Use of Solarization to Kill the Root Crown and Reduce the Seed Bank Viability of *Rubus armeniacus* Focke and *Cytisus scoparius* (L.) Link

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Abstract

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Himalayan blackberry (*Rubus armeniacus* Focke) and Scotch broom (*Cytisus scoparius* (L.) Link) are two common invasive species of the Pacific Northwest. While many methods currently exist to control these two species, both posses inherent characteristics and structures making them resistant to existent methods in the forms of aggressive vegetative growth and resprouting from root fragments and large persistent seed banks. The goal of this thesis is to explore the potential application of solarization as a control method for these two species. In a field trial, the effectiveness of solarization was to tested against several existent control methods focusing on the stem and root crown survivorship. In a subsequent greenhouse experiment, the seed banks of *R. armeniacus* and *C. scoparius* were subjected to solarization at varying soil temperatures. Results indicate that solarization does have the potential of killing root crowns and reducing the seed banks of *R. armeniacus* and *C. scoparius*. Clear plastic solarization was found to be more effective at increasing the soil temperature than black plastic and increases in soil temperature resulted in reduced root crown, stem, and seed bank survival. Further research in to solarization though will be required to best modify the technique to match the climate of the Pacific Northwest.

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1. Introduction

Invasive non-native species are a growing problem across the world, causing harm to the environment, economy and human health. They have been identified as the second greatest threat to biodiversity after habitat loss (Burdick, 2005; Frid *et al.*, 2009; NISC, 2008). Non-native species are those that have moved or been transported to, and have become established in, areas where they were not previously found (Boersma *et al.*, 2006). Invasive species are a subset of non-native species that for various reasons have established non-cultivated populations and have altered ecosystem processes.

Invasive plant species are a particular problem for disturbed habitats, such as brownfields, urban park trails and roadsides. These species are often able to dominate the local ecosystems by interrupting the natural succession of an area and suppressing the growth of native species (MacDougall and Turkington, 2005). They rapidly grow and overtake other native species, changing the structural and compositional diversity of an ecosystem (2006). Invasive species have also been found to decrease soil stabilization, alter fire frequency and intensity, excessively use available resources, release suppressors, and decrease the carrying capacity for wildlife and livestock over a landscape (NISC, 2006).

Invasive species are also responsible for large economic costs. In the United States alone, invasive species are responsible for almost $120 billion per year in damages to crops, losses in crop yields, and costs of control (Pimentel *et al.*, 2004).

Invasive plant species pose a threat to ecological services and the native biota composition in the Pacific Northwest. Unfortunately, controlling the spread and/or the eradication of invasive plants has proven difficult for a number of reasons. Simply removing the aboveground portions of these plants is often not enough. Invasive plants have evolved a number of attributes that help them to quickly colonize and repopulate a disturbed area and resist control efforts. These attributes include prolific seed production, the ability to reproduce asexually, aggressive growth, establishment, and the ability to exploit disturbed or marginal habitats (Boersma *et al.*, 2006).

The plants known as *Rubus armeniacus* (Himalayan Blackberry) and *Cytisus scoparius* (Scotch Broom) are two prime examples of the challenges faced in controlling invasive species. Both of these plants are common invasive species in the Pacific Northwest. They can be often found in disturbed and abandoned sites such as unused lots, pastures and in the right-of-way of many highways. Most restoration projects in the Pacific Northwest require the removal of at least one or both of these species. However, both of these species exhibit a number of adaptive traits that make them difficult to control. This thesis explores application of solarization and tests its potential as a control method for these two species.

2. Literature Review

2.1 *Rubus armeniacus*

Himalayan Blackberry or *Rubus armeniacus* is a fast growing perennial bramble that while known for producing tasty berries is also capable of growing vast thickets that shade out and outcompete native species.

Figure 1: Thicket of *R. armeniacus* with fruit

2.1.1 History and Distribution

R. armeniacus was introduced to the United States as the "Himalaya Blackberry" in 1885 by Luther Burbank as a cultivated crop (Caplan and Yeakley, 2006; Francis, *s.m.*; Hoshovsky, 2000a). The exact origin of the species is uncertain. According to Burbank, the seeds were given to him by an English traveler who collected them from the Himalayan Mountains (Markarian and Olmo, 1959). However these claims cannot be verified. No biological evidence has been found showing that *R. armeniacus* is native to

the Himalayan region (Hoshovsky, 2000a). It should be noted that *R. armeniacus* is almost indistinguishable from the Theodore Reimers variety of blackberries grown in England (Reported by Mallah 1954 in Hays 2012). This variety of blackberry has its origins in Germany and is named after the *Garteninspector* Theodore Reimers of Hamburg, Germany. An Englishman may have sent Burbank seeds, but they were of Western European origin and not Himalayan. Recent research has found that the wild progenitors of *R. armeniacus*, likely came from the Caucasus region of Europe (Caplan and Yeakley, 2006).

Burbank bred and vegetatively propagated a particularly vigorous F2-generation plant from his initial supplies of seeds. This variety, the "Himalaya Giant," was offered in his General catalog of 1893. By 1905, the U.S. Department of Agriculture acquired 200 plants after learning it was flourishing in the Puget Sound region of Washington. The USDA attempted to distribute these plants to ten states east of the Rockies, where they met with little success (Hays, 2012). By 1945, *R. armeniacus* escaped from agricultural land and was naturalized along the west. *Rubus armeniacus* can be found from California north to Alaska on the west coast and scattered through various states on the East coast (Figure 2) (Bennet, 2007; Murphy, 2006; USDA, 2013a)

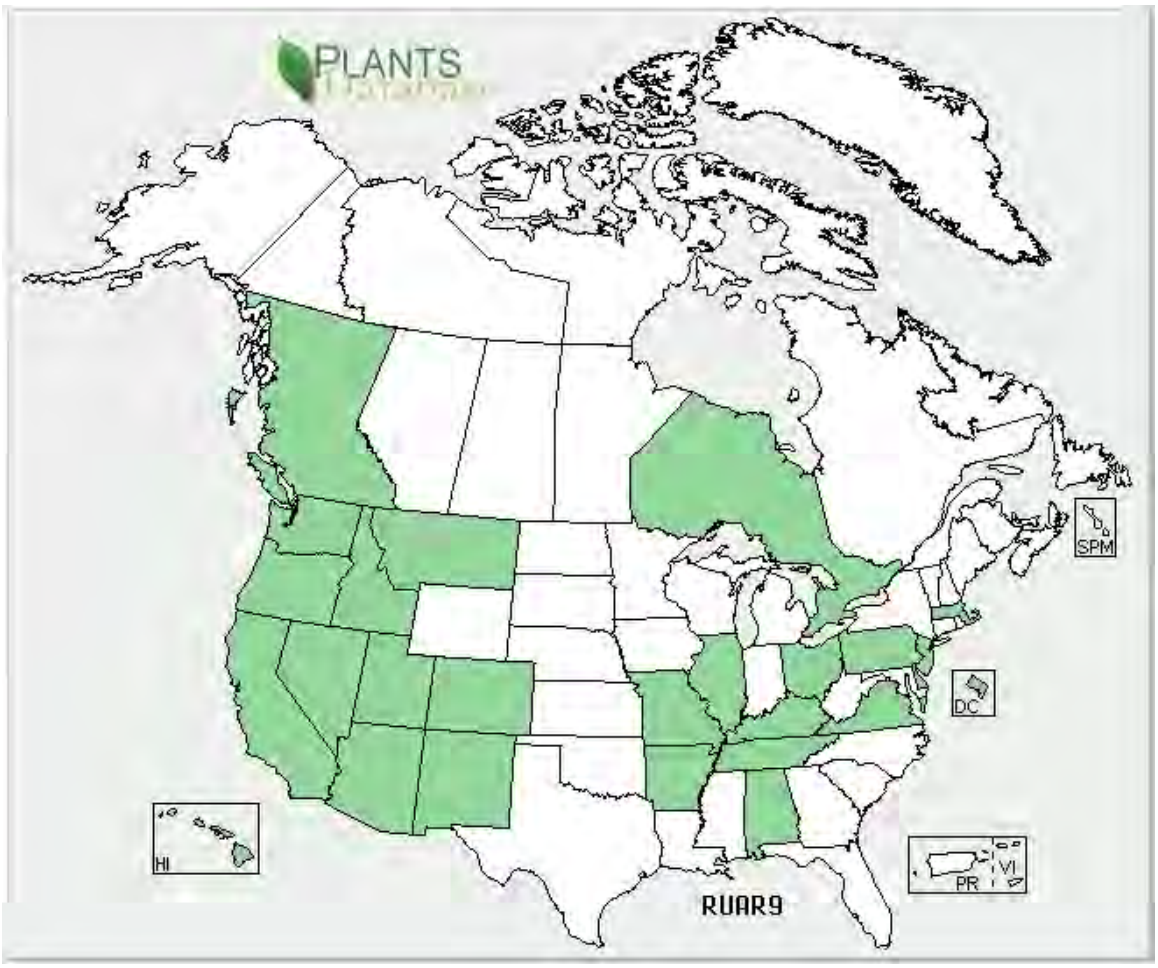


Figure 2: Distribution map of the *Rubus armeniacus* over the United States and Canada.
Note: USDA does not list *Rubus armeniacus* as being present in Alaska while the Alaska Natural Heritage program's Non-Native Plant Species database does list it under the synonym *Rubus discolor*.

2.1.2 General Description

R. armeniacus is a rambling evergreen perennial woody shrub, composed of trailing stout stems (Francis, *s.m.*). The shrub may reach up to 4 meters tall. The stems, referred to as canes, can reach a length of six to 12 meters long (20-40 feet) and are capable of root at the tips (Soll, 2004). The canes are strongly angled and furrowed, not rounded like other blackberries. These canes can create dense, impassable thickets with up to 525 canes per square meter (Soll, 2004) though generally ranging between 1.5-21.5

canes/m^2 (Bennet, 2007). Each cane only lives for 2-3 years, with new canes produced from the root crown each year (Thurston County, 2008). The canes are armored with well spaced, broad based, straight to slightly curved 6-10 mm long prickles (Hoshovsky, 2000a). These prickles help prevent browsing by herbivores (Caplan and Yeakley, 2006).

Figure 3: Line drawing of the flowers, fruit and stem of *R. armeniacus*. Illustration from Invasive Plants of California's Wildlands (Hoshovsky, 2000b)

R. armeniacus occurs primarily in areas with an average annual precipitation greater than 76 cm, up to an altitude of 1800m, and is capable of growing in a wide range of soils both acidic and alkaline (Amor, 1972). It can often be found colonizing moist disturbed sites such as pastures, forest plantations, riparian and right-of-way corridors (Amor, 1972, 1973). *R. armeniacus* seedlings require full sunlight for survival (Hoshovsky, 2000a).

The leaves are compound, each composed of 3-5 sharply toothed leaflets. When mature, these leaflets are usually glabrous (smooth) above and cano-pubescent to cano-tomentose beneath (Hoshovsky, 2000b). Leaflets are large and broad with the terminal leaflet roundish to broad oblong.

R. armeniacus has large terminal cluster inflorescence. The flowers possess 5 broad petals, white to rose colored, and reach a size of 2-2.5 cm across. The shrub produces shiny black fruit, up to 2 cm long, composed of large succulent drupelets. The berries generally form and ripen in the late summer on second year canes. After the canes bear fruit, they generally die though some canes can persist for several years before bearing fruit and die. (Hoshovsky, 2000a; Invasive Plant Council of BC, 2008).

2.1.3 Reproduction

R. armeniacus can reproduce sexually from seed and vegetatively from root crowns, root pieces, and stem cuttings (Thurston County, 2008). Sexually, a *R. armeniacus* thicket can produce 7,000-13,000 seeds per square meter (Amor, 1974; Bennet, 2007). Good seed crops occur nearly every year; however only 10% to 33% of the seeds typically germinate (Amor, 1972; Brinkman, 1974). Dense shade suppresses seed germination and seedling success. The seeds remain viable for many years which helps facilitate the rapid reinvasion of a site if the aboveground vegetation is removed (Brinkman, 1974).

Within thickets, few seeds germinate due to the dense canopy from the canes. Amor (1972) counted less than 0.4 seedlings per square meter near thickets. In a later paper, Amor (1974) found that seedlings receiving less than 44% of full sunlight did not survive. Animal assistance is required by *R. armeniacus* to help spread by seeds. Birds,

along with omnivorous mammals such as foxes, have long been seen as a method of transport of the seeds (Amor, 1974; Amor and Stevens, 1976; Brunner *et al.*, 1976; Soll, 2004). In addition, the passage of the seeds through the digestive tract helps germination (Barber, 1976; Francis, *s.m.*; Hoshovsky, 2000b).

R. armeniacus is such an effective invasive species not due to its high seed count but due to its aggressive vegetative reproduction. *R. armeniacus* can form daughter plants when first year canes come into contact with the ground with roots forming at the cane apices (Hoshovsky, 2000a). Amor (1974) observed canes growing to a height of 40 cm before they arched over and trailed on the ground. In optimal conditions, a cane of *R. armeniacus* can grow up to a length of 7 m in a single season allowing for the rapid spread and occupation of the adjacent area. Once rooted, these daughter plants are capable of fruiting the subsequent year or continue to vegetatively spread (Hoshovsky, 2000a). *R. armeniacus* also readily propagates from root pieces and cane cuttings (Amor, 1974). In less than two years, a single cane cutting can produce a thicket 5 m in diameter (Amor, 1973).

2.1.4 Impact of *Rubus armeniacus*

Within its introduced range, *R. armeniacus* has been found to be disruptive to native ecosystem processes. In the Pacific Northwest, *R. armeniacus* can be seen growing in disturbed areas such as abandoned fields and undeveloped lots. *R. armeniacus* often becomes the dominant vegetation species in areas it invades, outcompeting other shrubs,

small trees and herbaceous species (Astley, 2000; Thurston County, 2008). The large dense thickets the shrub creates, also reduces potential habitat for wildlife and livestock (Washington State Noxious Weed Control Board, 2010). Overall, *R. armeniacus* reduces native-plant and wildlife diversity and hinders the reestablishment of native species (Murphy, 2006). *R. armeniacus* is also a fire hazard when adjacent to buildings (Hoshovsky, 2000a) and a vector for diseases (Caplan and Yeakley, 2006). Hill and Purcell (1997) determined that blackberry is a significant host of the bacterial pathogen *Xylella fastidiosa* that causes Pierce's disease in grapevines and other economically important plants.

R. armeniacus does have some positive impacts. The berries of the plant provide sustenance for many birds and small mammals such as red fox, squirrels, coyotes, and black bear. Larger mammals such as deer, elk, beaver and rabbits feed on the buds and leaves (Alaska Natural Heritage Program, 2005). The berries of *R. armeniacus* are also collected by many people for consumption and sale (Washington State Noxious Weed Control Board, 2010). *R. armeniacus* is also an important source of nectar for the introduced honey bee - *Apis mellifera* (Murphy, 2006).

2.1.5 Control

Regardless of its tasty summer fruit and its favor in summer cobblers, milk shakes and other human consumables, the large dense monoculture stands of *R. armeniacus*, disrupt ecosystem succession and its high resource uptake necessitates the control of this

species. The western states including Alaska, Washington, Oregon, Idaho California, and Hawaii consider *R. armeniacus* an invasive species and require or recommend its control.

Control of *Rubus armeniacus* can be broken into several broad areas: manual, mechanical, chemical and biological. Each of these control methods has varying strengths and weakness. Successful control of *R. armeniacus* and most invasive species requires a mix of these varying techniques.

Manual

R. armeniacus can be controlled manually by removing and disposing of canes and root crowns. Either by hand or mechanically by mower, the canes are cut and removed allowing for easier access to the root crown origins of the canes. The root crown is then removed from the soil by hand (grubbed) with either a shovel or mattock (Soll, 2004). Care is taken to remove as much of the root crown and root fragments as possible to minimize risk of resprouting. The root crown and canes are then disposed of either off or on site. Restoration practitioners commonly use this technique on projects. Manual control has the advantage of being highly selective, allowing for the removal of the *R. armeniacus* without damaging the surrounding native vegetation (Hoshovsky, 2000a), and can be done by volunteers. In addition, physically removing the root crown from the soil prevents it from resprouting and taking over the site again. The primary downside of manual control is its high labor intensity and, if care is not taken to remove all the root and stem fragments, they can take root and sprout new canes. Manual control is also limited due to the topography and size of the site, manpower availability, and physical access to the site (Hoshovsky, 2000a).

Mechanical

Mechanical control methods help overcome the issues of the size of the site and manpower restrictions and reduce the labor intensity in removing the blackberry. Mechanized equipment is used to remove the aboveground vegetation by either chopping, cutting or mowing the canes. This method is relatively inexpensive and highly effective at removing the aboveground vegetation. With a relatively small crew, larger areas can be cleared of aboveground vegetation compared to that of a manual work party. Mechanical control, unlike manual, is non-selective so both desired and non-desired vegetation are removed from the site. In addition, most equipment cannot be safely operated on slopes greater than 30 percent, work best in sites with few obstructions (i.e. rocks, gullies, and stumps) and can compress the soil (Soll, 2004). Mechanical treatments also rarely remove the belowground vegetation, the root crowns and roots, so repeated mowing is required to exhaust the energy stored in the belowground structures. This means years might be required to actually clear blackberry from a site (Hoshovsky, 2000a).

Chemical

Herbicide

Herbicides offer another potential method of control for *R. armeniacus*. Herbicides can be particularly effective when combined with other control methods such as mechanical or manual cane removal but are also effective on their own. Chemicals such as glyphosate have been used effectively to control *R. armeniacus* by preventing roots from producing new canes. Spraying the foliage tends to be more effective during

the summer months (Hoshovsky, 2000a) while spot application on cut canes, injection into canes and spaying newly emerging plants tends to be more effective in the fall (Soll, 2004). There are constraints on the use of herbicides. Many herbicides such as glyphosate (Roundup) are not selective and can kill both native and non-native species. Spot spraying and cane injections negate much of the labor saving potential of herbicides. Legislation also exists that restricts if not bans the use of herbicides in some areas, especially near riparian areas or in certain watershed (i.e. Cedar River Watershed, WA). Each herbicide also can only be used under certain conditions. Knowledge and understanding of herbicide labels is needed to understand when each herbicide can or should be used. In addition, the application of herbicide may be restricted to state licensed practitioners depending on the circumstances.

Fire

Fire has also been used to control *R. armeniacus*. As thickets age, fuel accumulates in the form of dead canes and leaf material on the floor of the thickets. By itself, burning *R. armeniacus* effectively removes the dead aboveground debris but does not actually kill the plants due the root crown being protected from the fire, causing *R. armeniacus* to resprout afterwards (Tirmenstein, 1989). Repeated burnings can be used to exhaust the *R. armeniacus* seed bank and underground food reserves (Soll, 2004). Concerns about fire, smoke and the need for its control prevent burning from being utilized in many areas, and restricts it to being used for large patches only (Hoshovsky, 2000a).

Biological

There are two biological methods for control of *R. armeniacus*. One option is to use animals. Goats are the most widely used animal but sheep may be used. Goats prefer woody vegetation to most grasses and forbs and will either trample or browse all other vegetation. Fencing can be used to control where the goats go, providing a form of selectability. Goats, though, are best used to clear or suppress shrub regrowth of one to four years old canes rather than an initial clearing of mature vegetation. When confronted with mature *R. armeniacus*, goats will defoliate twigs and strip off the bark but will leave the older stems, which are too tough for them. Sheep can be used to replace mowing, after the initial clearing of the site (Hoshovsky, 2000a).

The most recent development of *R. armeniacus* biological control is the fungal rust *Phragmidium violaceum*. Discovered in Oregon in 2005, *P. violaceum* has been used as a biological control for *Rubus fruticosus* in Australia and New Zealand for years (Osterbauer *et al.*, 2005). *P. violaceum* causes summer defoliation of infected *R. armeniacus* shrubs and reduces tip rooting. The fungus was accidently released and was not part of a planned controlled dispersal. Currently, *R. armeniacus* in North America has shown no resistance to the fungus. However, due to the small initial release of the disease, resistance will likely develop, negating the potential of the fungus as a biocontrol method.

The use of shade to suppress *R. armeniacus* seedling establishment and vegetative growth has been successfully shown (Jones, 2004). Longterm control of *R. armeniacus* at sites often requires the establishment of some form of canopy. Canopy establishment may not be always possible at a site either due to ecosystem and environemntal restrictions,

legal restrictions, or stakeholder prefrences. An alternative method is needed for areas where the creation of shade is not an option.

Unfortunately for these various control methods, *R. armeniacus'* ability to easily and quickly propagate from stem and root fragments makes it difficult to control. In environmental restoration projects, staff and volunteers need to remove all of the root crowns via grubbing (dig them up). This process is labor intensive and not always completely effective. If any fragments remain in the soil, rapid reinvasion of the area occurs. If grubbing does not occur, repeated application of herbicides, mowing, or goat grazing is needed to exhaust the stored energy and nutrients in the *R. armeniacus* root crowns. These other treatments however require time, energy, and vigilance to work. An alternative method is needed to neutralize any of the remaining belowground material.

2.2 Cytisus scoparius

When traveling along the highways during the late spring and early summer of the Pacific Northwest, travelers often see the roadsides covered in a bright yellow flowering green shrub. While some of these flowers are from native species, the vast majority of them all come from one non-native invasive species: Scotch or Scot's broom - *Cytisus scoparius*.

