity laboratory study. (Photo from Erosion Control Technology Council Technical Guidance Manual, 2008: http://www.ectc.org/TermandIndex.asp).

Study Site

The field component of the study was conducted at Montana State University's Montana Agricultural Experiment Station (MAES) Horticulture Farm (45.68 N, 111.05 W) in Bozeman, Montana, USA. The site was a level agricultural field, tilled fallow with no herbicide for weed management for two years prior to the experiment. The soil, defined by the hydrometer method, was clay loam (36% sand, 36% silt, 28% clay).

The 30-year average (1971-2000) annual precipitation in Bozeman is 49.00 cm, with the highest annual averages occurring in April (4.75 cm), May (8.18 cm), June (7.26 cm), and September (5.00 cm) (Western Regional Climate Center, 2008). The annual precipitation during the three years of the experiment (40.75 cm, 44.21 cm, and 40.53 cm for 2006-2008 respectively) was below the 30-year average (Western Regional Climate Center, 2008). However, the cumulative off-season (October-May) precipitation that occurred each year of the experiment (27.86 cm, 33.38, and 27.87 cm for 2006-2008 respectively) was similar to

the 30-year average (27.62 cm; Western Regional Climate Center, 2008), demonstrating that the summer months were where the deficit occurred.

The 30-year average (1971-2000) daily maximum and minimum temperatures for the summer months over which the experiment was conducted (June-September) were 25 °C and 8 °C respectively (calculated from Western Regional Climate Center, 2008). Growing degree days (GDD) throughout 2006 and 2007 were higher than the 116 year average (1892-2008); however, in general GDD throughout 2008 were lower than 2006 and 2007 and thus similar to the historical average. Furthermore, the GDD for July of 2007 (1074) was a lot higher than for July 2006 (979) and July 2008 (849). Table 3.1 displays these GDD as well as the monthly averages (1892-2008).

Table 3.1 Growing degree days (GDD) for the four summer months (June-September) and the cumulative off-season (October-May) during the experimental period (2006-2008), as well as the long term average (1892-2008). GDD were calculated by the Western Regional Climate Center. Calculations use a 5 ºC base temperature.

GGD	June	July	August	September	Cumulative (October-May)
Average	**552**	**812**	**771**	**460**	**791**
2006	692	979	783	493	996
2007	663	1074	846	519	1061
2008	540	849	834	466	770

Multispecies Sod

The multispecies sod used for the experiment was sown with three grasses native to Montana (Dorn, 1984) mixed by weight: 27% *Festuca idahoensis* (Idaho fescue), 22% *Elymus lanceolatus* (thickspike wheatgrass), 17% *Agropyron smithii* (western wheatgrass) and one naturalized species, 34% *Poa compressa* (Canada bluegrass). The sod was purchased

from Bitterroot Turf Farm (Bitterroot, MT), where it had been cultivated for three years prior to acquisition for the experiments. Their sod management included watering 2.54 cm a week, mowing to 3.8 cm height twice a week (April-September), fertilizing three times a year (March, June, and September) with 25-10-10 fertilizer at 1,496 l/ha, and controlling broadleaf weeds as needed with 1.81 kg of Triplet (8.16% MCPP-p, 2.77% Dicamba dimethylamine salt, and 30.6% 2,4-dichlorophenoxy acetic acid) at 5.84 ai/l/ha. Two volunteer grasses, *P. pratensis* and *Festuca rubra* (red fescue) were observed in the sod on delivery. These two species were being grown in different sod mixtures adjacent to the multispecies sod at the turf farm.

Experimental Design

The experiment was of split-plot design blocked throughout with a water regime. Reinforcement materials were the main split. Two experiments (B_1 and B_2) were performed, displaced in start date by one year. B_1 was conducted during 2006 through 2008. B_1 was replicated in an adjacent plot (B_2) in 2007-2008. This design enabled replication in both space and time so that two years of first year (2006 (B_1) + 2007(B_2)) data and two years of second year (2007(B_1) + 2008(B_2)) data were collected and compared within and between years. Species composition of the sod in B_1 also continued to be monitored a third year (2008) for additional information. B_1 was replicated four times and B_2 was replicated six times within each of five rows that were spaced at incremetal distances away from the line source irrigation to create a water regime (Figure 3.2). Replicates were increased with the installation of B_2 to increase the detection of differences between treatments.

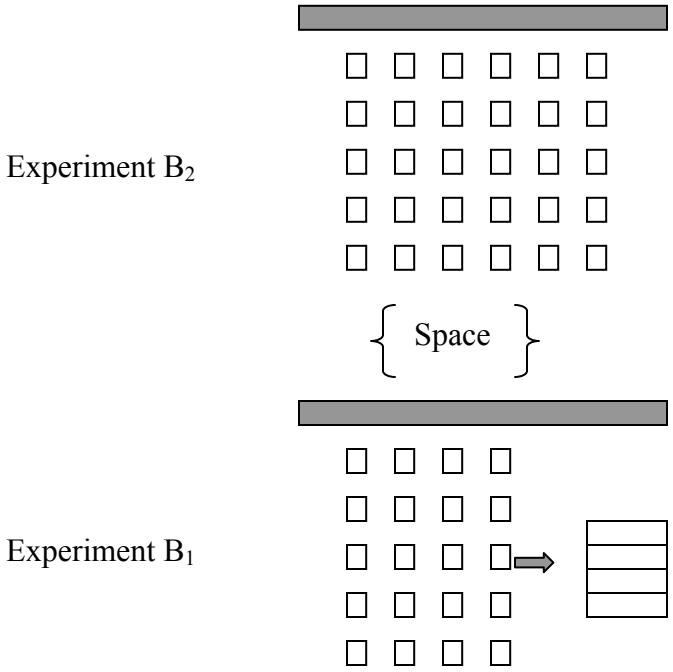


Figure 3.2. Field layout of experiments B_1 and B_2. Each plot was split (inlay) by four randomized reinforcement materials (nylon netting (control), 30% coconut: 70% straw, excelsior wood, and jute) laid beneath the sod. Symbols (□) represent each main plot. Gray lines represent the line source irrigation. Space (30 m) between experiments to avoid mixing water applications.

Irrigation is known to help plants establish (Carson & Pickett, 1990; Newman & Redente, 2001; Petersen et al., 2004). It is recommended that conventional sod in particular be kept moist for 10-14 days after being laid to help adhere the roots to the underlying soil (Christians, 2004). The most effective time to revegetate with sod is therefore when natural precipitation is likely at a seasonal high (Hardegree & Van Vactor 2004; Bay & Sher, 2008). All multispecies sod plots were watered everyday for 15 minutes for five days (total applied $\bar{x}$ = 3.76 cm, stdev=1.07 cm in B_1; $\bar{x}$ = 5.04 cm, stdev=0.46 cm in B_2) following installation to mimic high seasonal precipitation, the highest of which naturally occurs in Bozeman,

Montana in May (30-year (1971-2000) average is 8.18 cm; Western Regional Climate Center, 2008), a month before the experiment began. Whether or not this initial supplemental irrigation was critical to the multispecies sod establishment is unknown because a treatment withholding this initial water was not tested. After the initial watering in just the installation year, there were distinct water regime treatments throughout all experimental seasons in both B_1 and B_2.

The objective of the watering regime was for the plots receiving the highest water to obtain the equivalent of 2.54 cm of water a week, which is a typical watering rate for *P. pratensis* sod (Christians, 2004), and for the plots receiving the lowest water to obtain only natural precipitation. The remaining three rows of plots received a continuum between these extremes. Plots were irrigated three times per week (Monday, Wednesday, and Friday) from June through September (Table 3.2). If natural precipitation occurred between the scheduled irrigation the amount of precipitation was recorded and the irrigation volume modified appropriately.

The amount of moisture contacting the surface was recorded in B_1 in 2006 by five fence post rain gauges placed at ground level towards the center of the experiment, one in each of the five rows. To determine if water was being applied evenly, in 2007 and 2008 the rain gauges continued to be monitored as well as catch-cans that were strategically placed throughout both B_1 and B_2. The catch cans revealed that the water was being applied evenly in both B_1 and B_2.

Table 3.2. Exact dates supplemental irrigation was applied. *The delay in 2008 was due to technical problems with the pump.

Year	Dates
2006	June 5 – September 15
2007	June 5 – September 15
2008*	June 16 – September 19

The line source irrigation system provided a similar range of water application over the seasons (June-September) in all three years of B_1; however, application varied between years in B_2 with more water applied throughout the entire water regime in 2007 compared to 2008 (Table 3.3). This created a difference in cumulative water collected in B_1 compared to B_2 of each year. In 2007, B_2 received more water in the low water regime and slightly less water in the high water regime compared to B_1. In 2008, B_2 received less water in the low water regime and less water in the high water regime compared to B_1. The yearly cumulative water (cm) for each experiment were used in the data analysis. Variation throughout experiments and years was due to environmental factors such as wind during water application, evapo-transpiration from warm temperatures, and yearly natural precipitation differences.

Table 3.3. Range of cumulative water (June-September) collected for both B_1 and B_2 each year the experiments were conducted. Includes both irrigation and natural precipitation.

Experiment B_1	Range of Collected Cumulative Water from Low to High (cm)
2006	8.78 – 42.12
2007	9.20 – 42.00
2008	7.50 – 42.45
Experiment B_2	
2007	14.75 – 33.07
2008	6.20 – 32.10

The sod was laid in 2006 (B_1) and 2007 (B_2) in 2.4 m x 1.08 m plots, with four 0.42 m^2 subplots. Subplots were comprised of one of four reinforcement materials: coconut-straw (CS-3 Natural, Western Excelsior Corporation, Mancos, CO.), jute (loosely woven with 1.5 twists per inch, Western Excelsior Corporation, Mancos, CO.), excelsior wood (Excel S-2 Regular, Western Excelsior Corporation, Mancos, CO.), and nylon netting (control, came with the sod from Bitterroot Turf Farm, Tenax, USA) chosen to represent the range of products commercially available. Reinforcement material subplots were randomly laid under each sod plot.

Brassica napus (canola) was used as a surrogate weed to represent common annual non-indigenous invasive plant species in the Brassicaceae family. *B. napus* seed viability was determined by placing petri dishes (10 cm^2) with blotter paper containing twenty seeds each in an incubator at 23 ºC under twelve hours of light/dark for seven days. Seeds were kept consistently moist. There were five replicates per germination trial and the trial was repeated for each of the three years, 2006-2008, that *B. napus* seed was sown in the field experiment to standardize the number of viable sown seeds accordingly. During the first year 100 (equivalent to 238/ m^2) *B. napus* seeds were sown per 0.42 m^2 subplot on top of the soil but below the reinforcement materials and multispecies sod to represent weed seed bank. During the second year of the experiment 100 *B. napus* seeds were sown on top of the reinforcement material and multispecies sod subplots to represent weed seed rain.

B. napus sowing date was adjusted to allow for the yearly differences in GDD. Plots were sprayed in May of their second year with 2.72 kg of 2-4D Low Volatile 6 (2,4

dichlorophenoxy acetic acid) at 2.34 ai/l/ha to create plots free of volunteer weeds before beginning second year seeding and data collection.

Weed Suppression: Annual weed suppression was evaluated by assessing *B. napus* seedling emergence and survival in each multispecies sod and reinforcement material subplot throughout the water regime. Seedlings sown as either seed bank (first year) or seed rain (second year), were counted twice a week during the first month of the growing season, followed by once a week until harvest. All plants were harvested when seed was mature. Seed pods were seperated from the vegetative biomass and each dried in an oven at 49 °C for five days. Dry weight was recorded to indicate *B. napus* productivity.

Four (B_1) and six (B_2) 0.42 m^2 randomized bare ground control plots were set up adjacent to multispecies sod plots. Volunteer weeds were counted in both the sod and bare ground control. Species were identified and relative abundance recorded mid-season each year.

Multispecies Sod Establishment: Repeated measures of percent cover of each species and whether each species was actively photosynthesizing or senescing/dormant were taken in each subplot in September of each growing season to avoid interference with *B. napus*. Changes in plant community composition with treatment and time were documented using species richness and species diversity/evenness metrics. Species richness was defined as the number of species present in each multispecies sod subplot. Species diversity incorporated species richness, as well as the relative abundance or evenness of the different species distributions. The Simpson's Diversity Index

(Diversity=$1/(s\sum i=1)pi^2$)) was used to calculate species diversity where "pi" is the proportion of individuals of the i^{th} species in a community. The index is bound between 0-1, where 1 indicates an even distribution of species, and 0 indicates complete dominance by one species. Species richness and diversity were calculated incorporating all of the species present in each subplot. This included the originally sown sod species (*F. idahoensis*, *E. lanceolatus*, *A. smithii*, *P. compressa*), volunteer sod species (*P. pratensis* and *F. rubra*), unidentified senescing/dormant sod and unidentified newly photosynthesizing seedlings and ramets as two separate entities, as well as each volunteer weed species.

At the conclusion of the experiment (2008 after 3 years for B_1, 2007 after 2 years for B_2) above-ground biomass of 0.10 m^2 was harvested from each subplot and dried in an oven at 49 °C for five days. The dry weight was recorded by species.

Reinforcement Materials Affect on Soil Water Retention (Field Study): Soil gypsum blocks and Time Domain Reflectometry (TDR) were used to measure soil water potential and soil water content respectively beneath each reinforcement material to determine whether the materials improved soil water retention, which could benefit both sod and weed establishment. The soil gypsum blocks were manufactured by Delmhorst Instrument Company (Towaco, NJ). The principle is that the resistance of the steel electrodes encapsalated in gypsum ($CaSO_4$) blocks is proportional to the water content of the gypsum. A disadvantage of this technique is that all changes in soil conductivity, even those not related to soil moisture, are detected. Because of the potentially confounding results caused by the gypsum blocks, soil water content was measured with TDR technology in 2007. TDR is a method that uses a datalogger and associated software programs to measure the time it

takes for an electromagnetic wave to travel the length of a steel rod (TDR probe) and cable. This propagation velocity (k) is converted into a Ledieu soil water content value (θ=(k*0.1138)-0.1758) by subtracting the offset of the probe and cable.

The experiment was designed so that in B_1 in 2006 the soil gypsum blocks were randomized at both 2.54 cm and 15.24 cm beneath the reinforcement material and multispecies sod subplots (2 replicates per reinforcement material per water treatment). Gypsum block data were collected before and after each supplemental irrigation three times a week. The second season (2007) of B_1 data were collected using a portable TDR system composed of a Campbell Scientific CR1000 datalogger and TDR100 system. This system had a single probe that was placed in each subplot and then removed after each measurement was taken. In B_1 in 2007, the gypsum block data from the control subplot (nylon netting reinforcement material) continued to be monitored in close proximity (within 5 cm) of the TDR measurements. This allowed for evaluation between the gypsum block and TDR data.

In the second experiment, B_2, soil water content was collected mainly with TDR technology, however gypsum blocks were installed (at 2.54 cm and 15.24 cm depths) and monitored beneath the control subplots to add data to the gypsum block verses TDR evaluation. The TDR data were collected twice a week, once directly following supplemental irrigation and again 48 hrs later, right before the next supplemental irrigation. If natural precipitation occurred between supplemental irrigation, data collection was repeated later in the week when no natural precipitation occurred in the 48 hour interval. TDR data were collected in B_2 using a Cambell Scientific CR10x datalogger and TDR100 system. A TDR probe was randomly placed into the sod and each of the four reinforcement materials in the

high, medium, and low rows of the water regime, with three replicates per row. These probes were stationary throughout the entire experiment. The portable TDR system was created for B_1 so that two years of second year TDR data (B_1 and B_2) could be analyzed and compared to the two years of first year gypsum block and TDR data (B_1 and B_2).

Statistical Analysis

Analyses were conducted using R statistical software (www.R-project.org, 2007). Data were analyzed using general linear regression in either the quasi or Gaussian family, with the exception of the water absorption capacity laboratory experiment (see Appendix B for models). General linear regression was determined to be the appropriate test after various normality tests (density plots, boxplots, normal probability plots, correlation plots, and the R package Nortest) on the raw data and residuals showed generally non-normal data.

The water absorption capacity laboratory experiment was tested using single-factor analysis of variance (ANOVA) and Tukey multiple comparisons. The response variable was the weight of the water held by each reinforcement material. The independent variable was reinforcement material. Scatter plots of the gypsum block and TDR raw data revealed very inconsistent trends with many erroneous soil water values. The irregularity of these data suggested that there were confounding effects due to human and technological error. Consequently this section of the experiment was discarded (see Appendix D for more details).

B. napus proportional emergence and survival were analyzed bound between 0-1 using general linear regression. These analyses were performed in R using using the quasi family with a logit link function. Proportional emergence was calculated by the total number

of plants emerged 21 days after sowing, when emergence had leveled off, divided by the number of seeds sown. Proportional survival was calculated as the number of plants harvested divided by the emerged number of plants. Dry weights of the vegetative and seed biomass were analyzed using general linear regression assuming a Gaussian distribution. The independent variables for all analyses were: experiment (B_1 and B_2), time since the sod was transplanted (first year the sod was installed, or second or third year when it may be more established; also indicated seed bank sown *B. napus* the first year and seed rain sown *B. napus* the second year), reinforcement material, cumulative water (cm) collected throughout the water regime in each experiment during each experimental period (June-September) of each year, and the number of plants harvested (for biomass responses only).

To determine the establishment success of the multispecies sod the relative abundance of: volunteer weed species, senescing/dormant sod, *P. compressa* and *P. pratensis* (the dominant species); as well as species richness, species diversity, and the multispecies sod's final biomass were all analyzed either bound between 0-1 using general linear regression in the quasi family with a logit link function or using general linear regression assuming a Gaussian distribution. The independent variables for all analyses were: experiment (B_1 and B_2), time since sod was transplanted (first year the sod was installed, or second or third year when it may be more established; also indicated seed bank sown *B. napus* the first year and seed rain sown *B. napus* the second year), reinforcement material, and cumulative water (cm) collected in each experiment during each experimental period (June-September) of each year.

Results

Reinforcement Material Water Absorption Capacity (Laboratory Experiment)

In the laboratory tests all reinforcement materials had a significantly ($P<0.001$ for coconut-straw; $P<0.001$ for excelsior; $P<0.001$ for jute) higher water absorption capacity than the nylon netting control (Table 3.4). Tukey multiple comparisons determined a significant difference in the water absorption capacity between coconut-straw and excelsior wood ($P=0.049$), as well as between excelsior wood and jute ($P=0.002$). There was no significant difference between coconut-straw and jute ($P=0.354$) (Table 3.4).

Table 3.4. Mean water absorption capacity (weight of water held in material/ dry weight of material) of the four reinforcement materials. Standard deviations in parentheses.

Reinforcement Material	Water Absorption Capacity
Nylon Netting (Control)	0 (0) [a]
30% Coconut- 70% Straw	3.9 (0.74) [b]
Excelsior Wood	2.9 (0.14) [c]
Jute	4.5 (0.64) [b]

Weed Suppression

Seed Bank and Seed Rain Weed Emergence: In both seasons of B_1 and B_2 there was a difference ($P<0.001$) in proportion of sown *B. napus* emergence between the experiments with less *B. napus* plants emerging in B_1 compared to B_2. In B_1, no difference was found between the reinforcement materials ($P=0.300$), however there was a significant ($P<0.001$) interaction between the water regime and time since the sod was transplanted. The interaction suggested that during the first year, when the *B. napus* was sown as seed bank below the newly laid sod and reinforcement materials, there was no apparent trend in proportional

emergence throughout the water regime. However, during the second year, when *B. napus* was sown as seed rain on top of the multispecies sod and reinforcement materials, proportional emergence increased as the water regime increased, and considerably less *B. napus* emerged in the low-medium water application range compared to the first year of B_1, but in the high water levels first (seed bank sown) and second (seed rain sown) year emergence was similar (Figure 3.3 i & ii).

In B_2 there was a significant effect between the reinforcement materials ($P=0.003$) as well as a significant interaction between water and time since the sod was transplanted ($P<0.001$). More *B. napus* seedlings emerged in the control subplots than in any of the reinforcement material subplots (Figure 3.3 iii & iv). The data were then analyzed by reinforcement material to better understand the interaction term. In the control, excelsior, and jute treatments of B_2 there were no interactions. The main treatments of water regime ($P=0.002$ for excelsior; $P=0.026$ for jute; $P<0.001$ for control) and time since the sod was transplanted ($P<0.001$ for excelsior, jute, and control) indicated increased proportional *B. napus* emergence with increased water in both years, and considerably less *B. napus* emergence throughout the water regime the second year (seed rain sown) compared to the first year (seed bank sown) (Figure 3.3 iii & iv). However, within the coconut-straw treatment there was a significant ($P=0.044$) interaction between the water regime and time since the sod was transplanted that showed the same pattern found in B_1 of no trend in *B. na*pus emergence throughout the water regime the first year (seed bank sown), but an increase in emergence as the water regime increased in the second year (seed rain sown). Still there was considerably less *B. napus* emergence in the low-medium water application range

compared to the first year of B_2, but emergence became more similar at the higher water levels (Figure 3.3 iii & iv). Overall, for both experiments the proportional emergence of *B. napus* sown as seed bank and seed rain was greatly reduced in all treatments compared to the 100% germination rates observed in the laboratory.

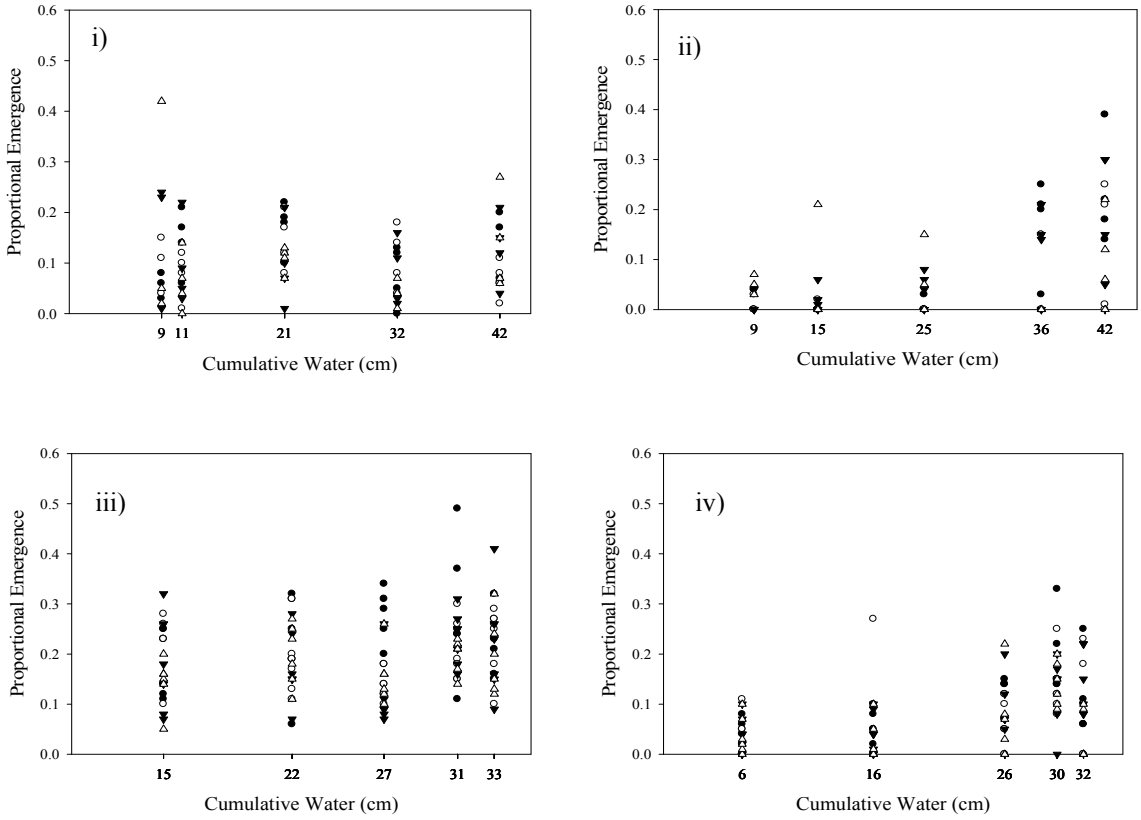


Figure 3.3. Proportional emergence of *B. napus*: i) experiment B_1 the first year (seed bank sown), ii) experiment B_1 the second year (seed rain sown), iii) experiment B_2 the first year (seed bank sown), iv) experiment B_2 the second year (seed rain sown). There was a significant interaction in B_1 between water and time since the sod was transplanted ($P<0.001$), as well as in the coconut-straw treatment ($P=0.044$) of B_2. In the excelsior, jute, and control treatments of B_2 significance was found in the water regime ($P=0.002$ for excelsior; $P=0.026$ for jute; $P<0.001$ for control) and time since sod was transplanted ($P=$ $P<0.001$ for excelsior, jute, and control). No significance was found between reinforcement materials of B_1. Symbols represent reinforcement materials (● nylon netting (control), ○ coconut-straw, ▼ excelsior, Δ jute). Note y-axis scale reduced from 1 to more clearly display reinforcement material symbols.

Volunteer Weed Emergence

The volunteer weeds that emerged in both the bare ground and nylon netting reinforcement material multispecies sod control subplots included: *Bromus inermis* (smooth brome), *Bromus tectorum* (cheatgrass) *Bromus anomalous* (nodding brome), *Agropyron repens* (quackgrass), *Amaranthus retroflexus* (redroot pigweed), *Erodium cicutarium* (stork's-bill), *Lamium amplexicaule* (henbit), *Cirsium arvense* (Canada thistle), *Malva rotundifolia* (round-leaved mallow), *Phleum pratense* (timothy), *Trifolium repens* (white clover), and *Taraxacum officinale* (dandelion). In both experiments more ($P<0.001$) volunteer weeds emerged in the bare ground control compared to the control multispecies sod subplots (Table 3.5), although it should be noted that the variance is better understood, due to increased replicates, in the multispecies sod subplots compared to the bare ground control. This trend was apparent in each year, even though the relative abundance of volunteer weeds decreased ($P=0.040$ for bare ground; $P=0.017$ for sod) in all plots over time (Table 3.5).

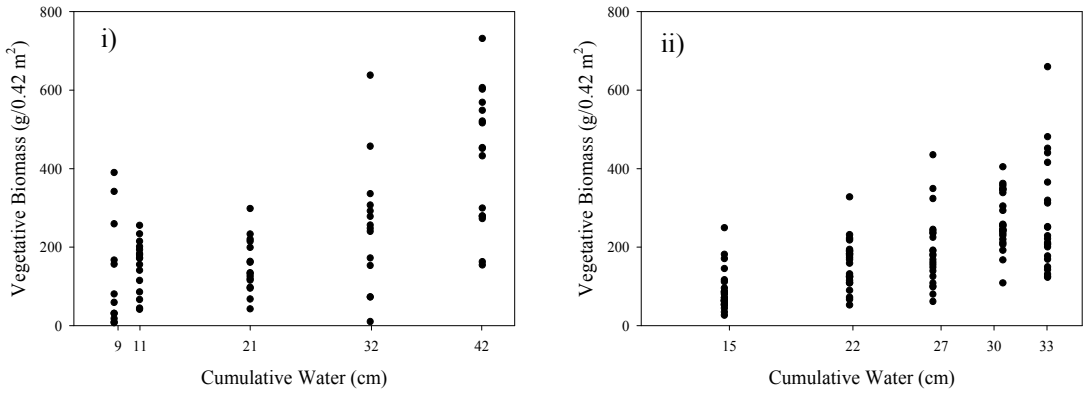
Table 3.5. Mean relative abundance (0.42 m^{-2}) of emerged volunteer weeds in B_1 and B_2 in the bare ground and multispecies sod control subplots over time. Standard deviations in parentheses.

