

# Introduction

The goal of this project was to develop and test non-herbicidal techniques that remove non-native plant or weed seeds from the top 2 inches of the soil. The Nature Conservancy (TNC) is currently restoring prairies in the Willamette Valley. Some areas of the Pacific Northwest have already seen loss of more than 99% of former native prairie and 90% oak savanna to agriculture, forest production, and development. In order for the land to be restored, all non-native vegetation must be removed, beginning with removal of unwanted vegetation and a reduction of weed seed density in the soil (Greg Fitzpatrick, 2006). Non-native or invasive plant species pose a serious threat to revegetation with native species, and the cost of weed management is prohibitive if herbicides are not used.

We tested two strategies to remove weed seeds from the soil. In the first project we worked collaboratively with mechanical engineering (ME) students to develop a machine that would kill seeds in the soil with heat. We tested weed seed survival after exposure to various temperatures and provided the data to the ME students that so that they could adequately design and build the machine. We also evaluated the efficacy of their machine after it was built. In the second project we measured the potential seed loss due to carabid beetle weed seed predation in a controlled environment. The non-native species of choice for these studies represented a broad range of environmental adaptability and included Pigweed (*Amaranthus retroflexus*), Oxeye Daisy (*Chrysanthemum leucanthemum*), Wild Carrot (*Daucus carota*), and False Brome (*Brachypodium sylvaticum*), Proso Millet (*Panicum miliaceum*), Hairy Nightshade (*Solanaceae*) or (*Solanum sarrachoides*) (see appendix I for more information on the characteristics of these species).

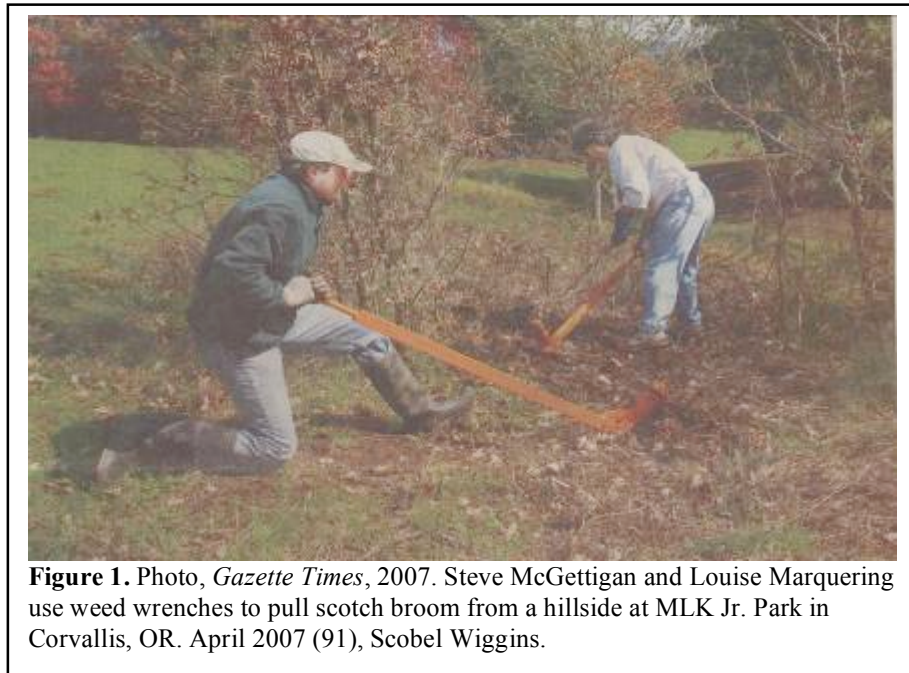
# Weed Control Strategies

A brief discussion follows of weed control strategies that were considered during the development phase of this project, their efficacy, and potential drawbacks. We met weekly for two years with the ME students to consider all opportunities for improving management of unwanted vegetation.

**Prescribed Field Burns and Localized Flame Weeding.** Prescribed field burns have become quite controversial in light of global warming and air quality. Farmers and those involved with weed management have been shifting to more directed applications of efficient burning fuels such as propane that burns weeds when they are small (Greg Purell-IPM, 2006). Treated plants are exposed to heat for just a brief period and only the exposed tissues may be disrupted initially. Flame weeding appears to provide substantial benefit by reducing the cost of hand hoeing and harvesting. Flaming does not appear to reduce subsequent weed emergence and may even increase the germination of some species (Ascard, 1995). However, unlike mechanical methods of weed control there is no soil disturbance to cause a further flush of seedlings to emerge (Bond W., G Davies, R J Turner, 2006). If the flaming event is very intense, soil temperatures may rise until weed seeds near the soil surface are killed. During fires for instance, seeds on the soil surface or in the litter layer may be exposed to temperatures in excess of 200°C (DeBano, 1982; Whelan, 1995).

**Hand Weeding.** Hand picking is a very effective way to remove the weeds from areas of interest, but may cost as much as \$500- \$10,000 an acre depending upon the crop. Due to close spacing of carrots (in-row spacing of less than ½ inch), crop culture precludes hand weeding. Not

only is hand-weeding effective in agricultural areas, but even in areas where the focus is restoration. In Martin Luther King Jr. Park in Corvallis, OR, a team is hand removing scotch broom using weed wrenches (Figure 1).



**Steam Sterilization.** Steaming is used in glasshouses to sterilize the soil and control both weeds and diseases prior to crop establishment. There has been renewed interest in methods of steam sterilization in the wake of concern over the use of methyl bromide (Anon, 1999; Trotter, 1991). In laboratory studies, the temperature needed to kill seeds of individual weed species by soil steaming varied between 65° and 75°C (Melander *et al.*, 2002). Steaming time depended on the temperature required but it took around 90 seconds to achieve 75°C (Bond W, G Davies, R J Turner, 2006). The steam raises the soil temperature to 70-100°C killing most weed seeds to a depth of at least 10 cm (White *et al.*, 2000a; 2000b). Only clover (*Trifolium* spp.) and other hard seeded legumes appear resistant to this treatment. Weed seeds in the soil below the treated layer

are unaffected and will germinate if the soil is disturbed to that depth. However, if there is no further cultivation following treatment, weed control can remain effective for two seasons. It is likely there are still seeds remaining below the layer of treated soil, however, they are most often in a state of dormancy until exposed to light. The machinery is slow moving and has work rates of 40-100 hours per ha of treated bed are likely (Bond W, G Davies, R J Turner, 2006).

**Herbicides.** The evolution of chemicals in agriculture began around WWII, when mass production of chemicals satisfied the fertilization and pest control needs of farmers. Although herbicides may work quite effectively, other costs must be considered such as the non-target effects on the environment or humans. Resistance to herbicides has developed in some non-native species because of overuse.