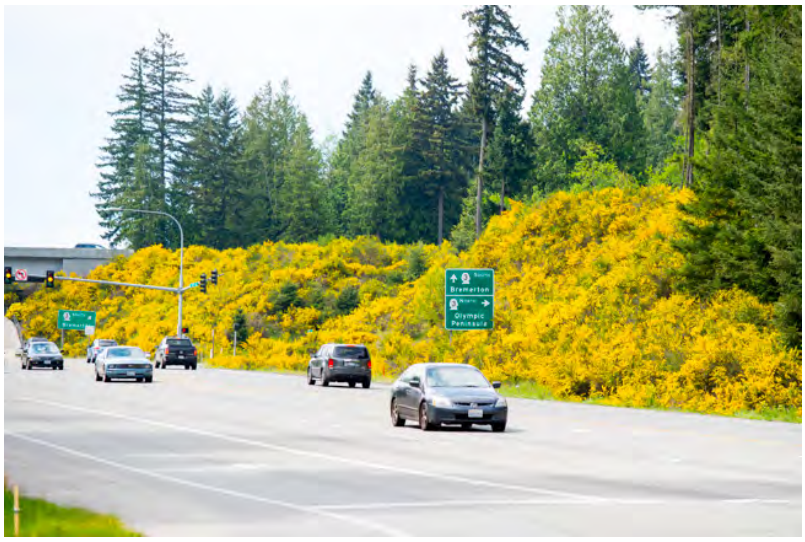


Figure 4: *C. scoparius* along Washington State road – image by Ryan Benoit (Benoit, 2013)

2.2.1 History and Distribution

C. scoparius was introduced as an ornamental plant to the West Coast in two locations at nearly the same time. *C. scoparius* was introduced to California in the 1850's (Gilkey, 1957) and to Vancouver Island by Captain Walter Colquhoun Grant in 1850 (Pojar and MacKinnon, 2004). By the 1860s, *C. scoparius* was commercially distributed by William C. Walker at the Golden Gate Nursery in San Francisco (Mountjoy, 1979). The species subsequently spread to other western states both naturally and by the Soil Conservation Service of the United States Department of Agriculture to prevent soil erosion and stabilize coastal dunes (McClintock, 1985; Schwendiman, 1977). By 1906 it had already been naturalized on Vancouver Island (Hoshovsky, 2001) and by 1925, *C. scoparius* was already being noted as weedy by W.L. Jepson, a noted Californian botanist at the turn of the 19th and 20th centuries (Mountjoy, 1979).

Able to quickly colonize and exploit recently disturbed sites, *C. scoparius* has become common along roads and paths near towns (Hoshovsky, 2001) and occasionally

forms pure stands for miles along highway and country roads (Gilkey, 1957), personal observation). *C. scoparius* is most successful in dry sandy soils in full sunlight and will grow well in soils with pH values ranging from 4.5 to 7.5 (Gill and Pogge, 1974) but can also invade pastures, cultivated fields, dry scrubland, native grasslands, dry riverbeds and other waterways (Gilkey, 1957; Johnson, 1982; Williams, 1981). *C. scoparius* has been documented in 8 Western and 21 Eastern states in the United States and 3 provinces in Canada (USDA, 2013b) (See Figure 5). Only in Washington, Oregon, California and Idaho is *C. scoparius* considered noxious (BONAP, 2011).

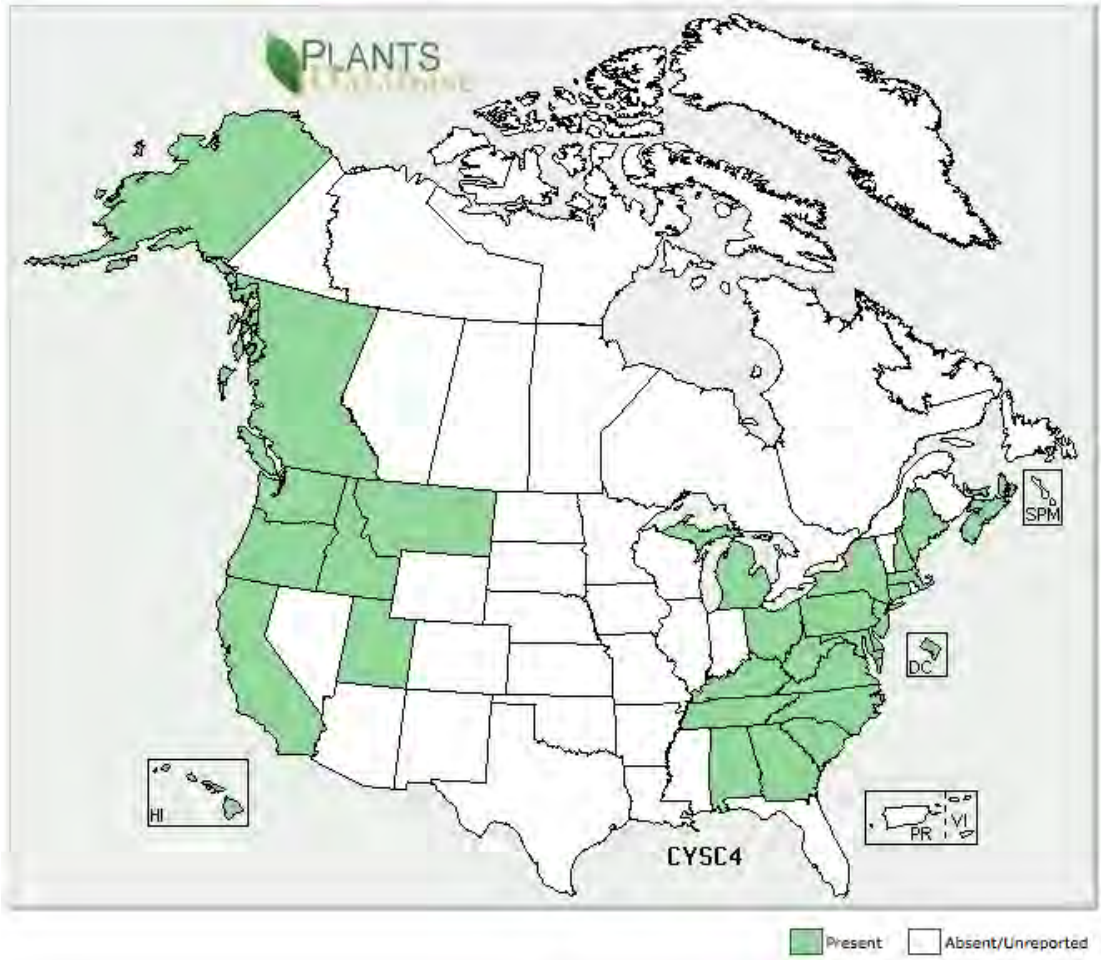


Figure 5: Distribution of *C. scoparius* over North America. Note: Prince Edwards is not marked on the map as having C. scoparius present, though it is listed as present by USDA and Rhode Island also has C. scoparius according to BONAP.

2.2.2 General Description

A member of the Fabaceae family from central and southern Europe (Hoshovsky, 2001), *C. scoparius* is a spindly deciduous perennial legume shrub that grows from 1 to 3 meters in height and can live for 10-20+ years (Hoshovsky, 2001; Pojar and MacKinnon, 2004; Sheppard *et al.*, 2002). The branches are strongly 5 angled and both the stems and branches are capable of photosynthesis year round (Pojar and MacKinnon, 2004). *C. scoparius* is also capable of nitrogen fixation via nodules in the roots (Helgerson *et al.*, 1984), which along with its high drought tolerance and photosynthetic stem help make it a successful colonizer of disturbed sites (Jones, 2006; Watt *et al.*, 2003; Williams, 1981).

The leaves are small (2-10 mm long), alternative, and are composed of 3 leaflets when near the base of the branches, becoming simple above. The plant has bright yellow flowers, that are occasionally tinged purple (Pojar and MacKinnon, 2004) or orange (personal observation), comprised of a typical “pea” flower shape, about 2 cm long. The flowers are usually borne solitary in axils, blooming between April and June (Hoshovsky, 2001).

2.2.3 Reproduction

Figure 6: *C. scoparius* ornamental variety in UBNA

While *C. scoparius* can be propagated via cuttings (Gill and Pogge, 1974) and can resprout when cut (Mountjoy, 1979), its primary method of reproduction is sexual. Flowering can begin in its second year (Jones, 2006). After the flowers have been fertilized, they produce seed pods that while initially green, harden and blacken as they mature, reaching a length of approximately 4 cm (Pojar and MacKinnon, 2004); personal observations). As the pods mature and dry, the two halves of each pod tend to warp in different directions, eventually snapping apart audibly and catapulting seeds over the surrounding area (Pojar and MacKinnon, 2004). Birds, water and insects may then further transport the seeds to new areas (Bossard, 1991; Jones, 2006).

Each pod contains 5-8 seeds (Hoshovsky, 2001) and individual shrubs can produce an average of 9,650 viable seeds per year (Bossard and Rejmanek, 1994). Of these seeds only about 45-50% will actually germinate (Gill and Pogge, 1974; Williams, 1981). The seeds possess a hard seed coat allowing them to remain viable for 60-80 years (Turner, 1933) and can germinate from a depth of 1 to 6 cm (Bossard, 1993; Williams, 1981). Approximately 35 percent of each seed crop becomes part of a rapidly developed

seed bank and can build up to over 2,000 seeds/sq ft (Jones, 2006). The lengthy life span of the seed bank is the reason why any long-term successful control of *C. scoparius* requires some method of neutralizing its seed bank in heavily infested areas.

2.2.4 Impacts of *Cytisus scoparius*

Cytisus scoparius is considered an invasive species for several reasons. The species is able to quickly colonize recently disturbed sites. After colonization, *C. scoparius* quickly creates dense monoculture stands that exclude and displace native plants, eliminating the community structure of prairies, woodlands and young forests (2000; Bossard and Rejmanek, 1994; Wearne and Morgan, 2004). *C. scoparius* infestation can attain a biomass of over 44,000 to 50,000 kg/hectare in only three to four years (Bossard and Rejmanek, 1994). The ability of *C. scoparius* to fix nitrogen, results in increased soil fertility, thereby altering native plant communities. Many of the native plants of the Pacific Northwest are adapted to relatively infertile soil conditions and compete poorly when extra nutrients are available. Other invasive species are better adapted at exploiting the additional nitrogen and are able to outcompete the native species (Jones, 2006). *Cytisus scoparius* may produce allelopathic compounds that actively suppress the establishment and growth of other species. This potentially mitigates the increase in nutrient availability (Grove *et al.*, 2012; Haubensak and Parker, 2004).

Figure 7: *C. scoparius* in a recently cleared forest in British Columbia – Image from (PFLA, 2013)

Cytisus scoparius is also a fire hazard and has been shown to increase the frequency and intensity of fires. With its dense stands and height, *C. scoparius* provides sufficient fuel for fire and can act as a ladder for surface fires to reach tree canopies or buildings when adjacent to them, increasing both the frequency and intensity of fires (Parsons 1992 as cited in (2000))

2.2.5 Control

As with *Rubus armeniacus*, control methods for *Cytisus scoparius* can be broken down into several broad categories: manual, mechanical, chemical, and biological.

Manual

Manual control for *Cytisus scoparius* involves either hand pulling or cutting over several years to remove the aboveground vegetation. This method is most effective at destroying seedlings or plants up to 1-1/2 meters tall (Hoshovsky, 2001). Cutting can be

particularly effective. Bossard and Rejmanek (1994) found that cutting the broom at the base of the plant at the end of the dry season significantly decreases the rate of resprouting. Plants cut in August had less than 10% of the shrubs resprout while those in March and May had 80-100% resprouting. Cutting has the advantage of not disturbing the soil, and therefore not bringing *C. scoparius* seeds to the surface and increasing their chance of germination. A common alternative to cutting is the use of a weed wrench to yank the entire plant out of the soil. There is no chance for plant resprouting with this method but it does disturb the soil and may increase the germination of seeds in the seed bank. Manual control is very labor intensive which can limit the amount of area cleared.

Mechanical

Mechanical methods for controlling *C. scoparius* involve mowing, cutting, or chopping. However, these mechanical methods can not be used on slopes greater than 30 percent, and can increase the risk of soil erosion and soil compaction. The mechanical treatments have the advantage of being more effective in clearing larger areas with a smaller crew than manual control methods.

Chemical

Herbicide

Herbicides have been successfully utilized to control *C. scoparius* and can be especially effective where weed infestations are very dense. 2,4-dichlorophenoxyacetic acid (2,4-D) is a commonly used herbicide to control *C. scoparius* both by itself and with additives such as diquat, picloram, dicamba, and sodium chlorate (Allo, 1960; Balneaves, 1981; Watt and Tustin, 1976). Glyphosate and triclopyr have been found to effectively

control Scotch broom through foliar applications (Sound Native Plants, 2011). Pre-emergent herbicides can also be used to suppress the seed bank, while native plants are planted and allowed to get established in order to shade out *C. scoparius*.

Fire

Fire has been proposed as a potential method for controlling *C. scoparius* since it burns readily. Also, burning is less costly than basal and stem herbicide treatments especially in conjuncture with a broadcast herbicide application. Fire is not utilized though in urban locations due to issues of smoke and need for control. In addition, there is some evidence that fire may actually stimulate *C. scoparius* seed germination (Hoshovsky, 2001).

Biological

There have been three insect biological controls released to try to contain *C. scoparius*, *Bruchidius villosus* - seed beetle, *Exapion fuscirostre* - seed weevil, and *Leucoptera spartifoliella* - wig-mining moth (2010). *Leucoptera spartifoliella* was released in California in 1960 and in Oregon in 1970 and by 1979 had reached Washington. The larvae damage the epidermis of the twigs, reducing the photosynthesis of the surface. However this has only had a minor impact in the spread of the shrub (Hoshovsky, 2001; Hulting *et al.*, 2008). *Exapion fuscirostre* was released in California in 1964, in 1983 in Oregon, and in the late 1980s in Washington. The larvae feed on developing seeds in the pods, destroying 20% to 80% of the seeds. Like *Leucoptera spartifoliella*, *Exapion fuscirostre* has had limited effect controlling *C. scoparius* (Hoshovsky, 2001). The most effective of all of these biocontrol methods is *Bruchidius*

villosus which when highly abundant can attack up to 90% of the *C. scoparius* pods on a shrub and can reduce seed production by 50% to 90%. This insect was accidently released on the East coast but after host specificity tests was introduced in Oregon in 1998 and in Washington in 1999 (Hulting *et al.*, 2008).

Figure 8a: *Bruchidius villosus* – Image from Schimming (2012a)

Figure 8b: *Exapion fuscirostre* – Image from Schimming (2012b)

Figure 8c: *Leucoptera spartifoliella* – modified from Coombs, (2011)

Livestock such as goats have been found to be effective in removing *C. scoparius* from a site; however it should be noted that *C. scoparius* contain toxic alkaloids in both the vegetation and seed coats that depress the heart and nervous system and as such is unpalatable to most livestock (Jones, 2006; Pojar and MacKinnon, 2004). Goats are less costly to utilize than mechanical and chemical control methods. They can negotiate slopes too steep to manage with machines and do not pose the environmental dangers inherent with herbicides. The goats when faced with mature bushes will defoliate twigs and strip off bark, but will leave standing the plant's main superstructure, which is too old and tough to tempt them (Hoshovsky, 2001).

As seen above, a plethora of control methods already exist for *Cytisus scoparius*; however none directly neutralize the greatest challenge to controlling this species, its

seed bank. An alternative method is needed that can reduce the viability of the seed bank quicker than the 60-80 years it naturally takes to deplete it.

2.3 Solarization

2.3.1 A New Solution

R. armeniacus and *C. scoparius* still continue to be challenges to control even though much effort has been spent trying to remove these species. Both species possess traits that make them resistant to current control methods. *R. armeniacus* possesses a root crown capable of quickly and prolifically producing canes and its stem and root fragments are capable of rapidly rooting and producing new daughter plants. *C. scoparius*, while easily controlled by mowing, quickly produces a large, persistent seed bank that requires constant maintenance to deplete. A new control method is needed that is capable of killing remnant root crowns and stem and root fragments of *R. armeniacus* and rapidly depleting the seed bank of *C. scoparius*. One potential method is solarization or plastic mulching.

2.3.2 What is Solarization?

Solarization is a commonly used agriculture process used to control pathogenic fungi, bacteria, nematodes, and weeds (Abdel-Rahim *et al.*, 1988; Bacha *et al.*, 2007; Egley, 1990; Elmore *et al.*, 1997; Rubin and Benjamin, 1984; Stapleton *et al.*, 2005; Stapleton *et al.*, 2002). It can promote earlier harvests, regulate soil moisture, and reduce fertilizer leaching, soil compaction, and root pruning (Dickerson, 2002; McCraw and Motes, 2007).

First pioneered as pest control method in the 1970's in Israel (Katan *et al.*, 1976), solarization is a simple non-chemical technique that uses thin plastic (polyethylene) sheets to capture radiant energy from the sun to heat the soil. Acting like a greenhouse, the sheets raise the soil temperature to lethal levels for many weeds and pathogens and cause physical, chemical and biological changes in the top 10 cm of soil (Benlïoğlu *et al.*, 2005; Cohen *et al.*, 2008; Elmore *et al.*, 1997).

Figure 9: Solarization of *R. armeniacus* with clear and black plastic

Unlike other control methods, solarization has been shown to kill the dormant parts of weeds and successfully reduce the seed bank of undesired species (Cohen *et al.*, 2008; Pfeifer-Meister *et al.*, 2007). This means that after clearing the aboveground vegetation of *R. armeniacus* and *C. scoparius*, solarization could potentially be used to kill any root crowns of *R. armeniacus* and *C. scoparius* and eliminate their respective seed banks in the soil.

2.3.3 How Does Solarization Work?

Solarization utilizes thin polyethelene sheets stretched taunt over the ground. The close contact of the sheets to the soil surface optimizes the transfer of thermal energy to the soil (Lamont, 1999). The sheets come in a variety of different widths, thicknesses and colors, each with different focus, and can be either smooth or embossed (McCraw and Motes, 2007). The two main colors used for solarization are clear and black plastic.

Black plastic is the most popular color used in commericial vegetable production, likely due to it ability to shade out weeds. Due to being black, the plastic absorbs most incident solar radiation, including visible, infrared and ultra- violet light. Much of the thermal energy, however, is lost to the atmosphere through convection and reradiation. The soil temperature under black plastic can be up 5°F higher at a 2-inch depth and 3°F higher at a 4-inch depth than bare soil at the same depths (Lamont, 1999).

Clear plastic is less popular with gardeners due to concerns of it enhancing seed germination. Clear plastic can raise soil temperatures during the daytime higher than can black plastic. At a 2-inch depth, clear plastic can reach 8-14°F, higher temperatures than bare ground. At a depth of 4 inches, solarization can also increase the soil temperature 6-14°F higher than bare ground too. This is due to a greater (85 to 95%) solar radiation transmittance. Clear plastic absorbs very little solar radiation. Water droplets that condense on the underside of clear plastic allow solar light (short-wave radiation) in, but block outgoing, long-wave infrared radiation (heat). In bare soil, this heat is normally lost to the atmosphere (Lamont, 1999).

Other colors for plastic do exist such as red, white, or silver/aluminum. Red plastic has been shown to help increase soil temperature, but is more often used to increase the quality of tomato yields and to control the severity of early blight on them. White and silver/aluminum plastic actually cool the soil and should not be used if weed control is the goal (Lamont, 1999; Lamont *et al.*, 1990). Wavelength-selective mulches have also been developed to selectively absorb photosynthetically active radiation, while transmitting solar infrared radiation. Also called infrared-transmitting mulches, these sheets exhibit similar soil-warming characteristics to that of clear plastics, just not as well (Lamont, 1999).

After the sheets have been laid out, the edges of the sheets are weighted down to create a seal over the surface of the soil. This helps maintain soil moisture over the site and prevent heat loss (Conway and Pickett, *s.m.*). Before the sheets are applied, either drip irrigation or a single thorough soaking of the ground to saturation, helps maximize the heating of the soil. Good soil moisture improves the thermal conduction of heat into the soil profile (Dickerson, 2002).

Much of the effectiveness of solarization depends on its duration, the light intensity, and the length of daytime during that duration (Ahmad *et al.*, 1996; Bacha *et al.*, 2007). Elmore *et al.* (1997) found that maxim heating occurs at the top 2 inches of soil, but the impact can still be measured at least 18 inches below the surface. They also found that solarization could increase the soil temperature by as much as 13°C in California.

Solarization has the side effect of promoting plant growth. Plants often grow faster in solarized soil. This could be due to several reasons. Solarization helps break down organic material in soil, releasing soluble nutrients such as nitrogen, calcium, magnesium, potassium, and fulvic acid to be used by other plants (Elmore *et al.*, 1997; Stapleton *et al.*, 1985). It can also alter the soil biota, reducing the population, or it can remove some potential pathogen from the soil and may increase the population of mycorrhizal fungi and bacteria (Elmore *et al.*, 1997; Stapleton and Devay, 1986). This is a useful trait in agriculture but may be come an issue when the plants being promoted are non-desired species. Adjustments in the technique are required so that only desired species take advantage of the favorable growing conditions.

2.3.4 Limitations of Solarization

Solarization is not a perfect control method, free of issues. Repeated solarization of a site has been shown to suppress native and overall biodiversity. One study, Pfeifer-Meister *et al.* (2007), found that while solarization initially resulted in greater plant cover, repeated solarization of a site reduced native and overall plant diversity more than the various herbicide and tilling treatments.