	2006	2007	2008
Bare Ground Control	0.2 (0.04)	0.1 (0.06)	0.1 (0.07)
Multispecies Sod	0.1 (0.12)	0.0 (0.05)	0.0 (0.01)

Seed Bank and Seed Rain Weed Survival: During the first year neither water nor reinforcement material had a significant ($P=0.424$ for water; $P=0.386$ for reinforcement material) effect on the proportional survival ($\bar{x}=0.95$, stdev=0.11) of *B. napus* seedlings that

had emerged in either experiment (P=0.082 for experiment). In the second season of both experiments very few *B. na*pus seedlings emerged and none survived more than several weeks ($\bar{x}$=0, stdev=0), resulting in a considerably reduced survival rate of emerged seedlings the second year compared to the first.

Seed Bank and Seed Rain Weed Productivity: In each experiment the vegetative biomass (P<0.001 for B_1; P<0.001 for B_2, Figure 3.4) and seed weight (P<0.001 for B_1; P<0.001 for B_2, Figure 3.5) of *B. napus* increased with increased cumulative water in the first growing season when *B. napus* was sown as seed bank. Furthermore, the number of harvested plants also increased total vegetative biomass (Figure 3.4) in both B_1 (P<0.001) and B_2 (P=0.010), as well as seed weight (Figure 3.5) in B_1 (P=0.009), but had no effect on seed weight in B_2 (P=0.358). No significance was found between the reinforcement materials. Because none of the seed rain sown *B. napus* seedlings that emerged the second year survived, the loss of productivity was apparent.



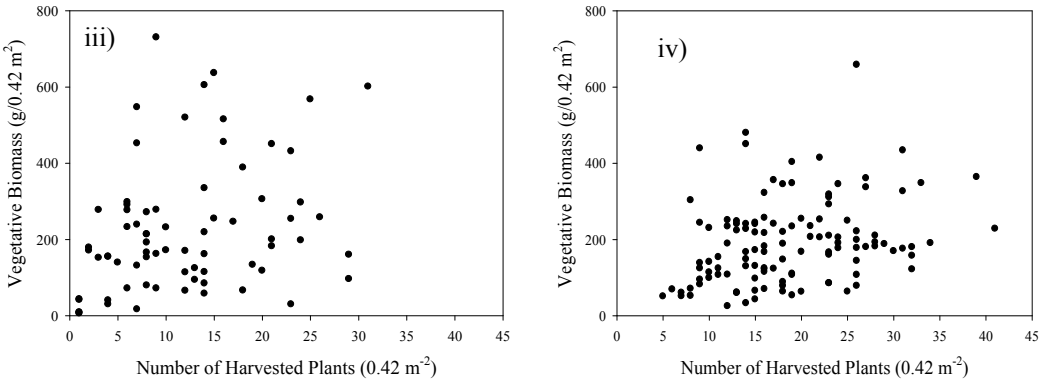


Figure 3.4. *B. napus* vegetative productivity in the first year: i) experiment B_1 by cumulative water (P<0.001), ii) experiment B_2 by cumulative water (P<0.001), iii) experiment B_1 by number of harvested *B. napus* plants (P<0.001), iv) experiment B_2 number of harvested *B. napus* plants (P=0.010).

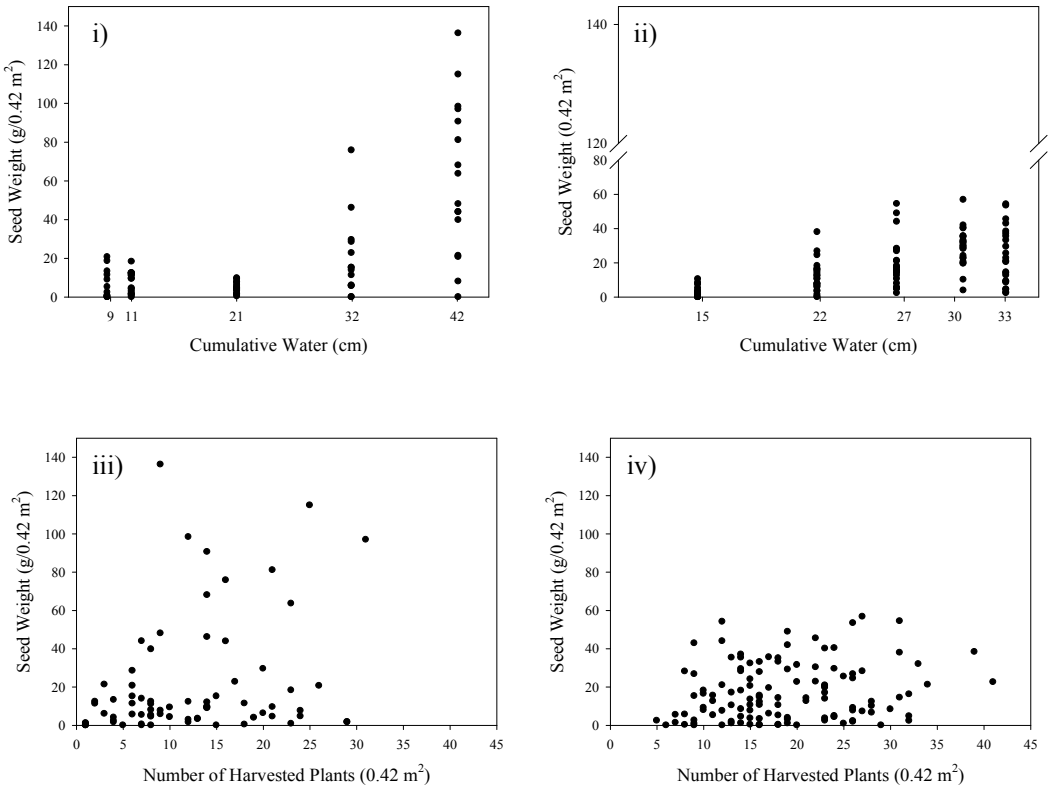


Figure 3.5. *B. napus* seed productivity in the first year: *B. napus* vegetative productivity in the first year: i) experiment B_1 by cumulative water (P<0.001), ii) experiment B_2 by cumulative water (P<0.001), iii) experiment B_1 by number of harvested *B. napus* plants (P=0.009), iv) experiment B_2 number of harvested *B. napus* plants (NS).

Overall Multispecies Sod Estblishment

Multispecies Sod Biomass: The dry weight of above-ground multispecies sod biomass at the conclusion of the study indicated that there was an increase ($P<0.001$) in vegetative biomass with increased cumulative water (Figure 3.6). The mean dry weight was 203.77 g (stdev=33.59 g) in the highest water regime and 152.10 g (stdev=22.78 g) in the lowest water regime. There was no difference ($P=0.236$) between experiments despite the fact that B_1 had been installed for three years and B_2 had only been installed for two years, nor a difference ($P=0.485$) between the different reinforcement materials.

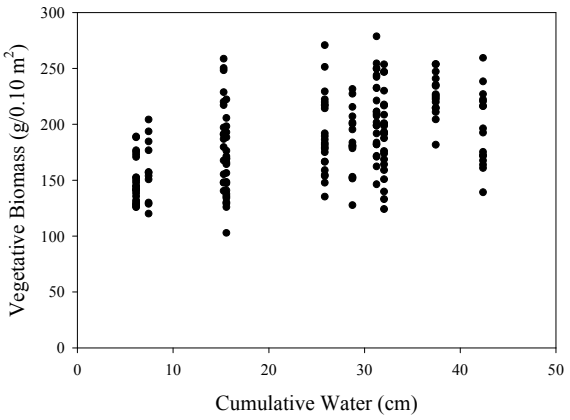


Figure 3.6. Multispecies sod biomass at the conclusion of the study (2008 after 3 years in B_1; 2007 after 2 years in B_2; $P<0.001$).

Relative Abundance of Senescing/Dormant Sod: The proportion of senescing/dormant sod was related to the time since the sod was transplanted ($P<0.001$ for B_1; $P<0.001$ for B_2) as well as to the water regime (Figure 3.7 for B_1 lowest and highest water regimes as an example). During the first growing season of each experiment the low water regime had more ($P<0.001$ for B_1; $P<0.001$ for B_2) senescing/dormant sod than the

high water regime. However, by the second (P=0.990 for B_1; P=0.315 for B_2) and third (P=0.405 for B_1) growing seasons the water regime did not have a significant effect and the relative abundance of senescing/dormant sod had decreased considerably. There was no difference in the reinforcement materials. Overall, the results suggest that the multispecies sod was able to establish and persist at all water levels, including the low water regime plots that received natural precipitation.

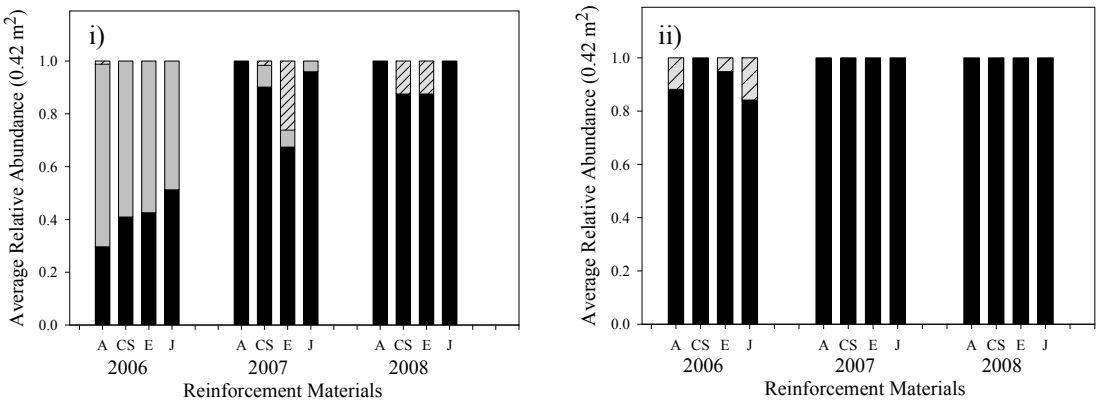


Figure 3.7. Mean relative abundance of: photosynthesizing sod (black), senescing/dormant sod (gray), and volunteer weeds (striped) in B_1: i) low water treatment in all years, 2006-2008, ii) high water treatment in all years, 2006-2008. Y-axis is the average relative abundance of all plots in a treatment. X-axis indicates reinforcement materials: A=nylon netting (control), E=excelsior, CS=coconut straw, J=jute. Significance was found in time since the sod was transplanted (P<0.001 for B_1; P<0.001 for B_2) and in the water regime of the first season (P<0.001 for B_1; P<0.001 for B_2).

Species Richness and Diversity: Sod and volunteer species were included in the species richness and diversity calculations. Overall, in all seasons of all experiments averaged throughout each highest and natural precipitation water regimes, the maximum mean species richness and species diversity were low, ($\bar{x}$=3.5, stdev=0.72 for species

richness; $\bar{x}$=0.4, stdev=0.17 for species diversity) (Table 3.6), suggesting that the multispecies sod was dominated by the two naturalized rhizomatous species *P. compressa* and *P. pratensis* (Figure 3.8).

To provide more insight, species richness was significantly (P<0.001) higher in B_2 compared to B_1, albeit this difference is less than one species. Reinforcement material had no significant effect on species richness or diversity in either experiment. For species richness both B_1 and B_2 had significant (P<0.001 for B_1; P<0.001 for B_2) interactions between the water regime and time since the sod was transplanted due to different patterns throughout the water regime over time. In B_1 during the first and second years there were no evident patterns in species richness throughout the water regime; however, during the third year of B_1 species richness increased in the high water regime compared to the low water regime, as well as was lower in both water regimes compared to the other years (Table 3.6). In B_2 during the first year there was no evident pattern in species richness throughout the water regime, but in the second year of B_2 species richness increased with increased water.

Species diversity had a similar trend to species richness. Although no difference (P=0.219) was found between experiments, there was a significant (P<0.001) interaction between water and the time since the sod was transplanted with no evident pattern the first year, but an increase in species diversity with increased cumulative water in both the second and third (B_1 only) years.

Table 3.6. Multispecies sod mean species richness in each experiment (B_1 and B_2) and mean species diversity in both experiments combined (year 3 B_1 only) per time since the sod was transplanted. Calculations for high and natural precipitation averaged throughout each water regime. Standard deviations in parentheses.

	B_1 Mean Species Richness	B_2 Mean Species Richness	Mean Species Diversity
Year 1			
High Water	2.3 (1.14)	2.8 (0.48)	0.2 (0.19)
Natural Precipitation	2.50 (0.8)	3.1 (0.80)	0.4 (0.15)
Year 2			
High Water	2.9 (0.50)	3.5(0.72)	0.4 (0.17)
Natural Precipitation	2.3 (0.98)	2.5 (0.61)	0.1 (0.12)
Year 3			
High Water	1.9 (0.68)	NA	0.3 (0.21)
Natural Precipitation	1.3 (0.45)	NA	0.1 (0.14)

Even though species richness and diversity did change throughout the study, when the sod arrived at MAES the two most dominant sod species (Figure 3.8) were *P. compressa* ($\bar{x}$=0.9 (stdev=0.12) in B_1; $\bar{x}$=0.9 (stdev=0.11) in B_2) and *P. pratensis* ($\bar{x}$=0.1 (stdev=0.12) in B_1; $\bar{x}$=0.1 (stdev=0.12) in B_2). The sod arrived almost completely free of *F. rubra* ($\bar{x}$=0.0 (stdev=0.00) in B_1; $\bar{x}$=0.01 (stdev=0.02) in B_2), senescing/dormant sod ($\bar{x}$=0.0 (stdev=0.01 in B_1; and $\bar{x}$=0.0 (stdev=0.04)), volunteer weeds ($\bar{x}$=0.0 (stdev=0.00) in both B_1 and B_2), and unidentified new grasses ($\bar{x}$=0.0 (stdev=0.00) in both B_1 and B_2).

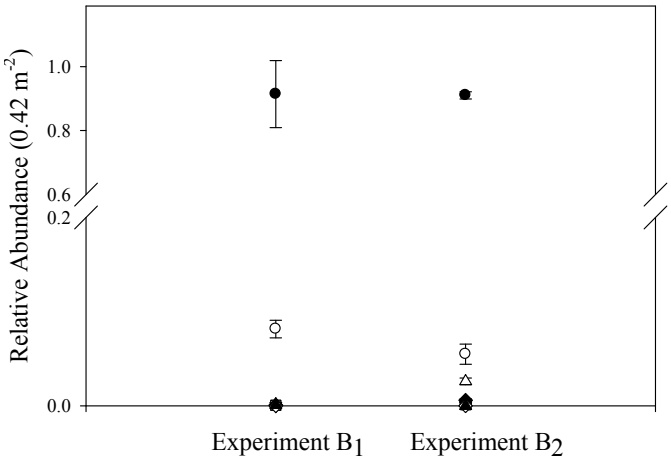


Figure 3.8. Relative abundance of species present in the sod when it arrived at MAES. Symbols represent each species (● *P. compressa*, ○ *P. pratensis*, ▼ *F. idahoensis*, Δ *E. lanceolatus*, ■ *A. smithii*, □ *F. rubra*, + volunteer weeds, ◊ senescing/dormant sod, ▲ unidentified mix) with standard error bars. "Unidentified mix" refers to species that were unidentifiable due to new seedling or ramet growth. Personal observation would suggest that most of these unidentified species were either *P. compressa* or *P. pratensis*.

Relative Abundance of *P. compressa* and *P. pratensis*: The relative abundance of *P. compressa* in each experiment had a significant ($P<0.001$ for B_1; $P<0.001$ for B_2) interaction between the water regime and time since the sod was transplanted. In all years the relative abundance of *P. compressa* decreased as the water regime increased, with the exception of the first year of B_1 which showed the opposite trend. No difference ($P=0.276$ for B_1; $P=0.93$ for B_2) was found between the reinforcement materials. In all years of both experiments the relative abundance of *P. pratensis* was positively related to an increase ($P=0.001$) in the water regime (Figure 3.9). There was no difference between experiments ($P=0.129$), reinforcement material ($P=0.650$), or time since the sod was transplanted ($P=0.723$) with the relative abundance of *P. pratensis*.

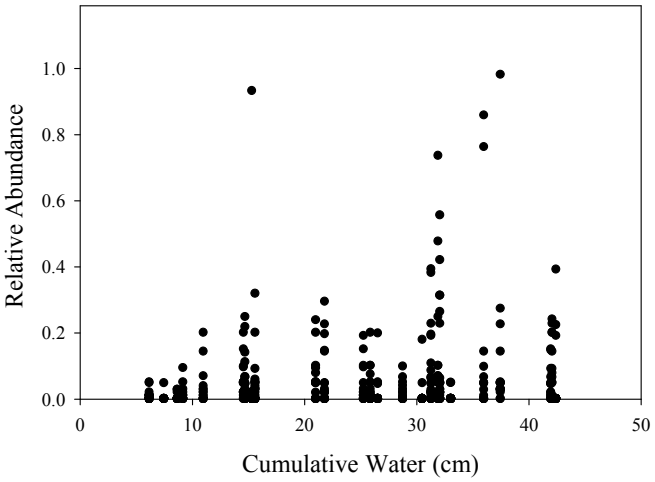


Figure 3.9. Relative abundance (0.42 m^{-2}) of *P. pratensis* throughout the water regime in all years of B_1 and B_2 (P=0.001).

Reinforcement Materials Affect on Soil Water Retention (Field Study)

Technical issues impacted the reliability of the data collected to evaluate the effect of the reinforcement materials on soil water retention in the field. Consequently, this section of the experiment has been discarded. Please see Appendix D for more details.

Discussion

Reinforcement Material Water Absorption Capacity

Other studies have found that erosion control mats can contribute to plant biomass by aiding with water retention and buffering soil temperatures (Sutherland et al., 1998). Wheat-straw and excelsior in particular have been shown to increase plant biomass and soil moisture content considerably (Muzzi et al., 1997; Grace et al., 1998; Sutherland et al., 1998; Petersen et al., 2004). On the other hand, even though the results from the laboratory experiment showed that jute had the highest water absorption capacity, several field studies have found

that seeded jute showed no significant difference in biomass or soil moisture content compared to bare ground control plots (Warren & Aschmann, 1993; Sutherland et al., 1998).

The water absorption capacity of the reinforcement materials tested in the laboratory were all higher ($P<0.001$) than the nylon netting control, suggesting that the materials could potentially aid soil moisture retention in the field and contribute to the growth of both the multispecies sod and the *B. napus* plants. Unfortunately sufficiently reliable field measurements were not collected to perform any analysis; however, the data that were valid suggested there was little difference in available soil water between the different reinforcement materials.

Weed Suppression

Seed Bank and Seed Rain Weed Emergence and Survival: The water regime and time since the sod was transplanted interaction ($P<0.001$ for B_1; $P<0.001$ for B_2), and in B_2 the reinforcement material ($P=0.003$), all contributed to a reduction in *B. napus* emergence. This reduction in *B. napus* emergence was likely due to a combination of the multispecies sod and reinforcement materials acting as a physical barrier, as well as to interspecific competition between *B. napus* seedlings and the established sod.

These results are consistent with other studies. For example, a greenhouse study by Bosy and Reader (1995) placed forb seeds that had already germinated beneath *P. pratensis* litter and found that emergence was reduced by 95-100% in comparison to the no-litter control. The size and shape of the seeds, as well as the thickness of the litter mat may be mainly responsible for determining germination and emergence success (Facelli & Pickett,

1991). Small seeds have less storage and so may not have the time and energy required to penetrate a litter mat (Facelli & Pickett, 1991). Even large seeds, with more storage, if confined underneath litter in a wet and shady environment without light can loose vigor (Sydes & Grime, 1981). *B. napus* seeds are relatively small, averaging 1.8-2.8 mm (Lamb & Johnson, 2004) and may be a good indicator of the effect of a physical vegetative barrier on the emergence of other annual weed seeds of similar size, such as *Lactuca serriola* (prickly lettuce), *Senecio vulgaris* (common groundsel), *Galium aparine* (bedstraw), *Erigeron canadensis* (Canada fleabane), *Chenopodium album* (lamb's quarters), *Salsola kali* (Russian thistle), *Digitaria sanguinalis* (large crabgrass), *Malva rotundifolia* (round-leaved mallow), *Lepidium densiflorum* (common peppergrass), *Brassica kaber* (wild mustard), and *Kochia scoparia* (kochia) (Royer & Dickinson, 1960).

Furthermore, seeds depend on light, as well as optimum soil temperatures and moisture, for germination and seedling emergence. While different species all have different vernalization, moisture, and light intensity, wavelength, and photoperiod germination requirements, some studies suggest that seeds kept in continuous darkness have very low germination compared to seeds that receive adequate sunlight (Chachalis & Reddy, 2000). Other studies suggest that seeds can germinate in complete darkness (Wesson & Wareing, 1960; Miguel & Soriano, 2006) but once the seeds have germinated light is required to photosynthesize for continued growth. The presence of plant litter, dense above-ground biomass or thatch in the case of multispecies sod, can act as a physical barrier inhibiting light by up to 95-99% (Weaver & Rowland, 1952; Sydes & Grime, 1981; Spence 1982; Vazquez-

Yanes et al., 1990). The reduction in light caused by the physical sod barrier may have further reduced *B. napus* and volunteer weed emergence.

Additionally, established plant communities have been found to inhibit seedling emergence because of decreased light conditions at the soil surface, as well as competition for resources (Wesson & Wareing, 1969; Kruk et al., 2006). The benefit of the multispecies sod is that it was grown prior to installation and was transplanted as a more established plant community. Established plant communities may also have a similar physical barrier effect on seed emergence as plant litter (described above) due to dense above-ground biomass. If the seeds are held in litter and are not in contact with soil, their germination may either be delayed or unsuccessful (Facelli & Pickett; 1991). For example, in the greenhouse most *Aristida longiseta* (red threeawn) seedlings died when they germinated within grass litter because their roots were not able to penetrate the soil (Fowler, 1986). Of the *B. napus* seeds that did emerge the second year when they were sown as seed rain, no seedlings that emerged survived more than a couple weeks. The overall reduction in proportional *B. napus* seed bank and seed rain emergence (0.80-0.98) the first year, as well as the fact that no seedlings survived the second year, indicates that more established plant communities may provide fewer microsites for seedling emergence and survival (Wesson & Wareing, 1969).

The aim of reinforcement material is to aid in multispecies sod transportation. The results from this experiment suggest an additional benefit in that in combination with multispecies sod annual weeds were suppressed. In B_2 the control subplots also contained significantly ($P=0.003$) more emerged seedlings than the reinforcement material subplots suggesting that reinforcement materials may additionally contribute to weed suppression by

creating a thicker physical barrier. Even though this effect was only significant in B_2 and not in B_1, it agrees with a greenhouse study conducted by Hamrick and Lee (1987) who found that the seedlings of *Carduus nutans* L. (nodding plumeless thistle) that germinated under a thick litter layer of plant stems, grass, and leaf fragments had a higher mortality rate then seedlings growing under less or no litter. They concluded that the energy it took to penetrate the thicker litter mat most likely caused mortality.

Seed Bank and Seed Rain Weed Productivity: When water is limited there is a general trend of decreased productivity (Villagra & Cavagnaro, 2005). In each experiment the vegetative biomass and seed weight of *B. napus* seedlings that survived until harvest was less in the low water regime compared to the high water regime. This concurs with other experiments. For example, a field study on the response of tall fescue cultivars to an irrigation gradient found a significant decrease in productivity indicated by dry matter yield at decreased water levels (Asay et al., 2001). Furthermore, Davis et al. (1998) found that herbaceous field vegetation biomass increased with increasing water input.

The requirement for water differs between plant species influencing the ecological range where each species can exist. Some plants can cope with water stress better than others (Villagra & Cavagnaro, 2005; Zegada-Lizarazu et al., 2006). Even though a plant's response to water is species dependent, and *B. napus* is a cultivated crop that has shown increased productivity with increased water in other studies (Pannu et al., 1992; Narang et al., 1993; Mathur & Wattal, 1996; Banuelos et al., 2002; Sarkar et al., 2007), the results from this study demonstrate a basic principle: decreased productivity can decrease weed seed rain, which in turn will reduce weed seed bank and overall reduce future invasions (Witkowski & Wilson,

2001; Williams & Harvey, 2002; Blumenthal et al., 2005; Davis, 2008; Richardson & Kluge, 2008).

Overall Multispecies Sod Establishment

Multispecies Sod Biomass: Similar to the *B. napus* vegetative and seed biomass, the dry weight of the above-ground multispecies sod biomass at the conclusion of the study indicated a significant ($P<0.001$) increase in vegetative biomass with increased cumulative water. These results continue to support that even though a plant community's response to irrigation is species dependent (Depuit et al., 1982; Depuit, 1984; Newman & Redente, 2001), in general adequate soil moisture contributes to plant establishment and productivity (Davis et al., 1998; Asay et al., 2001; Petersen et al., 2004; Villagra & Cavagnaro, 2005).

Multispecies Sod Establishment: Overall, the results suggest that the multispecies sod was able to establish and persist at all water levels including the natural precipitation plots. The fact that the proportion of senescing/dormant multispecies sod decreased from the first year in the second and third seasons, as well as the fact that the sod produced new seedlings and tillers, demonstrated that the sod had become established in the soil.

In general, when water or other resources are not limited, competition within a plant community can increase (Davis et al., 1998) changing species composition. The general trend throughout both experiments, especially in the second and third years when the sod was more established, was that species richness and species diversity increased with increased water. In general, the relative abundance of *P. compressa* decreased with increased water (the first year of B_2, as well as in B_1 and B_2 of subsequent years; however, because B_1 showed

opposite results to B_2 the first year these results are not conclusive) and the relative abundance of *P. pratensis* increased with increased water in all years. The changes in species richness and diversity were therefore generally related to differences between these two dominant species over time.

Dominant species have been shown to crowd out less dominant species causing a decline in species density and richness (Gurevitch, 1992). This decline is often observed after fertilizer has been applied (Stevens & Carson, 1999). The multispecies sod in the study was subject to intense management for three (B_1) and four (B_2) years. When the sod was transplanted to MAES the decline in species richness and diversity from what was originally sown (27% *F. idahoensis*; 22% *E. lanceolatus*; 17% *A. smithii*; and 34% *P. compressa* mixed by weight) was apparent.