**Solarization.** Solarization is a process of heating moist soil under plastic sheeting for around 6 weeks to trap solar radiation (Peachey *et al*, 2001). Long periods of clear sky are required for solarization to be effective, however. Soil temperatures must reach 65° C) for sufficient time to kill the weed seeds under the sheeting (Standifer *et al.*, 1984). Many studies have found weed development to be enhanced in cooler climates rather than hindered by the sheeting (Bond & Burch, 1989), whereas, covers applied in midsummer could prove to have some weed control benefits. Seeds buried deeper in the soil may not be killed by soil solarization and may even have enhanced survival (Peachey *et al*, 2001). However, if there is no soil disturbance following treatment, weed control may remain effective for two seasons (Sauerborn *et al.*, 1989). There are, however, some disadvantages to using solarization for weed control: loss of crop production for 6-8 weeks in summer; purchase and laying of costly sheeting (\$400 per acre) (Bogenholm, Vanessa, 2004) which limits its use to high value crops; and after use, the cost to use machinery

for both laying and lifting different forms of sheeting in the field and disposal. It is possible to reuse or recycle the plastic, but contamination with soil causes problems with the recycling of sheeting that has been laid in the field. (Bond, W, G Davies, R J Turner, 2006).

**Solar (UV) Radiation and Fresnel Lens.** A fresnel lens has been developed to concentrate sunlight into a narrow band at the soil surface to reach temperatures of 290°C in a few seconds. The wheeled device is pulled slowly between crop rows to wither and burn off the inter-row weeds. Under the full mid-day sun the mean soil surface temperatures reach 309 C with a 20 second exposure. The germination of fat-hen (*Chenopodium album*) and black bindweed (*Fallopia convolvulus*) seed left on or near the soil surface was reduced to zero by this treatment. Wild-oat (*A. fatua*) seed, however, retained 2% viability. This method has the greatest potential for killing seeds on the soil surface. Buried seeds, especially in moist soil, would require much longer exposure times for seed death to occur (Forcella & Burnside, 1994; Hoekstra, 1992; Johnson *et al.*, 1990).

**Tillage.** Increased weed seed germination often occurs following soil tillage or disturbance (Wesson and Wareing, 1969), and the effect may be greatest if tillage occurs during the day. Scopel *et al.* (1994) showed that daytime tillage increased seedling emergence of several winter annuals more than twofold over the emergence observed in the nighttime tillage treatment. Tillage causes both vertical redistribution of weed seeds and changes in soil's physical properties (Mohler, C. L. *et al.*, 1997). No-till cropping systems leave most seeds in the top 10 mm of the soil profile (Yenish *et al.*, 1992), while mould-board plowing tends to distribute seeds uniformly throughout the plow layer (Van Esso *et al.*, 1986) and chisel plowing and other reduced tillage systems have intermediate effects on vertical seed distribution in the soil. However, tillage also

damages soil aggregates, increasing the decomposition rate for soil organic matter (Hauser, S. et al., 2002).

**Microwave Radiation.** Microwave radiation utilizes ultra high frequency (UHF) electromagnetic energy with wavelengths much greater than those of light. Many factors determine the reaction of seeds to microwaves and tolerance may vary throughout species. Moist seeds were easier to kill than dry seeds (Rice & Putnam, 1977). The damage to seeds is likely to be due to heat (Davis *et al.*, 1973). Established plants were more susceptible than seedlings of the same species. Reliable lethal effects were observed on seeds in US soil using microwave generators drawn over field plots obtained at energy levels above  $70 \text{ J cm}^{-2}$  (Wayland *et al.*, 1973, 1975). However, the time required to reach seed killing temperatures in soil was a limiting factor in the application of this technique, at 92.6 and 1,037 hours/ha. The amount of energy required therefore determines the speed and amount of time necessary for efficient treatment of seeds. Operator safety must also be considered when evaluating this technology (Diprose *et al.*, 1984).

**Biological Controls** utilize living organisms, such as predators, parasitoids, and pathogens to control pest insects, weeds, or diseases. In some cases of biological control, a system is augmented to manipulate the presence of natural enemies through two general methods: mass production and periodic colonization or genetic enhancement of natural enemies (Landis, 1996). Augmentation is used where populations of a natural enemy are not present or cannot respond quickly enough to the pest population.

**Direct Soil Heating.** At present in the Netherlands, there is a self-propelled GPS-guided



Figure 2. cultivit.com

machine that cultivates and heat-treats the soil in a single operation, referred to as the Cultivit. The machine works friable soil to a depth of 35 cm heating it to 800 °C, with an integrated burner/exchanger blowing hot air, as it passes through the machine. The small machine can be used in limited areas for

specialist crops and in poly-tunnels. It is said to retard weed germination (cultivit.com). Thermal death point for several of the weed seed species has been determined (Hopkins, 1936). Most seeds were killed off by heating for 15 minutes at 100°C but to be certain, a temperature of 105°C is required for a mixture of seeds. Treatment works best when seeds have some moisture in them. Although this technique is for treatment of nematodes and other pathogens within the soil, these temperature regimes are paralleling those that have been identified for the 100 % kill of weed seeds in the soil.

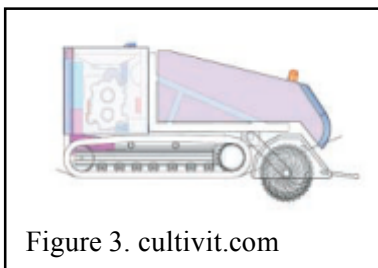


Figure 3. cultivit.com

Similar equipment is available commercially for killing weed seeds in field soil using dry heat, but was actually utilized to control soil borne diseases. The soil

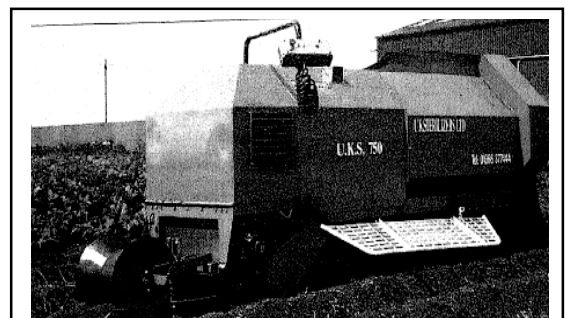


Figure 4. Williams, 1999

is cultivated and set in ridges. The worked ridge of soil is lifted, passed through a chamber heated to 68-70°C by a diesel-fired burner, and then deposited back onto the ground in a reformed ridge that provides a band of weed free soil. The depth of treatment required depends on the crop. It ranges from 10 cm for shallow rooted crops to 25 cm for potatoes. The dry heat system is slow but allows faster coverage of an area than

field steaming. The work rate with a 15 cm depth of soil is 1-2 ha/day, depending on the soil type (Williams, Mike, 1999).

While soil heating may destroy some soil borne pests such as weed seeds, direct heating may also destroy important physical or biological properties of the soil, including aggregate stability, pore size distribution, water repellency and runoff response, alterations in mineralization rates, biomass production, microbial species composition, carbon sequestration, changes in C:N ratio, and pH and nutrient availability (DeBano et al. 1976; Chandler et al 1983; Neary et al 1999; Gonzalez-Perez et al 2004). At soil temperatures between 100°C and 200°C, a mass loss of organic carbon occurs due to volatilization of organic matter constituents (Sertsu and Sánchez 1978). Organic matter starts to carbonize if soil temperatures are above 200°C (Hosking 1938). Heating the soil at 45 – 160°C has not been shown to change the visual appearance, percentage of organic matter, or the carbon-to-nitrogen ratio of humus. It has however, been observed that heating above 160°C decreased the pH of humus by 0.5 units (Pietikäinen, Janna, 1999). Kitur and Frye (1983) suggested that the decreased pH might be due to organic acids released in the soil. At 350°C structural changes in humic and fulvic acids occur and there is an increase in aromatic structures, which may be the cause of increased resistance of organic matter to microbial attack (Almendros et al. 1990, 1992).