Another issue is that solarization is not as effective at controlling perennial weeds as it is with annuals because perennials often having deeply buried rhizomes and deeper roots from which they can resprout (Elmore *et al.*, 1997). Solarization may even increase

weed populations at a site if soil temperature is only sufficient to warm the soil and not reach sub-lethal levels.

There are also concerns with disposal of the plastic. The sheets, if properly installed and stored, can last for several seasons but must be disposed of if rips and tears form in the plastic. This can result in a large amount of plastic waste (McCraw and Motes, 2007). Biodegradable plastic sheets do exist but only at the cost of losing durability with repeated use.

Finally, solarization as treatment is restricted to locations that have adequate light exposure and has been found to be less effective on sloped surfaces (Elmore *et al.*, 1997). Care will be needed to see if the site receives adequate sunlight at the ground level for an adequate period of time during the day and does not possess too great of a slope or internal depressions.

Even with these limitations, solarization provides a non-chemical alternative method to controlling invasive species. The challenges facing solarization may be overcome with modification and further research. Solarization's ability to effect the invasive species' seed banks and belowground structures cannot be ignored and must be considered as a possible control method.

3. Purpose and Need

With the continued widespread distribution of *C. scoparius* and *R. armeniacus* across the Pacific Northwest, new methods of control are needed. Both species possess traits that make them resistant to current control methods. *R. armeniacus* is capable of quickly resprouting from its root crown, rapidly recolonizing a cleared site while *C. scoparius* is capable within a few years of producing of large persistent seed bank that can last over 80 years.

Solarization is a potential control method that has been used to control weeds and their seed banks in other parts of the world. However, most of the research on and use of solarization has been done in areas that are in hotter climates than the Pacific Northwest. The overarching questions motivating this thesis are "Can solarization be used to kill *R. armeniacus* and *C. scoparius*?*"* "Can solarization kill the root crowns of *Rubus armeniacus* and *Cytisus scoparius*?" "Is solarization able to reduce the seed bank viability of *R. armeniacus* and *C. scoparius*?" And finally, "Is solarization even feasible in the Pacific Northwest?"

To answers the questions above, I implemented two experiments, one looking at the effect of solarization on established *R. armeniacus* and *C. scoparius* vegetation while the other focused on the effects of solarization on the seed banks of the two species. To determine the effect of solarization on established vegetation a field trial was conducted

in the Union Bay Natural Area. The second trial was a seed bank focused experiment in the greenhouse at the University of Washington's Center for Urban Horticulture. Both of the locations are part of the University of Washington Botanical Gardens and are located on the Seattle campus of the University of Washington in Seattle, Washington.

3.1 Objectives: Field Trial

The field test involved the establishment of 24 plots in areas primarily composed of either *R. armeniacus* or *C. scoparius*. The plots were situated in groups of four based on the distribution of the species in that area. Each of these four plots were randomly assigned one of four treatment options: control, mowed, black plastic and clear plastic. The control plots were subjected to no treatment while the mowed, black and clear plastic plots were all mowed and had residual stem material raked off. After mowing, but before plastic application, all plots were watered until soil saturation. The black and clear plastic solarization treatments were covered with the respective plastic. The plastic edges were sealed with a combination of bricks and gravel. With three replicates for each treatment, the experiment ran for six weeks or 42 days in the late summer of 2011. Stems and root crowns were counted just before treatment and again the following summer. Soil core samples were taken from each plot to see the effects of solarization on the seed bank species composition of the plots before and after treatments. The cores were divided into three sections corresponding to the depth 0-3 cm, 3-6 cm, and 6-9 cm and then mixed with potting soil to allow the seed bank to germinate, grow and be identified.

The objectives of the field trial were to:

I. Observe the effectiveness of the various treatments in reducing the populations of *R. armeniacus* and *C. scoparius*
II. Determine which of the treatments was superior at reducing the populations of the two species
III. Observe the effect of the treatments on non-target species

To achieve these objectives, I experimentally tested the following hypothesie:

3.1.1 Hypothesis 1:

Plants subjected to solarization will exhibit greater mortality as exhibited by lower Post/Pre treatment stem and root ratios.

Plants experience heat stress when the ambient temperature temporarily rises, typically 10-15 °C. Heat stress is a complex function of intensity (temperature in degrees), duration, and rate of increase in temperature. During heat stress plants experience a variety of morphological, physiological and biochemical changes, which can affect plant growth and development. At moderately high temperatures, injuries or death to plants may occur due to long-term exposure (Wahid *et al.*, 2007). Solarization can potentially supply heat over this long period needed to induce mortality for it has been shown to increase soil temperatures by up 15ºC compared to non-solarized soil (Elmore *et al.*, 1997).

3.1.2 Hypothesis 2:

Of the two solarization treatments, clear plastic exhibits the greatest increase mortality for the two species.

While both clear and black plastic mulches are able to raise the soil temperature above the ambient conditions (Tarara, 2000), clear plastic warms the soil to a higher temperature than black (McCraw and Motes, 2007). If solarization can indeed induce a fatal level of heat stress, clear plastic will be able to reach warmer temperatures resulting in a greater mortality for both species.

3.1.3 Hypothesis 3:

Solarization will alter the species composition of the seed bank to different degrees depending on the depth of the seed bank sample with the samples closest to the surface showing the greatest difference before and after while the lower depths are more similar before and after.

Long-term heat stress on developing seeds may result in loss of vigor leading to reduced emergence and seedling establishment (Wahid *et al.*, 2007). Solarization may be capable of directly killing seeds by damaging the seed coats, weakening the seeds defense against high temperatures (Cohen *et al.*, 2008). The increase in soil temperature during solarization is diminished by depth (Elmore *et al.*, 1997). Portions of seed banks that are closer to the surface will thus experience a greater increase in temperature than those at a lower depth. The greater temperature increase will result in an increase in seed mortality as shown by a greater difference in pre and post species assemblages compared to those assemblages at a lower depth which experience a diminished temperature increase.

3.2 Objectives: Greenhouse Experiment

This second experiment involved collecting *R. armeniacus* and *C. scoparius* seeds, subjecting half of each of the seeds to pretreatments (scarification and/or stratification) to represent a spectrum of new and old seeds. The seeds were then randomly divided into lots of 125 seeds and then planted. The experimental set up for each species was three replicates for three treatments (control/nothing, clear plastic, and black plastic) at four temperature regimes (20 °C, 30 °C, 40 °C and 50 °C), repeated for both pretreated and non-pretreated seeds. As with the field trial, the greenhouse experiment ran for six weeks or 42 days.

The objectives of this experiment were to:

I. Find the optimal average soil temperature needed to reduce seed viability

II. Determine whether heat stress alone was killing seeds or if there was some other factor inherent in solarization that further reduces seed bank viability

To achieve these objectives, I experimentally tested the following hypotheses:

3.2.1 Hypothesis 1:

Soil temperature will have a negative correlation with seed bank viability

At moderate temperatures, solarization can promote seed germination while at higher temperatures it causes seed mortality (McCraw and Motes, 2007; Wahid *et al.*, 2007). Thus, as soil temperature rises there should be a corresponding decrease in seed bank viability.

3.2.2 Hypothesis 2:

Pots covered with clear or black plastic will exhibit greater seed viability reductions than the control at all temperatures.

Plastic mulches have been shown to help reduce moisture loss (McCraw and Motes, 2007). If soils are too dry, (i.e. less than 70 percent of field capacity), weed seeds may not imbibe enough water to make them vulnerable to the increased heat (Elmore *et al.*, 1997). In addition, good soil moisture improves thermal conduction of heat into the soil profile (As reported by Katan, 1980 in Dickerson, 2002). Thus, even at the same temperature, pots with solarization sheets on top will exhibit a greater rate of seed mortality then pots with no plastic.

The results of these experiments should help determine the feasibility of solarization as an effective control method for *R. armeniacus* and *C. scoparius*. In addition, the results will determine how high the soil temperature must be to have a negative effect on the two species and which of the two commonly used plastics is most effective.

This thesis is a pilot study of the usefulness of solarization to controlling these weeds in the Pacific Northwest. I shall relate these finding to their application to habitat restoration and weed control, and to areas of future exploration and refinement of this technique.

4. Methods

To investigate the effectiveness of solarization as a control method for *R. armeniacus* and *C. scoparius*, I utilized two experiments. These included both a field trial and a greenhouse experiment to analyze the effect of solarization on well-established vegetation and its effect on the seed bank of the respective species. The field trial was conducted at the Union Bay Natural Area of the University of Washington over 42 days, focusing on the effect of solarization on established populations of the weeds. The trial size was limited by the availability and size of monoculture stands of the two invasive species. A smaller observation study looked at the effects of solarization on the seed banks of each plot by taking soil core samples from each plot and then allowing for the seeds to germinate and identifying the resulting species. The greenhouse trial provided a more quantitatively rigorous analysis on the effect of solarization on seed banks. Control of the initial quantity of seeds in each pot and at what temperature was possible, allowing for more in-depth exploration of whether solarization or general heat stress was responsible for reduced viability of the seeds. The specific materials and methods for these two experiments are detailed below.

4.1 The Field Trial

The Union Bay Natural Area (UBNA) is a 73.5 acre natural area managed by the University of Washington. Prior to 1912, the area was open water fringed by shoreline emergent wetlands. After the completion of the shipping channel to Lake Washington,

Figure 10: Arial view of UBNA - Photo courtesy of the University of Washington Botanical Gardens

the lake level dropped 9-12 feet, exposing former underwater delta and peat deposits. By 1916, the exposed area was rapidly colonized by emergent wetlands forming the Union Bay marsh. In 1926, the city of Seattle and the University of Washington began dumping household waste in the marsh, converting the area into the Montlake Landfill. The landfill was closed, covered, capped, and graded in 1966 with fill, rubble and soil from the Health Sciences expansion (Ewing, 2010). After the cap was installed, it was seeded with a variety of European grasses, but was soon infested with *R. armeniacus* and *C. scoparius*. By 1972, a management plan for the area had been established, balancing a variety of recreational, research, and ecological goals (Ewing, 2010). UBNA is annually mowed in the late summer, after the bird-nesting season, to control for *R. armeniacus* and *C. scoparius*. Scheduling and budget constraints occasionally prevent this from happening and by 2011, several fair sized stands of *R. armeniacus* and *C. scoparius* had been established across the northern half of UBNA.

The ground of UBNA is primarily composed of a mixture of densely compacted clay soils and gravel with a layer of organics on top. The thickness of the soil and cap beneath it vary, causing the water holding capacity and potentiality for root penetration to vary wildly in areas. UBNA receives approximately 96.7 cm of precipitation a year (University of Washington, 2013) and has a Mediterranean climate, with dry summers. The vegetation is a mix of native and non-native trees, shrubs, forbs, and grasses. The sites chosen within UBNA were areas dominated by *R. armeniacus* and *C. scoparius*.

The field trial was a 1x4 design involving a control, a mowed, clear, and black plastic treatments for each species. All plots were situated in stands of their respective invasive plant. Due to the size and shape of the stands, the orientation and relative position of each plot varied and was restricted to clumps of four. To reduce uncontrollable factors, each group of four plots had every treatment present. Treatment allocation was randomly assigned to each plot. (See Figure 11 for map of site)

Figure 11: Map of the Field Trial Plots and replicates- Image from Google Earth, BB- R. armeniacus, SB – C. scoparius

The four treatment types were selected to represent different possible control methods and help elucidate the effect of solarization. Control represented both what

would happen if a land manager did nothing to the stands of either species but also provide a base line from which to compare the three other treatments. All three other treatments-- mowed, clear, and black plastic-- where initially mowed prior to the experiment to remove the aboveground vegetation. Comparisons between the mowed and the two solarization treatments would allow for analysis of whether or not solarization brought any additional benefits to increasing the mortality of the root crowns of the invasive species. The two solarization treatments where set up exactly the same, only varying in the type of plastic used. Each type of plastic, clear or black, has its proponents. Thus each plastic was used in order to determine whether one plastic was more effective than the other. To ensure a fair comparison between both types of plastic, only plastic with a thickness of 102 μm was used. Thinner plastic sheets were available but only in clear.

The field experiment was conducted during the summer of 2011 and was comprised of two parts, first, the main stem and root crown study and second, the smaller seed bank analysis. The field trial utilized 24 10 ft by 10 ft plots with half the plots located in stands of *R. armeniacus* and the other half in stands of *C. scoparius*. The number of plots used was limited by patch size availability and access, in addition to labor restrictions. All stands of *R. armeniacus* and *C. scoparius* used were 2+ years old. Each plot was designated with a two letter code for what species was in it (*R. armeniacus*- "BB", *C. scoparius*- "SB"), followed by a letter designation of which clump (A, B, or C), followed by a number designation (1-4). Treatments were randomly assigned to each plot, with one representative of each treatment for every group.

The plots were established and had their stems and root crowns counted from July 8th to 10th and then those that needed to be were mowed between July 11th and 15th. A second hand cutting occurred July 22nd and 23rd to reduce stem height to the soil surface of all mowed plots.

Half the plots, *R. armeniacus* replicates B and C and *C. scoparius* replicate A, were started on July 30th, while the other plots began on August 2nd. The delay in start time was due to a water shortage. The day before the experiment began, each plot was watered until soil saturation, after which the plots that were to be solarized had the plastic laid over them and the edges sealed. The available water truck only had enough water to supply twelve plots, and was unable to be refilled until three days later at which time the remaining plots were watered and treated to join the experiment. Each plot was solarized for 42 days; thus the field trial ran for the first 12 plots from July 30th to September 9th, and the other 12 from August 2nd to September 12th. The stems and root crowns were recounted the following summer on July 28th and 29th, 2012.

4.1.1 Stem and Root Crown Counts

Stem and root crowns were counted for each plot by hand counting each plant in the plot. Solitary and multiple stems/canes from one central point were considered to be indicative of one root crown. Each stem/cane was also counted to provide a stem count for each plot. The stem and root crown counts of the mowed and solarized plots were counted after they had been initially mowed before treatment. The control plots were

counted by spray painting the base of each plant to prevent repeat counting. The following summer all plots were mowed to ensure ease and accuracy of counting.

4.1.2 Temperature Recording

The temperature of the plots was recorded by iButtons. Six iButtons were buried in each plot in a rig comprised of four bamboo stakes 9 cm long. The stakes were duct taped together with two iButtons alternating on the sides of the stakes at 1.5 cm, 4.5, and 7.5 cm depths so they could record the temperature in center of depths 0-3, 3-6, and 6-9 cm when buried (Figure 12). Two iButtons were hung randomly through every clump of four plots to record the ambient air temperature. The iButtons were set to record the temperature every three hours starting at midnight. Temperatures were recorded at 12:00 am, 3:00 am, 6:00 am, 9:00 am, 12:00 pm, 3:00 pm, 6:00 pm, and 9:00 pm for each day.

Figure 12: Two iButton rigs, each comprised of six DS1920 iButtons

After the 42 days were over, the plastic was removed from the solarized plots, the iButtons were dug up and the data downloaded using OneWireViewer to obtain the temperature data.

4.1.3 Soil Core Samples

Before the start of the main field experiment, soil core samples were taken on July 27th and 28th, with a 2.5" diameter steel pipe. One sample was taken from each plot with each core divided into three parts, corresponding to depths of 0-3 cm, 3-6 cm, and 6-9 cm. After the field trial ended, a second soil core sample was collected on September 10th and 13th for the after treatment composition of the seed banks. The soil samples were stored until August 29th to October 4th, 2012 at which time the seed samples were sifted to remove large rocks, twigs, grass, roots, other vegetative material and excess dirt. Samples were hand shaken and tumbled through a 4.75 mm, 2.00 mm and a 500 μm screen. Material that was caught by the 4.75 mm or passed through the 500 μm screen were discarded. The 4.75 mm screen separated large rocks, twigs, grass and roots from the rest of the material while allowing through smaller material such as finer roots, rocks and seeds. Anything that passed the 500 μm screen was too fine to be a seed and was often either sand or soil. Materials caught on the 2.00 mm and 50 μm screens were preserved.

On October 20th and 21st, 2012, the preserved material was mixed with Sunshine growers #3 mix and potted in 4" pots. The pots were initially filled with sufficient dry Sunshine Growers #3 soil to fill the pot. The dry growing medium was then poured into a

separate container where the seed bank soil sample was mixed into it. The resulting mix was placed back into the container and watered. Each pot was labeled as to what plot and depth it came from and whether it was collected before or after treatment. For every 12 seed samples, one pot filled with only soil was added to act as a seed rain control. The seed rain control pots were filled with Sunshine Growers #3 soil mix and intermixed with the other pots. A total of 156 pots were planted, 144 with post and pre seed bank samples and 12 seed rain controls (Figure 13)

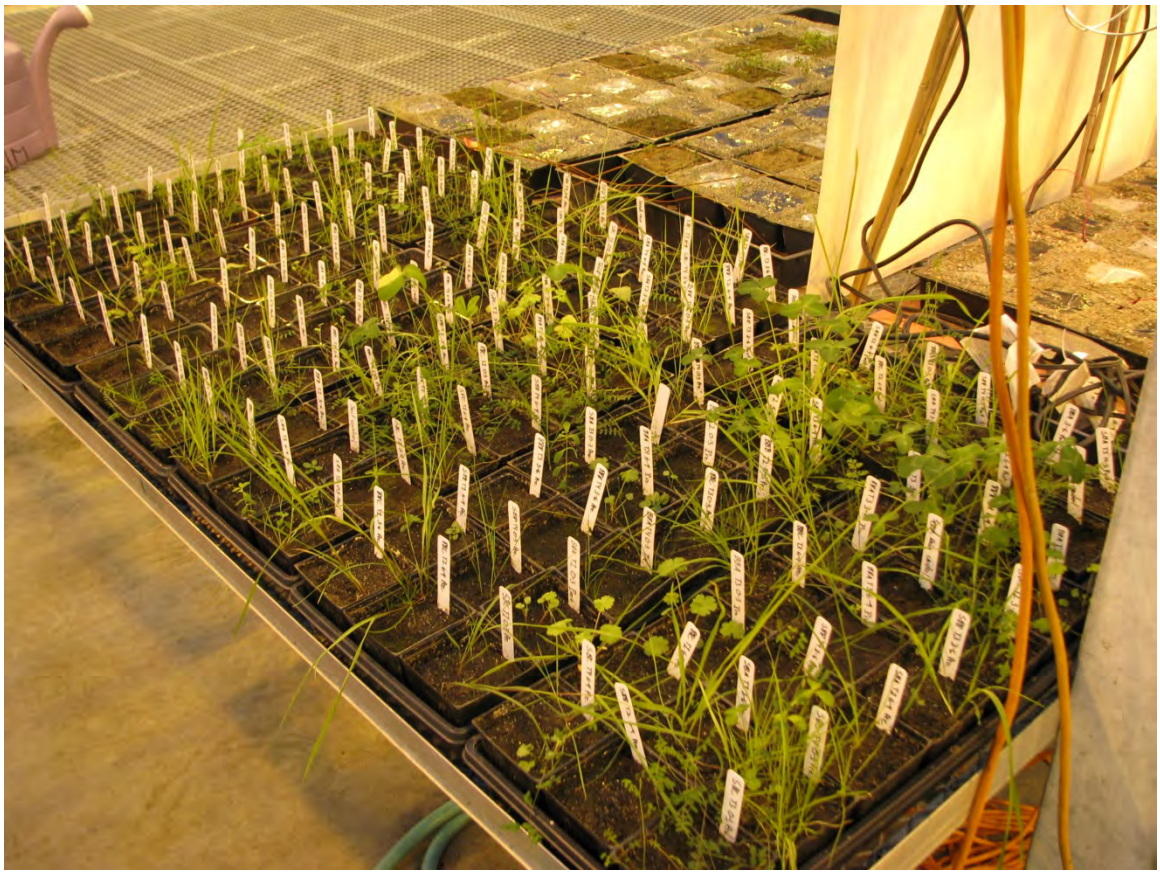


Figure 13: Germination flats of seed samples from field trial

The pots were randomly placed into larger 10” x 20” growing flats and watered as needed to germinate the seeds. The seeds pots were situated within the greenhouse at the University of Washington’s Center for Urban Horticulture (CUH). The greenhouse was kept at an average temperature of 20-22 °C with lights on from 7 am-10 pm from October

20th till December 12th, 2012, after which the lights were on from 7 am to 7 pm. The seeds were allowed to germinate and grow until February 18th and 19th, 2013, when identification was attempted for all seedlings.

4.2 The Greenhouse Experiment

The second main experiment was a focused study on the effects of solarization in reducing the seed bank viability of *R. armeniacus* and *C. scoparius* and helped augment the field trial study. It allowed for a quantitative assessment of the effects of solarization on the seed banks of *R. armeniacus* and *C. scoparius*. This second experiment was also able to determine if the reduction in seed bank viability was due to the increase in soil temperature alone or if solarization had an additional effect in reducing the seed viability. The experiment was designed to measure germination of both pretreated (scarified/stratified) and untreated seeds, with three pot treatments (control, clear plastic, or black plastic) across four temperature regimes 20°C, 30°C, 40°C, and 50°C. The temperatures were chosen to both mimic the temperatures seen in the field trial (20°C and 30°C) but also find an upper temperature threshold the seeds could not survive (40°C and 50°C). This experiment had several stages (1) seed collection and pre-treatment, (2) seed planting (3) run the experiment (4) stem counting and viability test.