This experiment and other studies emphasize the importance of initial species selection. Initial cultural practices, especially species selection, will influence the long term development of a plant community over time (Newman & Redente, 2001). Newman and Rendente (2001) found that after twenty years species that they had originally sown were still apparent. Furthermore, when comparing indigenous seed mixtures to non-indigenous seed mixtures, they found that non-indigenous seed mixtures had the lowest species richness because these species were often better competitors and dominated the plant communities (Newman & Redente, 2001). This was evident in the multispecies sod which, despite *P. pratensis* having never been sown, was dominated by *P. compressa* and *P. pratensis*. Overall the concept of indigenous or multispecies sod is important to plant community dynamics

because it potentially relates positively to ecological processes such as community stability, productivity, evolution, competition, and niche structure (McIntosh, 1967).

Conclusion

These experiments demonstrated that multispecies sod can provide rapid established vegetative cover over a range of water regimes, as well as reduce weed emergence and survival. The results also indicated that a reinforcement material, which may be used to transfer the sod from the sod farm to the revegetation site, may help to additionally suppress weeds relative to a nylon netting (control), but may not contribute significantly to the establishment success of the multispecies sod. Furthermore, the results emphasized that species selection for the multispecies sod should include careful attention to the goals and objectives of the revegetation site, especially if a true diversified community is a priority. Overall these results suggest that multispecies sod could be a useful revegetation technique.

CHAPTER 4

PERENNIAL WEED VEGETATIVE PROPAGULE SUPPRESSION BY MULTISPECIES SOD

Introduction

Plant species are continually being introduced to new areas around the globe. While many of these species and their populations do not cause problems, unwanted weeds cost the United States agriculture economy over $26.4 billion in crop losses annually (Pimental et al., 2000). Not only do weeds reduce agricultural productivity but they also create significant problems in natural parks and reserves, and can regularly complicate revegetation projects (D'Antonio & Meyerson, 2002). At the local scale, understanding the spatial distribution and rate of spread of weeds may lend insight into how to control them efficiently (Moody and Mack, 1988; Taylor & Hastings, 2004).

Invasive weed populations are defined as those increasing in density and/or spatial extent (Lehnhoff et al., 2008). Martinez-Ghersa and Ghersa (2006) distinguished between vegetative invasion by roots, rhizomes, or stolons as producing offspring in areas > 6 m from the initial site of introduction in 3 years (~2 m/yr), while invasion by seed and other propagules produces offspring in areas > 100 m from the initial site of introduction in less than 50 years (~0.5 m/yr). Despite the latter review paper, there are few data accurately defining the rate of spread of specific species, particularly in different habitats.

Three different spatial patterns have been proposed to describe plant invasion over time: phalanx, guerilla, and infiltration (Lovett, 1981; Wilson & Lee, 1989). The phalanx pattern suggests slow radial spread from an advancing front of tightly packed ramets that

generally exclude other plants from their dense clonal vicinity (Lovett, 1981). In contrast, the guerilla pattern suggests more rapid long distance dispersal of widely spaced ramets that maximize interspecific interference by infiltrating into surrounding vegetation (Lovett, 1981). The third pattern, infiltration, incorporates both phalanx and guerilla patterns suggesting that both short and long distance dispersal can occur at the same time, and that in subsequent generations this pattern continues from both primary and secondary sites (Wilson & Lee, 1989). Hence, invading plants may not strictly increase along a radiating front, but instead may radiate from multiple, sometimes disjunct foci from independent introductions and/or dispersal from a founder population (Baker, 1986; Moody & Mack, 1988). Whatever pattern an invasion follows, the process and rate of invasion involves a series of complex interactions between biotic and abiotic, natural, and human factors (Cousens, 1995; Rejmanek, 2000; Parker, 2001; Richardson et al., 2000). Two main factors include suitable microsite availability and propagule pressure (Kot et al., 1996; Neubert and Parker, 2004; Jongejans et al., 2007; Boedeltje et al., 2008).

Invasions into new areas most likely occur when no natural barriers exist (Johnstone, 1986; Bergelson et al., 1993). For example, disturbed environments are thought to be prone to invasion (Grime, 1979; Drake et al., 1989; Bergelson et al., 1993). The more disturbance, the more bare ground and thus resources available for new plant recruitment. When bare ground is occupied, interspecific competition from neighboring plants can reduce invasion

(Marshall, 1990; Bergelson et al., 1993; Elmore et al., 1997; Barney et al., 2005). The spread of invasion may therefore be contained or slowed by barrier zones (Taylor & Hastings, 2004) such as established plant communities (De Cauwer et al., 2006).

Increased propagule pressure has the potential to increase the chance that a species will establish (Levine, 2000; Rouget & Richardson, 2003; Von Holle & Simberloff, 2005) provided there is appropriate available habitat. Seed and the fruits that contain them, as well as vegetative structures, all contribute to propagule pressure and thus successful invasion in morphologically, physiologically, and genetically different ways (Martinez-Ghersa & Ghersa, 2006). While seeds have potential to increase the range of colonization and reduce inbreeding depression (Martinez-Ghersa & Ghersa, 2006), vegetative propagation can help to ensure local plant population expansion when seed production or seedling establishment is low (Kolar & Lodge, 2001; Martinez-Ghersa & Ghersa, 2006), and may even be important on a larger scale if dispersal is aided by human activities (Ghersa & Roush, 1993; Ghersa et al., 2000), such as cultivation or attachment to vehicles, or by natural processes such as rivers and animals.

Cultural activities including tilling, mowing, crop harvesting, and herbicide application, as well as herbivory and climatic variation, may all increase the risk of a plant's survival in a particular habitat and reduce the probability of its' asexual or sexual reproduction. For example, inadequate soil moisture can result in a species not producing seed (Baskin & Baskin, 1980). Even though vegetative propagation limits genetic diversity (mainly associated with reproduction by seed), vegetative propagules store large amounts of

resources. Large resource reserves give a plant the potential to be more resistant to stress, surviving disturbances and environmental fluctuations (Martinez-Ghersa & Ghersa, 2006).

Almost 40% of non-indigenous flora reproduce primarily vegetatively (Pyesk, 1997), including some of the most aggressive invaders (Barney et al., 2005). At certain scales, introduced clonal species may even cause more trouble to native ecosystems than species that produce by seed (Pyesk, 1997). *Cirsium arvense* (Canada thistle) is an aggressive perennial weed that is adapted to a wide range of environmental conditions (Moore, 1975; Sole et al., 2004) and is able to reproduce both vegetatively and from seed, making it one of the most harmful weeds in the world (Holm et al., 1991). While seed is the principal source for new *C. arvense* invasions (Hayden, 1934; Sole et al., 2004), seedling establishment has been shown to be secondary to ramets in terms of population growth (Lalonde & Roitberg, 1994; Laubhan & Shaffer, 2006; Strobach et al., 2008).

The objective of this experiment was to evaluate the vegetative invasion potential of *C. arvense* into two contrasting habitats: bare ground and multispecies sod under high and low amounts of supplemental irrigation. The intention was to use *C. arvense* as a target species to quantify the ability of newly transplanted multispecies sod to act as a buffer zone and reduce the vegetative spread of a perennial weed.

Methods

Study Site

The study was conducted at Montana State University's Montana Agricultural Experiment Station (MAES) Horticulture Farm (45.68 N, 111.05 W) in Bozeman, Montana,

USA. The site was a level agricultural field, tilled fallow with no herbicide for weed management for two years prior to the experiment. The soil, defined by the hydrometer method, was clay loam (36% sand, 36% silt, 28% clay).

The 30-year average (1971-2000) annual precipitation in Bozeman is 49.00 cm, with the highest annual averages occurring in April (4.75 cm), May (8.18 cm), June (7.26 cm), and September (5.00 cm) (Western Regional Climate Center, 2008). The annual precipitation during the three years of the experiment (40.75 cm, 44.21 cm, and 40.53 cm for 2006-2008 respectively) was below the 30-year average (Western Regional Climate Center, 2008). However, the cumulative off-season (October-May) precipitation that occurred each year (27.86 cm, 33.38, and 27.87 cm for 2006-2008 respectively) was similar to the 30-year average (27.62 cm) for these months (Western Regional Climate Center, 2008), demonstrating that the summer months were where the deficit occurred.

The 30-year average (1971-2000) daily maximum and minimum temperatures for the summer months over which the experiment was conducted (June-September) were 25 °C and 8 °C respectively (calculated from Western Regional Climate Center, 2008). Growing degree days (GDD) throughout 2006 and 2007 were higher than the 116 year average (1892-2008); however, in general GDD throughout 2008 were lower than 2006 and 2007 and thus similar to the historical average. Furthermore, the GDD for July of 2007 (1074) was a lot higher than for July 2006 (979) and July 2008 (849). Table 3.1 displays these GDD as well as the monthly averages (1892-2008).

Table 4.1 Growing degree days (GDD) for the four summer months (June-September) and the cumulative off-season (October-May) during the experimental period (2006-2008), as well as the long term average (1892-2008). GDD were calculated by the Western Regional Climate Center. Calculations use a 5 ºC base temperature.

GGD	June	July	August	September	Cumulative (October-May)
Average	**552**	**812**	**771**	**460**	**791**
2006	692	979	783	493	996
2007	663	1074	846	519	1061
2008	540	849	834	466	770

Multispecies Sod

The multispecies sod used for the experiment was sown with three grasses native to Montana (Dorn, 1984) mixed by weight: 27% *Festuca idahoensis* (Idaho fescue), 22% *Elymus lanceolatus* (thickspike wheatgrass), 17% *Agropyron smithii* (western wheatgrass) and one naturalized species, 34% *Poa compressa* (Canada bluegrass). The sod was purchased from Bitterroot Turf Farm (Bitterroot, MT) where it had been cultivated for three years prior to the experiments acquisition. Their management included watering 2.54 cm a week, mowing to 3.8 cm height twice a week (April-September), fertilizing three times a year (March, June, and September) with 25-10-10 fertilizer at 1,496 l/ha, and controlling broadleaf weeds as needed with 1.81 kg of Triplet (8.16% MCPP-p, 2.77% Dicamba dimethylamine salt, and 30.6% 2,4-dichlorophenoxy acetic acid) at 5.84 ai/l/ha. Two volunteer grasses, *Poa pratensis* (Kentucky bluegrass) and *Festuca rubra* (red fescue) were observed in the sod on delivery. These two species were being grown in different sod mixtures adjacent to the multispecies sod at the turf farm.

Experimental Design

The experiment was of split-plot design blocked by water. Main plots were hexagonal, with randomized subplots of habitat type (bare ground or multispecies sod) as the split treatment. The objective of the water treatments was for the plots receiving the high water level to obtain the equivalent of 2.54 cm of water a week, which is a typical watering rate for *P. pratensis* sod (Christians, 2004), and for the plots receiving the low water treatment to be placed far enough away from the main irrigation line that they would obtain only natural precipitation. All plots were hand watered everyday for five days (total applied $\bar{x}$ = 3.73 cm, stdev=0.04 cm) following installation to mimic the ideal time to revegetate during high seasonal precipitation (Hardegree and Van Vactor, 2004; Bay & Sher, 2008). Thereafter, high water plots were irrigated via a main irrigation line three times per week (Monday, Wednesday, and Friday) from June through September (Table 4.2). If natural precipitation occurred between the scheduled irrigation the amount of precipitation was recorded and the irrigation volume modified appropriately. The amount of moisture contacting the surface was recorded by two fence post rain gauges placed at ground level between the hexagon plots in each water level.

Table 4.2. Exact dates supplemental irrigation was applied. *The delay in 2008 was due to technical problems with the pump.

Year	Dates
2006	June 5 – September 15
2007	June 5 – September 15
2008*	June 16 – September 19

The cumulative water collected each year in the high and low water treatments were similar (Table 4.3), with the exception of the low water level in 2008 which received 12.45 cm of cumulative water, approximately two thirds of what it did in previous years (19.05 cm in 2006; 20.55 cm in 2007). Variation throughout years was due to environmental factors such as wind during high water application that sprayed water towards the natural precipitation plots, evapo-transpiration from warm temperatures, and yearly natural precipitation differences.

Table 4.3. Cumulative water (June-September) collected in the high and low water levels each year the experiment was conducted. Includes both irrigation and natural precipitation.

Year	High Cumulative Water (cm)	Low Cumulative Water (cm)
2006	37.48	19.05
2007	42.30	20.55
2008	40.85	12.45

Each hexagon (Figure 4.1) was divided into six 2 meter equilateral triangular sections (3.46 m²) and randomized so that three sections were left as a bare ground control and three sections were laid with multispecies sod. The vegetative propagules of *C. arvense* were planted as a small hexagon (0.23 m²) in the middle of each large hexagon. Each interior hexagon was planted with thirty-five 15 cm sections of *C. arvense* root on June 5, 2006 and subject to the same initial five day hand watering following sod installation. Roots were dug from a local organic garden on May 29, 2006, washed clean of soil, wrapped in moist paper towels, and stored in cold wet storage (4 °C) for 8 days until planting 2.54 cm below the soil surface. Hexagons where *C. arvense* did not emerge were replanted again on July 4, 2006 and again on May 28, 2007, however none of the replanted *C. arvense* ever emerged. The number of

emerging interior hexagon shoots was recorded on August 14, 2006 when the first ramet was found in a bare ground habitat subplot, suggesting that the *C. arvense* in the interior hexagons were mature enough to reproduce. Each large hexagon was replicated four times in each of the two different water levels, high and low.

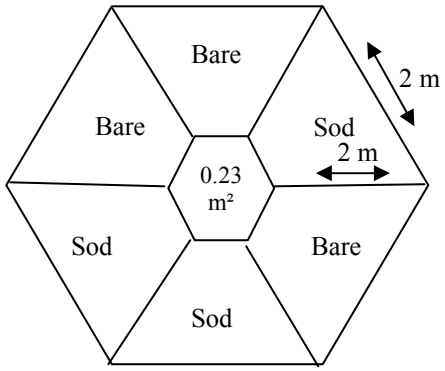


Figure 4.1. Example of hexagonal design. Each hexagon differed in that habitat type (bare ground or multispecies sod) was randomized around the interior (0.23 m²) hexagon. Each hexagon was repeated four times in each of the two water levels.

C. arvense vegetative propagules were assessed by counting and measuring the distance of new *C. arvense* shoot emergence in the appropriate bare ground and multispecies sod subplots. A measuring frame containing 16 equilateral (30 cm x 30 cm x 30 cm) triangles organized data collection for each bare ground or multispecies sod subplot. Measurements of ramet spreading distance into the bare ground or multispecies sod were taken as a direct line from the center of the interior hexagon to the new shoot. The number of *C. arvense* plants flowering was also documented. All data were collected once a month (June-September) over a four month growing season in 2006 and 2007, and in June and July of 2008. No *C. arvense* seedlings were observed in the subplots.

Volunteer weeds other than *C. arvense* were manually controlled. A pre-emergent granular herbicide Preen® (1.43% Trifluralin) was applied at a rate of 0.03 liters / 0.93 m^2 to all bare ground in the field the first year to reduce seed propagation.

Statistical Analysis

Analyses were conducted using R statistical software (www.R-project.org, 2007). Data were analyzed using general linear regression in the Gaussian family (see Appendix C for models).

In each hexagon *C. arvense* total ramet density, maximum distance *C. arvense* spread in the plot, and ramet flowering density were combined for each habitat type of each hexagon, and analyses were conducted on the mean of these combined data. Data were analyzed comparing July of each year (2006-2008). The independent variables were: hexagon ID, habitat type (bare ground control or multispecies sod), water level (cumulative water collected (cm) in each year of the experiment), initial number of emerged *C. arvense* plants in the interior hexagon (taken as July 4, 2006), and year (2006-2008). Because no ramets ever emerged despite replanting efforts in two interior hexagons, one in both the high and low water treatments, only three of the four hexagons per water treatment were analyzed.

Results and Discussion

Ramet Density

The density of *C. arvense* was affected by a significant (P=0.009) interaction between water and habitat. While no ramets had emerged outside any interior hexagon in July 2006, in 2007 in the multispecies sod habitat more ramets emerged in the high water treatment

compared to the low water treatment. These ramets were likely suppressed by the multispecies sod in 2008 after overwintering because in 2008 in the multispecies sod habitat, as well as in 2007 and 2008 in the bare ground habitat, there was a conisistent trend of more ramets emerged under the low water treatment, compared to the high water treatment (Table 4.4).

Even though *C. arvense* occurs in a large range of environments, *C. arvense* is often found in moist environments including wet and wet-mesic grasslands, sedge meadows, and irrigation ditches (Schroder et al., 1993; Pimental et al., 1999). Furthermore, a greenhouse study conducted by Sciegienka (2009) found that for every 10 ml increase in applied water, the likelihood that a *C. arvense* shoot would emerge increased by 10.5 suggesting that overall increased water increased *C. arvense* emergence. The fact that more ramets emerged in the low water treatment therefore contradicts what was expected.

Table 4.4. Mean ramet density (1.0 m^2) per water treatment in each habitat for July of each year. Standard deviations in parenthesis.

Year	Water (cm)	Bare Ground Habitat	Multispecies Sod Habitat
2006	37.48	0 (0)	0 (0)
	19.05	0 (0)	0 (0)
2007	42.30	2.22 (2.24)	0.67 (1.22)
	20.55	10.79 (10.81)	0.06 (0.13)
2008	40.85	10.98 (7.49)	1.18 (1.41)
	12.45	18.95 (14.61)	2.12 (2.58)

The data from this experiment supports the statement that disturbed environments are thought to be prone to weed invasion (Grime, 1979; Drake et al., 1989; Bergelson et al., 1993). There was a significant interaction between habitat and year ($P<0.001$) indicating that even though zero ramets were found in either habitat in July of 2006, in both 2007 and 2008

more ramets were found in the bare ground habitats compared to the multispecies sod habitats (Figure 4.2).

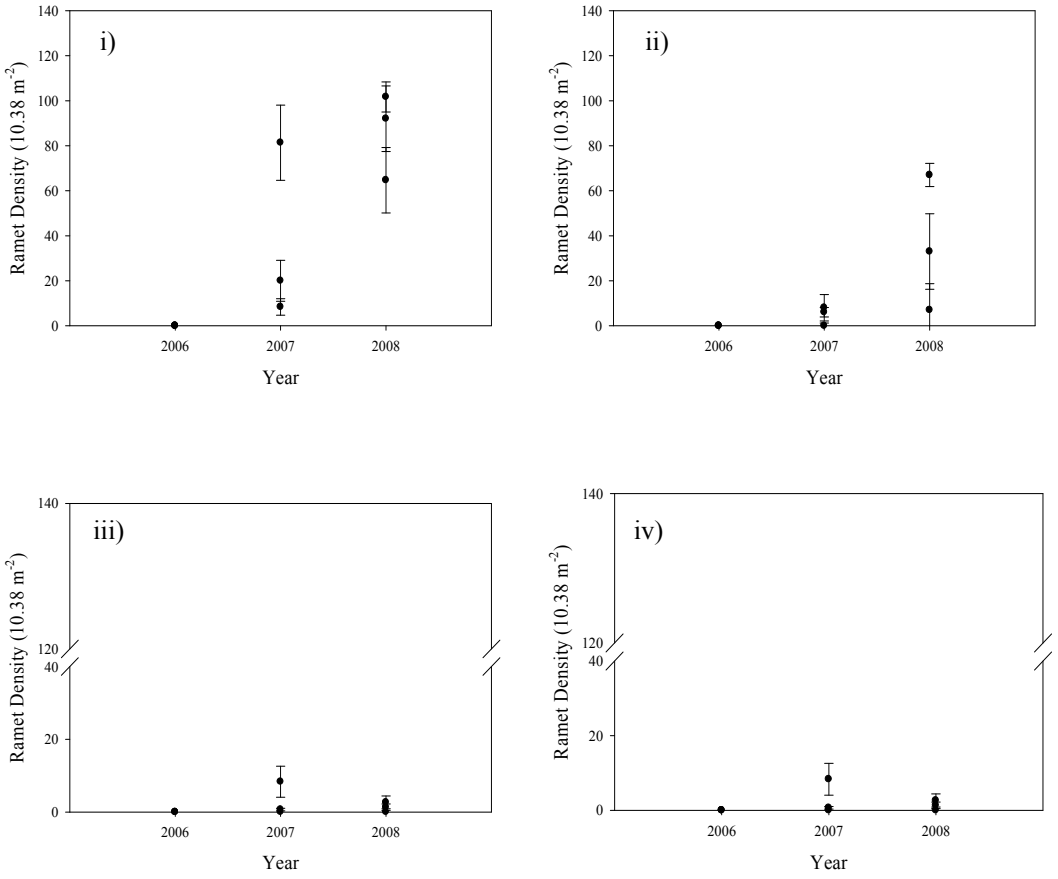


Figure 4.2. Mean *Cirsium arvense* ramet density (10.38 m^{-2}) from 2006-2008 in the: i) bare ground habitat in the low water treatment, ii) bare ground habitat in the high water treatment, iii) multispecies sod habitat in the low water treatment, iv) multispecies sod habitat in the high water treatment. There were significant interactions between habitat and year ($P<0.001$), and between water level and habitat ($P=0.009$). Symbols represent each hexagon with standard error bars.

These results suggest that overall the rate of weed invasion was much faster into the bare ground habitat compared to the multispecies sod habitat, and that high ($\bar{x} = 40.21$ cm, stdev=2.47) seasonal water application may have additionally slowed weed invasion.

More rapid invasion into a bare ground habitat compared to an established vegetative habitat (multispecies sod) is consistent with other studies. Barney et al. (2005) conducted a field experiment on the vegetative invasion of *Artemesia vulgaris* (mugwort) into turfgrass lawn and a fallow field in upstate New York, and found ten times more *A. vulgaris* ramets emerged in the fallow field compared to the turfgrass habitat. The same was true in a field experiment conducted by Marshall (1990) on the vegetative invasion of *Elymus repens* (quackgrass) in Great Britain. After three years plots sown with six perennial grasses had ten times less *E. repens* ramets than bare plots (Marshall, 1990). More specifically, De Cauwer et al. (2006) found that field margins composed of grasses and forbs significantly reduced the invasion of C. *arvense* compared to unsown adjacent communities. The results from these experiments, and mine, demonstrate that bare ground is more susceptible to invasion by horizontal roots, in this case *C. arvense*, than established vegetative habitats. The fact that the multispecies sod suppressed a considerable portion of *C. arvense* ramets suggests that it could be an effective revegetation tool to immediately suppress or buffer the vegetative propagules of C. *arvense* and other invasive weeds.

Ramet Maximum Distance

In general the mean maximum distance *C. arvense* ramets spread within each hexagon over time was further (P=0.005) and at a more rapid rate in the bare ground habitat ($\bar{x}$ = 0 cm, stdev=0 in 2006; $\bar{x}$ = 124.89 cm, stdev=48.02 in 2007; $\bar{x}$ = 166.11 cm, stdev=11.28 in 2008) compared to the multispecies sod habitat ($\bar{x}$ = 0 cm, stdev=0 in 2006; $\bar{x}$ = 49.11 cm, stdev=58.48 in 2007; $\bar{x}$ = 120 cm, stdev=54.32 in 2008), indicating that the multispecies sod was resisting *C. arvense* invasion, although there was variability between

hexagons. In both habitats this mean maximum distance increased (P<0.001 for bare ground; P<0.001 for sod) with time as the ramets became more established (Figure 4.3). No significance was found in the water treatment (P=0.174 for bare ground; P=0.594 for sod).

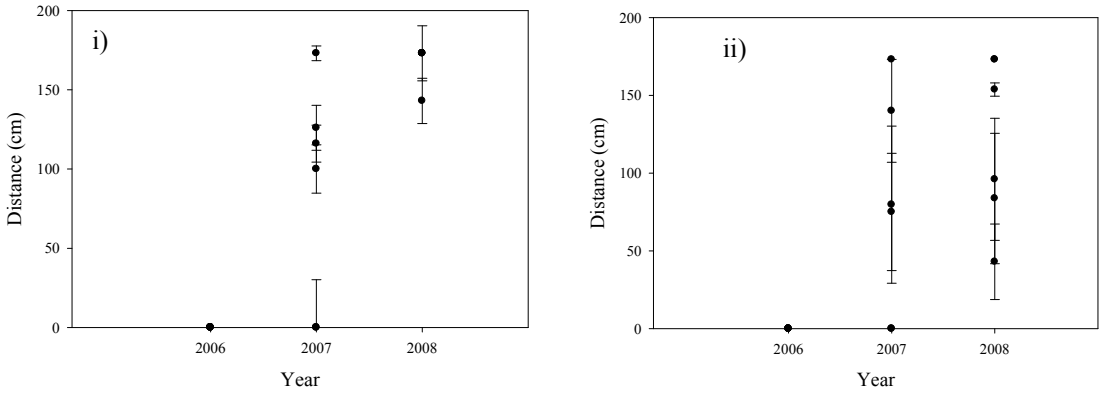
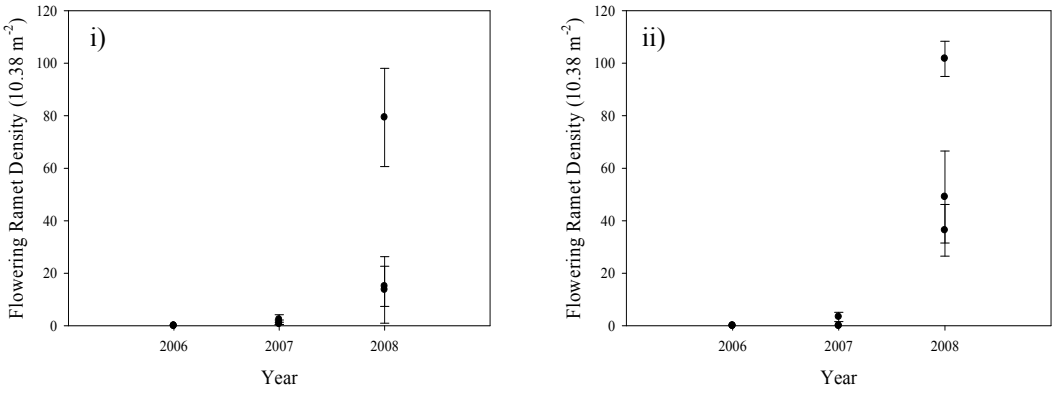


Figure 4.3. Mean maximum distance *C. arvense* ramets spread (10.38 m^{-2}) from the center of the interior hexagon to the furthest new shoot within a plot from 2006-2008: i) bare ground habitat (P<0.001), ii) multispecies sod habitat (P<0.001). Symbols represent each hexagon with standard error bars.

These results are again consistent with the study conducted by Barney et al. (2005) that found after three years the ramets of *A. vulgaris* had spread a maximum distance of 2 m from the initial planting in the fallow field and only 1.4 m from the initial planting in the turfgrass habitat. Furthermore, the results from a hexagonal designed field experiment that measured the effect of bare ground size and distribution on *Senecio vulgaris* invasion by seed, suggested that plants generally move further distances through large and underdispersed bare ground (Bergelson et al., 1993). Whether vegetative or seed propagules, these experiments and my data demonstrate that the spread of invasion has the potential to increase greatly when barriers such as established plant communities are removed and more susceptible bare ground exists.