Direct soil heating may also cause oxidation of metals and minerals commonly found in soil (table 1) (Khanna, A.S., 2002). After heat treatment of soil bands, some of these oxides will reside within the soil with possibly beneficial or problematic effects. When the soil is heated, the water converts to steam. If temperatures reach 105-300 °C, the sorbed water of montmorillonite, halloysite, vermiculite, and other various amorphous mineral matters is lost and only 8% of the

**Table 1.** Structures and thermal properties of selected oxides

Oxide	Structure	Melting point, °C	Boiling point, °C
$\alpha$ -Al <sub>2</sub> O <sub>3</sub>	D5 <sub>1</sub> (corundum)	2015	2980
$\gamma$ -Al <sub>2</sub> O <sub>3</sub>	(defect spinel)	$\gamma \rightarrow \alpha$	...
BaO	B1 (NaCl)	1923	~2000
BaO <sub>2</sub>	Tetragonal (CaC <sub>2</sub> )	450	d.800
BeO	Br (ZnS)	2530	~3900
CaO	B1 (NaCl)	2580	2850
CaO <sub>2</sub>	C11 (CaC <sub>2</sub> )	...	d.275
CdO	B1 (NaCl)	~1400	d.900
Ce <sub>2</sub> O <sub>3</sub>	D5 <sub>2</sub> (La <sub>2</sub> O <sub>3</sub> )	1692	...
CeO <sub>2</sub>	C1 (CaF <sub>2</sub> )	~2600	...
CoO	B1 (NaCl)	1935	...
Co <sub>2</sub> O <sub>3</sub>	Hexagonal	...	d.895
Co <sub>3</sub> O <sub>4</sub>	H1 <sub>1</sub> (spinel)	$\rightarrow$ CoO	...
Cr <sub>2</sub> O <sub>3</sub>	D5 <sub>1</sub> ( $\alpha$ -Al <sub>2</sub> O <sub>3</sub> )	2435	4000
Cr <sub>2</sub> O	Hexagonal (CdCl <sub>2</sub> )	...	d.400
Cr <sub>2</sub> O <sub>3</sub>	Cubic (Th <sub>3</sub> P <sub>4</sub> )	400	650
CuO	B26 monoclinic	1326	...
Cu <sub>2</sub> O	C3 cubic	1235	d.1800
FeO	B1 (NaCl)	1420	...
$\alpha$ -Fe <sub>2</sub> O <sub>3</sub>	D5 <sub>1</sub> (Haematite)	1565	...
$\gamma$ -Fe <sub>2</sub> O <sub>3</sub>	D5 <sub>2</sub> cubic	1457	...
Fe <sub>3</sub> O <sub>4</sub>	H1 <sub>1</sub> (spinel)	...	d. 1538
Ga <sub>2</sub> O <sub>3</sub>	Monoclinic	1900	...
HfO <sub>2</sub>	Cubic	2812	~5400
In <sub>2</sub> O <sub>3</sub>	D5 <sub>3</sub> (Sc <sub>2</sub> O <sub>3</sub> )	...	d.850
IrO <sub>2</sub>	C4 (TiO <sub>2</sub> )	...	d.1100
La <sub>2</sub> O <sub>3</sub>	D5 <sub>3</sub> (Sc <sub>2</sub> O <sub>3</sub> )	...	d.850
Li <sub>2</sub> O	C1 (CaF <sub>2</sub> )	~1700	1200
MgO	B1 (NaCl)	2800	3600
MnO	B1 (NaCl)	...	...
MnO <sub>2</sub>	C4 (TiO <sub>2</sub> )	...	d.535
Mn <sub>2</sub> O <sub>3</sub>	D5 <sub>3</sub> (Sc <sub>2</sub> O <sub>3</sub> )	...	d.1080
Mn <sub>3</sub> O <sub>4</sub>	H1 <sub>1</sub> (spinel)	1705	...
MoO <sub>3</sub>	Orthorhombic	795	...
Na <sub>2</sub> O	C1 (CaF <sub>2</sub> )	Subl. 1275	...
Nb <sub>2</sub> O <sub>5</sub>	Monoclinic	1460	...
Nd <sub>2</sub> O <sub>3</sub>	Hexagonal	~1900	...
NiO	B1 (NaCl)	1990	...
PbO	B10 tetragonal	888	...
Pb <sub>3</sub> O <sub>4</sub>	Tetragonal	...	d.500
PdO	B17 tetragonal	870	...
PtO	B17 (PdO)	...	d.550
Rb <sub>2</sub> O <sub>3</sub>	(Th <sub>3</sub> P <sub>4</sub> )	489	...
ReO <sub>2</sub>	Monoclinic	...	d.1000
Rh <sub>2</sub> O <sub>3</sub>	D5 <sub>1</sub> ( $\alpha$ -Al <sub>2</sub> O <sub>3</sub> )	...	d.1100
SiO	Cubic	~1700	1880
SiO <sub>2</sub>	$\beta$ cristobalite C9	1713	2230
SnO	B10 (PbO)	...	d.1080
SnO <sub>2</sub>	C <sub>4</sub> (TiO <sub>2</sub> )	1127	...
SrO	B1 (NaCl)	2430	~3000
Ta <sub>2</sub> O <sub>5</sub>	Triclinic	1800	...
TeO <sub>2</sub>	C <sub>4</sub> (TiO <sub>2</sub> )	733	1245
ThO <sub>2</sub>	C1 (CaF <sub>2</sub> )	3050	4400
TiO	B1 (NaCl)	1750	~3000
TiO <sub>2</sub>	C4 (Rutile)	1830	~2700
Ti <sub>2</sub> O <sub>3</sub>	D5 <sub>1</sub> ( $\alpha$ -Al <sub>2</sub> O <sub>3</sub> )	...	d.2130
Ti <sub>2</sub> O <sub>5</sub>	D5 <sub>3</sub> (Sc <sub>2</sub> O <sub>3</sub> )	717	d.875
UO <sub>2</sub>	C1 (CaF <sub>2</sub> )	2500	...
U <sub>3</sub> O <sub>8</sub>	Hexagonal	...	d.1300
VO <sub>2</sub>	C4 (TiO <sub>2</sub> )	1967	...
V <sub>2</sub> O <sub>3</sub>	D5 <sub>1</sub> ( $\alpha$ -Al <sub>2</sub> O <sub>3</sub> )	1970	...
V <sub>2</sub> O <sub>5</sub>	D8 <sub>7</sub> Orthorhombic	690	d.1750
WO <sub>2</sub>	C4 (TiO <sub>2</sub> )	~1550	~1430
B-WO <sub>3</sub>	Orthorhombic	1473	...
W <sub>2</sub> O <sub>5</sub>	Triclinic	Sub.~850	~1530
Y <sub>2</sub> O <sub>3</sub>	D5 <sub>3</sub> (Sc <sub>2</sub> O <sub>3</sub> )	2410	...
ZnO	B3 (wurtzite)	1975	...
ZrO <sub>2</sub>	C4 <sub>1</sub> monoclinic	2715	...