4.2.1 Seed Collecting and Pretreatment

The seeds collected for this experiment were split into two groups-- pretreated (scarified and/or stratified) or non-pretreated. This was done in order to mimic the age

spectrum of new seeds (non-pretreated) and old seeds (pretreated) and to see if new seeds or older seeds were more susceptible to solarization.

During the month of July of 2012, I collected seeds of *C. scoparius* from the Union Bay Natural Area. Seeds were collected from throughout the site to be as representative as possible of the local genome. Seeds were collected only from pods that had turned a dark brown to black and that easily split open when pressed on the margins, indicating that they were soon to be ejected from the pods as soon as the pods were sufficiently dry (Jones, 2006); personal observation). Additional seeds were harvested from opened pods, where seeds had been caught in the pod as it was warped when opened.

Seeds were soaked in water for 24 hrs. Detritus and seeds that floated after that period were discarded to remove nonviable seeds. Seeds were then dried and stored in the Miller Seed vault until November 14th, 2012. The seeds were weighed and split into two even sized groups. The pretreated *C. scoparius* seeds were scarified for 30 minutes in 0.98 molar sulfuric acid. The amount of acid used was 2:1 as recommend by Hartmann & Kestler's Plant Propagation Handbook (2011). After the 30 minutes, the acid seed solution was poured over a 500 μm metal screen and washed first with water and then with a mixture of water and baking soda to neutralize any remaining acid. The pretreated and non-pretreated seeds were then counted out into lots of 125 seeds and returned to the Miller Seed Vault until planted.

R. armeniacus seeds were collected during late July, 2012 in Lake Oswego, OR at multiple patches in a mile radius. Fruit was not collected at UBNA due to poor and late fruit production by *R. armeniacus* in the area.

Figure 14a: Combined apple sauce and screen

Figure 14b: Apple sauce removal of seeds

Figure 14c: Final screen cleaning of seeds

R. armeniacus fruit was initially pulped by the applesauce maker, removing much of the fruit flesh. The processed seeds were then rinsed with water and the remaining pulp was removed from the seeds using a 250 μm screen (Figure 14).

Seeds of many Rubus species are slow to germinate due to a hard, impermeable seed coat and a dormant embryo (U.S. Forest Service, 1948). Scarification and stratification were recommended methods to increase the germination of these species but no specific propagation method was found for *R. armeniacus*. A number of different propagation protocols were suggested for *Rubus* species involving the use of hot water and/or sulfuric acid for 15 minutes to 3 hours, and either a warm then cold stratification period or just one or the other for 3 months of each to 1 year of just one or the other (Dirr

and Heauser, 1987; Young and Young, 1992). I decided to use scarification and stratification to pretreat the seeds.

To determine how long to scarify the seeds, I ran a mini trial to determine the effect of different durations of sulfuric acid on the seed coat of *R. armeniacus* seeds at time intervals of 5, 10, 15, 30, 45, 60, 75, 90, 105, and 120 minutes. No change in seed coat color or hardness was noticed on seeds exposed to 90 minutes or less of sulfuric acid, while most of the seeds exposed to 120 minutes had turned to mush. The seeds exposed to 105 minutes (1 hr and 45 minutes) exhibited signs of seed coat weakening without turning to mush.

Based on this experiment and literature review, for the pretreated *R. armeniacus* seeds I decided to scarify seeds for 1 hr and 45 minutes in sulfuric acid followed by one month of warm stratification and two months of cold stratification.

The cleaned *R. armeniacus* seeds were split into two even groups. The untreated seeds were returned to the Miller Seed Vault for storage. The seeds to be pretreated were placed into a beaker and covered with sulfuric acid for 1 hr and 45 minutes and then poured out over a 250 μm screen and washed with water and baking soda to neutralize the acid. The seeds were rinsed again to remove any remaining baking soda. The seeds were then allowed to dry and placed inside paper towels, wrapped with moist sphagnum moss, placed into a Ziploc bag and placed in the summer growth chamber in the Center for Urban Horticulture for warm stratification. After one month the bag was moved to the winter growth chamber for cold stratification. The summer chamber had a light cycle of 6

am to 8 pm with the “day” temperature of 23.4°C and a “night” temperature of 14.1°C. The winter chamber had a light cycle of 7:30 am to 5:30 pm with a constant temperature of 5 °C (Table 1).

Stratification	Duration	Light Cycle	Temperature
Warm	1 month	6 am to 8 pm	23.4°C Day 14.1°C Night
Cold	2 months	7:30 am to 5:30 pm	5°C

Table 1: Summary of Stratification of *R. armeniacus* seeds

After stratification, both the pretreated and non-pretreated *R. armeniacus* seeds were divided into seed lots of 125 seeds and stored until planting.

4.2.2 Seed Planting

From November 27th through November 30th, 2012, I planted the non and pretreated seed lots of *C. scoparius* and *R. armeniacus* into 4.88 x 4.88 x 2.38 inch with Sunshine Growers #3 soil mix. The pots were filled to the brim with pre-moistened soil. The soil was then emptied into a larger container and one seed packet of 125 seeds was added to the soil. The seeds and soil were then thoroughly mixed together to ensure an even distribution of seeds throughout the soil. The soil seed mix was then returned to the pot and labeled with the respective species, with notations of whether the seeds had been pretreated or not. After all the seeds had been planted, all the pots were watered one more time to saturation. For both the pretreated and non-pretreated pots, one third of the pots were covered with clear plastic, another third with black plastic, while the last third were left uncovered. As with the field trial, 102 μm thick plastic sheets were used.

Each temperature regime received 36 pots. Of those pots, 18 came from each species, comprised of nine pretreated and nine untreated pots. For both pretreated and untreated pots, three had clear plastic, three black plastic and three as controls. The pots were randomly distributed within each of the temperature regimes* within 10” x 20” flats.

	Untreated			Pretreated		
Temperature	Control	Black	Clear	Control	Black	Clear
20C	3 pots	3 pots	3 pots	3 pots	3 pots	3 pots
30C	3 pots	3 pots	3 pots	3 pots	3 pots	3 pots
40C	3 pots	3 pots	3 pots	3 pots	3 pots	3 pots
50C	3 pots	3 pots	3 pots	3 pots	3 pots	3 pots

Table 2: Visualization of the Greenhouse Experiment

*The pots in the 50°C temperature regime were not as randomly mixed due to heating challenges. The plastic covered pots retained heat better than the control pots. When attempting to keep the control pots in 50°C range, while intermixed with the solarization pots, the plastic covered pots were registering temperatures in excess of 70°C. The solarization and the control pots were separated and heated independently to keep them in the target temperature ranges.

4.2.3 Running the Experiment

Heating was achieved for each of the temperature regimes in a variety of ways. The ambient temperature of the greenhouse easily achieved the 20°C temperature regime, so no additional heating method was needed. A single heating pad was used to raise the soil of the pots up to 30 °C. A Conviron Environmental Chamber, model E-15, was used to reach the 40°C temperature range while another heating pad and four heating lamps on bamboo poles where used to heat the soil for the 50 °C range. Due to heating issues, the

plastic covered and control pots of the 50 °C temperature regime were separated by a thin 1/8 inch Styrofoam board to reduce radiation spill over from the heating lamps. The small boards were used to separate the 30 °C and 50 °C flats. Timers were used for the heating so that the heat would match the light cycle of the greenhouse from 7 am-10 pm. Two of the heating lamps, those over the control 50 °C pots, were on throughout the light cycle of the greenhouse, while the two lamps over the plastic pots where on for one hour every other hour. The growth chamber was set to a matching light and heating schedule of 7 am-10 pm. The air temperature within the growth chamber was adjusted as needed to keep the 40 °C pots within the correct soil temperature ranges.

Figure 15: Conviron Environmental Chamber in the Center for Urban Horticulture

To ensure the temperatures in the pots remained in their appropriate ranges (Table 3) thermocouples where randomly scattered across the temperature regimes in all three pot treatments to allow daily temperature checks without disturbing the soil.

The experiment ran from November 30th, 2012 through January 11th, 2013. The temperature was checked several times a day to ensure that pots in each temperature

regime stayed in the appropriate ranges. Adjustments were done as needed to maintain the desired temperature.

Temperature	Range	Heating Method
20 °C	15-25 °C	Ambient Greenhouse Temp
30 °C	25-35 °C	1 Heating Pad
40 °C	35-45 °C	Growth Chamber
50 °C	45-55 °C	1 Heating Pad, 4 Heating Bulbs

Table 3: Summary of Temperature Regimes and Heating Methods

Figure 16: Photo of Greenhouse experiment, from left to right 20°C, 30°C, and 50°C. 40°C pots were in growth chamber

4.2.4 Stem Counting and Viability Testing

After the experiment, the number of sprouted seeds was counted in each of the pots. Each sprout was assumed to be representative of a single seed. The soil of each pot was then sifted through a 1.00 mm and a 500 μm screen to find any unsprouted seed. The recollected seeds were stored until they could be tested for viability.

Figure 17: Screens used to capture ungerminated seeds

A tetrazolium (TZ) test was used to test the viability of the recollected unsprouted seeds. The seeds were soaked overnight in moist paper towels at ~20ºC. The seeds were then placed in a beaker and covered with a 0.5 solution of TZ for 12 hours. Seeds were bisected and considered viable if stained red and non-viable if unstained or if they had turned to mush.

Tetrazolium Test

In a TZ test, enzymes in respiring living tissues alter the chemical 2,3,5-triphenyl tetrazolium chloride into the chemical, triphenyl formazan. Triphenyl formazan stains the living tissues red. In non-respiring, dead tissues the enzymes are not active and no staining occurs. For seeds, the respiring tissues are the embryos. As such, embryos stained red in a TZ test may be considered viable. This allows for TZ testing to rapidly provide an accurate estimation of the potential max viability of a seed lot (Hartmann *et al.*, 1988).

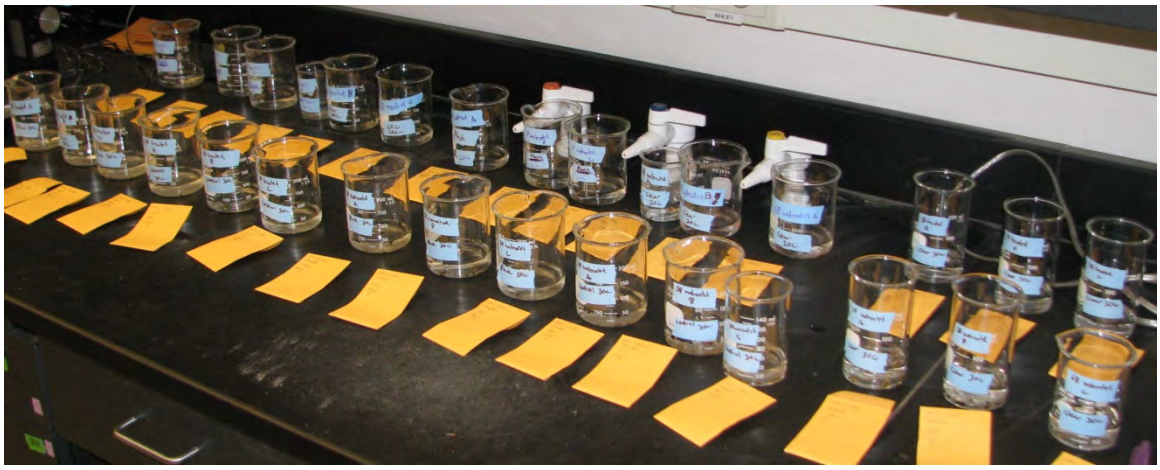


Figure 18: Tetrazolium testing of C. scoparius seeds

Seed viability was calculated for each pot by adding the number of sprouts and remaining viable seeds.

5. Results and Discussion

All the experiments helped provide insight into the potential of solarization as a control method for *C. scoparius* and *R. armeniacus* in the Pacific Northwest. They were not all successful. The seed banks of plots in UBNA were not similar enough in seed quantity and species composition to provide a statistically sound comparison for before and after treatment and only observational results were possible. In addition, for unknown reason, none of the *R. armeniacus* seeds germinated during the greenhouse experiment, preventing any assessment on the effects of solarization on seed bank viability of *R. armeniacus*.

In this section, the analytical techniques used and results found for each experiment will be presented.

5.1 The Field Trial

5.1.1 Field Trial Conditions

Air Temperature

The average daily air temperature of the field trial was 19.16 °C with the hottest average daily temperature being 24.25 °C and the coolest 15.99 °C (Figure 19). During the trial the air temperature varied over 30 °C, with the warmest recorded temperature at 37.25 °C and the coolest at 5.5 °C. During the trial, there was a total of 0.12 inches of

precipitation were recorded in the area at Sand Point, occurring on August 15th, 22nd, and September 8th. The greatest amount of precipitation occurred on August 22nd with 0.1 inches (National Climatic Data Center, 2011). The temperatures recorded from July 30th through August 4th are incomplete, with data missing from the 12:00 am and 3:00 am time slots. The iButtons were delayed in installation. From July 30th through August 4th, the daily temperature was recorded by hand with thermocouples. The missing data resulted in artificially high temperatures for that time period.

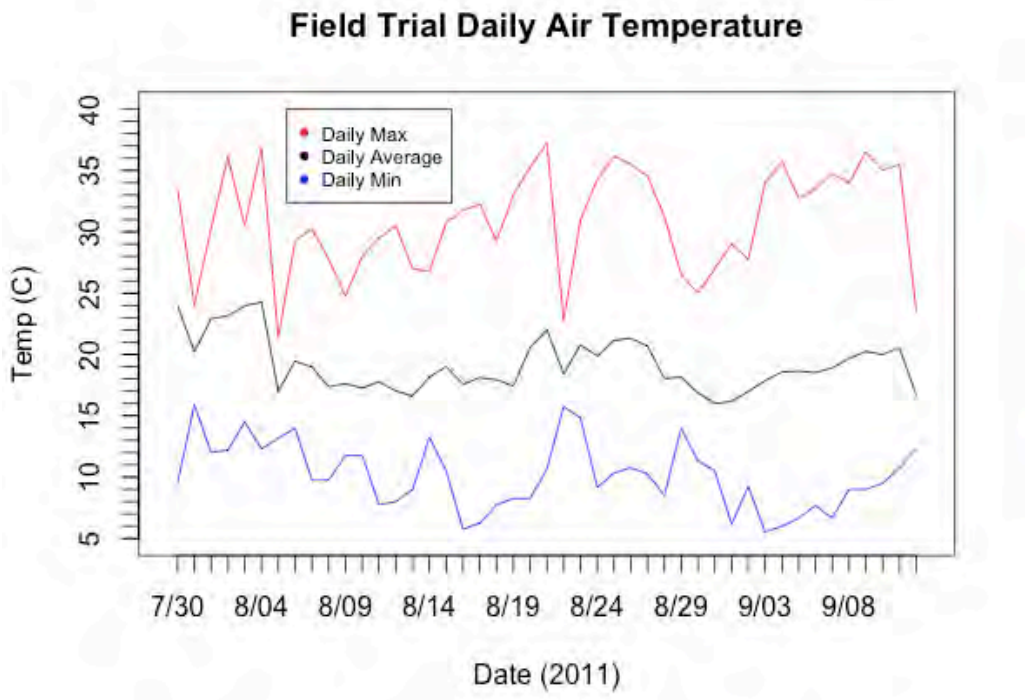


Figure 19: Daily air temperature variation across the field trial.

Concerns were raised that the summer of 2011 was cooler than normal (Sistek, 2011). Using minute-by-minute data from UW atmospheric sciences, subsequent analyses of the air temperature found no significant difference between the summer of 2011 and a 10-year average of 2003-2012 during the experiment window (Figure 20).

The average temperature for 2011 was 65.8 °F while the 10-year average was 65.1 °F (UW Atmospheric Sciences, 2011).

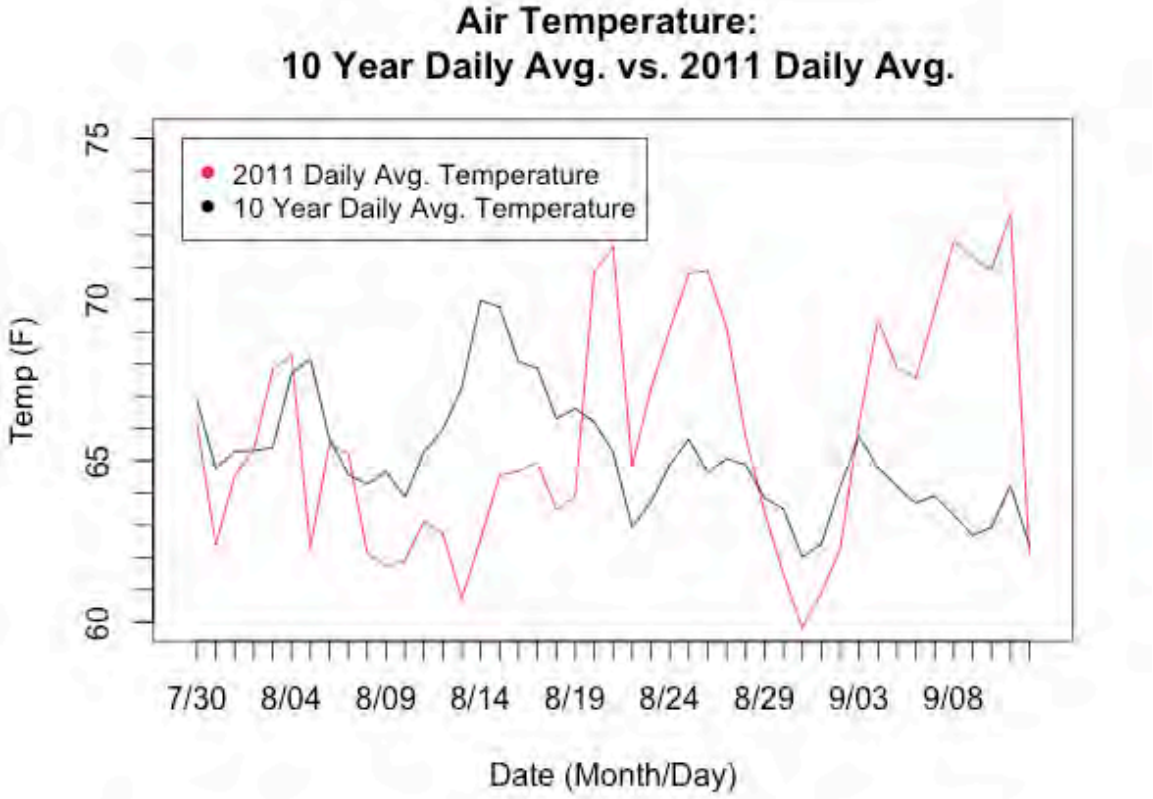


Figure 20: Comparison of the daily average for the 10-year period of 2003-2012 vs. the summer of 2011. The average daily temperature of 2011 was not significantly different from that of the 10-year average.

Stems and Root Crowns

To establish the effect of solarization and the various other treatments on *R. armeniacus* and *C. scoparius*, initial and post experiment counts of the root crowns and stems of the two species were taken. These counts varied widely from one another. Stem counts for *R. armeniacus* ranged from as few as 36 to as many as 252, while root crown counts varied from 15 to 67. A similar situation occurred in the *C. scoparius* plots with as few as 21 stems in a plot to 258, and ranged from 11 to 130 root crowns. These initial stem and root crown effects influenced the quantity of stems and root crowns found at the end of the experiment. To neutralize the effects of these initial conditions of the plots, the

effect of treatments between plots was compared on a value of survivorship, calculated for each plot by dividing the post count by the pre count of either the root crowns or stems for each plot. This created a standardized comparison between plots. The values of each plot can be found in Appendix II.

Stem and Root Crown Counting Issues

The control plots for both *R. armeniacus* and *C. scoparius* had noticeably lower initial root crown and stem counts than the other treatment plots. In the case of *R. armeniacus*, this was likely due to difficulties in accurately counting the stem and root crowns within the plot thickets. The post experiment counts of the stem and root crowns were on par with other treatment plots. This potentially created an artificially higher survivorship than was actually present on the site. The actual survivorship ratio was likely closer to 1.0 for both the stem and root crown counts. The lower pre-experiment control counts for *C. scoparius* are believed to simply be the result of chance as the post counts of the plots were similar to that of the pre counts for both stems and root crowns.

Stem and Root Crown Temperature Issues

The temperature data for the plots is artificially high for July 30th through August 4th due to initial programming issues. The plot temperatures for that time period were manually recorded using a temperature probe. The temperatures were unable to be recorded at midnight and 3:00 am, resulting in a higher average daily temperature for those days. By 3:00 pm on August 4th, all iButtons were installed and functioning, resulting in a more accurate assessment of daily temperatures.

The two iButtons at every depth were averaged to provide a more accurate recording of soil temperature at that time interval. However, some of the iButtons

malfunctioned during the experiment; they either did not record or misrecorded. The data from those iButtons was disregarded and/or utilized until the point malfunctions appeared.

Shading from grasses surrounding the plots was a major concern for all plots except for those in *R. armeniacus* replicate A. Due to budget and timing restraints, only *R. armeniacus* replicate A had the surrounding plants completely mowed. This complete mowing was likely the major factor for the near 5 °C increase in soil temperature shown in all treatments of *R. armeniacus* replicate A compared to replicates B and C. For most of the other plots, the surrounding grasses or plants were still present and likely cooled the plots resulting in lower plot temperatures. Care will need to be taken in subsequent experiments to ensure that the surrounding matrix of the plots is completely mowed.