Density of Flowering Ramets

Flower production is either an indicator of stress or most likely, in the case of this experiment, an indicator of successful plant establishment because it is able to reproduce. There was a significant (P=0.001) interaction between year and habitat with less flowers being produced in 2007 compared to 2008 when the *C. arvense* ramets had had more time to establish (Figure 4.4). Furthermore, there were significant interactions between both water and habitat (P=0.028), as well as between year and water (P=0.046) due to different patterns of flowering ramets in the different habitats and in the different water treatments over time. The mean number of flowering ramets was higher in the bare ground habitat compared to the multispecies sod habitat likely because the *C. arvense* density was so much higher in the bare ground habitat therefore there was a higher probability that one of these ramets would flower. More ramets flowered in the low water treatment of the bare ground habitat and in the high water treatment of the multispecies sod habitat in 2007 and 2008. This was especially apparent in 2008 when the plants were more established.



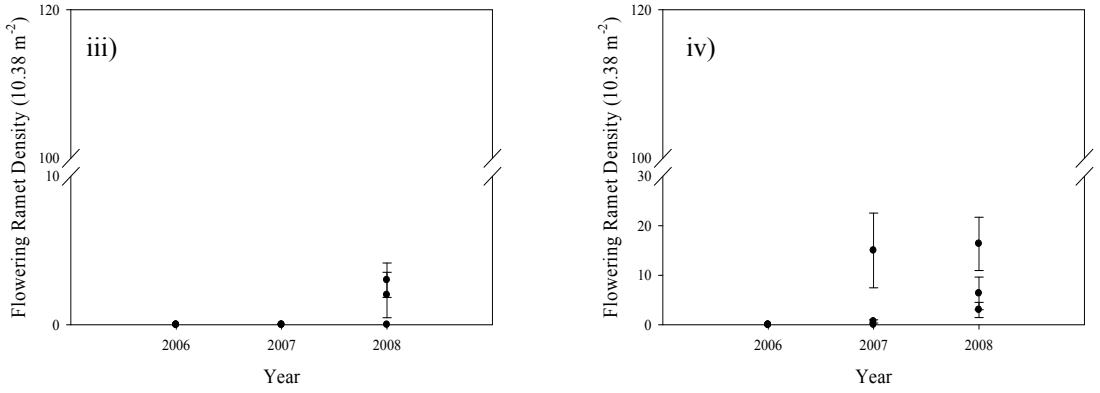


Figure 4.4. Mean flowering ramet density (10.38 m^{-2}) from 2006-2008: i) bare ground habitat in the low water treatment, ii) bare ground habitat in the high water treatment, iii) multispecies sod habitat in the low water treatment, iv) multispecies sod habitat in the high water treatment. There were significant interactions between year and habitat (P=0.001), water and habitat (P=0.028), and between year and water (P=0.046). Symbols represent each hexagon with standard error bars.

Conclusion

The rate of plant invasion is influenced by many different factors (Lonsdale, 1993; Parker, 2001; Richardson et al., 2000). This experiment demonstrates that microsite availability is one factor that can have a large effect on the invasability of a habitat. Between seasons, and especially in the low water treatment, more *C. arvense* ramets emerged and spread further and at a faster rate into the bare ground habitat compared to the multispecies sod habitat. Overall, the fact that the multispecies sod was able to suppress *C. arvense* ramets even under low water conditions suggests that it may be a useful revegetation technique to act as a buffer zone and reduce the vegetative spread of perennial weeds.

CHAPTER 5

OVERALL CONCLUSION/FUTURE RESEARCH

This study demonstrated that multispecies sod could be a useful revegetation tool because it can rapidly provide established vegetative cover under natural precipitation, as well as reduce weed emergence and survival. The multispecies sod was subject to a realistic water regime, as well as to both seed and vegetative propagule pressure. It proved to be an effective barrier to weed invasion at every level. Beyond the practical application, the results lend support to a basic plant community invasion theory that vegetative communities, as opposed to disturbed areas or bare ground, can be more resistant to invasion (Marshall, 1990; Bergelson et al., 1993; Elmore et al., 1997; Turnbull et al., 2000; Jutila & Grace, 2002; Barney et al., 2005; De Cauwer et al., 2006).

The first two experiments (A and B) both quantified the ability of the multispecies sod to establish in a semi-arid environment under a water regime that ranged from approximately 2.54 cm of water per week, to natural precipitation. Overall, the results demonstrated that the multispecies sod was able to establish and persist under natural precipitation. This is important because often areas in need of revegetation are too large to irrigate with any consistency. Furthermore, the results emphasized that multispecies sod species selection and cultural practices should reflect the specific goals and objectives of the revegetation site. The multispecies sod in this study became dominated by the naturalized specie *Poa compressa* (Canada bluegrass) within the three and four years that it was managed at the sod farm, despite being sown as only 34% (by weight) of the original sod

species mixture. If a true diversified plant community is a priority initial species selection and how sod production management influences the species should be considered.

In addition, the first experiment (A) revealed that the multispecies sod, an example of an established plant community, suppressed emergence of a considerable proportion of the surrogate weed, *Brassica napus* (canola), sown at six increasing densities as both seed bank and seed rain, regardless of the increased propagule pressure. Furthermore, during the first season the seedlings that did establish and survive to maturation produced less vegetative and seed biomass with decreased water. These results, as well as the additional reduction in *B. napus* emergence with no seedling survival the second season, and the reduced emergence of volunteer weeds over time as the sod became more established, strengthens the evidence that established plant communities may be more resistant to invasion.

The second experiment (B) confirmed the results of decreased *B. napus* emergence, survival, and productivity from the first experiment, except only one propagule density (100 seeds/0.42 m^2) was sown. The results also indicated that the reinforcement material, required to transfer the multispecies sod from the sod farm to the revegetation site, in combination with the multispecies sod helped to suppress *B. napus* and volunteer weeds, but did not contribute significantly to the establishment success of the multispecies sod. Because weeds were significantly reduced even in the nylon netting (control) treatment, a cost-benefit economic analysis should be conducted given specific site locations and budgets prior to determining what reinforcement material should be used.

The third experiment demonstrated that in addition to being effective at suppressing annual seeds (experiments A and B), the multispecies sod was also effective at suppressing

the vegetative propagules of an aggressive perennial weed, *Cirsium arvense* (Canada thistle) under both high and low water levels. The rate of invasion documented over the three seasons (2006-2008), helped to illustrate the invasion process of vegetative propagules into both bare ground and multispecies sod habitats. The results indicated that the multispecies sod significantly reduced the rate of invasion of *C. arvense* and may therefore be an effective barrier to reduce or contain weed invasions.

Future Research

The potential for further research on multispecies sod for revegetation is large. Foremost, testing the potential of multispecies sod composed of different combinations of indigenous species to reduce other weed species under natural precipitation could be useful at a more localized site specific scale. Additional studies could also have the potential to contribute to better understanding multispecies sod production plant community dynamics, specifically changes in species composition over time given different species sowing ratios and production management practices. Lastly, evaluating the success of multispecies sod on steep slopes, such as roadside embankments and downhill ski trails, could aid revegetation of these areas where vegetation establishment is typically difficult.

Implications for Practice

- Multispecies sod was able to suppress annual and perennial weed invasion, potentially reducing agrochemical application and thus weed control costs.

- Multispecies sod provided rapid vegetative cover and establishment, immediately providing competitive plant communities, aesthetic value, and potential erosion control.

- Multispecies sod was able to establish with no supplemental irrigation when laid during a supplemental peak moisture season, reducing natural resource consumption and easing installation practices.

- Multispecies sod can be a relatively expensive revegetation technique. It may be most useful in high priority areas and on steep slopes, however a cost-benefit economic analysis of specific site locations and budgets should be conducted.

- Multispecies sod mixtures have the potential to mimic native ecosystem diversity, helping to blend disturbed areas back into natural surroundings. However, more research is necessary to develop species mixtures that include high species richness and diversity while retaining sod properties.

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APPENDIX A

THE ESTABLISHMENT AND ANNUAL WEED SUPPRESSION POTENTIAL OF MULTISPECIES SOD R-CODE

(# explains action)

Emergence

Full Data Set With All Interactions

```
# Read data into R
A=read.table("seedallyears.txt",header=T)

# List data column names
names(A)

# Fit emergence model with all independent variables
emerg<-
glm(emergence~water*sown.density+water*SBorSR.sown+sown.density*SBorSR.sown
+water*transplant+sown.density*transplant+experiment,data=A,family=quasi(var="mu(1-
mu)",link=logit))

# Show model results table
summary(emerg)

# Difference found in water regime, seed bank or seed rain sown, time since sod was
transplanted, experiment, and sown density: seed bank or seed rain sown interaction
```

Full Data Set Without Non-significant Interactions

```
# Fit emergence model with all independent variables
emerg<-
glm(emergence~SBorSR.sown*sown.density+water+experiment+transplant,data=A,family=
quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(emerg)

# Difference found in water regime, seed bank or seed rain sown, sown density, experiment,
time since sod was transplanted, and seed bank or seed rain: sown density interaction
```

Experiment A_1 All Years Without Non-significant Interactions

```
# Fit emergence model with independent variables
emerg<-
glm(emergence~water*transplant+sown.density*transplant+SBorSR.sown,data=subset(A,ex
periment=='A1'),family=quasi(var="mu(1-mu)",link=logit))
```

```
# Show model results
summary(emerg)

# Difference found in water, time since sod was transplanted, seed bank or seed rain, sown
density, water: time since sod was transplanted interaction, and time since sod was
transplanted: sown density interaction.
```

B. napus Sown As Seed Bank In A_1 Without Non-significant Interactions (no significance found)

```
# Fit emergence model with independent variables
emerg<-
glm(emergence~water+sown.density,data=subset(A,SBorSR.sown=='SB'&experiment==
'A1'),family=quasi(var="mu(1-mu)",link=logit))

# Show model results
summary(emerg)
```

B. napus Sown As Seed Rain In A_1 Without Non-significant Interactions

```
# Fit emergence model with independent variables
emerg<-
glm(emergence~sown.density*transplant+water*transplant,data=subset(A,
SBorSR.sown=='SR'&experiment=='A1'),family=quasi(var="mu(1-mu)",link=logit))

# Show model results
summary(emerg)

 # Difference found in water, time since sod was transplanted, sown density: time since sod
was transplanted interaction, and water: time since sod was transplanted interaction
```

Experiment A_2 All Years Without Non-significant Interactions

```
# Fit emergence model with independent variables
emerg<-
glm(emergence~SBorSR.sown*sown.density+sown.density*transplant+water,data=subset(A,
experiment=='A2'),family=quasi(var="mu(1-mu)",link=logit))

# Show model results
summary(emerg)
```

Difference found in water, seed bank or seed rain, time since sod was transplanted, seed bank or seed rain: sown density interaction, and sown density: time since sod was transplanted interaction.

B. napus Sown As Seed Bank In A_2 Without Non-significant Interactions

```
# Fit emergence model with independent variables
emerg<-
glm(emergence~water+sown.density,data=subset(A,SBorSR.sown=='SB'&experiment==
'A2'),family=quasi(var="mu(1-mu)",link=logit))

# Show model results
summary(emerg)

# Difference found in density
```

B. napus Sown As Seed Rain In A_2 Without Non-significant Interactions

```
# Fit emergence model with independent variables
emerg<-
glm(emergence~sown.density*transplant+water,data=subset(A,SBorSR.sown=='SR'&experi
ment=='A2'),family=quasi(var="mu(1-mu)",link=logit))

# Show model results
summary(emerg)

# Difference found in water, density, time since the sod was transplanted, and density: time
since the sod was transplanted interaction
```

Volunteer Weeds in Multispecies Sod Control Sod Subplots vs. Bare Ground

Full Data Set With All Interactions (no significance found)

```
# Read data into R
A=read.table("control.weeds2.txt",header=T)

# List data column names
names(A)
```

```
# Fit volunteer weed relative abundance model with all independent variables
weeds<-
glm(weeds~water*sodORbareground+water*transplant+
sodORbareground*transplant+experiment,data=A,family=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(weeds)
```

Full Data Set Without Non-significant Interactions

```
# Fit volunteer weed relative abundance model with all independent variables
weeds<-
glm(weeds~water+sodORbareground+transplant+experiment,data=A,family=quasi(var="mu
(1-mu)",link=logit))

# Show model results table
summary(weeds)

# Difference found in experiment, sod or bare ground, and time since sod was transplanted
```

First Year Since Sod Was Transplanted Without Non-significant Interactions

```
# Fit volunteer weed relative abundance model with independent variables
weeds<-
glm(weeds~water+experiment+sodORbareground,data=subset(sod.transplant.age
==’1’),family=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(weeds)

# Difference found between experiments
```

Second Year Since Sod Was Transplanted Without Non-significant Interactions

```
# Fit volunteer weed relative abundance model with independent variables
weeds<-
glm(weeds~water+experiment+ sodORbareground,data=subset(sod.transplant.age
==’2’),family=quasi(var="mu(1-mu)",link=logit))
```

```
# Show model results table
summary(weeds)

# Difference found between the sod and bare ground
```

Survival

Full Data Set With All Interactions (no significance found)

```
# Read data into R
A=read.table("seedallyears.txt",header=T)

# List data column names
names(A)

# Fit survival model with all independent variables
surv<-
glm(survival~water*sown.density+water*SBorSR.sown+sown.density*SBorSR.sown+exper
iment,data=subset(A,transplant=='1'),family=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(surv)
```

Full Data Set Without Non-significant Interactions

```
# Fit survival model with all independent variables
surv<-
glm(survival~water+sown.density+SBorSR.sown+experiment,data=subset(A,transplant==
'1'),family=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(surv)

# Difference found in water
```

Weed Productivity

Vegetative Biomass Full Data Set With All Interactions

```
# Read data into R
A=read.table("seedallyears.txt",header=T)

# List data column names
names(A)

# Fit vegetative biomass model with all independent variables
veg<-
glm(veg.biomass~water*sown.density+water*SBorSR.sown+sown.density*SBorSR.sown+
experiment+final.plant.number,data=A)

# Show model results table
summary(veg)

# Difference found in water, experiment, number of harvested plants, and water: seed bank or
seed rain sown interaction
```

Vegetative Biomass Full Data Set Without Non-significant Interactions

```
# Fit vegetative biomass model with all independent variables
veg<-
glm(veg.biomass~water+sown.density+SBorSR.sown+experiment+final.plant.number,data=
A)

# Show model results table
summary(veg)

# Difference found in water, experiment, number of harvested plants, and water: seed bank or
seed rain sown interaction
```

Experiment A_1 Without Non-significant Interactions

```
# Fit vegetative biomass model with independent variables
veg<-
glm(veg.biomass~water*SBorSR.sown+water*sown.density+final.plant.number,data=subset
(A, experiment=='A1'))
```

```
# Show model results table
summary(veg)

# Difference found in water, sown density, number of harvested plants, water: seed bank or
seed rain interaction, and water: sown density interaction
```

Experiment A_2 Without Non-significant Interactions

```
# Fit vegetative biomass model with all independent variables
veg<-
glm(veg.biomass~water+sown.density+ SBorSR.sown +final.plant.number,data=subset(A,
experiment==’A2’))

# Show model results table
summary(veg)

# Difference found in water and number of harvested plants
```

Seed Biomass Full Data Set With All Interactions

```
# Read data into R
A=read.table(“seedallyears.txt”,header=T)

# List data column names
names(A)

# Fit seed biomass model with all independent variables
seed<-
glm(seed.biomass~water*sown.density+water*SBorSR.sown+sown.density*SBorSR.sown
experiment+final.plant.number,data=A)

# Show model results table
summary(seed)

# Difference found in water and number of harvested plants
```

Seed Biomass Full Data Set Without Non-significant Interactions

```
# Fit seed biomass model with all independent variables
seed<-
glm(seed.biomass~water+sown.density+SBorSR.sown+experiment+final.plant.number,data=
A)

# Show model results table
summary(seed)

# Difference found in water and number of harvested plants
```

Multispecies Sod Biomass

Full Data Set

```
# Read data into R
A=read.table("seedsodbiomass2.txt",header=T)

# List data column names
names(A)

# Fit sod biomass model with all independent variables
sod<-glm(sod.biomass~water+experiment,data=A)

# Show model results table
summary(sod)

# Difference found in water
```

Senescing/Dormnant Multispecies Sod

Full Data Set With All Interactions

```
# Read data into R
A= read.table("seeddiversity.txt",header=T)

# List data column names
names(A)
```

```
# Fit senescing/dormant relative abundance model with all independent variables
senescing/dormant <-
glm(senescing/dormant ~water*transplant+experiment,data=A,family=quasi(var="mu(1-
mu)",link=logit))

# Show model results table
summary(senescing/dormant)

# Difference found in water, time since sod transplanted, experiment, and water: time since
sod was transplanted interaction
```

Experiment A_1 All Years

```
# Fit senescing/dormant relative abundance model with independent variables
senescing/dormant <-
glm(senescing/dormant~water*transplant,data=subset(A,experiment==’A1’),family=quasi(v
ar="mu(1-mu)",link=logit))

# Show model results table
summary(senescing/dormant)

# Difference found in water, time since sod was transplanted, and water: time since sod was
transplanted interaction
```

Experiment A2 All Years

```
# Fit senescing/dormant relative abundance model with independent variables
senescing/dormant <-
glm(senescing/dormant~water*transplant,data=subset(A,experiment==’A2’),family=quasi(v
ar="mu(1-mu)",link=logit))

# Show model results table
summary(senescing/dormant)

# Difference found in water, time since sod was transplanted, and water: time since sod was
transplanted interaction
```

Species Richness

Full Data Set With All Interactions

```
# Read data into R
A= read.table("seeddiversity.txt",header=T)

# List data column names
names(A)

# Fit species richness model with all independent variables
rich<-
glm(richness~water*transplant+experiment,data=A,)

# Show model results table
summary(rich)

# Difference found in water, time since sod was transplanted, experiment, and water: time
since sod was transplanted interaction
```

Experiment A_1 All Years

```
# Fit species richness model with independent variables
rich<-
glm(richness~water*transplant,data=subset(A,experiment==’A1’))

# Show model results table
summary(rich)

#Difference found in time since sod was transplanted, and water: time since sod was
transplanted interaction
```

Experiment A_2 All Years

```
# Fit species richness model with independent variables
rich<-
glm(richness~water*transplant,data=subset(A,experiment==’A2’))

# Show model results table
summary(rich)
```

Difference found in water and water: time since sod was transplanted interaction

Species Diversity

Full Data Set With All Interactions

```
# Read data into R
A= read.table("seeddiversity.txt",header=T)

# List data column names
names(A)

# Fit species diversity model with all independent variables
div<-
glm(diversity~water*transplant+experiment,data=A,family=quasi(var="mu(1-
mu)",link=logit))

# Show model results table
summary(div)
```

Difference found in time since sod was transplanted and water: time since sod was transplanted interaction

Relative Abundance of *Poa compressa*

Full Data Set With All Interactions

```
# Read data into R
A= read.table("seeddiversity.txt",header=T)

# List data column names
names(A)
```

Fit relative abundance of *P. compressa* model with all independent variables

```
pcomp<-
glm(pcompressa~water*transplant+experiment,data=A,family=quasi(var="mu(1-
mu)",link=logit))
```

```
# Show model results table
summary(pcomp)

# Difference found in water, time since sod was transplanted, and water: time since sod was
transplanted interaction
```

Relative Abundance of *Poa pratensis*

Full Data Set With All Interactions (no significance found)

```
# Read data into R
A= read.table("seeddiversity.txt",header=T)

# List data column names
names(A)

# Fit relative abundance of P. pratensis model with all independent variables
pprat<-
glm(ppratensis~water*transplant+experiment,data=A,family=quasi(var="mu(1-
mu)",link=logit))

# Show model results table
summary(pprat)
```

Full Data Set Without Non-significant Interactions

```
# Fit relative abundance of P. pratensis model with all independent variables
pprat<-
glm(ppratensis~water+transplant+experiment,data=A,family=quasi(var="mu(1-
mu)",link=logit))

# Show model results table
summary(pprat)

# Difference found in water
```

Analysis Output Tables

Emergence

Full Data Set With All Interactions

Table 1. *B. napus* cumulative emergence over the first 21 days in A_1 and A_2 of all years.

	Estimate	Standard Error	t-value	p-value
Intercept	$-8.15e^{-01}$	$4.02e^{-01}$	-2.027	0.043
Water (cm)	$-7.66e^{-03}$	$1.33e^{-02}$	-0.575	0.565
Seed Bank/Seed Rain	$5.52e^{-01}$	$2.65e^{-01}$	2.079	0.038
Sown Density	$-9.06e^{-04}$	$4.63e^{-04}$	-1.957	0.051
Time Since Sod Was Transplanted	-2.33	$3.25e^{-01}$	-7.159	$1.86e^{-12}$
Experiment	$7.39e^{-01}$	$8.47e^{-02}$	8.734	$< 2e^{-16}$
Water: Seed Bank/Seed Rain	$-3.96e^{-03}$	$8.84e^{-03}$	-0.448	0.655
Water: Sown Density	$2.71e^{-06}$	$1.06e^{-05}$	0.255	0.799
Sown Density: Seed Bank/Seed Rain	$9.76e^{-04}$	$2.44e^{-04}$	3.998	$7.00e^{-05}$
Water: Time Since Sod Was Transplanted	$2.09e^{-02}$	$1.09e^{-02}$	1.908	0.057
Sown Density: Time Since Sod Was Transplanted	9.22e-06	2.88e-04	0.032	0.9745

Null deviance: 159.173 on 800 degrees of freedom, residual deviance: 93.535 on 790 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1307677).

Full Data Set Without Non-significant Interactions

Table 2. *B. napus* cumulative emergence over the first 21 days in A_1 and A_2 of all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-1.375	0.225	-6.105	$1.61e^{-09}$
Water (cm)	0.015	0.004	3.881	$1.13e^{-04}$
Seed Bank/Seed Rain	0.444	0.109	4.091	$4.72e^{-05}$
Sown Density	-0.001	$2.00e^{-04}$	-4.103	$4.50e^{-05}$
Experiment	0.718	0.084	8.548	$< 2e^{-16}$
Time Since Sod Was Transplanted	-1.783	0.111	-16.115	$< 2e^{-16}$
Seed Bank/Seed Rain: Sown Density	0.001	$2.34e^{-04}$	4.155	$3.61e^{-05}$

Null deviance: 159.173 on 800 degrees of freedom, residual deviance: 94.035 on 794 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1314680).

Experiment A_1 All Years Without Non-significant Interaction

Table 3. *B. napus* cumulative emergence over the first 21 days in A_1 of all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	0.774	0.578	1.338	0.182
Water (cm)	-0.039	0.018	-2.221	0.027
Time Since Sod Was Transplanted	-3.37	0.496	-6.802	$4.57e^{-11}$
Seed Bank/Seed Rain	1.103	0.164	6.723	$7.43e^{-11}$
Sown Density	-0.001	$5.35e^{-04}$	-2.206	0.028
Water: Time Since Sod Was Transplanted	0.036	0.014	2.47	0.014
Time Since Sod Was Transplanted: Sown Density	0.001	$4.15e^{-04}$	3.504	$5.19e^{-04}$

Null deviance: 56.719 on 350 degrees of freedom, residual deviance: 37.691 on 344 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1222883).

B. napus Sown As Seed Bank In A_1 Without Non-significant Interactions (no significance found)

Table 4. Seed bank *B. napus* cumulative emergence over the first 21 days in A_1 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-2.768	0.250	-11.093	$< 2e^{-16}$
Water (cm)	0.012	0.008	1.404	0.164
Sown Density	$3.24e^{-04}$	$3.02e^{-04}$	-1.073	0.286

Null deviance: 6.9485 on 99 degrees of freedom, residual deviance: 6.7127 on 97 degrees of freedom (Dispersion parameter for quasi family taken to be 0.07483622).

B. napus Sown As Seed Rain In A_1 Without Non-significant Interactions

Table 5. Seed rain *B. napus* cumulative emergence over the first 21 days in A_1 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	2.016	0.654	3.080	0.002
Water (cm)	-0.054	0.021	-2.568	0.011
Sown Density	$-7.03e^{-04}$	$6.27e^{-04}$	-1.123	0.263
Time Since Sod Was Transplanted	-3.440	0.538	-6.398	$7.95e^{-10}$
Sown Density: Time Since Sod Was Transplanted	0.001	$4.61e^{-04}$	2.639	0.009
Water: Time Since Sod Was Transplanted	0.043	0.016	2.673	0.008

Null deviance: 49.090 on 250 degrees of freedom, residual deviance: 30.164 on 245 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1385494).

Experiment A_2 All Years Without Non-significant Interactions

Table 6. *B. napus* cumulative emergence over the first 21 days of all years of A_2 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-0.521	0.258	-2.018	0.044
Water (cm)	0.027	0.005	5.130	$4.35e^{-07}$
Seed Bank/Seed Rain	0.333	0.121	2.744	0.006
Sown Density	$2.40e^{-04}$	$4.80e^{-04}$	0.499	0.618
Time Since Sod Was Transplanted	-1.426	0.165	-8.625	$< 2e^{-16}$
Seed Bank/Seed Rain: Sown Density	$9.58e^{-04}$	$2.72e^{-04}$	3.534	$4.53e^{-04}$
Sown Density: Time Since Sod Was Transplanted	-0.001	$4.28e^{-04}$	-2.868	0.004

Null deviance: 87.280 on 449 degrees of freedom, residual deviance: 48.935 on 443 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1148065).

B. napus Sown As Seed Bank In A_2 Without Non-significant Interactions

Table 7. Seed bank *B. napus* cumulative emergence over the first 21 days in A_2 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-1.450	0.236	-6.142	$7.24e^{-16}$
Water (cm)	0.010	0.008	1.309	0.192
Sown Density	$-9.81e^{-04}$	$1.87e^{-04}$	-5.249	$5.24e^{-07}$

Null deviance: 15.033 on 149 degrees of freedom, residual deviance: 12.263 on 147 degrees of freedom (Dispersion parameter for quasi family taken to be 0.08529941).

B. napus Sown As Seed Rain In A_2 Without Non-significant Interactions

Table 8. Seed rain *B. napus* cumulative emergence over the first 21 days in A_2 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-0.483	0.324	-1.490	0.137
Water (cm)	0.036	0.007	5.177	$4.19e^{-07}$
Sown Density	0.001	$5.40e^{-04}$	2.223	0.027
Time Since Sod Was Transplanted	-1.390	0.175	-7.950	$3.99e^{-14}$
Sown Density: Time Since Sod Was Transplanted	-0.001	$4.50e^{-04}$	-2.724	0.007

Null deviance: 72.193 on 299 degrees of freedom, residual deviance: 36.052 on 295 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1274214).

Volunteer Weeds in Multispecies Sod Control Sod Subplots vs. Bare Ground

Full Data Set With All Interactions (no significance found)

Table 9. Volunteer weed relative abundance in A_1 and A_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	-5.544	4.630	-1.198	0.232
Water	0.075	0.146	0.512	0.609
Sod/Bare Ground	3.954	3.743	1.057	0.292
Time Since Sod Was Transplanted	0.577	2.069	0.279	0.781
Experiment	0.709	0.536	1.322	0.187
Water: Sod/ Bare Ground	-0.034	0.100	-0.339	0.735
Water: Time Since Sod Was Transplanted	-0.026	0.063	-0.412	0.681
Sod/Bare Ground: Time Since Sod Was Transplanted	-2.391	1.424	-1.679	0.095

Null deviance: 70.809 on 263 degrees of freedom, residual deviance: 50.191 on 256 degrees of freedom (Dispersion parameter for quasi family taken to be 0.8083757).