water remains. At 300-540 °C, the hydroxyl water of kaolinite, halloysite, montronite, Fe-beideillite, Fe-illite, Fe-vermiculite, some chlorite and mostly amorphous mineral matter is lost. At 540- 900 °C, the hydroxyl water of Al, Mg-montmorillonite, hectorite, Mg-vermiculite, Mg-muscovite, talc and the remainder of water in the chlorite and amorphous mineral matter (2%) is lost (Jackson, M.L., 2005). Direct soil heating also may affect plant nutrient balance in the soil. In studies conducted by the *International Journal of Wildland Fire* (Doerr, Stefan H and Cerda, Artemi, 2005), nutrient and soil organic matter contents were increased for varying fire severities. The experiments indicate that, despite the initial fatal effect, heating the soils to temperatures <400 °C produces an enrichment of available nutrients and thus a stimulation of bacteria, whereas higher soil temps appear to have an overall detrimental effect on microorganisms until the recovery of

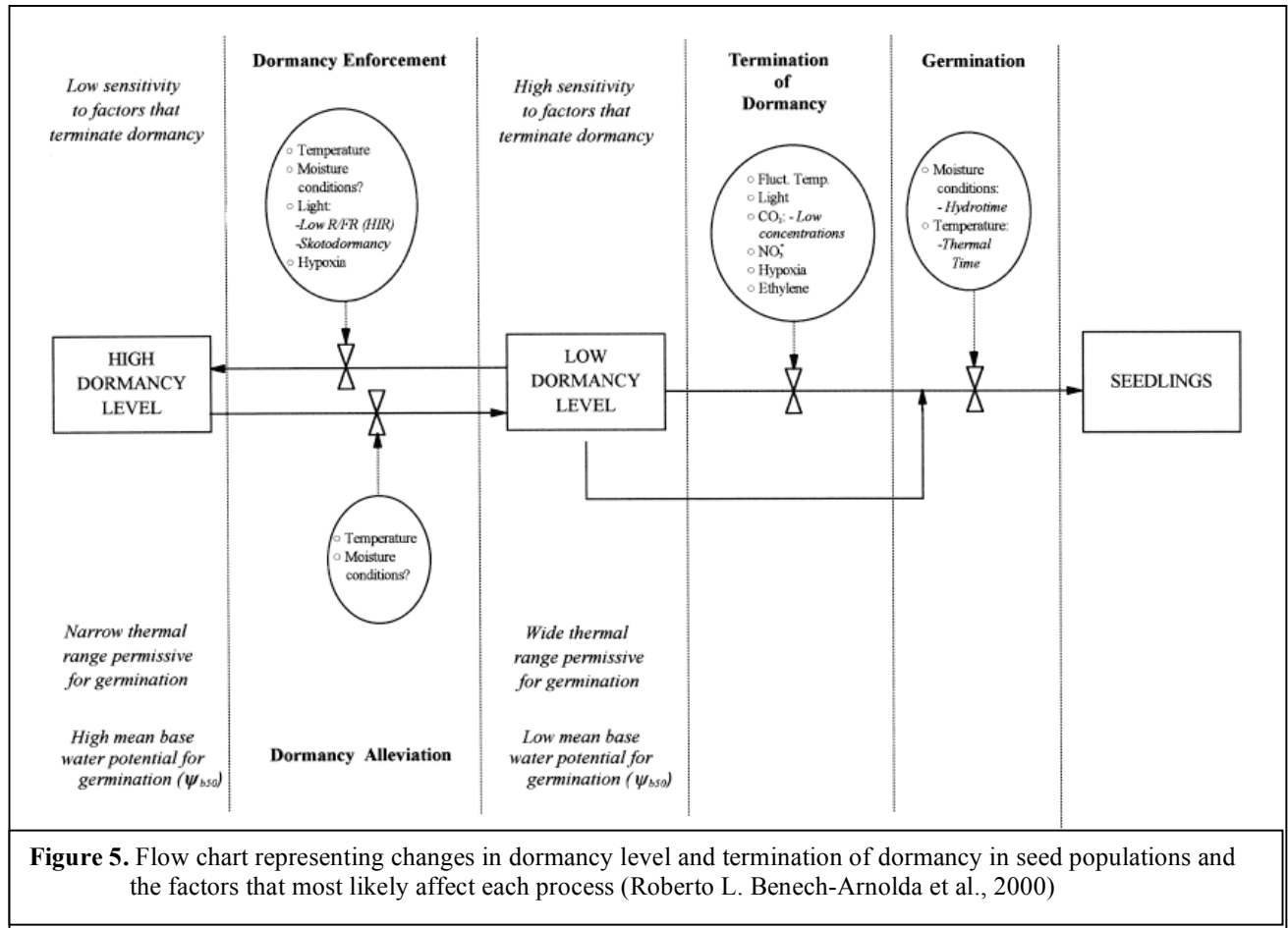
vegetation occurs (Doerr, Stefan H and Cerda, Artemi, 2005). When organic matter burns, it

leaves ash, charcoal and fire-altered material on the ground. Ash contains many of the inorganic elements that were bound in the vegetation or litter, with some lost to the atmosphere. An excess of base cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^{+}$ ) in the ash may lead to an increase in soil pH (Ahlgren and Ahlgren 1960; Raison 1979; Wells et al. 1979). Compared to other major nutrients, losses of Ca due to burning are minimal (Harwood and Jackson 1975). The concentrations of Mg and K increased after prescribed burning and wildfire; but after the first growing season, K was obviously lost through leaching, which was fire associated. The concentration of mineral nitrogen ( $\text{NO}_3^-$  and  $\text{NH}_4^+$ ) also increases after burning, although total nitrogen, which is mainly bound as organic compounds, is partly lost during burning (Kutiel and Naveh 1987; Gillon and Rapp 1989). The fertilizing effect of burning has been recognized in many studies (Austin and Baisinger, 1955; Smith and James, 1978; Kutiel and Naveh, 1987), and therefore burning has been used in agriculture and forestry to improve site productivity for centuries (see Appendix II for more information on effects to soil).

The response of non-target organisms to flaming has not been fully investigated, but there was no effect on the activity, density or variety of ground beetles (*Carabidae*) (Dierauer & Pfiffner, 1993). The microbial biomass at a depth of 0-5 mm was reduced by 19% when soils were flamed with open flame burners and they used a flame intensity of 4600 MJ/ha. Flaming had little effect on microbial biomass deeper in the soil. The soil temperature at 5 mm was raised by 4.0°C and at 10 mm by 1.2°C. Rahkonen *et al.* (1999) concluded that the threat that flaming poses to microorganisms is small. As noted in the International Journal of Wildland Fire, there was a rapid recovery of microbial diversity in soil after burning despite the persistent reduction of microbial community activity and the change in its structure (Doerr, Cerda, and Artemi, 2005).

Direct soil heating may not provide sufficient temperatures to kill weed seeds, and in some cases may enhance seed germination. Dormancy is a common attribute of many weed seeds and is defined as “an internal condition of the seed that impedes its germination under otherwise adequate hydric, thermal and gaseous conditions (Hilhorst, H.W.M. & C.M. Karssen, 1992).” A loss of seed dormancy implies that seed germination will proceed under a wide range of environmental conditions.