5.1.2 Effect of Treatment

The treatment used was found to be a significant factor in reducing the stem and root crown survivorship of both *R. armeniacus* and *C. scoparius* (Table 4). All treatments (mowed, black plastic and clear plastic) significantly reduced the survivorship of root crowns and stems of both species barring one exception. In the cases of *C. scoparius* stems and root crowns and *R. armeniacus* stems, the plots mowed, or solarized with black plastic and clear plastic all showed significant reductions in survivorship when compared to the control plots (Figure 21-a, c, d). The exception is in the case of *R. armeniacus* root crown survivorship where only the treatment of solarization with clear plastic showed significant reduction in survivorship from the control (Figure 21b).

Species	Survivorship	P value	R-squared
R. armeniacus	Stem	0.000155	0.8763
	Root Crown	0.038	0.4936
C. scoparius	Stem	0.001042	0.7997
	Root Crown	$2.71e^{-06}$	0.9553

Table 4: P and R-squared values of treatment on *R. armeniacus* and *C. scoparius* survivorship

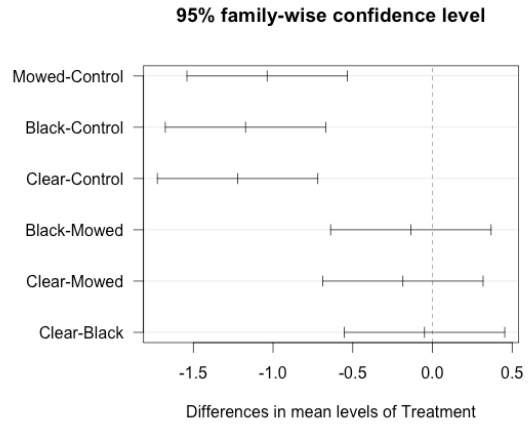


Figure 21a) Tukey HSD of R. armeniacus stem survivorship survivorship

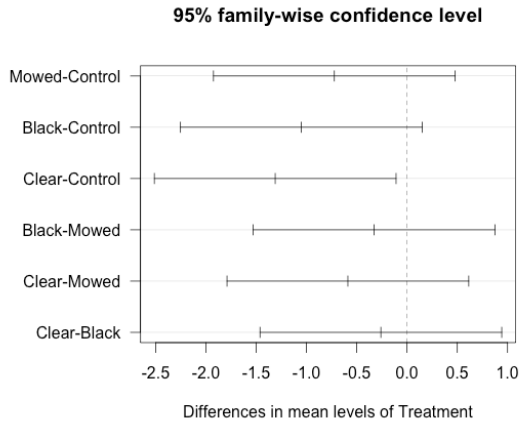


Figure 21b) Tukey HSD of R. armeniacus root crown

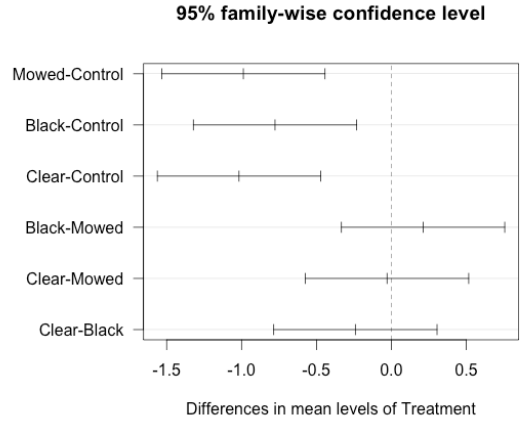


Figure 21c) Tukey HSD of *C. scoparius* stem survivorship

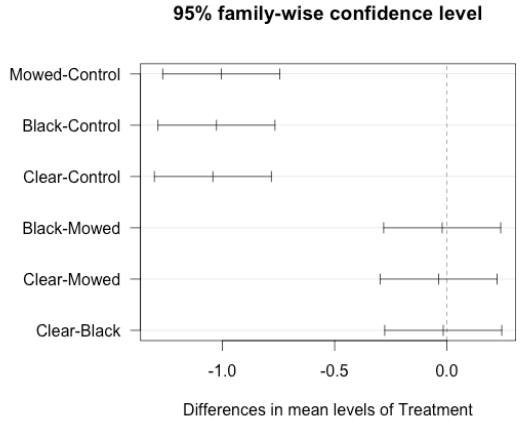


Figure 21d)Tukey HSD of *C. scoparius* root crown survivorship

Figure 21) Tukey's Honest Significance Test (HSD) plots of *C. scoparius* and *R. armeniacus* survivorship. The difference in mean levels is calculated by taking the mean values of each observation per treatment and dividing it by the standard error of the data. If the mean level is below 0.0 than the mean of the first treatment listed is less/lower than that of the second. If the error bars of the confidence level cross the 0.0 line, than there is no significant difference between the two treatments.

Between the treatments of mowed, black plastic and clear plastic, no significant difference was found. Variations in the difference of means between each treatment do suggest some trends. These trends must be viewed with caution due to the small sample size of each treatment. Subsequent investigation is needed to determine whether these are actual trends in the data or due to random chance.

Examination of the confidence intervals of *R. armeniacus* stems, root crowns, and *C. scoparius* root crown survivorship, show that both black and clear plastic (i.e. solarization) plots have slightly lower difference of means than that of the mowed plots. This suggests that solarization may be responsible for some additional loss of survivorship over that caused by cutting/mowing down the aboveground material. Data on the effect of the treatments on the stems of *C. scoparius* showed nearly no difference of means between the mowed and clear plastic plots but did show black plastic having a greater difference in mean than just mowing or use of clear plastic. The data suggests that there was an increase in stems in the black plastic plots (Figure 21c). For both species in both stems and root crowns, clear plastic had to some degree lower survivorship than that of black plastic. In the cases of *R. armeniacus* stems and *C. scoparius* root crown, the difference in means is close to zero while the root crown survivorship of *R. armeniacus* and *C. scoparius* stem survivorship differed more.

The role of treatment in reducing the survivorship of *R. armeniacus* and *C. scoparius* is to be expected since current control methods of both species includes mowing as a recommended treatment method and in the case of *C. scoparius*, Bossard

and Rejmanek (1994) had already shown the effect of cutting *C. scoparius* at its base at various times of the year. The slight depression of the difference of means of the solarization treatments over that of the mowed treatment suggests that solarization is responsible for some additional loss of survivorship, but additional research is needed to determine the validity of this trend.

5.1.3 Effect of Temperature

To determine whether there was an inherent characteristic in solarization or if heat stress alone was responsible for reducing *R. armeniacus* and *C. scoparius* viability and survivorship, temperature was analyzed as a potential factor both independently and in collaboration with the treatment.

Plot temperature was found to be a significant factor in reducing the stem and root crown survivorship of both *R. armeniacus* and *C. scoparius*. This held true for all depths and for overall plot temperature. The degree of significance and amount of variation explained in the data did vary depending on what depth or overall plot temperature was being analyzed (Tables 5).

R. armeniacus

Stem Survivorship

Depth	P value	R-squared
0-3 cm	0.001527	0.6156
3-6 cm	0.002017	0.5945
6-9 cm	0.02772	0.3383
Overall	0.002839	0.5672

Root Crown Survivorship

Depth	P value	R-squared
0-3 cm	0.007286	0.4827
3-6 cm	0.0079	0.4748
6-9 cm	0.004941	0.5192
Overall	0.003552	0.5483

C. scoparius

Stem Survivorship

Depth	P value	R-squared
0-3 cm	0.009932	0.4519
3-6 cm	0.02132	0.3691
6-9 cm	0.01655	0.3976
Overall	0.01516	0.4072

Root Crown Survivorship

Depth	P value	R-squared
0-3 cm	0.007265	0.483
3-6 cm	0.01129	0.4387
6-9 cm	0.007929	0.4745
Overall	0.008546	0.4671

Tables 5: P and R-squared values of treatment on stem and root crown survivorship of *R. armeniacus* and *C. scoparius*

For *R. armeniacus*, stems and root crowns varied on which depth temperature was more significant in reducing survivorship. In *R. armeniacus* stems, the average plot temperature at the depths of 0-3 cm followed then by the 3-6 cm were more significant at reducing stem survivorship then the overall plot temperature. Overall plot temperature however was more significant in reducing the survivorship of *R. armeniacus* than any of the individual three depths though the lowest depth (6-9 cm) was the next significant.

C. scoparius showed a different pattern where the top depth (0-3 cm) for both stem and root crown survivorship were more important than overall plot temperature. In both types of survivorship, the lowest depth of 6-9 cm was more significant than the middle depth of 3-6 cm. The position of overall plot temperature varied depending on whether stems or root crowns were being looked at in *C. scoparius*.

For stem survivorship, overall plot temperature was just slightly more significant than the temperature at 6-9 cm. For the root crowns, overall plot temperature was less significant than that of the temperature at 6-9 cm but still more so than that of 3-6 cm.

With both *R. armeniacus* and *C. scoparius* stem survivorship was most significantly affected by the temperature at the 0-3 cm depth; this suggests that a top surface heat is most beneficial at "searing" or suppressing the regrowth of stems from the meristem tissue of both species. The lower depth greater significance seen in both species for root crown survivorship suggests that it is the penetration of heat to lower temperatures that is more important in suppressing the growth and potentially killing the plant in question.

Due to the varying significances of the temperature at different depths and the infeasibility of heating soil only at a precise depth, average overall plot temperature was used for all plot temperature analysis unless otherwise mentioned. This will also provide a more practical and useful comparison for the public to understand and utilize the information.

5.1.4 Temperature and Treatment on Soil

Plot treatment had an effect on the soil temperature at all depths that remained the same for both *R. armeniacus* plots and *C. scoparius* plots. The treatment used on the plot had immediate effect on the relative temperature of the soil in comparison to the air temperature (Appendix I).

For all the control plots except Blackberry A, the soil temperatures of the plot followed the pattern of the air temperature, being warmest followed by the surface temperature at 0-3 cm and then getting progressively cooler the lower the depth. Blackberry A was the exception, for the average soil temperature at 6-9 cm was warmer than the temperature at all the other depths and air temperature. Some potential reasons for this odd event include: the soil at the 6-9 cm depth being insulated from the air temperature, the sensors at the depth were adjacent to something warm such as a pipe or something with metabolic activity, or some other unknown event took place.

In the mowed plots, the temperature profiles maintained the trend with soil closer to the surface being warmer than that of the lower depths. The air temperature was more similar to that of the soil temperature. In the cases of Blackberry B, C, and Scotch Broom A, the air temperature was often slightly lower than that of the soil temperatures. For Blackberry A, the air temperature was often at least 5 °C cooler than that of the soil temperatures at 0-3 cm and 6-9 cm and was about the same as the soil temperature at 6-9 cm. The similarity between soil and air temperature is potentially due to the removal of the shading effect of the aboveground vegetation present in the control plots.

Both the solarized treatments, black and clear plastic, showed the same trends with soil temperatures, at all depths, being greater than that of the ambient air temperature. That gap was greater in clear plots, suggesting that clear plastic was more effective at increasing the average soil temperature than black plastic. As with the mowed and control plots, the soil was warmest near the surface and became progressively cooler as the depth increased. The effect of solarization is likely mitigated by soil depth, with

upper soil areas acting as insulation for lower ones. Plant material and seeds closer to the surface of the soil will likely experience harsher conditions than those of lower temperature.

5.1.5 Overall Soil Temperature and Treatment Pattern

The shape of the relationship between stem/ root crown survivorship varied between the two species though one pattern held true for both. The soil temperature at every depth was significantly affected by the treatments (P value: 2×10^{-16}). At all depths, plots that were either mowed or had clear/black plastic were all warmer than the control plots. Plots that were solarized, had warmer soils than those just mowed, and plots with clear plastic were warmer than those with black (Figure 22).

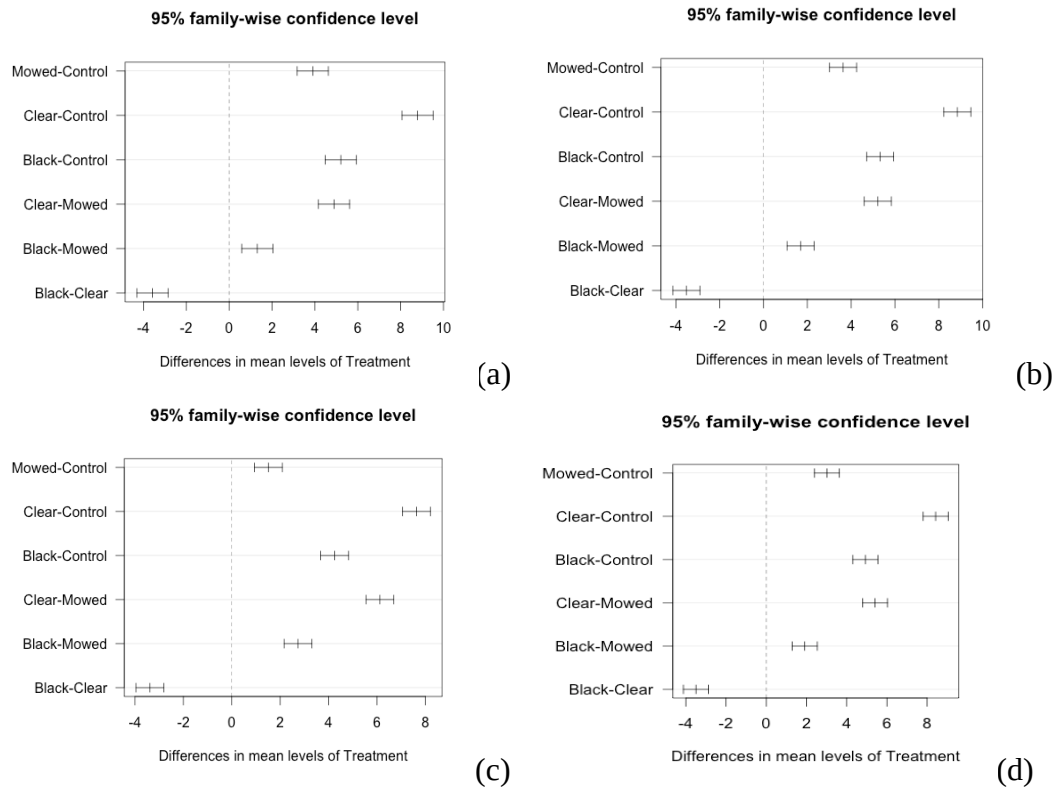


Figure 22: Tukey's HSD plots on the effect of treatment on soil temperature at depths of 0-3 cm (a), 3-6 cm (b), 6-9 cm (c), average plot temp (d). Confidnce bars above 0, indicate that the first treatment listed is warmer than that of the second.

The increase in soil temperature due to changes in treatment also corresponds to a decrease in stem and root crown survivorship for both species (Tables 6a and 6b).

Treatment	Stem Survivorship	Root Crown Survivorship	Avg. Plot Temperature
Control	1.62	1.95	17.09
Mowed	0.58	1.23	20.83
Black	0.45	0.90	23.22
Clear	0.40	0.64	26.85

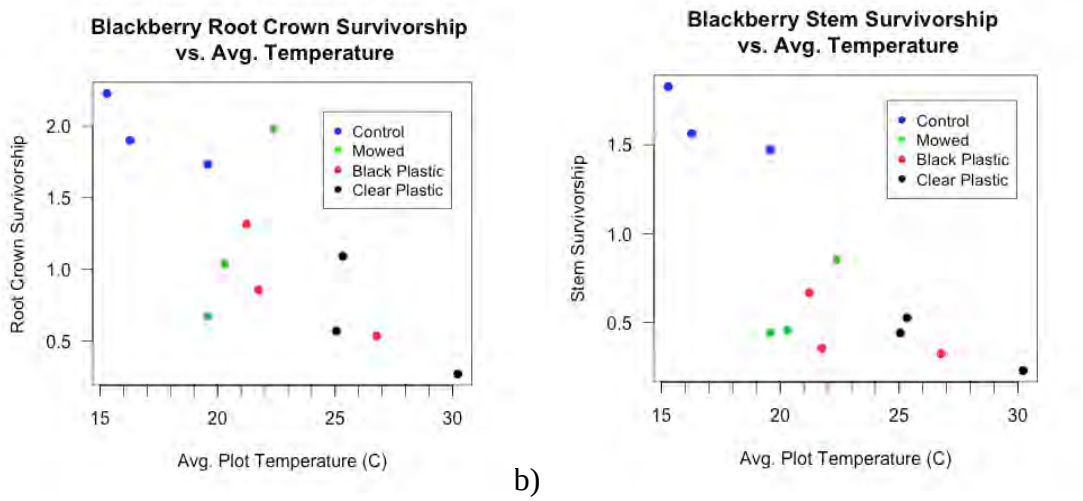
Table 6a: Overall stem and root crown survivorship vs. average plot temperature of *R. armeniacus*

Treatment	Stem Survivorship	Root Crown Survivorship	Avg. Plot Temperature
Control	1.05	1.09	16.75
Mowed	0.06	0.09	19.12
Black	0.28	0.07	20.67
Clear	0.04	0.05	24.11

Table 6b: Overall stem and root crown survivorship vs. average plot temperature of *C. scoparius*

5.1.6 *Rubus armeniacus* and Temperature

In *R. armeniacus*, a negative relationship was present between stem/root crown survivorship and plot temperature. As plot temperature increased, there was a decrease in survivorship. The exact nature of the relationship is currently unknown. With root crown survivorship (Figure 23a), a negative linear relationship is suggested by the data with a slope of -0.1152. Plot data of stem survivorship suggests something more along the lines of an inverse relationship (Figure 23b). The small sample size of each treatment type for both stems and root crowns prevents a more thorough analysis.



a) b)

Figure 23: Effect of average plot temperature on root crown (a) and stem (b) survivorship ratios of *R. armeniacus*

One thing of note about the *R. armeniacus* data is that while there is a general negative relationship between survivorship and plot temperature and while that the trend holds within the control, black plastic, and clear plastic plots, it does not hold within the mowed treated plots. The data show a positive relationship between survivorship and plot temperature. As plot temperature increased, the survivorship too increased. This trend

does not appear in the *C. scoparius* data. As such, this trend may be the product of the small sample size, so additional research is needed to whether this trend is true.

5.1.7 *Cytisus scoparius* and Temperature

For *C. scoparius*, the relationship between root crown/stem survivorship and temperature is less clear. While plot temperature was found to be a significant factor (Table 5), there is some question about whether this true significance or a product of the treatment. When viewed graphically, a break is present in survivorship between the stem/root crown survivorship of the control plots and those corresponding to that of mowed, black plastic, and clear plastic (Figure 24). This is quite different from that of the *R. armeniacus* plots, which showed a continuous decline in survivorships between treatments and temperature increase.

a) b)

Figure 24: Effect of average plot temperature on root crown (a) and stem (b) survivorship ratios of *C. scoparius*

Bossard and Rejmanek (1994) noted that cutting plants at the base at anytime during periods of reduced soil moisture resulted in a decrease in plant survival. The mowed and solarized plots had all of their above-ground vegetation removed which could

be responsible for the break seen and explain the rather flat, even level of stem and root crown survivorship in those plots. The increased soil temperatures for the mowed, black plastic and clear plastic plots could simply be due to the removal of the shading effect from the aboveground vegetation and subsequent heating from solar radiation capture in the solarization plots.

5.1.8 Effect of Treatment and Temperature

Individually, both plot temperature and plot treatment were found to be significant in reducing the survivorship of *R. armeniacus* and *C. scoparius*. These two factors were found to be highly correlated. Visually, this correlation can be seen in the temperature versus root crown or stem survivorship in Figures 23 and 24. Treatments tended to clump together around certain temperatures. This is understandable, since removal of aboveground vegetation as seen in the mowed and solarized plots, negates the shading effect of the vegetation on the soil temperature. The resultant increase in soil temperature is further increased by captured solar radiation in solarized plots.

Between the two factors, treatment had a greater effect on stem and root crown survivorship on *R. armeniacus* and *C. scoparius* than plot temperature. Beta coefficients of the two factors (Table 7) show that treatment had anywhere from roughly a 9x to 212x greater effect on survivorship than plot temperature.

Species	Survivorship	Avg. Temp	Mowed	Black Plastic	Clear Plastic	Mowed / Temp	Black/ Temp	Clear/ Temp
R. armeniacus	Stem	-0.032	-0.971	-0.917	-0.904	29.966	28.285	27.884
	Root Crown	-0.059	-0.688	-0.506	-0.736	11.749	8.644	12.565
C. scoparius	Stem	0.017	-0.844	-1.029	-1.144	49.557	60.372	67.128
	Root Crown	0.005	-1.047	-1.018	-1.081	205.906	200.207	212.576

Table 7: Beta coefficients of average plot temperature and varying treatments in combined models

Unexpectedly, a combined treatment and overall temperature model was a poorer model then temperature alone. In Table 8, only the stem survivorship of *R. armeniacus* shows an improved model fit with a greater adjusted R-square value compared to that of the treatment linear models (Table 4). For *R. armeniacus* root crown, *C. scoparius* stem and root crown survivorship, the combined model shows a lower model fit with poorer P and R-squared values. Compared to the temperature alone models however, the combined model does have a better model fit over the plot temperature at any depth or overall plot temperature.

This suggests that there are other factors involved in reducing stem and root crown survivorship than treatment or plot temperature, especially for the root crown survivorship of *R. armeniacus*. Some of these factors may include soil moisture, alterations in soil composition, gas/chemical build up and/or light penetration.