Full Data Set Without Non-significant Interactions

Table 10. Volunteer weed relative abundance in A_1 and A_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-1.405	1.285	-1.094	0.275
Water (cm)	0.014	0.021	0.701	0.484
Experiment	0.689	0.445	1.550	0.122
Sod/Bare Ground	-0.051	0.679	-0.076	0.940
Time Since Sod Was Transplanted	-1.959	0.520	-3.765	$2.06e^{-04}$

Null deviance: 70.809 on 263 degrees of freedom, residual deviance: 50.163 on 255 degrees of freedom (Dispersion parameter for quasi family taken to be 0.781312).

First Year Since Sod Was Transplanted Without Non-significant Interactions

Table 11. Volunteer weed relative abundance in A_1 and A_2 the first year. *Significant difference in experiments due to more weeds in A_2 compared to A_1. No further significance found when experiments were analyzed separately.

	Estimate	Standard Error	t-value	p-value
Intercept	-4.479	1.127	-3.974	<0.001
Water (cm)	0.010	0.019	0.536	0.593
Experiment	1.031	0.432	2.388	0.019*
Sod/Bare Ground	0.680	0.772	0.879	0.381

Null deviance: 44.278 on 109 degrees of freedom, residual deviance: 40.769 on 106 degrees of freedom (Dispersion parameter for quasi family taken to be 0.4018721).

Second Year Since Sod Was Transplanted Without Non-significant Interactions

Table 12. Volunteer weed relative abundance in A_1 and A_2 the second year.

	Estimate	Standard Error	t-value	p-value
Intercept	-1.736	1.297	-1.338	0.184
Water (cm)	0.007	0.029	0.210	0.834
Experiment	-0.736	0.621	-1.184	0.239
Sod/Bare Ground	-2.718	0.611	-4.447	$2.15e^{-05}$

Null deviance: 4.7568 on 109 degrees of freedom, residual deviance: 2.9361 on 106 degrees of freedom (Dispersion parameter for quasi family taken to be 0.09356369).

Survival

Full Data Set With All Interactions (no significance found)

Table 13. *B. napus* survival in A_1 and A_2 the first year. Second year not applicable because no plants that emerged survived until harvest.

	Estimate	Standard Error	t-value	p-value
Intercept	1.52	$7.67e^{-01}$	1.983	0.048
Water (cm)	$3.80e^{-02}$	$2.61e^{-02}$	1.453	0.147
Sown Density	$-8.78e^{-03}$	$9.34e^{-03}$	-0.94	0.348
Seed Bank/Seed Rain	$-5.30e^{-01}$	$6.77e^{-01}$	-0.782	0.435
Experiment	$-2.64e^{-01}$	$2.25e^{-01}$	-1.173	0.242
Water: Sown Density	$3.22e^{-05}$	$3.36e^{-04}$	0.096	0.924
Water: Seed Bank/Seed Rain	$5.93e^{-03}$	$2.11e^{-02}$	0.281	0.779
Sown Density: Seed Bank/Seed Rain	$1.02e^{-02}$	$6.66e^{-03}$	1.538	0.125

Null deviance: 116.64 on 289 degrees of freedom, residual deviance: 108.31 on 282 degrees of freedom (Dispersion parameter for quasi family taken to be 0.398386).

Full Data Set Without Non-significant Interactions

Table 14. *B. napus* survival in A_1 and A_2 in the first year without non-significant interactions. Second year not applicable because no plants that emerged survived until harvest.

	Estimate	Standard Error	t-value	p-value
Intercept	1.098	0.452	2.431	0.0157
Water (cm)	0.043	0.011	3.887	$1.26e^{-04}$
Seed Bank/Seed Rain	0.229	0.208	1.104	0.270
Sown Density	-0.003	0.003	-0.993	0.322
Experiment	-0.259	0.226	-1.147	0.252

Null deviance: 116.64 on 289 degrees of freedom, residual deviance: 109.30 on 285 degrees of freedom (Dispersion parameter for quasi family taken to be 0.4031237).

Weed Productivity

Vegetative Biomass Full Data Set With All Interactions

Table 15. *B. napus* vegetative biomass in A_1 and A_2 the first year. Second year not applicable because no plants that emerged survived until harvest.

	Estimate	Standard Error	t-value	p-value
Intercept	-127.814	44.327	-2.883	0.004
Water (cm)	5.740	1.324	4.335	$2.09e^{-05}$
Seed Bank/Seed Rain	48.557	37.67	1.289	0.199
Sown Density	-0.313	0.577	-0.542	0.588
Experiment	61.566	11.899	5.174	$4.60e^{-07}$
Number of Harvested Plants	2.842	0.714	3.979	$8.97e^{-05}$
Water: Seed Bank/Seed Rain	-2.607	1.096	-2.379	0.018
Water: Sown Density	0.019	0.018	1.073	0.284
Seed Bank/Seed Rain: Sown Density	-0.112	0.358	-0.314	0.754

Null deviance: 3738696 on 267 degrees of freedom, residual deviance: 2046794 on 259 degrees of freedom (Dispersion parameter for Gaussian family taken to be 7902.678).

Vegetative Biomass Full Data Set Without Non-significant Interactions

Table 16. *B. napus* vegetative biomass in A_1 and A_2 the first year without non-significant interactions. Second year not applicable because no plants that emerged survived until harvest.

	Estimate	Standard Error	t-value	p-value
Intercept	-155.137	31.182	-4.975	$1.18e^{-06}$
Water (cm)	6.866	0.813	8.443	$2.17e^{-15}$
Seed Bank/Seed Rain	42.759	31.989	1.337	0.182
Sown Density	0.156	0.200	0.78	0.436
Experiment	61.593	11.883	5.183	$4.38e^{-07}$
Number of Harvested Plants	2.795	0.708	3.946	$1.02e^{-04}$
Water: Seed Bank/Seed Rain	-2.620	1.095	-2.394	0.017

Null deviance: 3738696 on 267 degrees of freedom, residual deviance: 2057285 on 261 degrees of freedom (Dispersion parameter for Gaussian family taken to be 7882.32).

Experiment A_1 Without Non-significant Interactions

Table 17. Seed bank and seed rain *B. napus* vegetative biomass in A_1 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	7.620	44.796	0.17	0.865
Water (cm)	3.336	1.587	2.102	0.038
Seed Bank/Seed Rain	16.081	37.091	0.434	0.666
Sown Density	-1.681	0.621	-2.71	0.008
Number of Harvested Plants	4.068	1.073	3.792	$2.61e^{-04}$
Water: Seed Bank/Seed Rain	-3.018	1.308	-2.307	0.023
Water: Sown Density	0.071	0.021	3.324	0.001

Null deviance: 1406900 on 102 degrees of freedom, residual deviance: 608993 on 96 degrees of freedom (Dispersion parameter for Gaussian family taken to be 6343.678).

Experiment A_2 Without Non-significant Interactions

Table 18. Seed bank and seed rain *B. napus* vegetative biomass in A_2 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	19.115	31.307	0.611	0.5424
Water (cm)	4.872	0.931	5.236	$5.11e^{-07}$
Seed Bank/Seed Rain	-12.178	14.885	-0.818	0.415
Sown Density	0.161	0.275	0.586	0.559
Number of Harvested Plants	2.447	0.957	2.556	0.012

Null deviance: 1755379 on 164 degrees of freedom, residual deviance: 1345417 on 160 degrees of freedom (Dispersion parameter for Gaussian family taken to be 8408.859).

Seed Biomass Full Data Set With All Interactions

Table 19. *B. napus* seed biomass in A_1 and A_2. Second year not applicable because no plants that emerged survived until harvest.

	Estimate	Standard Error	t-value	p-value
Intercept	-9.168	5.000	-1.834	0.0679
Water (cm)	0.334	0.149	2.235	0.0263
Seed Bank/Seed Rain	3.536	4.249	0.832	0.406
Sown Density	-0.027	0.065	-0.419	0.676
Experiment	1.945	1.342	1.449	0.149
Number of Harvested Plants	0.228	0.081	2.834	0.005
Water: Seed Bank/Seed Rain	-0.103	0.124	-0.836	0.404
Water: Sown Density	0.002	0.002	0.954	0.341
Sown Density: Seed Bank/Seed Rain	-0.033	0.040	-0.809	0.419

Null deviance: 32986 on 267 degrees of freedom, residual deviance: 26044 on 259 degrees of freedom (Dispersion parameter for Gaussian family taken to be 100.5571).

Seed Biomass Full Data Set Without Non-significant Interactions

Table 20. *B. napus* seed biomass in A_1 and A_2 without non-significant interactions. Second year not applicable because no plants that emerged survived until harvest.

	Estimate	Standard Error	t-value	p-value
Intercept	-9.614	2.935	-3.276	0.001
Water (cm)	0.390	0.063	6.213	$2.03e^{-09}$
Seed Bank/Seed Rain	-1.117	1.269	-0.880	0.380
Sown Density	0.008	0.023	0.371	0.711
Experiment	1.920	1.340	1.432	0.153
Number of Harvested Plants	0.220	0.080	2.756	0.006

Null deviance: 32986 on 267 degrees of freedom, residual deviance: 26292 on 262 degrees of freedom (Dispersion parameter for Gaussian family taken to be 100.3504).

Multispecies Sod Biomass

Full Data Set

Table 21. Final multispecies sod biomass (2008 after 3 years in A_1; 2007 after 2 years in A_2).

	Estimate	Standard Error	t-value	p-value
Intercept	177.768	13.350	13.316	$< 2e^{-16}$
Water (cm)	1.170	0.269	4.354	$13.32e^{-05}$
Experiment	-8.338	6.225	-1.339	0.184

Null deviance: 107559 on 99 degrees of freedom, residual deviance: 85885 on 97 degrees of freedom (Dispersion parameter for Gaussian family taken to be 885.4117).

Senescing/Dormant Multispecies Sod

Full Data Set With All Interactions

Table 22. Senescing/dormant sod relative abundance in A_1 and A_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	1.549	0.102	15.236	$<2e^{-16}$
Water (cm)	-0.036	0.003	-11.050	$<2e^{-16}$
Experiment	-0.126	0.029	-4.353	$<2e^{-16}$
Time Since Sod Was Transplanted	-0.498	0.046	-10.854	$2.01e^{-05}$
Water: Time Since Sod Was Transplanted	0.013	0.002	7.794	$2.09e^{-13}$

Null deviance: 20.982 on 239 degrees of freedom, residual deviance: 10.272 on 235 degrees of freedom (Dispersion parameter for quasi family taken to be 0.04371041).

Experiment A_1 All Years

Table 23. Senescing/dormant sod relative abundance in A_1 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	1.306	0.105	12.453	$<2e^{-16}$
Water (cm)	-0.035	0.004	-9.079	$3.40e^{-15}$
Time Since Sod Was Transplanted	-0.402	0.050	-8.103	$6.11e^{-13}$
Water: Time Since Sod Was Transplanted	0.011	0.007	6.133	$1.23e^{-08}$

Null deviance: 11.6954 on 119 degrees of freedom, residual deviance: 4.8742 on 116 degrees of freedom (Dispersion parameter for quasi family taken to be 0.04201927).

Experiment A2 All Years

Table 24. Senescing/dormant sod relative abundance in A_2 in all years (2007-2008).

	Estimate	Standard Error	t-value	p-value
Intercept	2.272	0.172	13.212	$<2e^{-16}$
Water (cm)	-0.066	0.006	-10.923	$<2e^{-16}$
Time Since Sod Was Transplanted	-1.136	0.098	-11.547	$<2e^{-16}$
Water: Time Since Sod Was Transplanted	0.033	0.004	9.112	$2.85e^{-15}$

Null deviance: 8.9548 on 119 degrees of freedom, residual deviance: 3.4601 on 116 degrees of freedom (Dispersion parameter for quasi family taken to be 0.02982813).

Species Richness

Full Data Set With All Interactions

Table 25. Species richness in A_1 and A_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	2.370	0.463	5.112	$6.61e^{-07}$
Water (cm)	-0.030	0.015	-2.044	0.042
Time Since Sod Was Transplanted	-0.484	0.209	-2.316	0.021
Experiment	0.311	0.132	2.351	0.020
Water: Time Since Sod Was Transplanted	0.026	0.007	3.537	$4.87e^{-04}$

Null deviance: 239.73 on 239 degrees of freedom, residual deviance: 213.55 on 235 degrees of freedom (Dispersion parameter for Gaussian family taken to be 0.9087255).

Experiment A_1 All Years

Table 26. Species richness in A_1 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	2.736	0.471	5.806	$5.68e^{-08}$
Water (cm)	-0.023	0.018	-1.300	0.196
Time Since Sod Was Transplanted	-0.482	0.223	-2.160	0.033
Water:Time Since Sod Was Transplanted	0.021	0.008	2.650	0.009

Null deviance: 112.367 on 119 degrees of freedom, residual deviance: 98.386 on 116 degrees of freedom (Dispersion parameter for Gaussian family taken to be 0.8481518).

Experiment A_2 All Years

Table 27. Species richness in A_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	3.507	0.955	3.672	$3.65e^{-04}$
Water (cm)	-0.071	0.033	-2.127	0.036
Time Since Sod Was Transplanted	-0.945	0.546	-1.729	0.086
Water:Time Since Sod Was Transplanted	0.059	0.020	2.966	0.004

Null deviance: 125.70 on 119 degrees of freedom, residual deviance: 106.66 on 116 degrees of freedom (Dispersion parameter for Gaussian family taken to be 0.9195217).

Species Diversity

Full Data Set With All Interactions

Table 28. Species diversity in A_1 and A_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	-0.567	0.555	-1.022	0.308
Water (cm)	-0.022	0.018	-1.244	0.215
Time Since Sod Was Transplanted	-0.693	0.272	-2.552	0.011
Experiment	-0.0269	0.156	-0.172	0.863
Water: Time Since Sod Was Transplanted	0.026	0.009	2.880	0.004

Null deviance: 61.846 on 239 degrees of freedom, residual deviance: 56.493 on 235 degrees of freedom (Dispersion parameter for quasi family taken to be 0.2146586).

Relative Abundance of *Poa compressa*

Full Data Set With All Interactions

Table 29. Relative abundance of *P. compressa* in A_1 and A_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	-6.036	0.853	-7.076	$1.70e^{-11}$
Water (cm)	0.210	0.028	7.315	$4.03e^{-12}$
Time Since Sod Was Transplanted	3.428	0.451	7.593	$7.33e^{-13}$
Experiment	0.146	0.224	0.654	0.514
Water: Time Since Sod Was Transplanted	-0.104	0.015	-6.920	$4.25e^{-11}$

Null deviance: 148.08 on 239 degrees of freedom, residual deviance: 107.28 on 235 degrees of freedom (Dispersion parameter for quasi family taken to be 0.4523447).

Relative Abundance of *Poa pratensis*

Full Data Set With All Interactions (no significance found)

Table 30. Relative abundance of *P. pratensis* in A_1 and A_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	-5.607	2.165	-2.590	0.010
Water (cm)	0.050	0.058	0.874	0.383
Time Since Sod Was Transplanted	0.351	0.878	0.400	0.690
Experiment	-0.487	0.484	-1.007	0.315
Water: Time Since Sod Was Transplanted	0.006	0.025	0.229	0.819

Null deviance: 23.519 on 239 degrees of freedom, residual deviance: 19.528 on 235 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1726001).

Full Data Set Without Non-significant Interactions

Table 31. Relative abundance of *P. pratensis* in A_1 and A_2 in all years without non-significant interactions. Sod transplant age is marginally significant. When looked at separately there is the same trend of a significant increase in *P. pratensis* as water regime increases in sod transplant age 1 & 2. No significance found in A_1 in sod transplant age 3.

	Estimate	Standard Error	t-value	p-value
Intercept	-6.017	1.284	-4.687	$4.69e^{-06}$
Water (cm)	0.062	0.020	3.163	0.002
Experiment	-0.485	0.485	-1.000	0.318
Time Since Sod Was Transplanted	0.543	0.276	1.969	0.050

Null deviance: 23.519 on 239 degrees of freedom, residual deviance: 19.537 on 236 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1727489).

APPENDIX B

THE ESTABLISHMENT AND ANNUAL WEED SUPPRESSION POTENTIAL OF MULTISPECIES SOD IN COMBINATION WITH FOUR REINFORCEMENT MATERIALS R-CODE AND ANALYSIS OUTPUT TABLES

(# explains action)

Water Absorption Capacity of Reinforcement/Erosion Mat Materials (Laboratory Study)

Full Data Set With All Interactions

```
# Read data into R
A=read.table("labmaterials.txt",header=T)

# List data column names
names(A)

 # Fit water absorption capacity model with all independent variables
mat<-aov(absorption~material,data=A)

# Show model results table
summary(mat)

# Tukey multiple comparison at 95% family-wise confidence level to distinguish difference
TukeyHSD(mat)

# Difference found in material
```

Emergence

Full Data Set With All Interactions

```
# Read data into R
A=read.table("finalall.txt",header=T)

# List data column names
names(A)

# Fit emergence model with independent variables
emerg<-
glm(Emergence~water*transplant+water*material+material*transplant+experiment,data=A,
family=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(emerg)
```

Difference found in water, time since the sod was transplanted, experiment, and water: time since the sod was transplanted interaction

Full Data Set With Without Non-significant Interactions

```
# Fit emergence model with all independent variables
emerg<-
glm(Emergence~water*transplant+material+experiment,data=A,family=quasi(var="mu(1-
mu)",link=logit))

# Show model results table
summary(emerg)
```

Difference found in water, material, time since the sod was transplanted, experiment, and water: time since the sod was transplanted interaction

Experiment B_1 Without Non-significant Interactions

```
# Fit emergence model with all independent variables
emerg<-
glm(Emergence~water*transplant+material,data=subset(A,experiment=='B1'),family=quasi(
var="mu(1-mu)",link=logit))

# Show model results table
summary(emerg)
```

Difference found in water, time since sod was transplanted, and water: time since sod was transplanted interaction

Experiment B_2 Without Non-significant Interactions

```
# Fit emergence model with all independent variables
emerg<-
glm(Emergence~water*transplant+material,data=subset(A,experiment=='B2'),family=quasi
(var="mu(1-mu)",link=logit))

# Show model results table
summary(emerg)
```

Difference found in water, material, time since sod was transplanted, and water: time since sod was transplanted interaction

Experiment B_2 Control Reinforcement/Erosion Mat Material Without Non-significant Interactions

```
# Fit emergence model with independent variables
emerg<-
glm(Emergence~water+transplant,data=subset(A,experiment=='B2'&material=='control'),
family=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(emerg)
```

Difference found in water and time since sod was transplanted

Experiment B_2 Coconut-straw Reinforcement/Erosion Mat Material Without Non-significant Interactions

```
# Fit emergence model with independent variables
emerg<-
glm(Emergence~water*transplant,data=subset(A,experiment=='B2'& material=='coconut-
straw'),family=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(emerg)
```

Difference found in time since sod was transplanted and water: time since sod was transplanted interaction

Experiment B_2 Excelsior Reinforcement/Erosion Mat Material Without Non-significant Interactions

```
# Fit emergence model with independent variables
emerg<-
glm(Emergence~water+transplant,data=subset(A,experiment=='B2'&material=='excelsior'),f
amily=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(emerg)
```

```
# Difference found in water and time since sod was transplanted
```

Experiment B_2 Jute Reinforcement/Erosion Mat Material Without Non-significant Interactions

```
# Fit emergence model with independent variables
 emerg<-
glm(Emergence~water+transplant,data=subset(A,experiment=='B2'&material=='jute'),family
=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(emerg)

#Difference found in water and time since sod was transplanted
```

Volunteer Weeds in Control Multispecies Sod Subplots vs. Bare Ground

Full Data Set With All Interactions (no significance found)

```
# Read data into R
A=read.table("control.weeds2.txt",header=T)

# List data column names
names(A)

# Fit volunteer weed relative abundance model with all independent variables
weeds<-
glm(weeds~water*sodORbareground+water*transplant+
sodORbareground*transplant+experiment,data=A,family=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(weeds)

# Difference found in sod or bare ground: time since sod was transplanted interaction
```

Full Data Set Without Non-significant Interactions

```
# Fit volunteer weed relative abundance model with all independent variables
weeds<-
glm(weeds~water+transplant +sodORbareground
+experiment,data=A,family=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(weeds)

# Difference found in sod or bare ground and time since sod was transplanted
```

Control Multispecies Sod Without Non-significant Interactions

```
# Fit volunteer weed relative abundance model with independent variables
weeds<-
glm(weeds~water+transplant+experiment,data=subset(A,sodORbareground
=’sod’),family=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(weeds)

# Difference found in time since sod was transplanted
```

Bare Ground Control Without Non-significant Interactions

```
# Fit volunteer weed relative abundance model with independent variables
weeds<-
glm(weeds~water+transplant+experiment,data=subset(A,sodORbareground
=’bareground’),family=quasi(var="mu(1-mu)",link=logit))

# Show model results table
summary(weeds)

# Difference found in time since sod was transplanted
```

Survival

Full Data Set With All Interactions (no significance found)

```
# Read data into R
A=read.table("allyears.everythingwithGGD.txt",header=T)

# List data column names
names(A)

# Fit survival model with all independent variables
surv<-
glm(Survival~water*material+experiment,data=subset(transplant==’1’),family=quasi(var="
mu(1-mu)",link=logit))

# Show model results table
summary(surv)
```

Full Data Set Without Non-significant Interactions (no significance found)

```
# Fit survival model with all independent variables
surv<-
glm(Survival~water+material+experiment,data=A,family=quasi(var="mu(1-
mu)",link=logit))

# Show model results table
summary(surv)
```

Weed Productivity

Vegetative Biomass Full Data Set With All Significant Interactions

```
# Read data into R
A=read.table("allyears.everythingwithGGD.txt",header=T)

# List data column names
names(A)
```

```
# Fit vegetative biomass model with all independent variables
bio<-
glm(veg.biomass~water*material+experiment+final.plant.number,data=subset(A,transplant=
=’1’))

# Show model results table
summary(bio)

# Difference found in water, experiment, and number of harvested plants
```

Vegetative Biomass Full Data Set Without Non-significant Interactions

```
# Fit vegetative biomass model with all independent variables
bio<-
glm(veg.biomass~water+material+experiment+final.plant.number,data=A)
summary(bio)

# Show model results table
summary(bio)

# Difference found in water, experiment, and number of harvested plants
```

Experiment B_1 Without Non-significant Interactions

```
# Fit vegetative biomass model with independent variables
>bio<-
glm(veg.biomass~water+material+final.plant.number,data=subset(A,experiment=='B1'&
transplant=='1'))

# Show model results table
summary(bio)

# Difference found in water and number of harvested plants
```

Experiment B_2 Without Non-significant Interactions

```
# Fit vegetative biomass model with independent variables
bio<-
glm(veg.biomass~water+material+final.plant.number,data=subset(A,experiment=='B2'&
transplant=='1'))


# Show model results table
summary(bio)

# Difference found in water and number of harvested plants
```

Seed Biomass Full Data Set With All Interactions

```
# Read data into R
A=read.table("allyears.everythingwithGGD.txt",header=T)

# List data column names
names(A)

 # Fit seed biomass model with all independent variables
seed<-glm(seed.biomass~water*material+experiment+final.plant.number,data=A)

# Show model results table
summary(seed)

# Difference found in water, experiment, and number of harvested plants
```

Seed Biomass Full Data Set Without Non-significant Interactions

```
# Fit seed biomass model with all independent variables
seed<-glm(seed.biomass~water+material+experiment+final.plant.number,data=A)

# Show model results table
summary(seed)

# Difference found in water, experiment, and number of harvested plants.
```

Experiment B_1 Without Non-significant Interactions

```
# Fit seed biomass model with independent variables
 seed<-
glm(seed.biomass~water+material+final.plant.number,data=subset(A,experiment=='B1'&
transplant=='1'))

# Show model results table
summary(seed)

# Difference found in water and number of harvested plants
```

Experiment B_2 Without Non-significant Interactions

```
# Fit seed biomass model with independent variables
seed<-
glm(seed.biomass~water+material+final.plant.number,data=subset(A,experiment=='B2'&
transplant='1'))

# Show model results table
summary(seed)

# Difference found in water
```

Multispecies Sod Biomass

Full Data Set With All Interactions

```
# Read data into R
A=read.table("final.sodbiomass.reinforce.txt",header=T)

# List data column names
names(A)

 # Fit weed final sod biomass model with all independent variables
sodbio<-glm(biomass~water*material+experiment, data=A)

# Show model results table
summary(sodbio)
```

```
# Difference found in water
```

Full Data Set Without Non-significant Interactions

```
# Fit weed final sod biomass model with all independent variables
sodbio<-glm(biomass~water+material+experiment,data=A)

# Show model results table
summary(sodbio)

# Difference found in water
```

Senescing/Dormant Multispecies Sod

Full Data Set With All Interactions

```
# Read data into R
A=read.table("REALfinalallyears.txt",header=T)

# List data column names
names(A)

# Fit senescing/dormant sod relative abundance model with all independent variables
senescing/dormant <-
glm(senescing/dormant ~material*water+material*transplant+water*transplant+experiment,
family = quasi(var = "mu(1-mu)",link = logit),data = A)

# Show model results table
summary(senescing/dormant)

# Difference found in water, time since sod was transplanted, and experiment
```

Full Data Set Without Non-significant Interactions

```
# Fit senescing/dormant sod relative abundance model with all independent variables
senescing/dormant <-
glm(senescing/dormant ~material+water+transplant+experiment, family = quasi(var =
"mu(1-mu)",link = logit),data = A)
```

```
# Show model results table
summary(senescing/dormant)

# Difference found in water, time since sod was transplanted, and experiment
```

Experiment B_1 Without Non-significant Interactions

```
# Fit senescing/dormant sod relative abundance model with independent variables
senescing/dormant <-
glm(senescing/dormant ~material+water+transplant,family = quasi(var = "mu(1-mu)",link =
logit),data = subset(A, experiment=='B1'))

# Show model results table
summary(senescing/dormant)

# Difference found in water and transplant
```

Experiment B_1, First Year Since Sod Was Transplanted Without Non-significant Interactions

```
# Fit senescing/dormant sod relative abundance model with all independent variables
senescing/dormant <-
glm(senescing/dormant ~material+water,family = quasi(var = "mu(1-mu)",link = logit),data
= subset(A,transplant=='1'&experiment=='B1'))

# Show model results table
summary(senescing/dormant)

# Difference found in water
```

Experiment B_1, Second Year Since Sod Was Transplanted Without Non-significant Interactions (no significance found)

```
# Fit senescing/dormant sod relative abundance model with independent variables
senescing/dormant <-
glm(senescing/dormant material+water,family = quasi(var = "mu(1-mu)",link = logit),data =
subset(A,transplant.=='2'&experiment=='B1'))

# Show model results table
summary(senescing/dormant)
```

Experiment B_1 Third Year Since The Sod Was Transplanted Without Non-significant Interactions (no significance found)

```
# Fit senescing/dormant sod relative abundance model with independent variables
senescing/dormant <-
glm(senescing/dormant ~ material+water, family = quasi(var = "mu(1-mu)",link = logit),data
= subset(A,transplant=='3'&experiment=='B1'))

# Show model results table
summary(senescing/dormant)
```