Dormancy is classified as either primary or secondary. Primary dormancy refers to the innate dormancy possessed by seeds when they are dispersed from the mother plant. Secondary dormancy refers to a dormant state that is induced in non-dormant seeds by unfavorable conditions for germination, or re-induced in once-dormant seed after a sufficiently low dormancy had been attained. Primary dormancy develops in seeds when they are on the mother plant (Hilhorst, H.W.M. & C.M. Karssen, 1992). Seeds may cycle between primary and secondary dormancy as depicted in the chart below.



## PROJECT 1: Effect of direct-heat on weed seed survival.

### Materials and methods

The first project in the study determined the effect of heat on weed seed survival. We explored how intense heat treatments over short durations could inhibit seed germination to provide beneficial outcomes for agriculture and native land restoration.

Weed seeds were exposed to temperatures of 40°, 60°, 80°, 100°, 120°, 150°, and 200°C in an AIM small electric kiln for 5, 10, or 15 seconds. Temperature was monitored with a Campbell

Scientific CR10X with a copper constantan thermocouple. Ten weeds seeds were exposed to the specified temperature, and then germinated on blotter paper in a Petri dish in a germination chamber at 20° nighttime and 30°C daytime with both fluorescent and incandescent lighting. Seed survival was estimated by the number of seeds that germinated. Seeds were checked daily until no further germination was observed. Seeds were considered “germinated” when the radicle emerged. Each temperature and time treatment was replicated 9 to 11 times (total of 90 to 100 seeds were treated). GA-3 (1500 ppm) was used to stimulate germination for false brome (*Brachypodium sylvaticum*) and hairy nightshade (*Solanum sarrachoides*) seeds. Weed species tested were oxeye daisy (*Chysanthemum leucanthemum*), pigweed (*Amaranthus retroflexus*), wild carrot (*Daucus carota*), false brome (*Brachypodium sylvaticum*), nightshade (*Solanum sarrachoides*), and proso millet (*Panicum miliaceum* L.). The effects of heat on seed survival were compared by analysis of variance, and percent germination was correlated with estimates of seed weight.

Students from the Department of Mechanical Engineering (ME) utilized our heat efficacy data to design a heat chamber device able to pick up soil and achieve sufficient temperatures (°C) for efficient weed seed kill in the field. Meetings with ME students were held weekly for two years. Within this time a full understanding of project was created as information from the laboratory studies was incorporated into construction. The device was tested in the spring of 2007 and 2008 at the OSU Horticulture Vegetable Farm. Three variables were tested: burner height above the soil, speed of device or residency time of soil in the heating chamber, and the effect of heat on 4 weed seed species (see appendix IV).

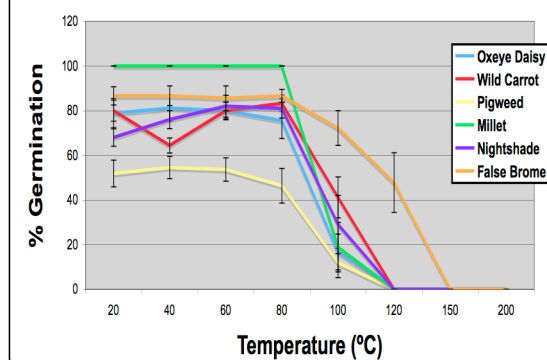
## Results and discussion

A simple analysis of variance (ANOVA) indicated differences in seed survival due to species and time of exposure to heat (Table 2). Average percent germination of un-imbibed seeds (Figure 6) ranged from 70-90%. All species showed a very similar trend towards total kill at around 120°C with the exception of False Brome. Nightshade and wild carrot germination increased between 60°C to 85°C, then decreased rapidly towards total seed kill.

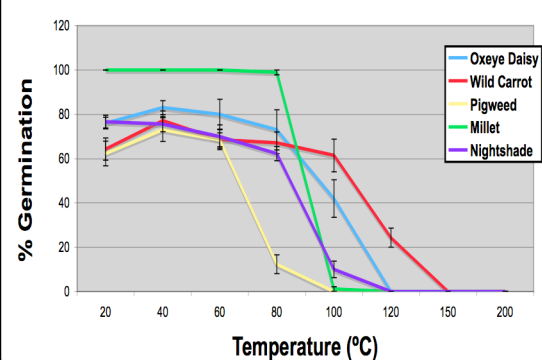
Survival of imbibed seeds after 5 sec of heat was lower than for un-imbibed seeds at the same temperature (Figure 7). Most species had a survival range of 60% to 80% when imbibed

**Table 2.** Effect of species, time of exposure to heat, and imbibition on seed survival from 20-100°C at 20°C intervals.

	Oxeye Daisy		Wild Carrot		Pigweed		Millet		Nightshade		False Brome	
<i>Factors</i>	<i>F</i>	<i>P-value</i>	<i>F</i>	<i>P-value</i>	<i>F</i>	<i>P-value</i>	<i>F</i>	<i>P-value</i>	<i>F</i>	<i>P-value</i>	<i>F</i>	<i>P-value</i>
<b>Temperature</b>	56	<0.001	14.8	<0.001	12.28	<0.01	785	<0.001	54	<0.001	18	<0.001
<b>Time</b>	2.8	NS	3.1	<0.05	<0.01	NS	1.2	NS	2.1	NS	4.2	NS



**Figure 6.** Percent germination ( $\pm$  SE) of un-imbibed seeds of six weed seeds exposed to heat for 5 seconds. N=11 for pigweed and 9 for all others.

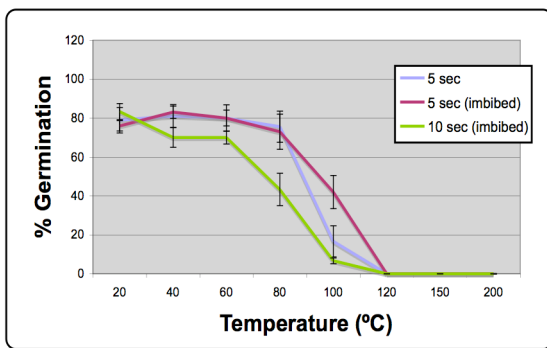


**Figure 7.** Percent germination ( $\pm$  SE) of imbibed seeds of five weed seeds exposed to heat for 5 seconds. N=13 for oxeye daisy, wild carrot, and pigweed and 9 for all others.

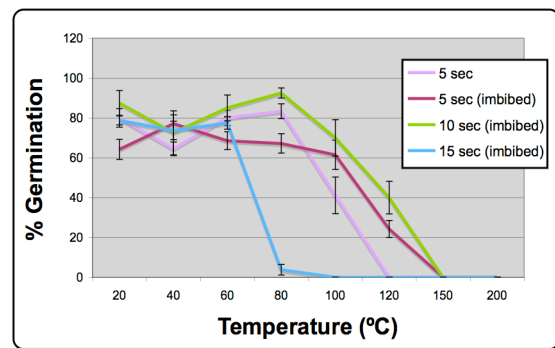
instead of the 70% to 90% seen in the un-imbibed seeds. An exception was wild proso millet; survival remained high for temperatures of 40°, 60°, 80C, but then dropped quickly to 100% mortality at 100°C. Pigweed was the only species with increased survival at about 40°C when imbibed, but then survival decreased rapidly to total seed kill at 100°C.