Treatment and Temperature			
Species	Survivorship	P value	R-squared
R. armeniacus	Stem	0.0004675	0.8837
	Root Crown	0.06973	0.4798
C. scoparius	Stem	0.004636	0.7721
	Root Crown	2.70×10^{-05}	0.949

Table 8: P and R-squared values of combined treatment and temperature models

5.1.9 Field Trial Summary

Based on the actual survivorship of *R. armeniacus* and *C. scoparius* from the field trial, an initial analysis of the data would come to the conclusion that solarization is not superior to just mowing in controlling *R. armeniacus* and *C. scoparius*. Statistically, neither of the two solarization treatments were significantly different from mowing nor was clear plastic superior to black plastic.

This initial conclusion is misleading however. The experiment was limited by the small sample size of the experiment. Each treatment only had three replicates so variations in the data had a greater influence than they might otherwise have had. In addition, there is some indication that a subsequent larger scale trial may show solarization to have a greater effect then what was shown in this pilot study. For both species, temperature was shown as a significant factor in reducing survivorship. While not as great of a factor as treatment, especially in the case of *C. scoparius*, temperature was still a factor. Both the solarization treatments had higher average temperatures than that of either the control or mowed plots and of the two solarized plots, the clear plastic plots always had the higher average temperature. Clear plastic raised soil temperatures 8.63 °C over the control and 5.59 °C over the mowed. Black plastic raised soil temperature 5.08 °C over the control and 2.05 °C over mowed. Subsequent trials likely would see the same pattern and potentially find a significant difference between the mowed and solarized plots and the clear and black solarized plots as suggested by the pair-wise comparisons between treatments and survivorship (Figure 21).

5.2 Seed Bank Experiment

The goal of this experiment was to see the effects of the varying treatments on seed bank composition. Species composition was first attempted after the samples were screened and then again after species germination.

5.2.1 Seed Identification

As the seed bank samples were sifted to remove the rocks and twigs, an initial identification was attempted of the *R. armeniacus* and *C. scoparius* seeds present in plot seed banks (Appendixes III and IV). The observed seed bank was fragmentary and inconsistent with *R. armeniacus* and *C. scoparius* seeds not being present in every respective plot or depth. When seeds were present, an average of 7.69 *R. armeniacus* and 4.18 *C. scoparius* seeds were found in the pre-treatment seed banks. In the post-treatment plots, when found, there was an average of 9.0 *R. armeniacus* seeds and 2.79 *C. scoparius* seeds present.

More post-treatment plots were found to have *R. armeniacus* and *C. scoparius* seeds than pre treatment plots. Of the 36 samples of pre treatment *R. armeniacus*, only seven had *R. armeniacus*, while seeds were found in 27 of the 36 post treatment samples. For *C. scoparius* only 11 pre treatment samples had *C. scoparius* seeds visible compared to 17 post treatment samples. In addition, not all of the corresponding species replicate depths (samples from a plot at a certain depth) registered seed presence in both the pre and post treatment samples. It was expected that due to the large seed production capacity

of both species that each would have rather large well-developed seed banks but the data suggest that this was not true.

The low seed bank development of both species may be due to UBNA typically being mowed annually in the late summer/early fall. If timed right, much of the *R. armeniacus* fruit crop could be mowed before it ripens and then it either drops onto the ground or is consumed by animals. The seed bank would gradually become depleted as more seeds germinate but are unable to replace their number due to mowing. For *C. scoparius* the low seed bank may be due to relative immaturity of the patches along with seed predation from biocontrols.

Interestingly, the data do suggest that many of the *C. scoparius* sites were former *R. armeniacus* patches by the presence of relatively high numbers of *R. armeniacus* seeds in the 6-9 cm depths. This is understandable since much of the Union Bay Natural Area was covered by *R. armeniacus* before active management began.

5.2.2 Germinant Identification

Actual seed bank composition was to be determined by germination of the seed bank. While a number of species were found before and after treatment, their numbers were too random to analyze quantitatively (Appendix V). Some observational conclusions were suggested from what was available.

The species composition of the sites was altered by solarization. While difficult to tell from the seed bank data in Appendix III, the photos below taken in April 2012 show species and structural difference between treated and untreated field sites (Figure 25).

Figure 25a) Field effect of solarization in *R. armeniacus* patch

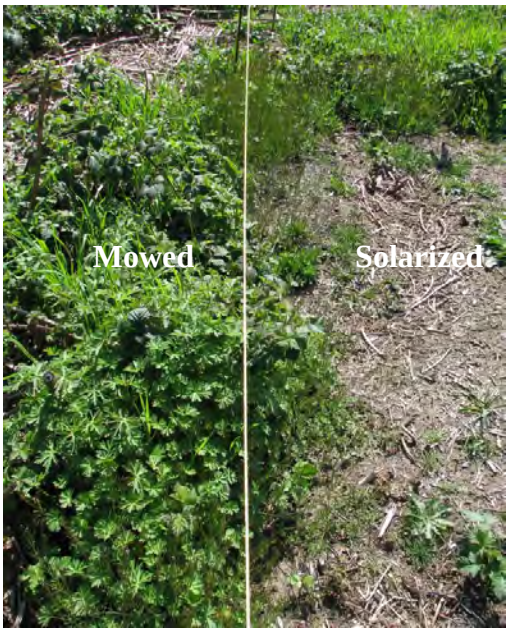


Figure 25b) Effect of solarization on *R. armeniacus*

Figure 25c) Effect of solarization on *C. scoparius*

Oddly, while over five hundred *R. armeniacus* seeds were recovered in the seed banks samples, not one of them germinated during the trial (Appendix V). It is possible

that many of those seeds were non-viable since *R. armeniacus* has a seed bank viability of only 10% to 33% (Amor, 1972; Brinkman, 1974). However, none of them germinating seems unusual. Many of the seeds, especially those from the lower depths, likely had been in the soil long enough to have undergone stratification, so embryo dormancy seems unlikely. Possibly, the seed coats remained too thick for many of the seeds to imbibe water and germinate or more viable seeds had already germinated and sprouted and the seeds observed were the remnant non-viable ones.

The effect of solarization on the seed bank is unable to be determined from the fragmentary nature of the data (Table 9). In the post-treatment samples, *C. scoparius* germination was more often observed in the mowed and control plots than in the solarized plots. This suggests that solarization may have been neutralizing or reducing the viability of the *C. scoparius* seed bank. The relatively few *C. scoparius* observed in the pre treatment samples suggest that this observation may be due to random chance. *C. scoparius* seeds did germinate in post solarized treatment samples indicating that if solarization was reducing seed bank viability, it was not killing all of the seeds. Other species, beside *C. scoparius*, also survived solarization including a variety of grasses, *Geranium carolinianum, Juncus sp*., *Daucus carota*, *Trifolium* sp., *Vicia* sp., *Cirsium* sp., *Hypericum perforatum*, *Plantago* sp., and *Stellaria* sp. (Appendix V). Not all seeds are equally susceptible to solarization (Egley, 1990; Rubin and Benjamin, 1983), potentially these species are more resistant to solarization. In addition, many of these solarized plots only reached an average soil temperature of 21-25° C. Higher temperatures may be needed to neutralize the seed banks of these species. Only *Rubus armeniacus* replicate A,

reached average solarized soil temperatures of 30°C and since many of these species were not found in the pre-treatment samples, no comparison is possible.

The fragmentary data and relatively few seeds observed before and after treatment prevent any potential conclusions on the effect of seed depth on solarization effectiveness. A repeat of this experiment, with more soil core samples taken from plots or in areas with a more developed seed bank, could potentially provide statistically testable results showing the effect of seed depth on seed survivorship. Due to limitation in labor, only a single soil core sample was taken in each plot before and after the treatment. This was a significant reduction from the three to five samples recommended by other literature sources. It is expected that lower seeds would be more insulated from the effect of solarization and would likely maintain higher survivorship rates.

	Pre			Post		
Depth	Replicate	Treatment	Quantity	Replicate	Treatment	Quantity
0-3 cm	SBA	Control	2	SBA	Control	1
				SBA	Black	1
	SBB	Control	1	SBB	Clear	1
				SBC	Mowed	2
				SBC	Control	1
3-6 cm	SBA	Clear	3	BBA	Mowed	1
	SBB	Control	2	SBC	Control	1
				SBC	Mowed	1
6-9 cm	SBB	Control	5	SBA	Control	1
				SBA	Black	1
				SBB	Control	9
	SBB	Black	1	SBC	Control	1
				SBC	Mowed	3
				SBC	Black	1

Table 9: Germination of *C. scoparius* in seed bank samples

The inconclusive nature of these results prevents any pro or negative recommendation for solarization on the seed banks of *R. armeniacus* and *C. scoparius*. Additional information is needed before any conclusion can be reached. Retrials of this experiment should be done in areas that are known not to have been mowed to ensure a more complete and developed seed bank. More than just one soil core sample should also be taken from each site to further minimize the chance of a fragmentary seed bank record. Modifications of this experiment may also be needed to achieve results on effect of solarization on *R. armeniacus*, such as increasing the length of time for plant germination to occur or utilizing direct tests on seed viability such as tetrazolium testing.

5.3 Greenhouse Experiment

To discover a heating threshold at which *R. armeniacus* and *C. scoparius* are unable to grow and a threshold at which they die due to heat stress, and to determine whether it was heat stress alone or some inherent characteristic of solarization that was reducing seed viability, a greenhouse trial was utilized. The greenhouse allowed for control of the soil temperature regardless of the treatment used on the soil and provided a relatively similar environment free of outside factors such as wind or shade. Three factors that could reduce seed viability were studied: seed pretreatment, plot treatment, and plot temperature.

R. armeniacus and *C. scoparius* seeds were separately planted at four different temperatures with one of three treatments placed upon their pots. The seeds in the pots were either newly collected seeds or scarified seeds to represent older seeds in the soil.

The trial ran for six weeks following the example of the field trial. At the end of the trial, there was clear evidence of germination, sprouting, growth, and death of *C. scoparius* seeds. No *R. armeniacus* seed germinated during the experiment, preventing any meaningful analysis of the effect of solarization on *R. armeniacus* seeds. Statistical analysis was possible for the *C. scoparius* seeds, the results of which will be presented and explored below.

The lack of *R. armeniacus* seed germination during the experiment may been caused by several factors. One factor is seed viability. *R. armeniacus* has a naturally low seed viability (Amor, 1972; Brinkman, 1974). This low viability may have been further suppressed if the seeds had not been fully mature when the fruit was picked. In addition, the scarification and stratification treatments may have also reduced seed viability. Scarification does do damage to the seed coat, making the seeds more susceptible to pathogens reducing seed viability (Hartmann *et al.*, 2011). The stratification time used may have also been insufficient to break dormancy too. Not all of the seeds were non-viable since *R. armeniacus* germination was observed in several of the 20°C and 30°C pots well after the duration of the experiment. A larger seed bank in the pots may have been needed in order to observe sufficient germination to make comparisons or a longer wait time after the temperature manipulation to see seed germination.

Unexpectedly, the biocontrol *Bruchidius villosus* was discovered among the *C. scoparius* seeds collected at the Union Bay Natural Area (UBNA). No previous documentation noted their presence at the site. Due to the insect's predation on the seeds collected, insects found were immediately killed and the seeds were float tested before

being used. Seeds that were floated tended to be either hollowed, predated seeds or ones with developing *B. villosus* larvae present inside.

5.3.1 Seed Pretreatment

Alone, pretreatment was not found to be a significant factor in affecting the seed viability of *C. scoparius* (p-value 0.1447). However, when modeled with plot treatment and temperature, scarification does become significant (p-value 0.0201). Unscarified seeds had a lower viability than the scarified seeds (10.58% vs. 13.96%).

These results may be due to early sprouting of the scarified control seeds. Earlier sprouting helped inflate the viability score of the scarified control pots since any stems seen were counted toward the seed viability. The unscarified control pot seeds did not germinate as quickly as the scarified ones so the higher soil temperatures killed the seeds before they could germinate and sprout. Removal of the control plots of the pretreated and non-treated seeds reduced the seed viability of scarified seeds to 9.8 % and the unscarified seeds to 10.2%.

5.3.2 Pot Treatment

Seed bank viability was significantly reduced by pot treatment (p-value 0.017). Alone, pot treatment had an R-squared value of 0.08536. In a combined model though, treatment was even more significant and had a p-value of 0.0001.

Both solarization treatments, black and clear plastic, significantly reduced the seed viability of *C. scoparius* seeds in comparison to the control pots (Figure 26). While

not significantly different, black plastic may have been more effective in reducing the seed bank viability of the *C. scoparius* seeds than clear plastic as seen in the positive difference in means between clear and black plastic and the greater beta coefficient for black (-7.6 vs. -5.6, black and clear plastic respectively).

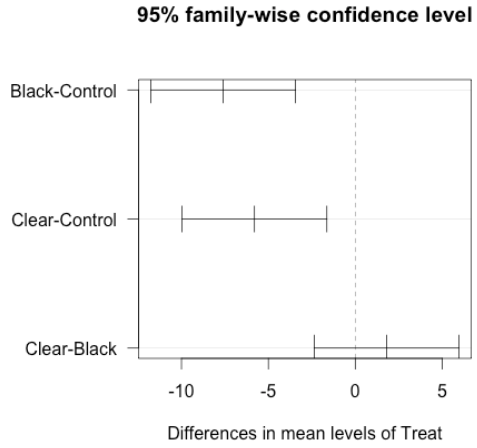


Figure 26: Tukey's HSD of pot treatment, "Black" and "Clear" refer to which plastic was used while control is no plastic. The lower difference in mean levels of "Black-Control" and "Clear-Control" indicate that both black and clear plastic treatments have lower seed bank viabilities in comparison to the control. The last comparison, "Clear-Black", indicates that clear plastic had a higher seed bank viability than the black plastic.

5.3.3 Pot Temperature

Pot temperature was also significant in reducing seed viability (p-value 1.088×10^{-10}). By itself, pot temperature had an R-square value of 0.4923. As pot temperature increased, there was decrease in seed viability. Each successive increase in soil temperature resulted in a significant decrease in seed bank viability until it reached 40 °C at which point there was no significant difference between 40 °C and 50 °C (Figure 27). The data suggests that increasing to 50°C may not further reduce seed bank viability and might actually result in an increase in seed bank viability. The slight increase may indicate that at higher temperatures, seeds sense the hostile environment and do not germinate, making them less susceptible to heat stress. More likely, the slight increase was due to the small sample size and is not indicative of anything.

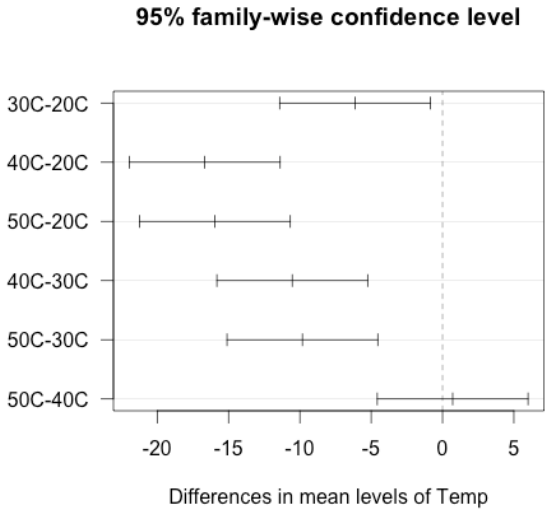
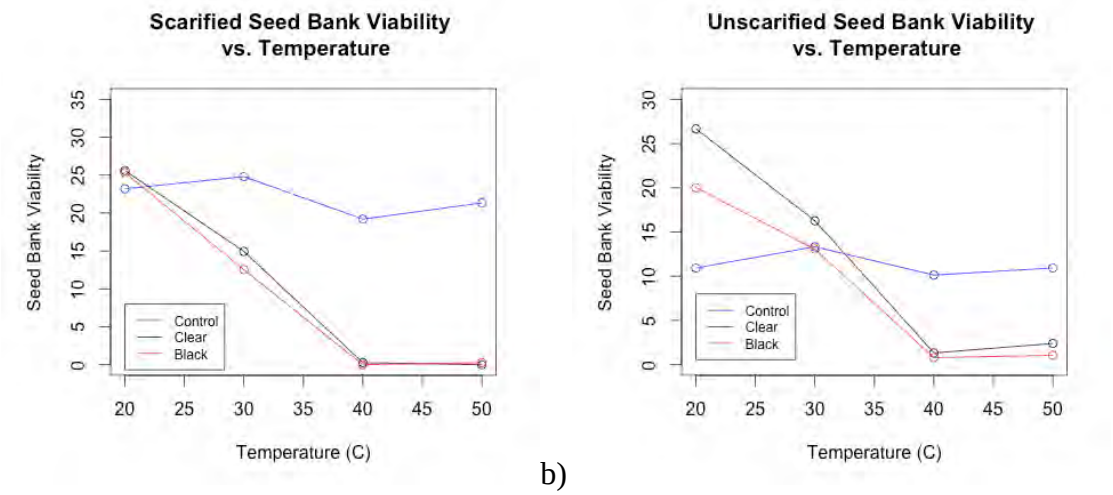


Figure 27: Pair-wise comparison of pot temperature regimes 20 °C through 50 °C in 10°C intervals. Increases in temperature resulted in lower survivorship as seen by the negative difference in mean levels.

Temperature graphs of both scarified and unscarified seeds (Figure 28) confirm the decrease in seed bank viability as soil temperature increases, but show that the similarity between the 40 °C and 50 °C temperature ranges may be due to the fact that seed bank viability reaches near 0%.



a) b)

Figure 28) Visualization of the effect plot treatment and soil temperature have on scarified (a) and unscarified (b) seeds.

The control pots of the scarified and unscarified seeds stayed relatively stable across the temperatures ranges at 22.1% and 10.5% respectively. However, the seed bank viability for scarified and unscarified solarized pots was over 20% (Table 10) at the 20°C

temperature level and had similar decreases in seed viability due to increase in soil temperature. This suggests that solarization may mimic the potential that scarification has for breaking the seed coat, making the seeds more susceptible to heat stress and increased mortality. Cohen *et al.* (2008) found similar results in a case study with *Acacia saligna.* The researchers found that moist heating was more effective than dry heating in killing seeds. Increasing soil moisture and temperature are more effective in breaking seed dormancy than heat alone.

The increase in seed viability due to solarization was to be expected. The plastic sheets used for solarization have long been used as plastic mulch by gardeners to warm the soil and encourage early germination and growth of seeds. At cooler temperatures, the plastic sheets promote plant growth instead of suppressing it.

Unscarified			Scarified		
Temp	Treatment	Avg. Seed Bank Viability	Temp	Treatment	Avg. Seed Bank Viability
20°C	Control	10.93	20°C	Control	23.20
	Black	20.00		Black	25.33
	Clear	26.67		Clear	25.60
30°C	Control	13.33	30°C	Control	24.80
	Black	13.07		Black	12.53
	Clear	16.27		Clear	14.93
40°C	Control	10.13	40°C	Control	19.20
	Black	0.80		Black	0.00
	Clear	1.33		Clear	0.27
50°C	Control	10.93	50°C	Control	21.33
	Black	1.07		Black	0.27
	Clear	2.40		Clear	0.00

Table 10: Average seed bank viability

5.3.4 Combined Model

A combined model of pretreatment, pot treatment, and soil temperature has a p value of 2.43×10^{-13} but an R squared value of only 0.6232. This suggests that while all three of the factors are significant (Table 11), the model itself is incomplete. Other variables besides pretreatment, treatment, and soil temperature are influencing seed bank viability. As with the field trial, some of these other factors may include soil moisture, light penetration, or chemical changes in the soil. Gamliel and Stapleton (1993) found that during solarization, biotoxic volatiles such as aldehydes (formaldehyde and acetaldehyde) and sulfur compounds including isothiocyanates form from the break down of organic matter and accumulate underneath the polyethylene sheets. These chemicals could potentially be part of the missing models for both seeds and root crown and stem survivorship. Additional testing would be needed to determine whether any of these factors play a role in affecting seed bank viability.

Factor	Sq	Mean	Sq	F value	Pr(>F)
Scarification	1	205	205.4	5.68	0.020096
Treatment	2	757	378.6	10.47	0.000114
Temperature	3	3501	1166.9	32.27	6.81×10^{-13}
Residuals	65	2350	36.2		

Table 11: ANOVA summary of combined seed solarization model

6. Experimental Summary

The results of the experiment suggest that solarization can be used as a potential method of control for *R. armeniacus* and *C. scoparius* in the Pacific Northwest. Between the field trial and greenhouse experiment, solarization was found to reduce survivorship of the two invasive species, just as effectively as mowing alone. Unlike mowing however, solarization has the potential to significantly reduce the seed banks of the two species.

The field trial showed that solarized plots had a higher average soil temperature than that of the control and mowed plots. Both plot treatment and soil temperatures were found to be significant factors in reducing the stem and root crown survivorship. This is important for even though the field trial found no significant difference between solarization and mowing treatments in reducing survivorship, additional research would likely show a difference due to the higher average temperature achieved in solarized plots. The analysis of the effect of solarization on the field trial seed banks is inconclusive and cannot be used to either support or reject the potential use of solarization to control *C. scoparius* and *R. armeniacus*.

The greenhouse trial further supports the potential for solarization to control *R. armeniacus* and *C. scoparius*. No other control method currently utilized affects the seed bank of either species. In the greenhouse experiment, the control pots, which could also stand in for mowed pots, maintained seed viability as soil temperature increased.