Experiment B_2 Without Non-significant Interactions

```
# Fit senescing/dormant sod relative abundance model with independent variables
senescing/dormant <-
glm(senescing/dormant ~material+water+transplant, family = quasi(var = "mu(1-mu)",link =
logit),data = subset(A, experiment=='B2'))

# Show model results table
summary(senescing/dormant)

# Difference found in water, reinforcement material, and time since sod was transplanted
```

Experiment B_2, First Year Since Sod Was Transplanted Without Non-significant Interactions

```
# Fit senescing/dormant sod relative abundance model with all independent variables
senescing/dormant <-
glm(senescing/dormant ~material+water, family = quasi(var = "mu(1-mu)",link = logit),data
= subset(A,transplant=='1'&experiment=='B2'))

# Show model results table
summary(senescing/dormant)

# Difference found in water
```

Experiment B_2 Second Year Since Sod Was Transplanted Without Non-significant Interactions (no significance found)

```
# Fit senescing/dormant sod relative abundance model with all independent variables
senescing/dormant <-
glm(senescing/dormant~material+water, family = quasi(var = "mu(1-mu)",link = logit),data
= subset(A,transplant=='1'&experiment=='B2'))

# Show model results table
summary(senescing/dormant)
```

Species Richness

Full Data Set With All Interactions

```
# Read data into R
A=read.table("REALfinalallyearstxt",header=T)

# List data column names
names(A)

# Fit species richness model with all independent variables
rich<-
glm(richness~material*water+material*transplant+water*transplant+experiment,data=A)

# Show model results table
summary(rich)

# Difference found in water, time since sod was transplanted, experiment, and water: time
since sod was transplanted interaction
```

Full Data Set Without Non-significant Interactions

```
# Fit species richness model with all independent variables
rich<-glm(richness~water*transplant+material+experiment,data=A)

# Show model results table
summary(rich)
```

```
# Difference found in water, time since sod was transplanted, experiment, and water: time since sod was transplanted interaction
```

Experiment B_1 Without Non-significant Interactions

```
# Fit species richness model with all independent variables
rich<-glm(richness~transplant*water+material,data=subset(A, experiment==’B1’))

# Show model results table
summary(rich)

#Difference found in water, time since sod was transplanted, and water: time since sod was transplanted interaction
```

Experiment B_2 Without Non-significant Interactions

```
# Fit species richness model with all independent variables
rich<-glm(richness~transplant*water+material,data=subset(A, experiment==’B2’))

# Show model results table
summary(rich)

# Difference found in water, time since sod was transplanted, and water: time since sod was transplanted interaction
```

Species Diversity

Full Data Set With All Interactions

```
# Read data into R
A=read.table("REALfinalallyears.txt",header=T)

# List data column names
names(A)

# Fit species diversity model with all independent variables
div<-
glm(diversity~material*water+material*transplant+water*transplant+experiment, family = quasi(var = "mu(1-mu)",link = logit),data = A)
```

```
# Show model results table
summary(div)

# Difference found in water, time since sod was transplanted, and water: time since sod was
transplanted interaction
```

Full Data Set Without Non-significant Interactions

```
# Fit species diversity model with all independent variables
div<-
glm(diversity~water*transplant+material+experiment, family = quasi(var = "mu(1-mu)",link
= logit),data = A)

# Show model results table
summary(div)

# Difference found in water, time since sod was transplanted, and water: time since sod was
transplanted interaction
```

Relative Abundance of *P. compressa*

Full Data Set With All Interactions

```
# Read data into R
A=read.table("REALfinalallyears.txt",header=T)

# List data column names
names(A)

# Fit relative abundance of P. compressa model with all independent variables
pcomp<-
glm(pcomp~material*water+material*transplant+water*transplant+experiment, family =
quasi(var = "mu(1-mu)",link = logit),data = A)

# Show model results table
summary(pcomp)

# Difference found in time since sod was transplanted, experiment, and water: time since sod
was transplanted interaction
```

Full Data Set Without Non-significant Interactions

```
# Fit relative abundance of P. compressa model with all independent variables
pcomp<-
glm(pcomp~material*water+material*transplant+water*transplant+experiment, family =
quasi(var = "mu(1-mu)",link = logit),data = A)

# Show model results table
summary(pcomp)

# Difference found in water, time since sod was transplanted, experiment, and water: time
since sod was transplanted interaction
```

Experiment B_1 Without Non-significant Interactions

```
# Fit relative abundance of P. compressa model with independent variables
pcomp<-
glm(pcompressa~water*transplant+material, family = quasi(var = "mu(1-mu)",link =
logit),data = subset(A,experiment==’B1’))

# Show model results table
summary(pcomp)

# Difference in water, time since sod was transplanted, and water: time since sod was
transplanted interaction
```

Experiment B_2 Without Non-significant Interactions

```
# Fit relative abundance of P. compressa model with independent variables
pcomp<-
glm(pcompressa~water*transplant+material, family = quasi(var = "mu(1-mu)",link =
logit),data = subset(A,experiment==’B2’))

# Show model results table
summary(pcomp)

# Difference in water and water: time since sod was transplanted interaction
```

Relative Abundance of *P. pratensis*

Full Data Set With All Interactions (no significance found)

```
# Read data into R
read.table("REALfinalallyears.txt",header=T)

# List data column names
names(A)

# Fit emergence model with all independent variables
pprat<-
glm(pprat~material*water+material*transplant+water*transplant+experiment, family =
quasi(var = "mu(1-mu)",link = logit),data = A)

# Show model results table
summary(pprat)
```

Full Data Set With Without Non-significant Interactions

```
# Fit emergence model with all independent variables
pprat<-
glm(pprat~material+water+transplant+experiment, family = quasi(var = "mu(1-mu)",link =
logit),data = A)

# Show model results table
summary(pprat)

# Difference found in water
```

Analysis Output Tables

Table 1. Water absorption capacity of reinforcement/erosion mat materials (laboratory study).

	Degrees of Freedom	Sum of Squares	Mean sum of squares	F-value	P-value
Material	3	48.699	16.233	66.293	$9.711e^{-08}$
Residuals	12	2.938	0.245	-	-

Table 2. Tukey multiple comparisons of reinforcement material absorption capacity in the laboratory.

Material	Difference	Lower	Upper	p-value
coconut-straw: control	3.939	2.900	4.978	$5.00e^{-07}$
excelsior: control	2.895	1.856	3.934	$1.38e^{-05}$
jute: control	4.543	3.504	5.581	$1.00e^{-07}$
excelsior: coconut-straw	-1.044	-2.083	-0.005	0.049
jute: coconut-straw	0.604	-0.435	1.642	0.354
jute: excelsior	1.648	0.609	2.686	0.002

Emergence

Full Data Set With All Interactions

Table 3. *B. napus* cumulative emergence over the first 21 days in B_1 and B_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	0.136	0.540	0.252	0.801
Water (cm)	-0.058	0.018	-3.247	0.001
Material	0.082	0.136	0.61	0.542
Time Since Sod Was Transplanted	-3.219	0.384	-8.377	$1.03e^{-15}$
Experiment	0.634	0.088	7.201	$3.18e^{-12}$
Water: Time Since Sod Was Transplanted	0.082	0.011	7.445	$6.42e^{-13}$
Water: Material	-0.008	0.004	-1.812	0.071
Time Since Sod Was Transplanted: Material	0.017	0.077	0.223	0.824

Null deviance: 39.618 on 391 degrees of freedom, residual deviance: 23.116 on 384 degrees of freedom (Dispersion parameter for quasi family taken to be 0.06009871).

Full Data Set Without Non-significant Interactions

Table 4. *B. napus* cumulative emergence over the first 21 days in B_1 and B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-0.004	0.397	-0.011	0.991
Water (cm)	-0.060	0.014	-4.379	$1.54e^{-05}$
Material	-2.577	0.280	-9.197	$< 2e^{-16}$
Time Since Sod Was Transplanted	-0.100	0.035	-2.836	0.005
Experiment	0.638	0.087	7.295	$1.71e^{-12}$
Water: Time Since Sod Was Transplanted	0.065	0.010	6.674	$8.67e^{-11}$

Null deviance: 39.618 on 391 degrees of freedom, residual deviance: 23.676 on 386 degrees of freedom (Dispersion parameter for quasi family taken to be 0.06070649).

Experiment B_1 Without Non-significant Interactions

Table 5. *B. napus* cumulative emergence over the first 21 days in B_1 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	1.269	0.716	1.772	0.078
Water (cm)	-0.09	0.023	-3.987	$1.05e^{-04}$
Time Since Sod Was Transplanted	-3.14	0.571	-5.504	$1.61e^{-07}$
Material	-0.078	0.075	-1.041	0.300
Water: Time Since Sod Was Transplanted	0.088	0.017	5.115	$9.62e^{-07}$

Null deviance: 15.577 on 151 degrees of freedom, residual deviance: 11.177 on 147 degrees of freedom (Dispersion parameter for quasi family taken to be 0.08142813).

Experiment B_2 Without Non-significant Interactions

Table 6. *B. napus* cumulative emergence over the first 21 days in B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	1.228	0.561	2.189	0.030
Water (cm)	-0.048	0.020	-2.390	0.018
Time Since Sod Was Transplanted	-2.791	0.427	-6.540	$3.79e^{-10}$
Material	-0.109	0.037	-2.958	0.003
Water: Time Since Sod Was Transplanted	0.065	0.015	4.255	$3.02e^{-05}$

Null deviance: 21.624 on 239 degrees of freedom, residual deviance: 11.863 on 235 degrees of freedom (Dispersion parameter for quasi family taken to be 0.04658566).

Experiment B_2 Control Reinforcement/Erosion Mat Material Without Non-significant Interactions

Table 7. *B. napus* cumulative emergence over the first 21 days in the control reinforcement/erosion mat material of B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-1.234	0.376	-3.281	0.002
Water (cm)	0.040	0.011	3.704	$4.81e^{-04}$
Time Since Sod Was Transplanted	-1.002	0.166	-6.042	$1.23e^{-07}$

Null deviance: 5.8029 on 59 degrees of freedom, residual deviance: 2.9228 on 57 degrees of freedom (Dispersion parameter for quasi family taken to be 0.04629691).

Experiment B_2 Coconut-straw Reinforcement/Erosion Mat Material Without Non-significant Interactions

Table 8. *B. napus* cumulative emergence over the first 21 days in the coconut-straw reinforcement/erosion mat of B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	1.131	1.108	1.02	0.312
Water (cm)	-0.059	0.042	-1.423	0.160
Time Since Sod Was Transplanted	-2.525	0.764	-3.307	0.002
Water: Time Since Sod Was Transplanted	0.058	0.028	2.057	0.044

Null deviance: 5.8978 on 59 degrees of freedom, residual deviance: 3.4709 on 56 degrees of freedom (Dispersion parameter for quasi family taken to be 0.06280309).

Experiment B_2 Excelsior Reinforcement/Erosion Mat Material Without Non-significant Interactions

Table 9. *B. napus* cumulative emergence over the first 21 days in the excelsior reinforcement/erosion mat treatment of B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-1.694	0.392	-4.322	$6.27e^{-05}$
Water (cm)	0.036	0.011	3.207	0.002
Time Since Sod Was Transplanted	-0.724	0.170	-4.267	$7.55e^{-05}$

Null deviance: 4.3190 on 59 degrees of freedom, residual deviance: 2.7369 on 57 degrees of freedom (Dispersion parameter for quasi family taken to be 0.04519846).

Experiment B_2 Jute Reinforcement/Erosion Mat Material Without Non-significant Interactions

Table 10. *B. napus* cumulative emergence over the first 21 days in the jute reinforcement/erosion mat treatment of B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-1.092	0.418	-2.610	0.0116
Water (cm)	0.027	0.012	2.289	0.026
Time Since Sod Was Transplanted	-1.141	0.191	-5.965	$1.64e^{-07}$

Null deviance: 5.1326 on 59 degrees of freedom, residual deviance: 2.8655 on 57 degrees of freedom (Dispersion parameter for quasi family taken to be 0.04436308).

Volunteer Weeds in Control Multispecies Sod Subplots vs. Bare Ground

Full Data Set With All Interactions (no significance found)

Table 11. Volunteer weed relative abundance in B_1 and B_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	1.1947	1.998	0.598	0.551
Water	-0.061	0.038	-1.608	0.110
Sod/Bare Ground	-1.596	1.523	-1.048	0.297
Time Since Sod Was Transplanted	1.344	1.213	1.108	0.270
Experiment	-0.463	0.391	-1.182	0.239
Water:Sod or Bare Ground	0.057	0.032	1.787	0.076
Water:Time Since Sod Was Transplanted	0.004	0.020	0.205	0.838
Sod/Bare Ground: Time Since Sod Was Transplanted	-1.867	0.939	-1.989	0.049

Null deviance: 15.9170 on 139 degrees of freedom, residual deviance: 7.3991 on 132 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1255112).

Full Data Set Without Non-significant Interactions

Table 12. Volunteer weed relative abundance in B_1 and B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	2.743	1.023	2.682	0.008
Water (cm)	-0.001	0.003	-0.183	0.855
Sod or Bare Ground	-2.497	0.418	-5.971	$1.97e^{-08}$
Time Since Sod Was Transplanted	-0.829	0.314	-2.637	0.009
Experiment	-0.510	0.419	-1.217	0.226

Null deviance: 15.9170 on 139 degrees of freedom, residual deviance: 8.5844 on 135 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1482383).

Control Multispecies Sod Without Non-significant Interactions

Table 13. Volunteer weed relative abundance in the control multispecies sod plots of B_1 and B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-1.289	1.855	-0.695	0.489
Water (cm)	0.053	0.033	1.614	0.109
Time Since Sod Was Transplanted	-2.303	0.954	-2.416	0.017
Experiment	-0.923	0.674	-1.369	0.174

Null deviance: 8.9566 on 115 degrees of freedom, residual deviance: 6.5839 on 112 degrees of freedom (Dispersion parameter for quasi family taken to be 0.149532).

Bare Ground Control Without Non-significant Interactions

Table 14. Volunteer weed relative abundance in the bare ground control plots of B_1 and B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-0.926	0.508	-1.823	0.083
Water (cm)	-0.001	0.002	-0.374	0.713
Time Since Sod Was Transplanted	-0.390	0.177	-2.196	0.040
Experiment	-0.181	0.252	-0.717	0.482

Null deviance: 0.88127 on 23 degrees of freedom, residual deviance: 0.70788 on 20 degrees of freedom (Dispersion parameter for quasi family taken to be 0.03361976).

Survival

Full Data Set With All Interactions (no significance found)

Table 15. *B. napus* survival in B_1 and B_2 of the first year. Second year not applicable because no emerged plants survived.

	Estimate	Standard Error	t-value	p-value
Intercept	4.422	1.469	3.011	0.002
Water (cm)	-0.003	0.051	-0.052	0.959
Material	-0.297	0.454	-0.654	0.514
Experiment	-0.676	0.393	-1.721	0.087
Water: Material	0.007	0.018	0.391	0.696

Null deviance: 29.201 on 194 degrees of freedom, residual deviance: 27.973 on 190 degrees of freedom (Dispersion parameter for quasi family taken to be 0.2789365).

Full Data Set Without Non-significant Interactions (no significance found)

Table 16. *B. napus* survival in B_1 and B_2 of the first year without non-significant interactions. Second year not applicable because no emerged plants survived.

	Estimate	Standard Error	t-value	p-value
Intercept	3.976	0.867	4.588	$8.09e^{-06}$
Water (cm)	0.018	0.020	0.802	0.424
Material	-0.130	0.150	-0.868	0.386
Experiment	-0.674	0.385	-1.751	0.082

Null deviance: 29.201 on 194 degrees of freedom, Residual deviance: 28.016 on 191 degrees of freedom (Dispersion parameter for quasi family taken to be 0.2685213).

Weed Productivity

Vegetative Biomass Full Data Set With All Significant Interactions

Table 17. *B. napus* vegetative biomass in B_1 and B_2 the first year. Second year not applicable because no emerged plants survived until harvest.

	Estimate	Standard Error	t-value	p-value
Intercept	46.652	55.478	0.841	0.401
Water (cm)	7.476	1.919	3.896	$1.36e^{-04}$
Material	-0.455	18.357	-0.025	0.980
Experiment	-77.196	16.195	-4.767	$3.77e^{-06}$
Number of Harvested Plants	4.511	0.948	4.76	$3.87e^{-06}$
Water: Material	0.439	0.694	0.629	0.530

Null deviance: 3561100 on 191 degrees of freedom, residual deviance: 1920251 on 186 degrees of freedom (Dispersion parameter for Gaussian family taken to be 10323.93).

Vegetative Biomass Full Data Set Without Non-significant Interactions

Table 18. *B. napus* vegetative biomass in B_1 and B_2 the first year without non-significant interactions. Second year not applicable because no emerged plants survived until harvest.

	Estimate	Standard Error	t-value	p-value
Intercept	19.781	35.334	0.56	0.576
Water (cm)	8.578	0.783	10.954	$< 2e^{-16}$
Material	10.296	6.681	1.541	0.125
Experiment	-77.047	16.167	-4.766	$3.77e^{-06}$
Number of Harvested Plants	4.492	0.946	4.75	$4.03e^{-06}$

Null deviance: 3561100 on 191 degrees of freedom, residual deviance: 1924335 on 187 degrees of freedom (Dispersion parameter for Gaussian family taken to be 10290.56).

Experiment B_1 Without Non-significant Interactions

Table 19. *B. napus* vegetative biomass in B_1 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-71.427	50.045	-1.427	0.158
Water (cm)	8.316	1.127	7.379	$2.53e^{-10}$
Material	10.311	12.915	0.798	0.427
Number of Harvested Plants	6.114	1.669	3.664	$4.79e^{-04}$

Null deviance: 2071983 on 73 degrees of freedom, residual deviance: 1045051 on 70 degrees of freedom (Dispersion parameter for Gaussian family taken to be 14929.30).

Experiment B_2 Without Non-significant Interactions

Table 20. *B. napus* vegetative biomass in B_2 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-124.369	40.501	-3.071	0.003
Water (cm)	9.497	1.227	7.740	$4.39e^{-12}$
Material	8.675	7.307	1.187	0.238
Number of Harvested Plants	2.935	1.119	2.622	0.010

Null deviance: 1438237 on 117 degrees of freedom, residual deviance: 848194 on 114 degrees of freedom (Dispersion parameter for Gaussian family taken to be 7440.295).

Seed Biomass Full Data Set With All Interactions

Table 21. *B. napus* seed biomass in B_1 and B_2 the first year. Second year not applicable because no emerged plants survived until harvest.

	Estimate	Standard Error	t-value	p-value
Intercept	-9.275	9.225	-1.005	0.316
Water (cm)	1.353	0.319	4.239	$3.53e^{-05}$
Material	0.075	3.053	0.025	0.980
Experiment	-9.024	2.693	-3.351	$9.76e^{-04}$
Number of Harvested Plants	0.450	0.158	2.855	0.005
Water: Material	0.024	0.116	0.203	0.839

Null deviance: 91462 on 191 degrees of freedom, residual deviance: 53099 on 186 degrees of freedom (Dispersion parameter for Gaussian family taken to be 285.4758).

Seed Biomass Full Data Set Without Non-significant Interactions

Table 22. *B. napus* seed biomass in B_1 and B_2 the first year without non-significant interactions. Second year not applicable because no plants survived until harvest.

	Estimate	Standard Error	t-value	p-value
Intercept	-10.7206	5.8706	-1.826	0.069
Water (cm)	1.412	0.1306	10.854	$< 2e^{-16}$
Material	0.654	1.11	0.589	0.557
Experiment	-9.016	2.686	-3.357	$9.55e^{-04}$
Number of Harvested Plants	0.449	0.1576	2.858	0.005

Null deviance: 91462 on 191 degrees of freedom, residual deviance: 53110 on 187 degrees of freedom (Dispersion parameter for Gaussian family taken to be 284.0124).

Experiment B_1 Without Non-significant Interactions

Table 23. *B. napus* seed biomass in B_1 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-27.022	9.212	-2.933	0.00
Water (cm)	1.484	0.208	7.154	$6.55e^{-10}$
Material	1.013	2.377	0.426	0.671
Number of Harvested Plants	0.824	0.307	2.684	0.009

Null deviance: 65223 on 73 degrees of freedom, residual deviance: 35413 on 70 degrees of freedom (Dispersion parameter for Gaussian family taken to be 505.8949).

Experiment B_2 Without Non-significant Interactions

Table 24. *B. napus* seed biomass in B_2 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-19.236	5.591	-3.440	$8.12e^{-4}$
Water (cm)	0.170	0.169	7.741	$4.36e^{-12}$
Material	0.161	1.009	0.160	0.873
Number of Harvested Plants	0.143	0.155	0.924	0.358

Null deviance: 25632 on 117 degrees of freedom, residual deviance: 16165 on 114 degrees of freedom (Dispersion parameter for Gaussian family taken to be 141.8004).

Multispecies Sod Biomass

Full Data Set With All Interactions

Table 25. Final multispecies sod biomass (2008 after 3 years in B_1; 2007 after 2 years in B_2).

	Estimate	Standard Error	t-value	p-value
Intercept	171.830	16.466	10.435	$<2e^{-16}$
Water	1.096	0.514	2.133	0.034
Material	-6.402	4.977	-1.286	0.200
Experiment	-5.866	4.958	-1.183	0.238
Water: Material	0.202	0.185	1.093	0.276

Null deviance: 269046 on 190 degrees of freedom, residual deviance: 197409 on 186 degrees of freedom (Dispersion parameter for Gaussian family taken to be 1061.337).

Full Data Set Without Non-significant Interactions

Table 26. Final multispecies sod biomass (2008 after 3 years in B_1; 2007 after 2 years in B_2) without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	159.429	11.936	13.357	$< 2e^{-16}$
Water	1.607	0.213	7.532	$2.07e^{-12}$
Material	-1.475	2.105	-0.7	0.485
Experiment	-5.901	4.961	-1.19	0.236

Null deviance: 269046 on 190 degrees of freedom, residual deviance: 198676 on 187 degrees of freedom (Dispersion parameter for Gaussian family taken to be 1062.436).

Senescing/Dormant Multispecies Sod

Full Data Set With All Interactions

Table 27. Senescing/dormant sod relative abundance in B_1 and B_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	7.695	1.856	4.145	$4.05e^{-05}$
Material	-0.324	0.600	-0.54	0.589
Water (cm)	-0.271	0.088	-3.09	0.002
Time Since Sod Was Transplanted	-4.645	1.546	-3.004	0.003
Experiment	-0.745	0.272	-2.737	0.006
Material: Water	0.024	0.016	1.486	0.138
Water: Time Since Sod Was Transplanted	0.048	0.068	0.711	0.477
Material: Time Since Sod Was Transplanted	0.035	0.489	0.072	0.943

Null deviance: 102.698 on 467 degrees of freedom, residual deviance: 25.439 on 460 degrees of freedom (Dispersion parameter for quasi family taken to be 0.244707).

Full Data Set Without Non-significant Interactions

Table 28. Senescing/dormant sod relative abundance in B_1 and B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	6.016	1.061	5.671	$2.50e^{-08}$
Material	0.081	0.154	0.530	0.596
Water (cm)	-0.156	0.026	-5.969	$4.75e^{-09}$
Time Since Sod Was Transplanted	-3.950	0.771	-5.122	$4.45e^{-07}$
Experiment	-0.787	0.376	-2.093	0.037

Null deviance: 102.698 on 467 degrees of freedom, residual deviance: 26.100 on 463 degrees of freedom (Dispersion parameter for quasi family taken to be 0.4838778).

Experiment B_1 Without Non-significant Interactions

Table 29. Senescing/dormant sod relative abundance in B_1 without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	4.683	0.801	5.849	$1.74e^{-08}$
Material	-0.010	0.144	-0.066	0.947
Water (cm)	-0.155	0.024	-6.45	$6.81e^{-10}$
Time Since Sod Was Transplanted	-3.226	0.560	-5.763	$2.71e^{-08}$

Null deviance: 67.424 on 227 degrees of freedom, residual deviance: 12.739 on 224 degrees of freedom (Dispersion parameter for quasi family taken to be 0.2624221).

Experiment B_1, First Year Since Sod Was Transplanted Without Non-significant Interactions

Table 30. Senescing/dormant sod relative abundance in B_1 the first year without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	1.476	0.373	3.956	$1.75e^{-04}$
Material	-0.021	0.105	-0.203	0.840
Water (cm)	-0.154	0.017	-8.943	$2.39e^{-13}$

Null deviance: 30.6608 on 75 degrees of freedom, residual deviance: 9.4305 on 73 degrees of freedom (Dispersion parameter for quasi family taken to be 0.130498).

Experiment B_1, Second Year Since Sod Was Transplanted Without Non-Significant Interactions (no significance found)

Table 31. Senescing/dormant sod relative abundance in B_1 the second year without non-significant interactions.

	Estimate	Standard Error	t-value	P-value
Intercept	39.564	3362.260	0.012	0.991
Material	0.237	0.142	1.663	0.101
Water (cm)	-4.420	343.965	-0.013	0.990

Null deviance: 3.1875 on 75 degrees of freedom, residual deviance: 1.0576 on 73 degrees of freedom (Dispersion parameter for quasi family taken to be 0.01303245).

Experiment B_1 Third Year Since Sod Was Transplanted Without Non-significant Interactions (no significance found)

Table 32. Senescing/dormant sod relative abundance in B_1 the third year without non-significant interactions.

	Estimate	Standard Error	t-value	P-value
Intercept	-4.805	1.910	-2.516	0.014
Material	-0.143	0.606	-0.236	0.814
Water (cm)	-0.046	0.055	-0.839	0.405

Null deviance: 1.1053 on 75 degrees of freedom, residual deviance: 1.0517 on 73 degrees of freedom (Dispersion parameter for quasi family taken to be 0.06648804).

Experiment B_2 Without Non-significant Interactions

Table 33. Senescing/dormant sod relative abundance in B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	7.561	1.855	4.076	$6.25e^{-05}$
Material	0.231	0.106	2.176	0.0305
Water (cm)	-0.176	0.020	-8.625	$9.49e^{-16}$
Time Since Sod Was Transplanted	-7.014	1.739	-4.033	$7.43e^{-05}$

Null deviance: 30.955 on 239 degrees of freedom, residual deviance: 11.908 on 236 degrees of freedom (Dispersion parameter for quasi family taken to be 0.08739667).

Experiment B_2, First Year Since Sod Was Transplanted Without Non-significant Interactions

Table 34. Senescing/dormant sod relative abundance in B_2 the first year without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	0.559	0.656	0.852	0.396
Material	0.233	0.143	1.637	0.104
Water (cm)	-0.177	0.028	-6.444	$2.70e^{-09}$

Null deviance: 20.503 on 119 degrees of freedom, residual deviance: 11.647 on 117 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1566992).