Oxeye daisy 5 sec. and 5 sec. imbibed treatments showed a very similar trend. The 10 sec imbibed had a higher percent germination for control and a drastic drop below the other treatments. All treatments for oxeye daisy had total kill at 120 °C. Wild Carrot seeds survived poorly when subjected to the 15 sec imbibed treatment with total kill at 100°C. Total kill for all other wild carrot treatments ranged from 120°C-150°C. The imbibed treatment for pigweed experiences a greater increase in germination than the un-imbibed. Imbibed pigweed seeds are more susceptible to heat treatments showing 100% kill at 100°C, whereas, the 5 sec. (unimbibed) treatment experiences 100% kill at 120°C. Nightshade survived unsuccessfully when imbibed, and did not experience an increase in germination. However, total kill is established at 120°C for both nightshade treatments. The results for percent germination of millet are virtually equivalent to each other. A difference only exists at the final temperature where 100% kill is achieved.

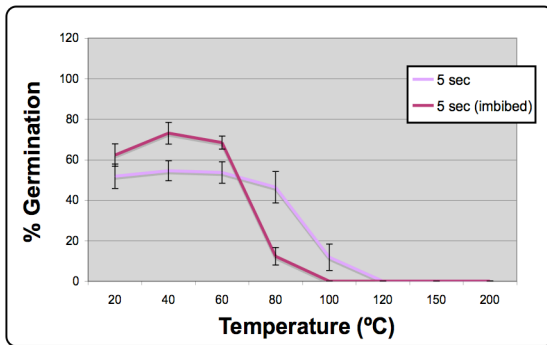
False Brome treatments followed the same trend until 60-80°C, and percent germination decline as temperature increased. However, the 10 sec. imbibed treatment displays poor germination below that of un-imbibed. Most seeds at 10 sec (imbibed) have 100% kill at 120°C, whereas, not until 150°C do we see 100% kill of un-imbibed seeds.



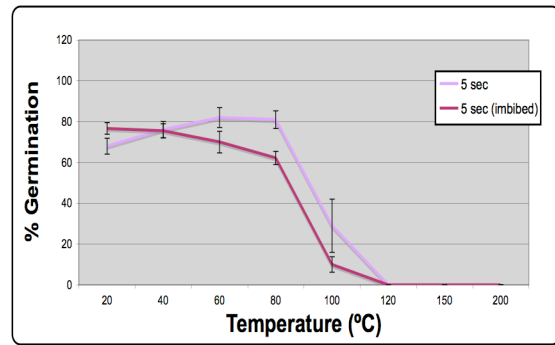
**Figure 8 (a).** Percent germination ( $\pm$  SE) of oxeeye daisy seeds after varied heat treatments. N=9 for 5 sec., 13 for 5 sec. (imbibed), 9 for 10 sec. (imbibed).



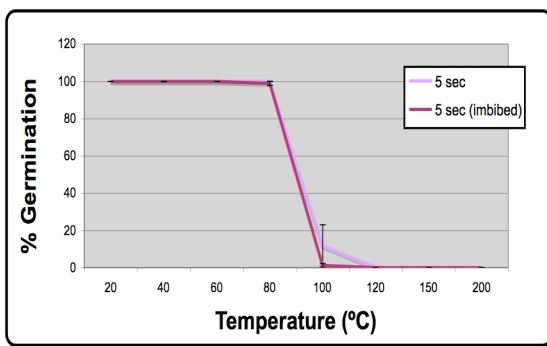
**Figure 8 (b).** Percent germination ( $\pm$  SE) of wild carrot seeds after varied heat treatments. N=9 for 5 sec., 13 for 5 sec. (imbibed), 4 for 10 sec. (imbibed), and 8 for 15 sec. (imbibed).



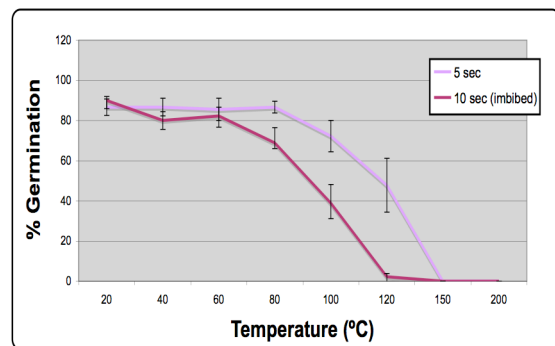
**Figure 8 (c).** Percent germination ( $\pm$  SE) of pigweed seeds after varied heat treatments. N=11 for 5 sec., 13 for 5 sec (imbibed).



**Figure 8 (d).** Percent germination ( $\pm$  SE) of nightshade seeds after varied heat treatments. N=10 for 5 sec. and 9 for 5 sec. (imbibed).

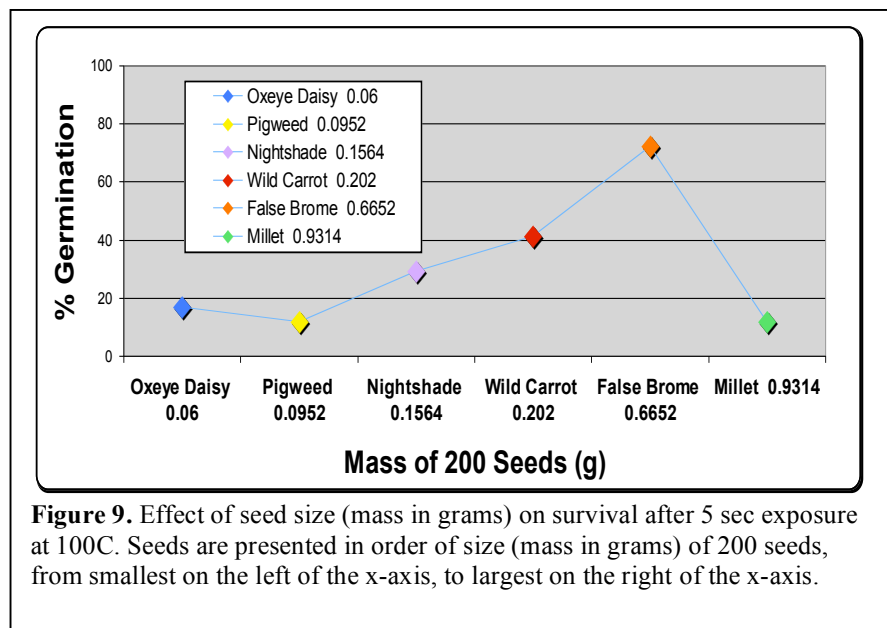


**Figure 8 (e).** Percent germination ( $\pm$  SE) of millet seeds after varied heat treatments. N=9 for 5 sec. and 5 sec. (imbibed).



**Figure 8 (f).** Percent germination ( $\pm$  SE) of false brome seeds after varied heat treatments. N=9 for 5 sec. and 10 sec. (imbibed).