Only the solarized pots showed a steady decrease in seed viability as soil temperature increased.

Based on the results of the experiment, I would recommend using clear plastic for solarizing the two invasive species. The data from the greenhouse experiment might suggest black plastic as the better choice due to lower seed viability, however the data assumes equal soil temperatures between black and clear plastic. The field trial showed that the clear plastic solarization plots had a higher average temperature than any of the other treatments. The fact that black plastic absorbs solar radiation but does not transmit it to the soil reduces its ability to heat up the soil, negating its advantage over clear plastic. Higher temperatures resulted in lower stem and root crown survivorship and seed viability. Clear plastic is best suited to achieving the necessary temperatures to rapidly degrade the viable seed bank and kill any belowground vegetation.

Black plastic as a method of weed control could potentially be more useful than clear plastic when adequate soil temperatures are unlikely to occur, such as in areas with cooler air temperatures or more shading. Black plastic could be used to shade out established light-dependent species and suppress seed germination until the seeds naturally degrade in the soil and are unable to germinate.

6.1 Future Areas of Research

Additional research into the use of solarization to control *R. armeniacus* and *C. scoparius* is needed before it can be widely implemented to control these species. The

small sample size for all the experiments creates difficulties in getting clear conclusions. All of these experiments should be repeated again but on a larger scale. The greenhouse experiment in particular should be repeated but with a new protocol for procuring and breaking the dormancy of the *R. armeniacus* seeds. The naturally poor seed viability of *R. armeniacus* (Amor, 1972; Brinkman, 1974) does not account for the lack of germination seen during the experiment. Research into solarization can also be expanded in several new directions such as the time duration and seasonality of the experiment, material use and set up, and investigation into other factors that influence survivorship and viability.

6.1.1 Duration and Seasonality

The seasonality and duration for solarizing needs to be investigated for adjustments. Literature recommends solarizing for 6-8 weeks. For this trial, six weeks was originally chosen in order to maximize the day length (closer to the summer solstice), air temperature, and lack of precipitation. Future work can be done in lengthening the duration of solarization to 8 weeks or longer. Most of the current research in solarization has been done in warmer locations so a shorter time duration was effective. In climates such as the Pacific Northwest, a longer solarization time may work better in reducing survivorship. An earlier start date may also be something to investigate since by August, the day length is appreciable shorter as this time is closer to the summer solstice and days then noticeably shorten during the 6-week treatment.

6.1.2 Material Use and Set Up

The material used to solarize is also open to investigation. The polyethylene sheets used to solarize come in a variety of thicknesses. In this investigation, 102 μm thick polyethylene sheets were used. Thinner and thicker types of plastic exist for both clear and black plastic. Changes in material thickness and composition may alter the amount of radiation absorbed, reflected, or refracted by the material. These changes may also alter the durability of the plastic. Thicker materials are more durable but may absorb more of the radiation from the sun and not release it into the soil. Plastic waste is also a matter of concern. As sheets develop holes, they become less effective for solarization and must be disposed of. Biodegradable sheets could be used to help mitigate this waste but these may result in reduced durability and alter the ability of the plastic to capture, reflect and refract the light.

One potential modification of solarization, for the Pacific Northwest would be the use of the double-tent technique. For this experiment, only a single sheet applied directly to the ground was used. However this method does not reach the highest potential temperature increase solarization can achieve. The double-tent technique uses layers of plastic with a space of 3 to 7 cm between each to heat the soil. Ben-Yaphet *et al.* (Ben-Yephet *et al.*, 1987), used 6.3 cm polyvinylchloride pipes to separate the sheets of plastic and found that the technique could raise soil temperature an additional 10 °C above that of a single sheet. This technique is more expensive and labor intensive and is likely limited to smaller size patches.

Large scale set up for solarization also needs to be investigated. The scale of solarization will influence how an area will or can be set up. During the field trial,

surviving root crowns and stems were most often found along the borders of the plots suggesting these areas were cooler than the interior portions. On larger scales, work needs to be done looking into ways to help minimize this edge effect while still maintaining a close contact between the plastic sheets and the soil. The use of sprayable mulches is also something to consider and research to see if they too are useable for solarization.

Shading and slope are also matters of concern. In the field experiment, only 4 plots belonging to *R. armeniacus* replicate A, had the surrounding vegetation completely mowed, preventing shading from the adjacent vegetation. All the other plots had at least one or more sides being shaded by adjacent tall grasses/shrubs or were shaded earlier in the evening by nearby trees. This likely resulted in cooler average soil temperatures and reduced the effectiveness of solarization in those plots. Additional research is needed to determine how much shade a solarized plot can tolerate or solar radiation is needed in order to reduce survivorship. The topography of the site can also influence the effectiveness of solarization by creating microclimate patches more tolerable to the weeds.

6.1.3 Other Factors

In addition to exploring new ways to make solarization more effective, research should also be done to help better understand how solarization works. Soil moisture, gases build up and chemical alterations in the soil may all help effect survivorship and viability. By better understanding how these factors or others alter during solarization,

more accurate models may be produced, and new or refinements on existing methods for controlling invasive species may be developed.

6.2 Conclusion

While much of the data collected in this pilot study does not give a hard resolution on whether solarization would be an effective method of control for invasive species in the Pacific Northwest, the data are supportive of the hypothesis that it might work. The soil in replicate *R. armeniacus* replicate A, did reach an average temperature of over 30 °C in the clear plastic solarization plots. This was high enough to kill most of the root wads and stems in the plot with surviving individuals restricted to the cooler edges. In addition, 30° C was high enough to show reductions in seed bank viability in the greenhouse trial.

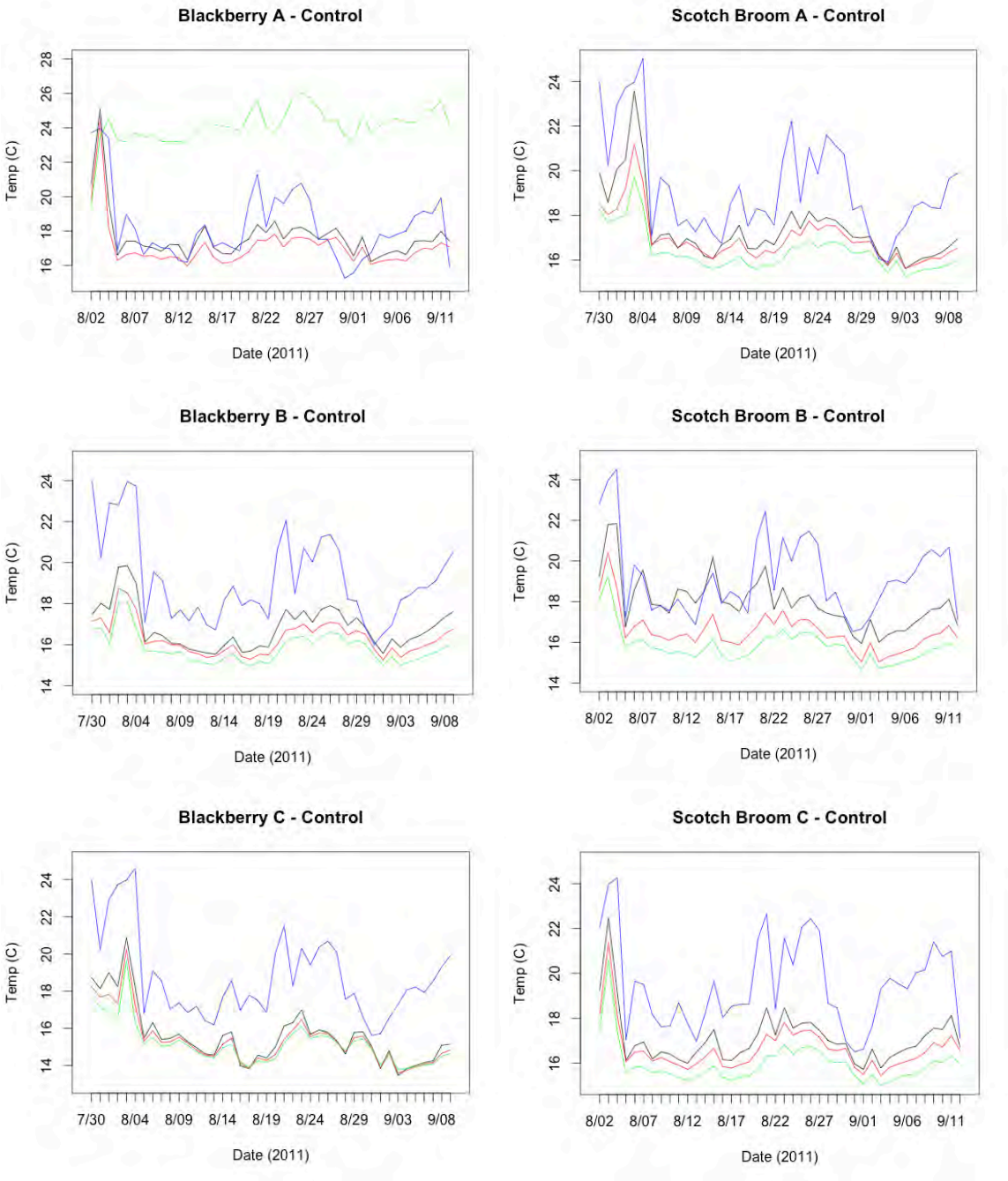
Solarization will require more research before it can be applicable on a massive scale but it should not be ignored as a potential control method in the Pacific Northwest. With our relatively long dry summers, there is plenty of solar radiation available for solarization to take advantage of. Solarization has much merit by being a non-chemical control method capable of killing the belowground vegetation and seed bank of invasive species. It is relatively cheap and it can be repeated as needed over potential large areas by a small work crew. As a control method, it can be left untended in otherwise inaccessible areas such as highway medians.

It is conceivable that solarization may become a useful tool for restoration ecologists who wish to eliminate the existent seed bank in a highly invasive species infested area while not removing the topsoil. Sites could be cleared of the aboveground vegetation in the early summer, with the plastic laid down and left on site through the entire summer till early to late fall. At this time, additional site prep could occur and the new vegetation material or seeds could be installed to take advantage of the winter rains. The polyethylene sheets have the added effect of preventing soil erosion and run off while the vegetation is removed.

Solarization offers a new potential solution to the problems posed by a number of otherwise uncontrollable invasive species in areas with sufficient solar radiation. The technique should not be used in areas where there are number of plants that a site manager wishes to preserve but only used when a blank slated is needed. In particular, solarization can become a useful tool in helping control invasive species that develop large long-lasting seed banks or that are prone to rapidly resprouting from near surface roots and stems. Solarization gives ecological restorationists the opportunity to reclaim large areas of land from aggressive invasive species and give our native species an adventitious start when installed after the plastic is removed.

Appendix I: Temperature Profiles of Plots

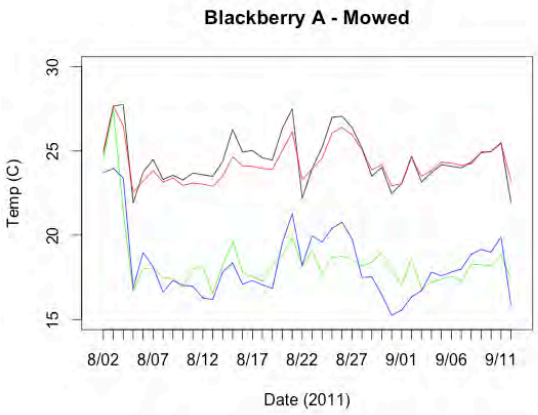
Control

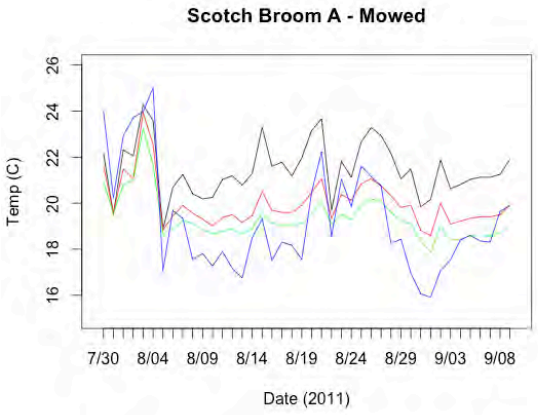


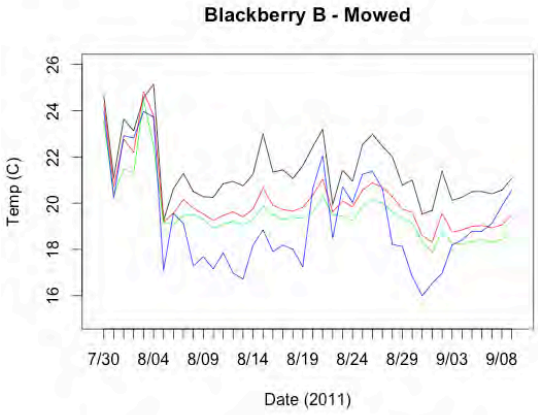
Line Color and Depth

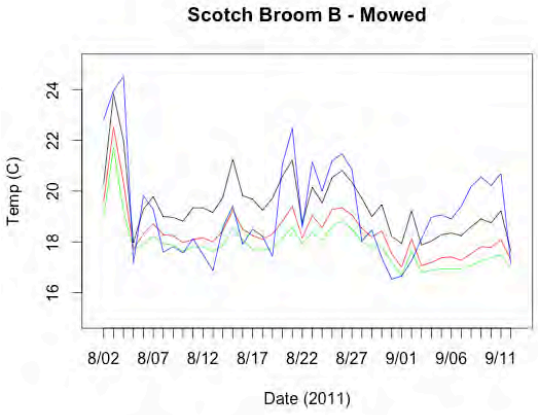
Blue = Air	Red=3-6 cm
Black=0-3 cm	Green=6-9 cm

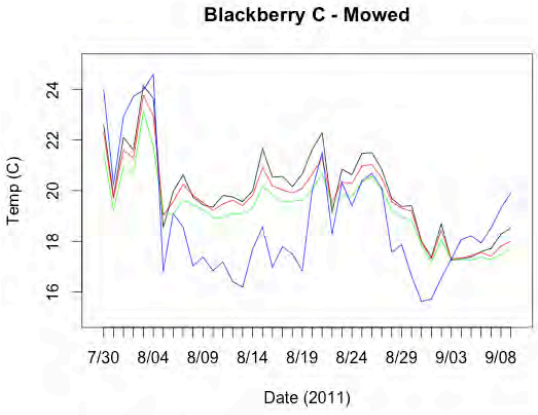
Mowed

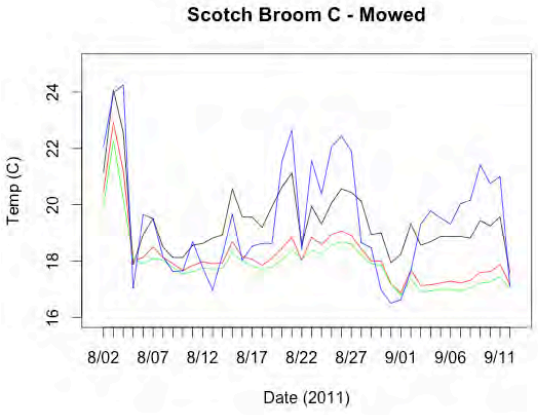








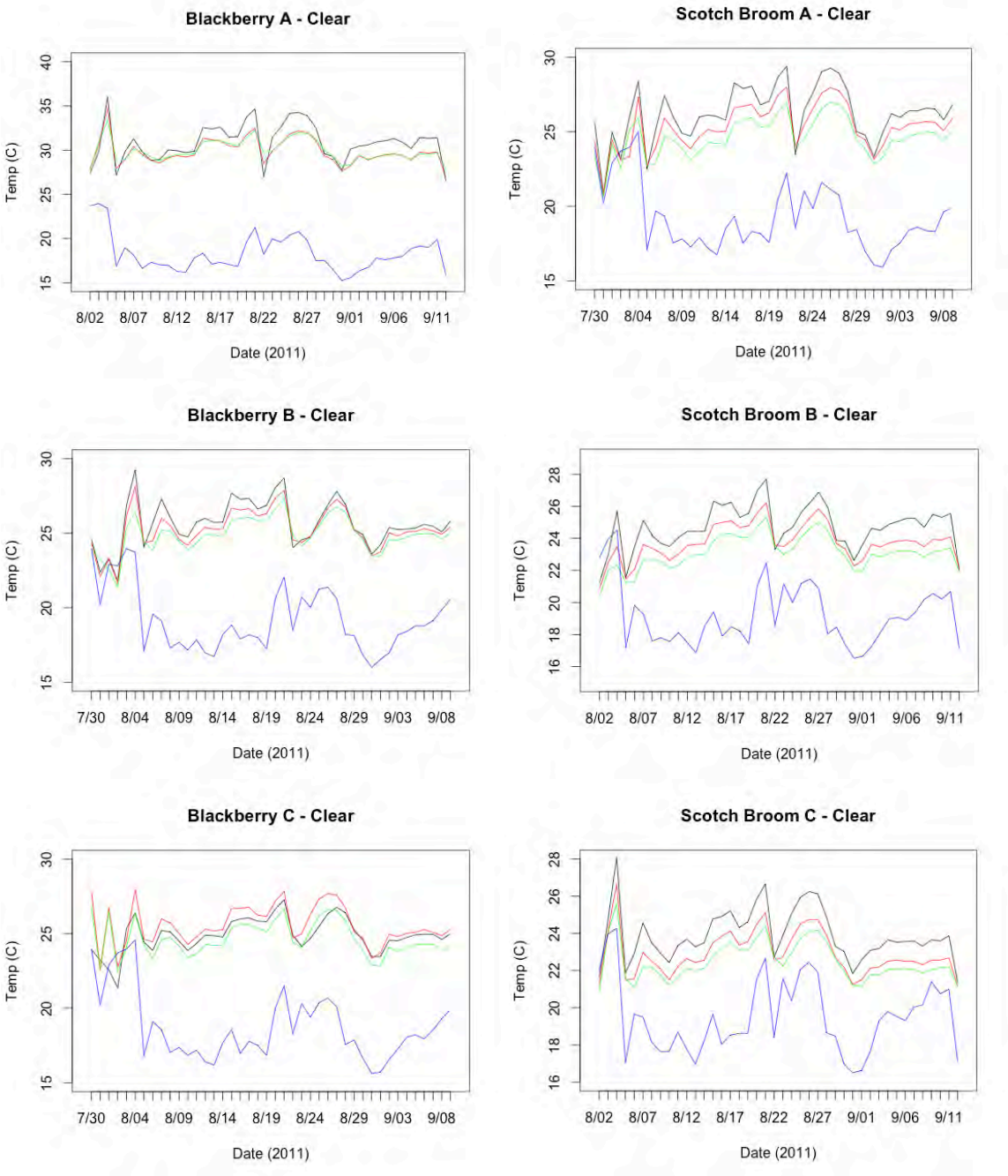




Line Color and Depth

Blue = Air	Red=3-6 cm
Black=0-3 cm	Green=6-9 cm

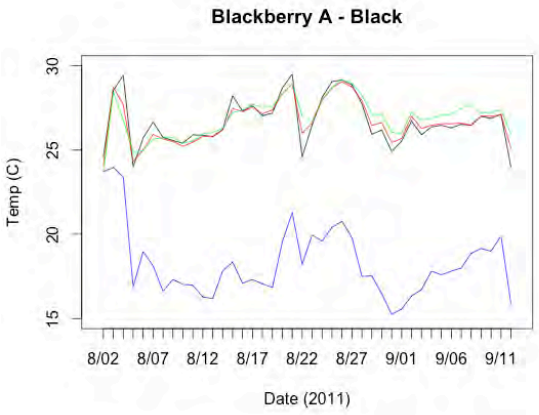
Clear

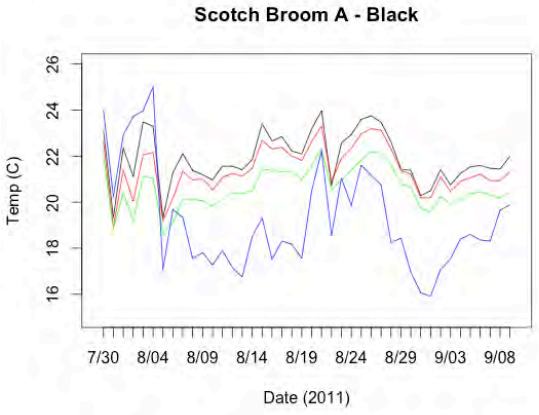


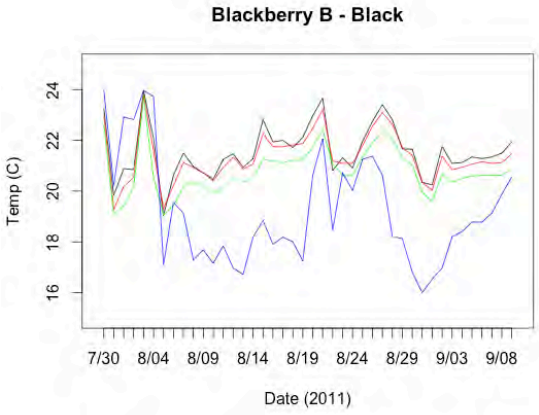
Line Color and Depth

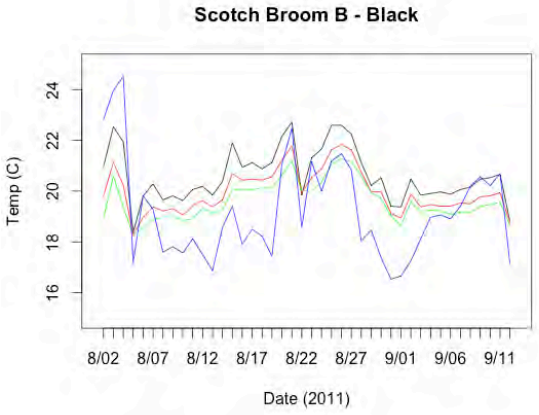
Blue = Air	Red=3-6 cm
Black=0-3 cm	Green=6-9 cm