Experiment B_2 Second Year Since Sod Was Transplanted Without Non-significant Interactions (no significance found)

Table 35. Senescing/dormant sod relative abundance in B_2 the second year without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-6.558	1.924	-3.408	8.98e-4
Material	-0.186	0.609	-0.305	0.761
Water (cm)	-0.070	0.070	-1.010	0.315

Null deviance: 0.24537 on 119 degrees of freedom, residual deviance: 0.22971 on 117 degrees of freedom (Dispersion parameter for quasi family taken to be 0.01340412).

Species Richness

Full Data Set With All Interactions

Table 36. Species richness in B_1 and B_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	2.703	0.427	6.327	$5.93e^{-10}$
Material	0.077	0.118	0.654	0.514
Water (cm)	-0.030	0.013	-2.333	0.020
Time Since Sod Was Transplanted	-0.585	0.183	-3.199	0.001
Experiment	0.479	0.083	5.804	$1.21e^{-08}$
Material: Water	0.001	0.003	0.329	0.743
Material: Time Since Sod Was Transplanted	-0.081	0.048	-1.678	0.094
Water: Time Since Sod Was Transplanted	0.022	0.005	4.526	$7.66e^{-06}$

Null deviance: 390.38 on 467 degrees of freedom, residual deviance: 318.94 on 460 degrees of freedom (Dispersion parameter for Gaussian family taken to be 0.6933386).

Full Data Set Without Non-significant Interactions

Table 37. Species richness in B_1 and B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	2.989	0.321	9.300	$< 2e^{-16}$
Water (cm)	-0.027	0.010	-2.739	0.006
Material	-0.037	0.035	-1.074	0.283
Time Since Sod Was Transplanted	-0.787	0.138	-5.707	$2.05e^{-08}$
Experiment	0.479	0.083	5.792	$1.29e^{-08}$
Water: Time Since Sod Was Transplanted	0.022	0.005	4.524	$7.74e^{-06}$

Null deviance: 390.38 on 467 degrees of freedom, residual deviance: 320.93 on 462 degrees of freedom (Dispersion parameter for Gaussian family taken to be 0.6946517).

Experiment B_1 Without Non-significant Interactions

Table 38. Species richness in B_1 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	3.754	0.317	11.854	$< 2e^{-16}$
Water (cm)	-0.030	0.011	-2.829	0.0051
Time Since Sod Was Transplanted	-0.821	0.141	-5.825	$1.97e^{-08}$
Material	-0.060	0.045	-1.312	0.1908
Water: Time Since Sod Was Transplanted	0.021	0.005	4.163	$4.49e^{-05}$

Null deviance: 158.21 on 227 degrees of freedom, residual deviance: 131.36 on 223 degrees of freedom (Dispersion parameter for Gaussian family taken to be 0.5890415).

Experiment B_2 Without Non-significant Interactions

Table 39. Species richness in B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	4.550	0.664	6.849	$6.45e^{-11}$
Water (cm)	-0.070	0.025	-2.795	0.006
Time Since Sod Was Transplanted	-1.365	0.367	-3.718	$2.51e^{-04}$
Material	-0.012	0.050	-0.245	0.806
Water: Time Since Sod Was Transplanted	0.057	0.014	3.992	$8.78e^{-05}$

Null deviance: 199.00 on 239 degrees of freedom, residual deviance: 174.89 on 235 degrees of freedom (Dispersion parameter for Gaussian family taken to be 0.7442073).

Species Diversity

Full Data Set With All Interactions

Table 40. Species diversity in B_1 and B_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	1.579	0.504	3.131	0.002
Material	0.021	0.135	0.155	0.877
Water (cm)	-0.088	0.017	-5.218	$2.75e^{-07}$
Time Since Sod Was Transplanted	-1.924	0.262	-7.335	$1.01e^{-12}$
Experiment	0.127	0.102	1.232	0.218
Material: Water	0.003	0.004	0.583	0.560
Material: Time Since Sod Was Transplanted	-0.054	0.063	-0.855	0.393
Water: Time Since Sod Was Transplanted	0.0591	0.007	8.524	$2.22e^{-16}$

Null deviance: 111.90 on 467 degrees of freedom, residual deviance: 86.35 on 460 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1860888).

Full Data Set Without Non-significant Interactions

Table 41. Species diversity in B_1 and B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	1.631	0.386	4.223	$2.90e^{-05}$
Water (cm)	-0.081	0.012	-6.501	$2.08e^{-10}$
Material	-0.001	0.042	-0.018	0.986
Time Since Sod Was Transplanted	-2.059	0.211	-9.764	$< 2e^{-16}$
Experiment	0.125	0.102	1.231	0.219
Water: Time Since Sod Was Transplanted	0.059	0.007	8.568	$< 2e^{-16}$

Null deviance: 111.895 on 467 degrees of freedom, residual deviance: 86.507 on 462 degrees of freedom (Dispersion parameter for quasi family taken to be 0.1839168).

Relative Abundance of *P. compressa*

Full Data Set With All Interactions

Table 42. Relative abundance of *P. compressa* in B_1 and B_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	-1.445	0.800	-1.806	0.072
Material	0.201	0.215	0.932	0.352
Water (cm)	0.039	0.026	1.518	0.130
Time Since Sod Was Transplanted	2.725	0.464	5.87	$8.36e^{-09}$
Experiment	-0.368	0.158	-2.334	0.020
Material: Water	0.002	0.007	0.29	0.772
Material: Time Since Sod Was Transplanted	-0.155	0.102	-1.516	0.130
Water: Time Since Sod Was Transplanted	-0.056	0.012	-4.728	$3.03e^{-06}$

Null deviance: 213.63 on 467 degrees of freedom, residual deviance: 164.81 on 460 degrees of freedom (Dispersion parameter for quasi family taken to be 0.4357112).

Full Data Set Without Non-significant Interactions

Table 43. Relative abundance of *P. compressa* in B_1 and B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-0.976	0.655	-1.49	0.137
Water (cm)	0.044	0.020	2.161	0.031
Material	0.016	0.067	0.235	0.815
Time Since Sod Was Transplanted	2.328	0.391	5.959	$5.04e^{-09}$
Experiment	-0.366	0.164	-2.236	0.026
Water: Time Since Sod Was Transplanted	-0.055	0.012	-4.544	$7.05e^{-06}$

Null deviance: 213.63 on 467 degrees of freedom, residual deviance: 165.84 on 462 degrees of freedom (Dispersion parameter for quasi family taken to be 0.4707181).

Experiment B_1 Without Non-significant Interactions

Table 44. Relative abundance of *P. compressa* in B_1 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-2.703	0.707	-3.824	$1.7e^{-04}$
Water (cm)	0.132	0.024	5.55	$8.08e^{-08}$
Material	-0.107	0.098	-1.091	0.276
Time Since Sod Was Transplanted	2.708	0.429	6.314	$1.45e^{-09}$
Water: Time Since Sod Was Transplanted	-0.082	0.013	-6.283	$1.72e^{-09}$

Null deviance: 88.973 on 227 degrees of freedom, residual deviance: 64.338 on 223 degrees of freedom (Dispersion parameter for quasi family taken to be 0.4240146).

Experiment B_2 Without Non-significant Interactions

Table 45. Relative abundance of *P. compressa* in B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	5.624	1.185	4.746	$3.61e^{-06}$
Water (cm)	-0.267	0.043	-6.201	$2.50e^{-09}$
Material	0.129	0.076	1.687	0.093
Time Since Sod Was Transplanted	-1.308	0.712	-1.838	0.067
Water: Time Since Sod Was Transplanted	0.098	0.026	3.756	$2.18e^{-04}$

Null deviance: 120.536 on 239 degrees of freedom, residual deviance: 64.684 on 235 degrees of freedom (Dispersion parameter for quasi family taken to be 0.2845591).

Relative Abundance of *P. pratensis*

Full Data Set With All Interactions (no significance found)

Table 46. Relative abundance of *P. pratensis* in B_1 and B_2 in all years.

	Estimate	Standard Error	t-value	p-value
Intercept	-2.368	1.176	-2.014	0.045
Material	-0.334	0.327	-1.022	0.307
Water (cm)	0.021	0.033	0.626	0.532
Time Since Sod Was Transplanted	-0.524	0.519	-1.009	0.313
Experiment	-0.349	0.229	-1.524	0.128
Material: Water	0.002	0.009	0.209	0.834
Material: Time Since Sod Was Transplanted	0.1778	0.124	1.434	0.152
Water: Time Since Sod Was Transplanted	0.004	0.013	0.318	0.7503

Null deviance: 70.287 on 467 degrees of freedom, residual deviance: 65.660 on 460 degrees of freedom (Dispersion parameter for quasi family taken to be 0.2285961).

Full Data Set With Without Non-significant Interactions

Table 47. Relative abundance of *P. pratensis* in B_1 and B_2 in all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-3.547	0.649	-5.468	$7.44e^{-08}$
Water (cm)	0.034	0.010	3.276	0.001
Material	0.043	0.094	0.454	0.650
Time Since Sod Was Transplanted	0.053	0.149	0.354	0.723
Experiment	-0.354	0.233	-1.52	0.129

Null deviance: 70.287 on 467 degrees of freedom, residual deviance: 66.205 on 463 degrees of freedom (Dispersion parameter for quasi family taken to be 0.2371212).

APPENDIX C

PERENNIAL WEED VEGETATIVE PROPAGULE SUPPRESSION BY MULTISPECIES SOD (# explains action)

Mean *Cirsium arvense* Ramet Density

Full Data Set With All Interactions

```
# Read data into R
A=read.table("alljuly2.txt",header=T)

# List data column names
names(A)

# Fit density model with all independent variables
density<-
glm(number.in.plot~year*water+year*habitat.bare.sod+water*habitat.bare.sod+hexagon+
interior.density,data=A)

# Show model results table
summary(density)

# Difference found in year, year: habitat interaction, and water: habitat interaction
```

Full Data Set Without Non-significant Interactions

```
# Fit density model with all independent variables
density<-
glm(number.in.plot~year*habitat.bare.sod+water*habitat.bare.sod +hexagon+
interior.density,data=A)

# Show model results table
summary(density)

# Difference found in year, water, year: habitat interaction, and water: habitat interaction
```

Mean Maximum Distance *C. arvense* Ramets Spread With All Interactions

Full Data Set With All Interactions

```
# Read data into R
A=read.table("alljuly2.txt",header=T)
```

```
# List data column names
names(A)

# Fit distance model with all independent variables
distance<-
glm(max.distance.in.plot~year*water+year*habitat.bare.sod+water*year+hexagon+
interior.density,data=A)

# Show model results table
summary(distance)

# Difference found in year
```

Full Data Set Without Non-significant Interactions

```
# Fit distance model with all independent variables
distance<-
glm(max.distance.in.plot~year+habitat.bare.sod+water+hexagon+interior.density,data=A)

# Show model results table
summary(distance)

# Difference found in year and habitat
```

Bare Habitat Without Non-significant Interactions

```
# Fit distance model with independent variables
distance<-
glm(max.distance.in.plot~year+water+hexagon+interior.density,data=subset(A,
habitat.bare.sod==’bare’))

# Show model results table
summary(distance)

# Difference found in year
```

Multispecies Sod Habitat Without Non-significant Interactions

```
# Fit distance model with independent variables
distance<-
glm(max.distance.in.plot~year+water+hexagon+interior.density,data=subset(A,
habitat.bare.sod==’sod’))

# Show model results table
summary(distance)

# Difference found in year
```

Mean *Cirsium arvense* Flowering Ramet Density With All Interactions

Full Data Set With All Interactions

```
# Read data into R
A=read.table("alljuly2.txt",header=T)

# List data column names
names(A)

# Fit flowering density model with all independent variables
flower<-
glm(flowering.in.plot~year*water+year*habitat.bare.sod+water*habitat.bare.sod
+hexagon+interior.density,data=A)

# Show model results table
summary(flower)

# Difference found in year, year: water interaction, year: habitat interaction, and water:
habitat interaction
```

Analysis Output Tables

Mean *Cirsium arvense* Ramet Density

Full Data Set With All Interactions

Table 1. *Cirsium arvense* ramet density in July of all years.

	Estimate	Standard Error	t-value	p-value
Intercept	-28.271	22.084	-1.28	0.211
Year	43.419	8.364	5.191	$1.82e^{-05}$
Water (cm)	-0.138	0.664	-0.207	0.837
Bare/Sod	-4.237	17.180	-0.247	0.807
Hexagon ID	0.991	1.349	0.734	0.469
Interior Hexagon Density	-0.434	0.795	-0.547	0.589
Year:Water	-0.484	0.264	-1.831	0.078
Year:Bare/Sod	-26.787	5.751	-4.658	$7.63e^{-05}$
Water:Bare/Sod	1.124	0.393	2.863	0.008

Null deviance: 27641.6 on 35 degrees of freedom, residual deviance: 5340.8 on 27 degrees of freedom (Dispersion parameter for Gaussian family taken to be 197.8093).

Full Data Set Without Non-significant Interactions

Table 2. *Cirsium arvense* ramet density in July of all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	0.960	15.888	0.06	0.952
Year	30.037	4.234	7.093	$1.02e^{-07}$
Bare/Sod	-5.271	17.877	-0.295	0.770
Water (cm)	-1.228	0.306	-4.015	$4.04e^{-04}$
Hexagon ID	0.632	1.390	0.455	0.653
Interior Hexagon Density	-0.052	0.798	-0.065	0.949
Year: Bare/Sod	-26.766	5.987	-4.47	$1.18e^{-04}$
Water: Bare/Sod	1.150	0.408	2.816	0.009

Null deviance: 27642 on 35 degrees of freedom, residual deviance: 6004 on 28 degrees of freedom (Dispersion parameter for Gaussian family taken to be 214.4306).

Mean Maximum Distance *C. arvense* Ramets Spread With All Interactions

Full Data Set With All Interactions

Table 3. Maximum distance *C. arvense* ramets spread in July of all years.

	Estimate	Standard Error	t-value	p-value
Intercept	-73.743	64.492	-1.143	0.263
Year	89.323	24.425	3.657	0.001
Water (cm)	0.069	1.938	0.036	0.972
Bare/Sod	28.189	50.168	0.562	0.579
Hexagon ID	-0.503	3.940	-0.128	0.899
Interior Hexagon Density	0.799	2.320	0.345	0.733
Year:Water	-0.240	0.772	-0.312	0.758
Year:Bare/Sod	-23.684	16.793	-1.41	0.170
Water:Bare/Sod	-0.778	1.1465	-0.678	0.503

Null deviance: 192326 on 35 degrees of freedom, residual deviance: 45546 on 27 degrees of freedom (Dispersion parameter for Gaussian family taken to be 1686.882).

Full Data Set Without Non-significant Interactions

Table 4. Maximum distance *C. arvense* ramets spread in July of all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-24.535	37.079	-0.662	0.513
Year	70.830	8.319	8.514	$1.68e^{-09}$
Water (cm)	-0.864	0.620	-1.393	0.174
Bare/Sod	-41.568	13.602	-3.056	0.005
Hexagon ID	-0.810	3.857	-0.21	0.835
Interior Hexagon Density	1.100	2.211	0.497	0.623

Null deviance: 192326 on 35 degrees of freedom, residual deviance: 49651 on 30 degrees of freedom (Dispersion parameter for Gaussian family taken to be 1655.019).

Bare Habitat Without Non-significant Interactions

Table 5. Maximum distance *C. arvense* ramets spread in the bare habitat in July of all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-62.328	46.632	-1.337	0.204
Year	82.698	10.862	7.614	$3.83e^{-06}$
Water (cm)	-0.443	0.811	-0.546	0.594
Hexagon ID	1.383	5.206	0.266	0.795
Interior Hexagon Density	0.092	2.876	0.032	0.975

Null deviance: 101943 on 17 degrees of freedom, residual deviance: 18338 on 13 degrees of freedom (Dispersion parameter for Gaussian family taken to be 1410.577).

Multispecies Sod Habitat Without Non-significant Interactions

Table 6. Maximum distance *C. arvense* ramets spread in the multispecies sod habitat in July of all years without non-significant interactions.

	Estimate	Standard Error	t-value	p-value
Intercept	-30.883	59.839	-0.516	0.614
Year	59.016	13.153	4.487	$6.12e^{-10}$
Water (cm)	-1.219	0.988	-1.234	0.239
Hexagon ID	-2.432	5.937	-0.41	0.689
Interior Hexagon Density	1.787	3.551	0.503	0.623

Null deviance: 75526 on 17 degrees of freedom, residual deviance: 26888 on 13 degrees of freedom (Dispersion parameter for Gaussian family taken to be 2068.345).

Mean *Cirsium arvense* Flowering Ramet Density With All Interactions

Full Data Set With All Interactions

Table 7. Density of flowering *C. arvense* ramets in July of all years.

	Estimate	Standard Error	t-value	p-value
Intercept	-37.525	21.372	-1.756	0.090
Year	38.468	8.094	4.752	$5.92e^{-05}$
Water (cm)	0.252	0.642	0.392	0.698
Bare/Sod	1.144	16.626	0.069	0.946
Hexagon ID	1.017	1.306	0.779	0.443
Interior Hexagon Density	-0.401	0.769	-0.522	0.606
Year:Water	-0.535	0.256	-2.092	0.046
Year:Bare/Sod	-21.036	5.565	-3.78	0.001
Water:Bare/Sod	0.884	0.380	2.326	0.028

Null deviance: 17799 on 35 degrees of freedom, residual deviance: 5002 on 27 degrees of freedom (Dispersion parameter for Gaussian family taken to be 185.2579).

APPENDIX D

THE COMBINED EFFECT OF MULTISPECIES SOD AND REINFORCEMENT MATERIAL ON SOIL MOISTURE RETENTION: A FIELD STUDY

Introduction

In addition to the other objectives detailed in Chapter 2, experiments B_1 and B_2 were intended to evaluate the effect of multispecies sod, in combination with four reinforcement materials, on soil water retention in the field. Technical issues interfered with the data collection. Consequently, this section of the experiment is reported here. This appendix details the data collection procedure and the technical issues from experiments B_1 and B_2 in hope that future studies involving gypsum block and Time Domain Reflectometry (TDR) data go more smoothly.

Literature Review on Problems Associated with Gypsum Block and TDR Data Collection

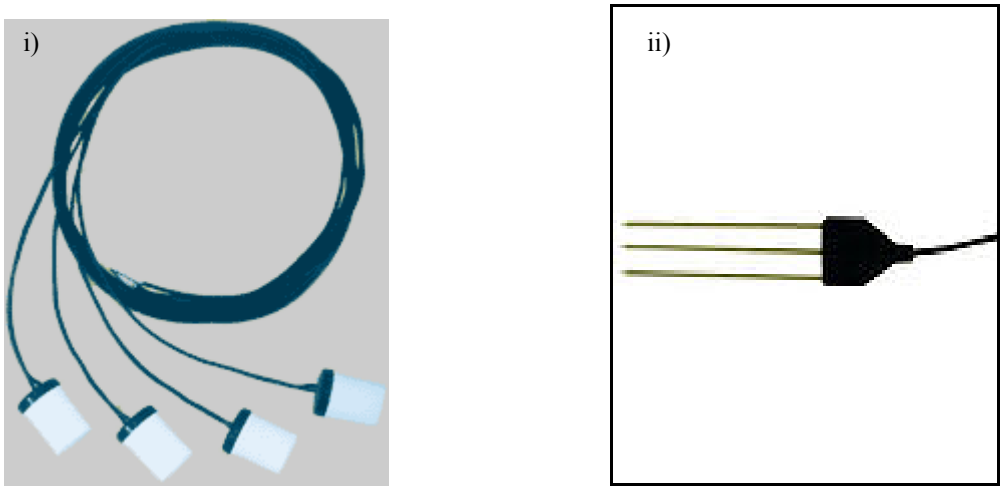
Gypsum blocks (Figure 1 i) measure soil water potential. They are one of the soil moisture techniques in widest use (Perrier & Marsh, 1958) because they are affordable and fairly simple to use. The principle is that the resistance of the steel electrodes encapsalated in gypsum ($CaSO_4$) blocks is proportional to the water content of the gypsum. While some studies have found gypsum block data to be reliable (Bouyoucos & Mick, 1947; Stenitzer, 1993) others have found the reliability of the data to be limited (Perrier & Marsh, 1958; Zazueta & Xin, 1994; Polak & Wallach, 2001; Hillel, 2004).

Water content as well as soil composition, texture and soluble salt concentration all affect electrical resistance in soil (Hillel, 2004). Gypsum block's equilibrium with soil moisture can also be affected by hysteresis (a lag response to a change in force), inadequate soil contact, and soil temperature (Hillel, 2004). Furthermore, gypsum blocks have the

tendency to disintegrate in wet soil or when in contact with plant roots creating inconsistent deterioration between the sensors over time (Perrier & Marsh, 1958; Hillel, 2004). For these reasons, in general, soil moisture measured by gypsum blocks is thought to have limited accuracy (Perrier & Marsh, 1958; Zazueta & Xin, 1994; Hillel, 2004). Prevost et al. (1990) found that gypsum blocks were only accurate up to 3 bars and occasionally were not able to register values between 0-0.3 bars, limiting the accurate range of the sensors. Additionally, Aho and Weaver (in press) state that gypsum block readings have high variability in dry soils, and that gypsum block readings underestimate soil water potentials when the surrounding soil has been wetted recently. My experiment required frequent and regular irrigation in the high water regime, as well as contained very dry soil in the low water regimes, suggesting potentially confounding results caused by the gypsum blocks and their limited range of accuracy.

As an alternative to gypsum blocks, Time Domain Reflectometry (TDR) (Figure 1 ii) was used to measure soil water content (not soil water potential as with gypsum blocks) in 2007. Gypsum blocks continued to be monitored to calibrate the relationship between soil water potential and soil water content. TDR is method that uses a datalogger to record the time it takes for an electromagnetic wave to travel the length of a steel rod (TDR probe). The datalogger is programmed to determine the start and end of the probe and produce a propagation velocity waveform that can be converted into a dielectric constant (k) (see Kirkham, 2005 for full mathmatical equations). The k value can then be used in either the Ledieu ($\theta = k\,(0.1138) - 0.1758$) (Ledieu et al., 1986) or Topp ($\theta = -5.3 \times 10^{-2} + 2.9 \times 10^{-2}(k) - 5.5 \times 10^{-4}(k)^2 + 4.3 \times 10^{-6}(k)^3$ (Topp et al., 1980) equation to calculate soil water content.

The datalogger can be programmed to make this calculation automatically. Even though some scientists disagree (Herkelrath et al., 1991; Dirksen & Dasberg, 1993), the relationship between *k* and volumetric water content is generally thought to be independent of soil type and density (Topp et al., 1980; Patterson & Smith, 1981; Ledieu et al., 1986) thereby validating the general use of either the Ledieu or Topp equation for any soil type.



Gypsum block
(Image from www.esf.edu)

TDR probe
(Image from www.campbellsci.ca)

Figure 1. Gypsum block and TDR probe illustrations.

A TDR probe consists of two or three rods. The benefit of having rods spaced further apart (two-rod design) is that the magnitude of measured resistance increases across the rods as well as the design makes it easier to insert the rods into soil without hitting an obstacle (Robinson et al., 2003). A three rod design has a smaller sampling area, and may be slightly more accurate because it is a more balanced design (Zegelin et al., 1989; Whalley, 1993).

While the TDR technique is generally thought of as one of the more reliable in-situ, non-radioactive options for measuring soil water (Cary & Fisher, 1983; Ledieu et al., 1986) some studies have found limitations to TDR accuracy (Hook & Livingston, 1995; Mastrorilli et al., 1998; Noborio, 2001; Castiglione & Shouse, 2003). One of the main errors in TDR measurements can be from the travel time analysis (Hook & Livingston, 1995) used to determine apparent propagation velocity. There is a certain degree of ambiguity to determining the second reflection point in a TDR waveform (Figure 2), that could be influenced by the soil's texture, electrical conductivity, and density, as well as by the probe system (Lin, 2003). This suggests that a waveform could be misinterpreted by the TDR system if something in the soil interrupts the waveforms continuity and as a result the second reflection is misplaced. For example, Mailapalli et al. (2008) studied TDR performance by calculating the absolute prediction error (APE) and the root mean square error (RMSE) and found both errors to be larger in a cropped field compared to a bare field subject to the same irrigation rate, suggesting that the roots from the crops may interfere with the TDR waveform. Furthermore, cracks in the soil have been shown to complicate soil water calculations (Mastrorilli et al., 1998) by accumulating air and water (Hokett et al., 1992) that do not accurately represent the general soil composition. Wet soil may also cause a wave propagation to be dispersive, making it more difficult to clearly define exact arrival times to calculate the propagation velocity (Lin, 2003).

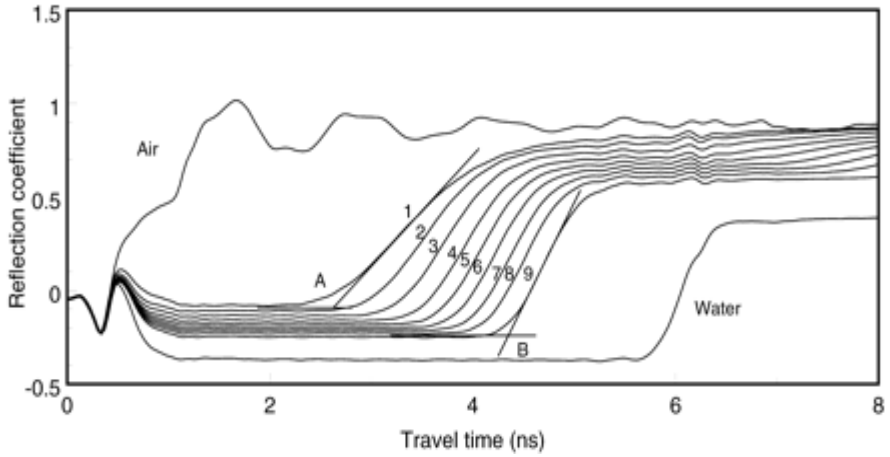


Fig 2. Waveforms collected in air, water, and propanol–water mixtures. Water increases from waveforms 1 through 9. Fitted tangent lines at reflection points are demonstrated at locations A and B (Robinson et al. (2003), Figure
from http://vzj.scijournals.org/cgi/content/figsonly/2/4/444).

The length of the probe (Kane & Stein, 1985), use of long cables (Heimovaara, 1993; Hook & Livingston, 1995), presence of dissolved ions (Hook & Livingston, 1995), and soil temperature (Or & Wraith, 1999) have also all been shown to cause travel time errors. Additionally, high soil electrical conductivity can inhibit the second reflection in a TDR waveform (Jones & Or, 2001) because attenuation of electromagnetic waves decreases the amplitude of the reflected signal (Noborio, 2001).

Even though gypsum blocks and TDR have been used to measure soil moisture since 1940 (Bouyoucos & Mick, 1947) and 1975 (Davis & Chudobiak, 1975) respectively, the variation in results throughout different studies suggests that both techniques have limitations.