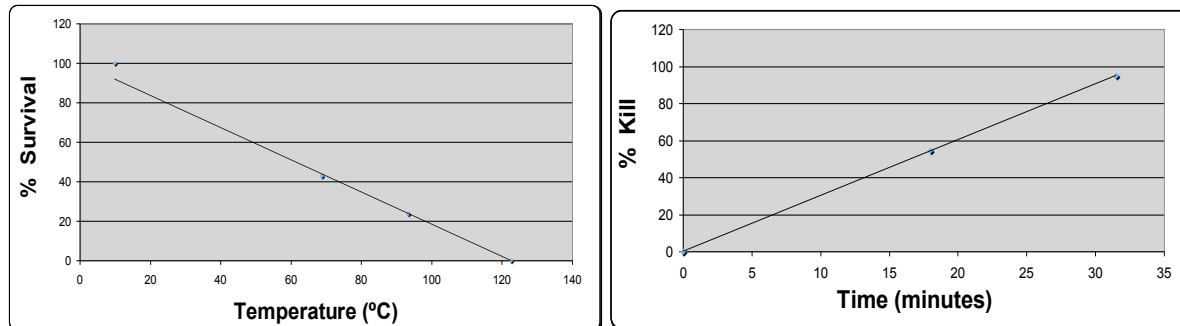
ANOVA indicated a relationship between seed size and percent germination at 100°C for chosen and that different size classes of seeds are represented by different species with a range of seed sizes (mass in grams). As seed size (mass in grams) increased, seed survival also increased with the same amount of exposure to heat. The trend was consistent among species with the exception of a few outliers. As can be seen in fig. 9, millet seed did not conform to the general pattern, with percent germination well below the expected value at 100°C.



In summary, nearly all species over all treatments experienced an increase in germination up to 60°C, then germination (seed survival) dropped quickly as the temperature approached 100°C. Imbibed treatments, for most species, showed a greater percent germination at 20°C. Seeds of some species were more sensitive to heat than others. Imbibed seeds were more susceptible to heat than unimbibed seeds. Seed size seemed to reflect sensitivity to heat treatments.

We attempted to apply the above information to ‘real world’ situations so that we could estimate the potential of treating soil with heat to kill weed seeds in field situations. Because of inconsistencies in procedure and outcome over 2 years, only a brief discussion is presented in this thesis, including the potential and cost of using soil heating equipment to reduce the weed seed bank. The development of the machine is presented in appendix I.

Weed seeds were added to sterilized soil in 2007 and 2008, and the soil was run through the soil heating machine. The soil temperatures achieved in 2008 were more realistic than in 2007, and therefore the data from 2008 were used to estimate the practicality of heating soil to kill weed seeds. The treated soil was collected and seed emergence measured in the greenhouse under optimum germination conditions. The maximum temperature achieved was approximately 70°C and this produced a maximum mortality rate of 43%. Assuming a linear relationship between residency time in the machine and soil temperature, and between soil temperature and seed mortality, we estimated that a residency time of 32 sec in the soil heating machine would be needed to kill 95% of the seeds (Fig. 10a). The cost to achieve 95% kill was estimated at \$75.60/A if a 10 cm wide by 5 cm deep band of soil was treated and crops were planted on 75 cm rows. The speed of the machine would be approximately 0.1 mph and would take 8.25 hrs/A if treating 4 rows at a time (Table 4).



**Figure 10(a) (L).** Effect of soil temperature in the weed seed killer machine on seed survival. The trend line from 70 to 125°C was extrapolated using a linear model from actual seed survival data when seeds were exposed to temperatures from 20 to 75°C for 18 seconds.

**Figure 10(b) (R).** Effect of residence time in the weed seed killer machine on seed survival. Trend line is based on predicted seed survival in Figure A. A predicted residence time of 32 sec would be needed to kill 95% of the seeds.

**Table 4.** Estimated cost of propane at four speeds in the field for agriculture and restoration use

Residency Time (sec)	ft/sec	Mph	30 inch row	Propane use	Gallons used	Cost/gallon	Total cost/acre if treating partial field (10 cm wide by 5 cm deep band with a row spacing of 75 cm)	Total cost/acre if entire field
12	0.6	0.4	8.3	1.1	9.4	\$ 3.00	\$ 28.40	\$ 226.9
18	0.4	0.3	12.4	1.1	14.1	\$ 3.00	\$ 42.50	\$ 340.3
24	0.3	0.2	16.6	1.1	18.8	\$ 3.00	\$ 56.70	\$ 453.7
32	0.23	0.1	22.1	1.1	25.1	\$ 3.00	\$ 75.60	\$ 605

## PROJECT 2: Beetle Predation

### Materials and methods

Three experiments were conducted during the summer of 2007. Experiments measured the effect of seed plate amendments on carabid seed predation, determined the feeding preferences of *P. melanarius*, and measured the differences in male/female feeding behavior.

The first experiment determined whether weed seed consumption by carabids would be influenced by the amendments used to repel earthworms. For all studies, *Pterostichus melanarius* ground beetles were captured using pitfall traps at the OSU Horticulture Research Farm (highway 34 Corvallis, Oregon) and my home (south Corvallis, Oregon). Beetles were placed in 8-gallon storage bins (2 ft. x 1 ft. x 1.5 ft.), which were filled with potting mix and soil with debris from Horticulture farm to a depth of 2-3 inches. Petri dishes (90 mm) were filled with Presto patch, water, and 1 or 2 g of mustard powder. Mustard powder was the amendment of choice because it is a strong irritant to earthworms (Lawrence *et al.*, 2002). After the presto patch hardened, the Petri dishes were placed in the tubs and placed so that the top of the dish was flush with the soil. A constant density of 6 *Pterostichus melanarius* was maintained within the soil bins. One weed seed species (pigweed: *Amaranthus retroflexus*) was used to track predation and observe behavior. A total of 20 seeds were continually kept on the seed plates, and seed loss recorded daily. Each bin was replicated 6 times.

The second experiment determined seed predation preferences and rates of *Pterostichus melanarius* using a variety of economically significant invasive weed seed species. Bins were

constructed as described above. Once again, 6 *Pterostichus melanarius* were placed in bins to simulate natural populations. Petri platters containing the seeds of redroot pigweed (*Amaranthus retroflexus*), hairy nightshade (*Solanum sarrachoides*), wild proso millet (*Panicum milaceum* L.), wild carrot (*Daucus carota*), and oxeye daisy (*Chrysanthemum leucanthemum*) were placed on seed plates. Seeds were added to the plates as they were consumed, so that a density of 20 seeds was continually kept on each seed plate. As seeds were removed, we tracked seed loss as seeds were removed from the petri dishes, taking into account germination and caching of seeds. For all purposes in this study, a cached seed (more than 2" from point of origin-seed platter) was counted as seed loss. We also evaluated the potential predation and consumption of slug eggs and corn pollen grains by *P. melanarius*. This beetle is a known predator of adult slugs, and a possible predator of slug eggs. Observations in farm fields also suggested that these beetles consume corn pollen from corn tassels that had fallen to the ground after the corn was 'topped'. Over two 24-hour periods, in separate experiments, 30 slugs eggs and 10 stamens containing pollen grains were placed on Petri platters as described above.