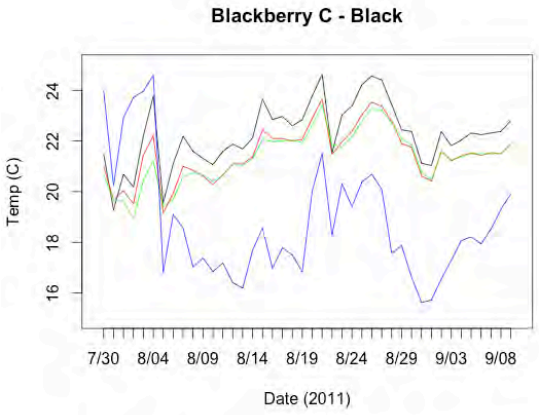
Black

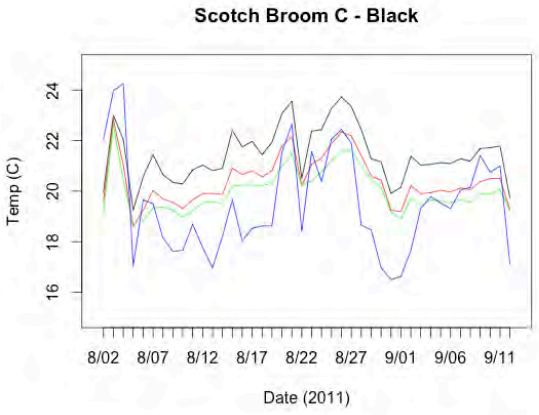












Line Color and Depth

Blue = Air	Red=3-6 cm
Black=0-3 cm	Green=6-9 cm

Appendix II: Field Trial Plot Data

Rubus armeniacus

Pre Stem Count	Pre Root Count	Post Stem Count	Post Root Count	Stem Survivorship	Root Crown Survivorship	Rep	Treatment	Avg. Air Temp	Avg. 0-3 cm Temp	Avg. 3-6 cm Temp	Avg. 6-9 cm Temp	Avg. Plot Temp
232	67	53	18	0.228	0.269	A	Clear	17.813	30.865	29.850	29.950	30.222
176	56	57	30	0.324	0.536	A	Black	17.813	26.685	26.684	26.937	26.769
239	53	204	105	0.854	1.981	A	Mowed	17.813	24.496	24.239	18.349	22.362
36	15	53	26	1.472	1.733	A	Control	17.813	17.584	17.019	24.138	19.580
112	30	175	57	1.563	1.900	B	Control	18.625	16.756	16.256	15.796	16.270
252	57	168	75	0.667	1.316	B	Black	18.625	21.552	21.341	20.786	21.226
252	52	115	54	0.456	1.038	B	Mowed	18.625	21.353	20.042	19.496	20.297
175	44	92	48	0.526	1.091	B	Clear	18.625	25.725	25.307	24.949	25.327
141	42	50	36	0.355	0.857	C	Black	18.281	22.294	21.519	21.410	21.741
163	49	72	33	0.442	0.673	C	Mowed	18.281	19.893	19.625	19.228	19.582
161	65	71	37	0.441	0.569	C	Clear	18.281	24.949	25.566	24.662	25.059
93	35	170	78	1.828	2.229	C	Control	18.281	15.506	15.263	15.090	15.286

Cytisus scoparius

Pre Stem Count	Pre Root Count	Post Stem Count	Post Root Count	Stem Survivorship	Root Crown Survivorship	Rep	Treatment	Avg. Air Temp	Avg. 0-3 cm Temp	Avg. 3-6 cm Temp	Avg. 6-9 cm Temp	Avg. Plot Temp
43	25	63	32	1.465	1.280	A	Control	18.469	17.268	16.881	16.307	16.826
258	102	21	6	0.081	0.059	A	Mowed	18.469	21.454	19.948	19.288	20.230
222	130	12	5	0.054	0.038	A	Clear	18.469	26.270	25.383	24.657	25.436
158	94	51	10	0.323	0.106	A	Black	18.469	21.896	21.440	20.618	21.318
122	82	56	6	0.459	0.073	B	Black	18.734	20.596	19.971	19.614	20.061
22	12	2	2	0.091	0.167	B	Mowed	18.734	19.395	18.315	17.838	18.516
21	12	18	13	0.857	1.083	B	Control	18.734	17.911	16.480	15.777	16.723
25	11	1	1	0.040	0.091	B	Clear	18.734	24.707	23.763	23.133	23.868
67	38	56	35	0.836	0.921	C	Control	19.313	17.048	16.571	15.925	16.514
65	40	3	1	0.046	0.025	C	Black	19.313	21.446	20.407	19.987	20.613
78	38	1	1	0.013	0.026	C	Clear	19.313	23.909	22.892	22.460	23.087
47	24	1	1	0.021	0.042	C	Mowed	19.313	19.354	18.149	17.885	18.463

Rep = Replicate, indicates which clump, the plot belongs to. Temperatures are recorded in Celsius, Avg. 0-3

Appendix III: Pre-treatment Initial Seed Identification

	Depth (cm)	Control	Mowed	Black	Clear
BBA	0-3	NSO	NSO	NSO	NSO
	3-6	NSO	NSO	NSO	NSO
	6-9	NSO	NSO	NSO	1 *R. armeniacus*
BBB	0-3	NSO	NSO	NSO	NSO
	3-6	NSO	NSO	3 *R. armeniacus*	2 *R. armeniacus*
	6-9	NSO	16 *R. armeniacus*	NSO	NSO
BBC	0-3	NSO	NSO	NSO	NSO
	3-6	NSO	2 R. armeniacus	1 *R. armeniacus*	NSO
	6-9	22 *R. armeniacus*	NSO	NSO	NSO
SBA	0-3	5 *C. scoparius*	1 *R. armeniacus*	1 *C. scoparius*	1 *C. scoparius*
	3-6	NSO	NSO	1 *C. scoparius*	4 *C. scoparius*
	6-9	NSO	NSO	2 *C. scoparius*	2 *C. scoparius*
SBB	0-3	6 Unknown	1 *R. armeniacus* 2 Unknown	1 *C. scoparius*	NSO
	3-6	2 Unknown	NSO	13 *C. scoparius* 7 *R. armeniacus*	9 *R. armeniacus*
	6-9	8 *C. scoparius* 21 *R. armeniacus*	14 *R. armeniacus*	2 Unknown	12 *R. armeniacus*
SBC	0-3	NSO	7 *R. armeniacus* 4 Unknown	3 Unknown	8 *C. scoparius* 2 *R. armeniacus*
	3-6	NSO	NSO	NSO	NSO
	6-9	1 *C. scoparius* 3 *R. armeniacus*	NSO	2 Unknown	NSO

NSO- No Seeds Observed, does not mean no seeds were present

Appendix IV: Post-treatment Initial Seed Identification

	Depth (cm)	Control	Mowed	Black	Clear
BBA	0-3	1 R. armeniacus	11 R. armeniacus	5 R. armeniacus	5 R. armeniacus
				1 Unknown	
	3-6	NSO	1 R. armeniacus	3 R. armeniacus	1 R. armeniacus
	6-9	NSO	6 R. armeniacus	4 R. armeniacus	3 R. armeniacus
			2 C. scoparius	3 Unknown	
BBB	0-3	10 R. armeniacus	2 Unknown	2 R. armeniacus	NSO
		1 Unknown			
	3-6	8 R. armeniacus	1 R. armeniacus	3 R. armeniacus	2 Unknown
	6-9	24 R. armeniacus	16 R. armeniacus	10 R. armeniacus	NSO
BBC	0-3	1 R. armeniacus	3 R. armeniacus	16 R. armeniacus	1 R. armeniacus
			2 Unknown		
	3-6	1 R. armeniacus	NSO	6 R. armeniacus	NSO
		2 Unknown			
	6-9	3 R. armeniacus	11 R. armeniacus	16 R. armeniacus	
			1 C. scoparius		
SBA	0-3	7 C. scoparius	NSO	1 C. scoparius	NSO
				1 Unknown	
	3-6	2 Unknown	3 Unknown	NSO	NSO
	6-9	1 C. scoparius	NSO	NSO	1 R. armeniacus
SBB	0-3	3 C. scoparius	5 R. armeniacus	4 Unknown	2 C. scoparius
		3 R. armeniacus	1 C. scoparius		1 R. armeniacus
		4 Unknown			5 Unknown
	3-6	4 R. armeniacus	7 R. armeniacus	22 R. armeniacus	1 C. scoparius
		1 Unknown		1 Unknown	11 R. armeniacus
					3 Unknown
	6-9	13 C. scoparius	1 C. scoparius	65 R. armeniacus	4 R. armeniacus
		20 R. armeniacus	22 R. armeniacus		
SBC	0-3	1 C. scoparius	3 C. scoparius	1 C. scoparius	4 C. scoparius
			1 R. armeniacus	1 R. armeniacus	1 R. armeniacus
				1 Unknown	8 Unknown
	3-6	2 C. scoparius	3 R. armeniacus	1 C. scoparius	33 R. armeniacus
		1 Unknown	4 Unknown	3 R. armeniacus	
	6-9	NSO	5 C. scoparius	4 Unknown	7 R. armeniacus
			30 R. armeniacus		4 Unknown

NSO- No Seeds Observed, does not mean no seeds were present

Appendix V: Seed Bank Identification

Rubus armeniacus replicate A

		Pre		Post	
Treatment	Depth (cm)	Quantity	Species	Quantity	Species
Control	0-3	3	*Juncus* sp.	1	Grass Morphotype 2
		1	Grass Morphotype 6	2	*Geranium carolinianum*
		1	Grass Morphotype 1	1	*Hypericum perforatum*
	3-6	1	*Juncus* sp.	4	Grass Morphotype 4
		1	Grass Morphotype 2	1	Grass Morphotype 2
		1	*Stellaria* sp.	1	*Juncus* sp.
	6-9	1	*Geranium carolinianum*	2	Grass Morphotype 2
		1	Grass Morphotype 3		
		1	*Stellaria* sp.		
		1	*Juncus* sp.		
Mowed	0-3	1	*Geranium carolinianum*	1	*Daucus carota*
				1	Grass Morphotype 2
	3-6	1	*Juncus* sp.	1	*Cytisus scoparius*
		3	Grass Morphotype 1	3	Grass Morphotype 3
		1	*Daucus carota*	1	Grass Morphotype 2
	6-9	1	*Trifolium dubium*	2	*Juncus* sp.
		1	*Juncus* sp.	1	Grass Morphotype 2
Black	0-3	1	*Geranium carolinianum*	1	*Juncus* sp.
				1	*Geranium carolinianum*
				1	*Daucus carota*
				1	Grass Morphotype 1
	3-6	1	Grass Morphotype 2	5	*Geranium carolinianum*
		2	*Juncus* sp.	2	*Daucus carota*
				1	*Juncus* sp.
	6-9	1	*Juncus* sp.	1	*Juncus* sp.
				1	Grass Morphotype 5
Clear	0-3	1	*Juncus* sp.	2	*Geranium carolinianum*
				1	Grass Morphotype 1
				1	*Juncus* sp.
	3-6	3	*Geranium carolinianum*	3	*Geranium carolinianum*
		1	*Rumex crispus*	2	*Juncus* sp.
	6-9	1	*Geranium carolinianum*	3	*Juncus* sp.
		1	*Daucus carota*	1	Grass Morphotype 4

Rubus armeniacus replicate B

		Pre		Post	
Treatment	Depth (cm)	Quantity	Species	Quantitiy	Species
Control	0-3	1	Grass Morphotype 1	2	Grass Morphotype 4
				1	Grass Morphotype 7
		1	Grass Morphotype 4	1	Grass Morphotype 1
				1	*Juncus* sp.
	3-6	3	Grass Morphotype 1	1	Grass Morphotype 1
				1	Grass Morphotype 3
	6-9	2	Grass Morphotype 1	1	Grass Morphotype 8
				1	Grass Morphotype 4
Mowed	0-3	4	Grass Morphotype 1	6	Grass Morphotype 4
				2	*Vicia* sp.
	3-6	0	Plants	2	Grass Morphotype 1
				2	Grass Morphotype 4
	6-9	1	Grass Morphotype 4	6	Grass Morphotype 6
		1	Grass Morphotype 1		
		2	*Vicia* sp.		
Black	0-3	1	Grass Morphotype 1	2	*Vicia* sp.
		7	Grass Morphotype 3		
	3-6	0	Plants	1	*Geranium carolinianum*
				1	Grass Morphotype 2
	6-9	1	Grass Morphotype 4	1	*Juncus* sp.
				1	Grass Morphotype 1
Clear	0-3	1	Grass Morphotype 2	0	Plants
		4	Grass Morphotype 6		
	3-6	0	plants	1	*Trifolium repens*
	6-9	2	*Vicia* sp.	2	Grass Morphotype 1
		1	Grass Morphotype 4		

Rubus armeniacus replicate C

		Pre		Post	
Treatment	Depth (cm)	Quantity	Species	Quantitiy	Species
Control	0-3	1	Grass Morphotype 1	2	Grass Morphotype 6
		1	*Hypericum perforatum*	1	*Plantago* sp.
	3-6	3	Grass Morphotype 1	1	Grass Morphotype 1
				1	Grass Morphotype 3
				1	*Vicia* sp.
	6-9	1	*Trifolium repens*	2	Grass Morphotype 6
				1	*Juncus* sp.
Mowed	0-3	6	Grass Morphotype 1	12	Grass Morphotype 4
		2	*Juncus* sp.		
	3-6	3	Grass Morphotype 1	1	*Juncus* sp.
		1	Grass Morphotype 4	4	Grass Morphotype 1
		1	*Hypericum perforatum*		
	6-9	2	*Juncus* sp.	3	*Juncus* sp.
		1	Grass Morphotype 1	1	*Cirsium* sp.
Black	0-3	1	Grass Morphotype 1	1	Grass Morphotype 1
		1	*Juncus* sp.	1	*Cirsium* sp.
		2	Grass Morphotype 4		
	3-6	1	Grass Morphotype 1	4	Grass Morphotype 4
	6-9	1	*Daucus carota*	3	Grass Morphotype 4
		1	*Geranium carolinianum*	1	*Juncus* sp.
Clear	0-3	1	*Juncus* sp.	5	Grass Morphotype 1
		1	Grass Morphotype 1		
		1	*Plantago* sp.		
	3-6	1	*Juncus* sp.	4	Grass Morphotype 6
		1	Grass Morphotype 6	1	Grass Morphotype 1
				1	Grass Morphotype 4
	6-9	3	Grass Morphotype 1	1	*Daucus carota*

Cytisus scoparius replicate A

		Pre		Post	
Treatment	Depth (cm)	Quantity	Species	Quantitiy	Species
Control	0-3	2	Grass Morphotype 1	1	*Trifolium pratense*
		2	Grass Morphotype 4	1	*Cytisus scoparius*
		1	Grass Morphotype 7	1	*Stellaria* sp.
		2	*Hypericum perforatum*	2	Grass Morphotype 5
		2	*Cytisus scoparius*	12	Grass Morphotype 4
	3-6	3	*Hypericum perforatum*	1	*Trifolium pratense*
		1	Grass Morphotype 2	5	Grass Morphotype 4
		1	Grass Morphotype 8	2	*Hypericum perforatum*
				1	*Daucus carota*
	6-9	3	*Hypericum perforatum*	2	*Daucus carota*
		2	Grass Morphotype 1	1	*Vicia* sp.
				1	*Cytisus scoparius*
Mowed	0-3	3	*Hypericum perforatum*	0	Plants
	3-6	2	Grass Morphotype 2	1	Grass Morphotype 4
		1	*Hypericum perforatum*	12	*Hypericum perforatum*
				1	*Plantago* sp.
	6-9	1	Grass Morphotype 2	1	*Daucus carota*
				1	Grass Morphotype 4
				3	Grass Morphotype 1
				4	*Hypericum perforatum*
Black	0-3	2	*Hypericum perforatum*	2	*Hypericum perforatum*
		3	Grass Morphotype 4	1	*Cytisus scoparius*
				6	Grass Morphotype 4
	3-6	4	*Hypericum perforatum*	1	*Juncus* sp.
		1	Grass Morphotype 2	1	*Plantago* sp.
	6-9	2	*Hypericum perforatum*	1	*Geranium carolinianum*
		1	Grass Morphotype 8	1	*Hypericum perforatum*
		1	*Rumex crispus*	1	*Cytisus scoparius*
Clear	0-3	2	*Hypericum perforatum*	3	Grass Morphotype 2
		1	Grass Morphotype 2		
	3-6	1	Grass Morphotype 2	3	Grass Morphotype 2
		1	*Plantago* sp.	1	*Hypericum perforatum*
		1	*Hypericum perforatum*	1	*Vicia* sp.
		3	*Cytisus scoparius*		
	6-9	2	*Hypericum perforatum*	2	Grass Morphotype 4
		1	*Trifolium repens*	2	Grass Morphotype 1

Appendix V Key
Grass Morphotype 1- Red base, flat/wide blades, clumping
Grass Morphotype 2 - Green base clumped, wide blade
Grass Morphotype 3 - Red base, single stalk, wide blade
Grass Morphotype 4 - Green base, single stalk, wide blade
Grass Morphotype 5 - Tall Grass - (1 1/4 between segments; 12" high)
Grass Morphotype 6 - Reddish base, clumping, narrow blade
Grass Morphotype 7 - Red/white stripped base, single stalk
Grass Morphotype 8 - Green base, clumped, narrow blade

Cytisus scoparius replicate B

		Pre		Post	
Treatment	Depth (cm)	Quantity	Species	Quantitiy	Species
Control	0-3	5	Grass Morphotype 4	13	Grass Morphotype 4
		2	*Vicia* sp.	2	*Vicia* sp.
		1	*Cytisus scoparius*		
	3-6	2	*Cytisus scoparius*	1	Grass Morphotype 1
		1	Grass Morphotype 2	1	Grass Morphotype 2
	6-9	5	*Cytisus scoparius*	9	*Cytisus scoparius*
Mowed	0-3	12	Grass Morphotype 4	6	Grass Morphotype 4
		1	*Vicia* sp.		
	3-6	3	Grass Morphotype 1	2	Grass Morphotype 4
		2	Grass Morphotype 2		
	6-9	0	plants	0	plants
Black	0-3	3	Grass Morphotype 4	8	Grass Morphotype 4
				1	*Stellaria* sp.
	3-6	1	*Vicia* sp.	1	Grass Morphotype 2
				1	*Stellaria* sp.
	6-9	1	*Stellaria* sp.	0	Plants
		1	*Cytisus scoparius*		
Clear	0-3	0	plants	1	*Cytisus scoparius*
				2	*Vicia* sp.
				5	Grass Morphotype 4
	3-6	0	plants	2	*Vicia* sp.
	6-9	0	Plants	1	Grass Morphotype 4

Cytisus scoparius replicate C

		Pre		Post	
Treatment	Depth (cm)	Quantity	Species	Quantitiy	Species
Control	0-3	3	Grass Morphotype 1	11	Grass Morphotype 1
		3	Grass Morphotype 4	1	*Cytisus scoparius*
		1	*Hypericum perforatum*	1	*Stellaria* sp.
				1	*Plantago* sp.
	3-6	1	*Trifolium pratense*	2	*Juncus* sp.
		1	Grass Morphotype 1	4	Grass Morphotype 6
				1	*Cytisus scoparius*
	6-9	3	Grass Morphotype 1	4	Grass Morphotype 4
Mowed	0-3	9	Grass Morphotype 1	2	*Cytisus scoparius*
		1	*Trifolium pratense*	7	Grass Morphotype 4
		1	*Vicia* sp.		
	3-6	4	Grass Morphotype 6	9	Grass Morphotype 4
		1	Grass Morphotype 8		
	6-9	1	Grass Morphotype 1	5	Grass Morphotype 2
		1	Grass Morphotype 7	3	*Cytisus scoparius*
		1	*Vicia* sp.		
Black	0-3	5	Grass Morphotype 4	4	*Hypericum perforatum*
		1	Grass Morphotype 1	5	Grass Morphotype 4
		1	*Veronica* sp.		
	3-6	2	Grass Morphotype 1	2	*Hypericum perforatum*
				1	*Cytisus scoparius*
		3	*Hypericum perforatum*	1	*Vicia* sp.
				4	Grass Morphotype 1
				3	Grass Morphotype 2
	6-9	1	*Hypericum perforatum*	2	Grass Morphotype 4
		1	Grass Morphotype 1	4	*Vicia* sp.
Clear	0-3	3	*Vicia* sp.	10	Grass Morphotype 4
				3	*Vicia* sp.
	3-6	2	Grass Morphotype 1	4	Grass Morphotype 1
				1	Grass Morphotype 2
	6-9	4	Grass Morphotype 6	5	Grass Morphotype 2
				1	*Vicia* sp.

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