Data Collection for Experiments B_1 and B_2

Gypsum block data were collected using soil gypsum blocks and a soil moisture meter (KS-D1) manufactured by Delmhorst Instrament Company (Towaco, NJ). The KS-D1 manual (Delmhorst, 2009) states that the interpretation of the moisture meter readings is "soil moisture tension" on a scale of 5.0-100.0, and that "readings outside of this range should be disregarded". The data collected from B_1 and B_2 began within range, but quickly deteriorated for unknown reasons (Figure 3). The electrical conductivity (ECe) of the soil in the experimental field is 0.4 ds/m and so should not have interfered with the gypsum block readings. It can only be assumed that the problems known to be associated with gypsum block data, such as variability in dry soil (Prevost et al., 1990), hysteresis from fluctuations between dry and wet soil (Hillel, 2004), and deterioration of blocks over time and in the presence of plant roots (Perrier & Marsh, 1958; Hillel, 2004), were relevant to this experiment. Furthermore, the gypsum block accuracy range of 0.3-3.0 bars that Prevost et al. (1990) found corresponds to Dehlmhorst moisture readings roughly between 37-95. Even though Dehlmhorst claims that moisture meter readings between 5.0-100.0 are accurate (Dehlmhorst, 2009), Prevost et al.'s (1990) accuracy findings may lend some insight into the large variability within my data, especially in the natural precipitation treatment where the soils presumably became very dry, thus below a Dehlmhorst 37 reading, over time. Because the gypsum block data was so inconsistent during the summer of 2006 (Figure 3), indicating potentially counfounded results, the primary technique used to collect soil moisture data in 2007 became TDR.

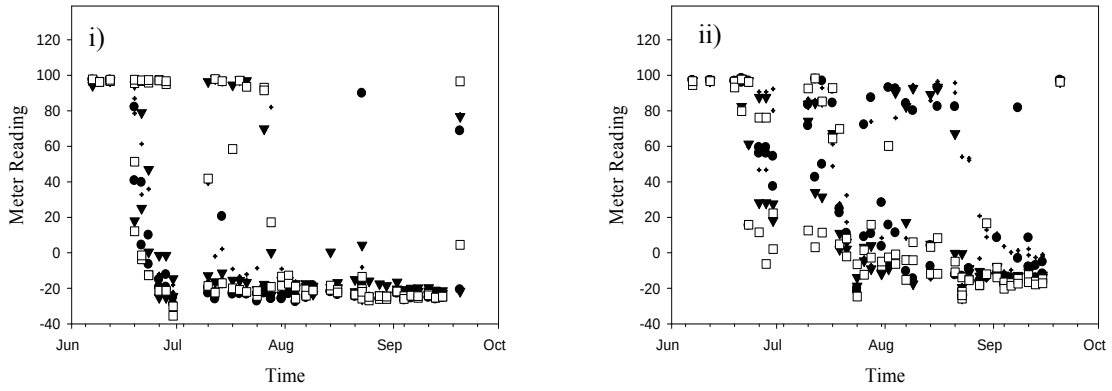


Figure 3. Dehlmhorst moisture meter readings per reinforcement material at 15.24 cm below the reinforcement materials and multispecies sod in 2006. Data from the morning before supplemental irrigation was applied on days with no natural precipitation within the previous 24 hours: i) low water regime, ii) high water regime. Symbols represent each reinforcement material (● coconut-straw, + excelsior, ▼ jute, □ control).

Time Domain Reflectometry (TDR) data in B_1 and B_2 were collected using CR10x (stationary system) and CR1000 (portable system) dataloggers, TDR100's, and SDMX50SP multiplexers, along with LoggerNet 3.3.1 and PCTDR software to write programs and to communicate with the dataloggers. All products are manufactured by Campbell Scientific, Inc. (Logan, Utah). It was predetermined that even though there was a small timing difference between the data collected with the stationary system (by the data logger) compared to the portable system (timing activated by human), the results should have been similar enough that the data could have been compared and analyzed together, as long as the system used was included as a covariate in analysis.

The downfall of data collected from B_1 and B_2 was mainly a combination of technological and human error. In 2007 thirty-six probes were constructed by hand (see TDR probe construction instructions, pg. 226). Constructing probes by hand has the

advantage of costing less as well as custom design (Robinson et al., 2003). Because so many probes were needed for adequate replications in the experiment, purchasing commercial probes was not feasible. The first human error began during this construction process. Each constructed probe was tested by a cable tester (1502B Tektronix, Richardson, TX), prior to being solidified in Epoxy, to determine the working function of the probe. In retrospect, I was not qualified to determine the difference between a good waveform and a mediocre waveform based on my limited TDR knowledge. What I thought to be good waveforms have since been proven to be mediocre if not bad waveforms from further analysis of the field collected waveforms with a more qualified soil physicist. Figure 4 demonstrates how waveforms change in different media with different moisture. For example a waveform in water should take more time than a waveform in air. The position of the tangent lines are also very important. Baker and Allmaras (1990) detailed how an algorithm can be used to determine the initial and final reflection points for these tangent lines. In their method, the maximum derivative of the data is the tangent line slope at the final reflection (demonstrated in Figure 4, water). The intersection between this tangent line and the horizontal line (the minimum value between the initial and final reflection) is the final refection point (Baker & Allmaras, 1990). The initial reflection point is found in a similar manner (Baker & Allmaras, 1990). To the best of my knowledge this can be simplified by the "hump" (a reflection of the TDR probe handle) that initiates the waveform being referred to as the initial reflection point. The time it takes to travel the "hump" of the probe handle is determined in probe calibration and subtracted from the propagation velocity as an offset in the water content equation. The final reflection point is then at the exact point in time when the waveform begins to ascend

again. Faults in my constructed probes were a result of my misinterpreting the waveform as well as potentially weak soldering bonds because I am not skilled fabricator.

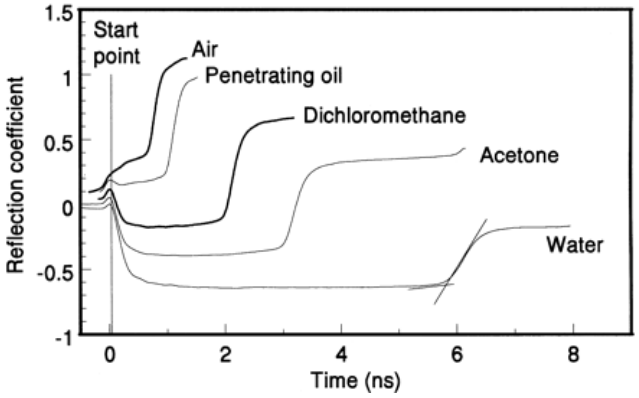


Figure 4. Waveforms that demonstrate the increase in travel time as permittivity increases. Tangent lines shown in the water waveform. Time is measured between these intersections (Robinson et al. (2003), Figure from http://vzj.scijournals.org/cgi/content/figsonly/2/4/444).

The soil water content in B_1 and B_2 was determined by the Ledieu equation. The typical range of Ledieu values under field conditions is 0.1-0.55. This is determined from a table (Table 1) produced by Curtis and Defandorf (1929) that demonstrates that the *k* of water (0.80) is much larger than soil constitutes therefore making it reasonable to determine soil water content by measuring the apparent *k* (Hoekstra & Delaney, 1974). Soil in the field rarely is completely saturated due to air and other gas bubbles, as well as swelling soil textures (Hillel, 2004). Furthermore, the lowest state of dryness achieved in the field is referred to as “air dryness” which can be variable compared to the more controlled and yet arbitrary laboratory “oven-dryness” (Hillel, 2004), which infers that soil is rarely free of water content in the field.

Table 1. Dielectric constants of major soil textures and soil constituents (Curtis & Defandorf, 1929).

Material	Dielectric Constant
Air	1
Water	80 at 20 °C
Ice	3 at 5 °C
Basalt	12
Granite	7–9
Sandstone	9-11
Dry loam	3.5
Dry sand	2.5

When it was discovered that many of the Ledieu values in my experiments were out of range, the data loggers were reprogrammed to collect TDR waveforms as well as Ledieu values. This is something that should have been in the program from the very beginning because it enables one to look at the actual waveform that *k* is being calculated from to determine if the datalogger software is correctly interpreting where the tangent lines should be. If the software algorithms are not accurately reading the waveform because of a rock, air pocket, or some other disturbance in the soil that could alter the waveform pattern, one can calculate *k* by looking at the waveform and using other software to fit tangent lines.

Some of the probes showed a consistent trend in Ledieu values collected in B_1 and B_2 over the entire season, but other probes had very sporadic patterns suggesting that something was confounding the Ledieu values and the data should not be read as accurate (Figure 6). Furthermore, of the probes that were showing consistent seasonal trends, within a reinforcement material treatment the results between the replicates were often very different (Figure 7). This suggested that there was either no difference between the reinforcement materials, or there were other unknown confounding factors. I determined that if the sporadic

data was discarded there were not enough replicates left in each treatment to perform accurate statistics.

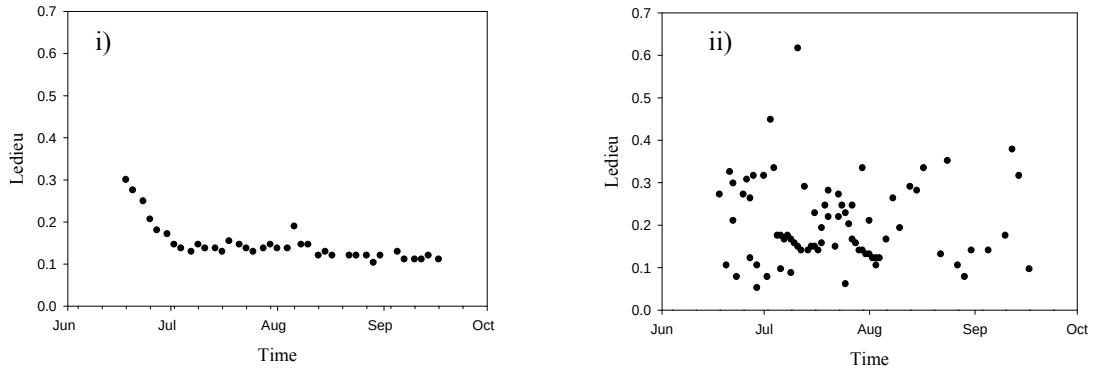


Figure 6. Ledieu values collected over the entire 2007 season in the morning before supplemental irrigation was applied on days with no natural precipitation within the previous 24 hours. Figures demonstrate data from two different probes in the coconut straw reinforcement treatment in the middle water regime: i) consistent trend of Ledieu values as should be expected, ii) sporadic Ledieu value trend.

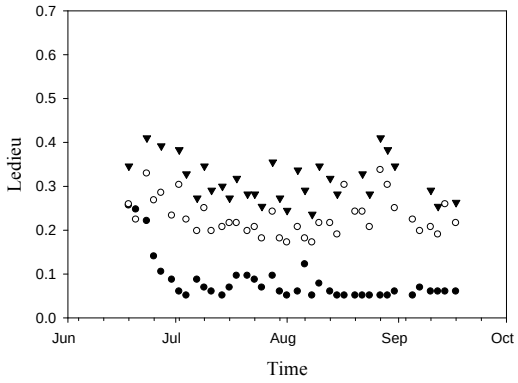


Figure 7. Ledieu values collected over the entire 2008 season in the morning before supplemental irrigation was applied on days with no natural precipitation within the previous 24 hours. Figures demonstrate data from three different probe replicates in the jute reinforcement treatment in the high water regime. Symbols represent different probes (▼probe 1, ○ probe 2, ● probe 3).

The second human error causing the failure of accurate TDR data collection may have been from problems associated with programming the dataloggers. Getting a datalogger program to work accurately and consistently was very much limited by my lack of

knowledge in real-time and CR basic programming languages. The first program installed collected measurements every hour because despite numerous literature reviews and conversations with industry technicians, I could not figure out how to get the datalogger to collect what was of interest to the experiment, data twice a day before and after watering. This hourly data collection accumulated very quickly and became very large files. Because of the immensity of these files, when I collected data from the datalogger I made the mistake of looking only at the last couple days worth of collection to make sure the data was being collected. This was not sufficient evidence, however, as at the end of the season when I pasted all the collected files together I realized that the datalogger was overwriting data collected earlier in each collection sequence. Despite the immense time that I put into trying to collect soil moisture data, I learned a lot, but failed to retain accurate results.

Overall, the key to successful soil water content data collection is a combination of a skilled fabricator to construct precise TDR probes, a technician fluent in computer programming to program the dataloggers, a professional soil scientist to analyze the waveforms, and a diligent graduate student who has time to analyze the data on a weekly basis to make sure everything is working accurately. Hopefully the information contained in this appendix will help future data collection using gypsum blocks or TDR run more smoothly.

TDR Probe Construction Instructions

Materials

1) Stainless steel metal rods (0.32 cm–0.28 cm diameter) cut 0.65–1.27 cm longer than the desired measured soil depth. (Supplier: Ace Hardware, Bozeman, Montana or http://www.mcmaster.com/) * Thicker rods are better at withstanding continuous insertion and removal if using a portable TDR system. *Probe lengths between 0.1-1.0 m are most accurate (Topp & Davis, 1985).

2) RG58 Coaxial cable with BNC connector. (Supplier: http://www.cyberguys.com/templates/searchproducts.asp?categoryID=485) .

3) Epoxy- # 2 medium grade, Part A (resin) and part B (hardener). Epoxy measuring cups. (Supplier: http://www.systemthree.com/index_2.asp).

4) Sauder (silver preferable), solder gun and solder torch (Supplier: Ace Hardware, Bozeman Montana).

5) Silicone gasket maker (i.e. Permatex Sensor Safe Blue RTV 6B) (Supplier: Ace Hardware, Bozeman Montana).

6) PVC pipe (2.54 cm +) (Supplier: Ace Hardware, Bozeman Montana) Sandpaper (Supplier: Ace Hardware, Bozeman Montana).

7) Metal grinder (Supplier: Montana State University Plant Growth Center Workshop, Bozeman, Montana).

8) Electrical Tape (Supplier: Ace Hardware, Bozeman Montana).

9) Wood construction jig (Figure 8) (Supplier- homemade).

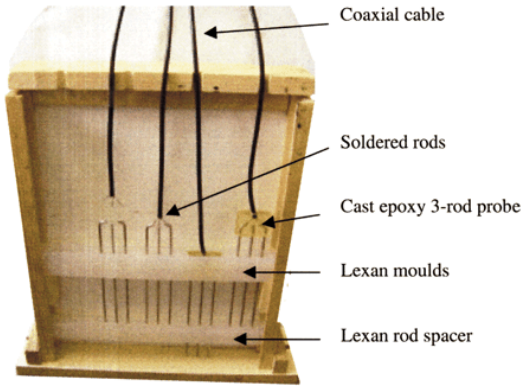


Figure 8. TDR wood construction jig. (Robinson et al. (2003), figure from http://vzj.scijournals.org/cgi/content/figsonly/2/4/444).

Procedure

1) Grind metal rods so that one end is flat and the other side is a sharp pointy cone. The latter end will be what gets inserted into the soil and the flat end will be soldered onto. Sandpaper the flat end to create a better soldering surface.

2) Place rods in wood construction jig (Figure 8) for stability. The rods can be inserted into drilled holes at the base of jig to help keep straight alignment. Place jig on top of newspaper or an old sheet to protect the workbench surface.

3) Strip (non BNC end, BNC attaches to TDR100) coaxial cable insulation about 10 mm to expose shield and signal wires, as well as to allow enough length to reach the spaced rods.

4) In a three-rod design, separate the shield wires into two sections and solder one to each of the outside rods, and the center signal wires to the center rod. In the two-rod design, solder the signal wires to one rod and the shield wires to the other rod.

Soldering tips: Heat the steel rod with the solder torch until it is hot. Stainless steel is a very tough metal to solder onto as it requires intense heat. Once there is a sufficient soldered connection do not move the rods or wire until completely cool to avoid severing the connection.

5) Make sure that the shield and signal wires, or the metal rods they are soldered to, are not touching each other in any way. Wrap electrical tape around the wire to ensure that the weight of the epoxy when it is poured does not cause anything to touch that was not touching before.

6) Now is a good time to test your probe to make sure that it is working properly before it becomes solidified in Epoxy. A cable tester (1502B Tektronix, Richardson, TX) is useful for this. Be sure to interpret your waveforms carefully.

7) When you place the probe into it's final position in the wooden jig make sure the signal rod is exactly level if not slightly higher than the outer rods to add confidence to the TDR100's ability to find the final reflection point of the waveform. If the signal rod is longer than the shield rods the probe may malfunction.

8) Cut PVC into 2.54 cm+ lengths (sufficient to encompass the end of the coaxial cable and soldered section of rods). Thread coaxial cable through PVC so that the PVC sits flat on the wooden construction jig.

9) Apply a thick layer of silicone to the base of the PVC as well as all around it in any areas where there may be potential gaps. The silicone is what keeps the liquid Epoxy contained until it hardens.

10) Mix Epoxy as instructed on Epoxy container. Stir vigorously to ensure adequate mixing and thus adequate hardening. Pour Epoxy into the PVC so that it covers the soldered area of the probes as well as the seam between the stripped and insulated coaxial cable.

11) Let sit for 24+ hours until the Epoxy hardens. Lift completed TDR probe out of wooden construction jig and wash off silicone with hot water and soap.

Calibrating Probes, and Wiring and Installing Data Logger

If probes are manufactured in house be sure to calibrate each probe via instructions in the Campbell Scientific, Inc. TDR probes (CS605, CS610, CS630, CS635, CS640, CS645) manual because they likely all have slightly different lengths and this needs to be incorporated into each instruction in your program. Furthermore, calibrate each probe and run your program in the laboratory with all the multiplexers connected exactly as they will be in the field because the determined cable length includes the connections between the data logger and multiplexers. In general cable length should not exceed 24 m (see Heimovaara,

(1993) for more discussion on the relationship between probe, cable length, and data accuracy).

Wiring instructions can be obtained from both the Campbell Scientific, Inc. datalogger and TDR100 manuals. LoggerNet software also has a good resource called Short Cut that will help you write a program as well as display a wiring diagram for any Campbell Scientific, Inc. device (i.e. thermacouples), although the TDR100 command may or may not be included at this time. The engineers at Campbell Scientific, Inc. can also be useful for any questions that might arise. Make sure that there is 12 volt power going to not only the datalogger, but to each multiplexer as well. A car battery (covered so it is protected from the environment) with a solar panel is a good way to keep the datalogger charged. Volt meters are also useful to have with you every time you are problem solving with the datalogger to rule out insufficient power supply as a main cause or error. A grounding rod needs to be hammered into the ground and attached to the main datalogger to prevent lightning damage in the field. Lastly, the dataloggers and multiplexers are contained in waterproof cases with the wire connections protruding from a small opening on the side. Make sure to fill any remaining gaps in these openings with a sponge or bandana to avoid rodent damage inside this case.

Datalogger Programs

The following are condensed datalogger programs for this experiment installed in the CR10x and CR1000 respectively (the full programs can be found on the Montana State University weed laboratory server at: \\seedbank\data$\theses\stark\dataloggerprograms).

Please note that there are also example programs in Campbell Scientific, Inc.'s TDR100 manual. TDR engineers at Campbell Scientific are also very helpful resources. Additional useful tips include: 1) make sure there are enough locations in your program to document each data reading, including the Ledieu value as well as all the waveform points, 2) Campbell Scientific, Inc. refers to *k* as LA/L, 3) note the probe offset changes in each TDR command because the probes are all slightly different in their probe handle and rod length.

CR10x Datalogger TDR program (written in LoggerNet 3.3.1 Edlog)

```
;CR10X
;Program: JStark_V1.csi
;Date: July 1, 2008
;Measure TC's & TDR probes
;
;Modify program JStark_V1.csi
;New Program: JennStark_V1A.csi
;Date: June 19,2008
;Move P92 Instruction that sets the output flag high up in the program
;
*Table 1 Program
  01: 3600      Execution Interval (seconds) ;Run program every hour

1:  If time is (P92) ;Set Flag 1 high every morning at 6:00
 1: 0000     Minutes (Seconds --) into a
 2: 360      Interval (same units as above)
 3: 11       Set Flag 1 High
2:  If time is (P92) ;Set Flag 1 high every morning at 9:00
 1: 0000     Minutes (Seconds --) into a
 2: 540      Interval (same units as above)
 3: 11       Set Flag 1 High

3:  If Flag/Port (P91) ;If flag 1 is high (6 and 9 AM) then make measurements and record
data
 1: 11       Do if Flag 1 is High
 2: 30       Then Do
```

```
; measure CR10X temp and TC's on multiplexer. It is good to keep track of the temperature
to rule it out as an error causing factor.
    4:  Internal Temperature (P17)
     1: 2        Loc [ DL_TempC  ]

    5:  Do (P86)
     1: 44       Set Port 4 High

    6:  Beginning of Loop (P87)
     1: 0        Delay
     2: 32       Loop Count

        7:  Do (P86)
         1: 75       Pulse Port 5

        8:  Excitation with Delay (P22)
         1: 1        Ex Channel
         2: 0        Delay W/Ex (0.01 sec units)
         3: 1        Delay After Ex (0.01 sec units)
         4: 0        mV Excitation

        9:  Thermocouple Temp (DIFF) (P14)
         1: 1        Reps
         2: 1        2.5 mV Slow Range
         3: 2        DIFF Channel
         4: 1        Type T (Copper-Constantan)
         5: 2        Ref Temp (Deg. C) Loc [ DL_TempC  ]
         6: 3     -- Loc [ Temp_C_1  ]
         7: 1        Multiplier
         8: 0        Offset

    10:  End (P95) ; end TC multiplexer measurement loop

    11:  Do (P86)
     1: 54       Set Port 4 Low
; measure TDR100 probes (Ledieu value)
    12:  Do (P86)
     1: 48       Set Port 8 High

    13:  TDR100 Measurement (P119)
     1: 0        SDM Address
     2: 0        La/L for Water Content
     3: 1101     MMMP Mux & Probe Selection
```

```
 4: 64       Waveform Averaging
 5: 1        Vp
 6: 251      Points
 7: 6.5      Cable Length (meters)
 8: 2        Window Length (meters)
 9: .16      Probe Length (meters)
10: .01      Probe Offset (meters)
11: 35       Loc [ TDR1_1    ]
12: .1138    Multiplier
13: -.1758   Offset
```

;Repeat P119 (line 13) instruction for collecting Ledieu value for each probe (changing MMMP mux & probe selection address, window length, probe length, and probe offset for each probe if they are not all exactly uniform in size. If they are uniform a loop in the program can be created to repeat the first P119 instruction for each probe).

;beg. output theta

```
15:  Do (P86)
 1: 10       Set Output Flag High (Flag 0)

16:  Set Active Storage Area (P80)
 1: 1        Final Storage Area 1
 2: 201      Array ID

17:  Real Time (P77)
 1: 1220     Year,Day,Hour/Minute (midnight = 2400)

18:  Sample (P70)
 1: 36       Reps
 2: 35       Loc [ TDR1_1    ]

19:  Resolution (P78)
 1: 1        High Resolution

20:  Serial Out (P96)
 1: 71       Storage Module
```

; Measure TDR 100 Probes (Waveform)

```
21:  TDR100 Measurement (P119)
 1: 0        SDM Address
 2: 1        Waveform
 3: 1101     MMMP Mux & Probe Selection

 4: 64       Waveform Averaging
 5: 1        Vp
 6: 260      Points
 7: 6.5      Cable Length (meters)
 8: 2        Window Length (meters)
 9: .16      Probe Length (meters)
10: .01      Probe Offset (meters)
11: 100      Loc [ WF_1      ]
12: 1        Multiplier
13: 0        Offset

22:  Do (P86)
 1: 48       Set Port 8 High

23:  Do (P86)
 1: 10       Set Output Flag High (Flag 0)

24:  Set Active Storage Area (P80)
 1: 1        Final Storage Area 1
 2: 1        Array ID

25:  Real Time (P77)
 1: 1220     Year,Day,Hour/Minute (midnight = 2400)

26:  Resolution (P78)
 1: 0        Low Resolution

27:  Sample (P70)
 1: 260      Reps
 2: 100      Loc [ WF_1      ]
```

;Repeat P119 (line 21) instruction for collecting waveforms for each probe (changing MMMP mux & probe selection address, window length, probe length, and probe offset for each probe if they are not all exactly uniform in size. If they are uniform a loop in the program can be created to repeat the first P119 instruction for each probe). Make sure there are enough locations at the end of the program for all the data (especially waveform points) collected.

;beg. output theta

```
    28:  Do (P86)
     1: 58       Set Port 8 Low

     29:  Serial Out (P96)
     1: 71       Storage Module

    30:  Do (P86) ;Set Flag 1 low so no further measurements are made until 6 or 9 AM
     1: 21       Set Flag 1 Low

31:  End (P95)

*Table 2 Program
  01: 00        Execution Interval (seconds)

End Program

*Table 3 Subroutines

End Program
```

CR1000 Datalogger TDR program (written in LoggerNet 3.3.1 CR Basic)

```
'Declare Public Variables
'Example:
Public batt_volt
Public Panel_temp
Public LaL(1)
Public LaL2(1)
Public Ledieu(1)
Public ToppVWC(1)
Public Flag(2)
public WavPT(260)
public MuxChan
public Ec
Dim I

'Declare Constants
'Topp Equation Dielectric Constants
const a0=-0.053
const a1=0.0292

const a2=-0.0005
```

```
const a3=0.0000043

const high=true

const low=false

'Define Data Tables

DataTable(Data_TDR,1,-1)
	Minimum (1,batt_volt,IEEE4,0,False)
	Average(1,Panel_temp,IEEE4,0)
	Sample (1,LaL(),IEEE4)
	sample (1,Ledieu(),FP2)
	sample (1,ToppVWC(),FP2)
	sample (1,Ec,FP2)
EndTable
'
DataTable(TDR_Wave,1,64)
	'sample(1,Muxchan,IEEE4)
	sample(260,WavPT(),FP2)
EndTable

'Main Program
BeginProg
	'SDMSpeed(50)
	'
	Scan (10,Sec,0,0)
		PanelTemp (Panel_Temp,250)
		Battery (Batt_volt)
		'
		If TimeIntoInterval(0,10,Sec) Then Flag(1)=High
		If TimeIntoInterval(0,10,Sec) then flag(2)=high '
		If Flag(1)=High Then
			SW12(1)
			Delay(1,2,Sec)
			TDR100 (LaL(1),0,0,0001,64,1,251,5.7,2,.158,0.085,1,0)
			For I=1 to 1
				LaL2(I)=LaL(I)^2
			Next I
			For I=1 to 1
				ToppVWC(I)=a0+a1*LaL2(I)+a2*LaL2(I)^2+a3*LaL2(I)^3
			Next I
			For I=1 to 1
			TDR100 (Ec,00,3,0001,64,1,251,5.7,2,.158,0.085,1,0)
```

```
                Next I
                For I=1 to 1

                TDR100 (Ledieu VWC(),0,0,0001,64,1.0,251,5.7,2,.158,0.085,.1138,-
                        0.1758)
                Next I
                '
                CallTable Data_TDR
                Flag(1)=0
                SW12(0)
                endif

        If Flag(2)=High Then
                SW12(1)
                Delay(1,2,Sec)

                TDR100(WavPT(),0,1,1001,64,1,251,5.7,2,.158,0.085,1,0)
                '
                Flag(2)=0
                SW12(0)
                CallTable TDR_Wave
                endif
                '
                'PortsConfig(&B00000111,&B00000000)
                '
        Next Scan
EndProg
```