The third experiment examined the individual predation rates of male and female *Pterostichus melanarius*. The carabids were sexed (Fig. 11) and placed in individual containers (4" x 4" x 1.5") to observe differences in predation efficacy between sexes. Again 20 seeds of one weed species (pigweed) were constantly kept on a plain Petri platter to track predation of male and female carabids.

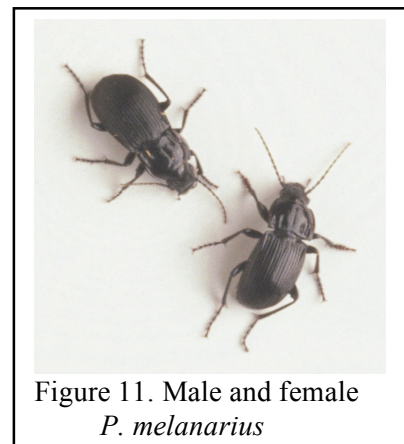
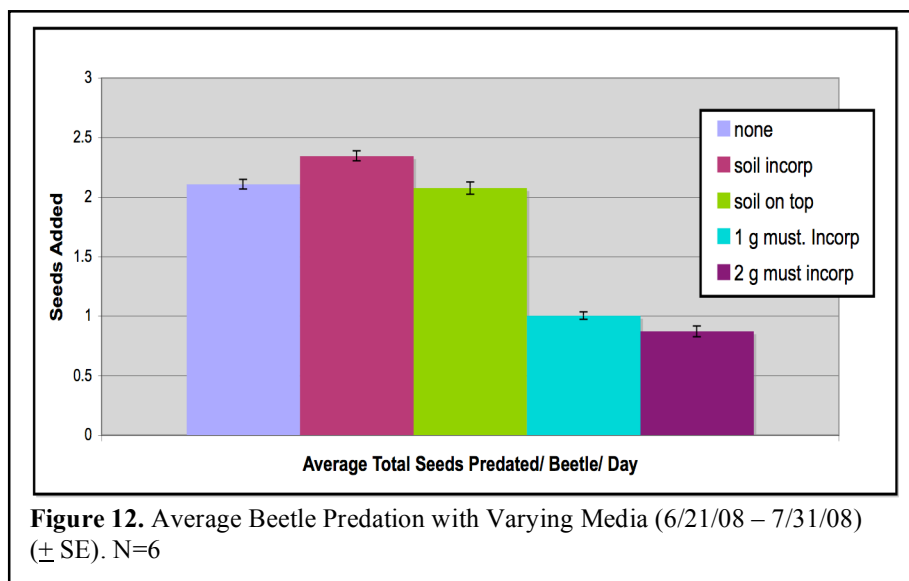


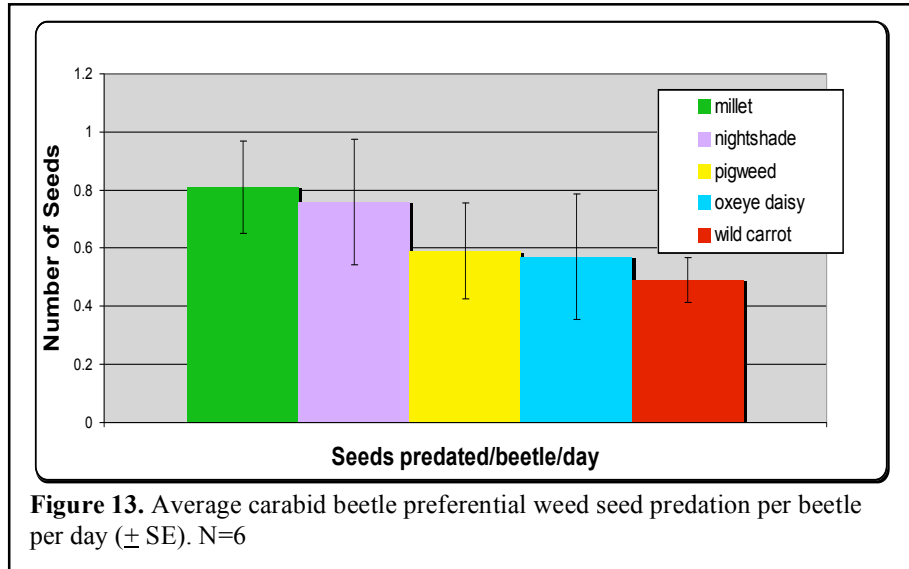
Figure 11. Male and female *P. melanarius*

## Results and discussion

Predation rates were determined by the media used in the Petri dishes ( $P < 0.001$ ) (Fig. 12). Seed predation in seed plates containing no mustard, soil on top, and soil incorporated into the media had greater predation rates than seed dishes containing 1 g and 2 g of mustard incorporated. For the three medias of choice (none, soil on top, and soil incorporated) 2.0-2.3 *Amaranthus retroflexus* seeds were predated/beetle/day, whereas only 0.87-1.0 seeds were predated/beetle/day for mustard incorporated media (Fig. 12). The mustard containing media deterred seed removal by the carabid beetles. However, in some cases the mustard may have killed the earthworms.

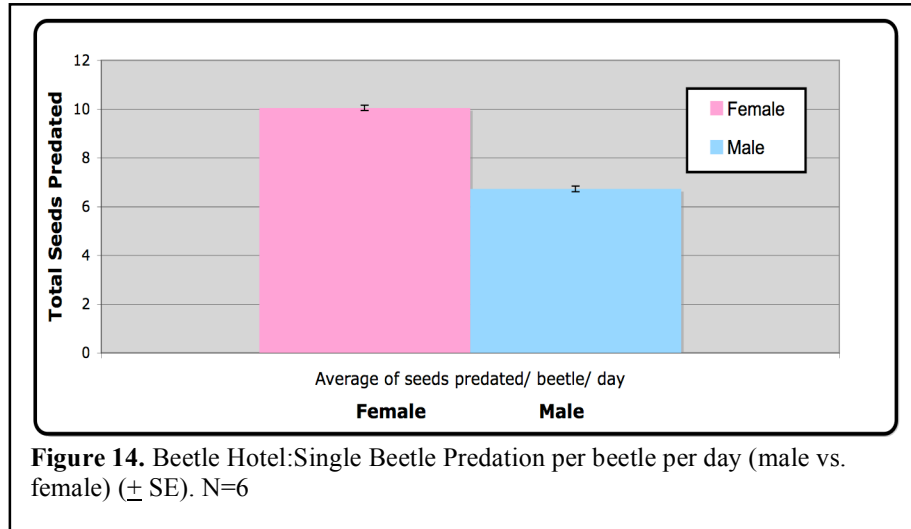


The second experiment demonstrated that *Pterostichus melanarius* preferred wild proso millet seeds (0.81 seeds/beetle/day) over wild carrot (0.49 seeds/beetle/day) (Fig 13). Overall, as observed in Fig. 13, an individual beetle predated  $\approx 3.22$  seeds per day. Not only did carabids show a preference for specific weed seeds, but they also preferred slug eggs over weed seeds.



We observed an interesting pattern of *P. melanarius* burrowing and caching seeds. Carabids burrowed at a 45° angle to the surface, creating habitats below the soil surface and under Petri platters. This behavior also was seen in field plots, where beetles burrowed underneath seed stations at the same angle. Carabids cached mostly larger millet seeds below the surface in burrows. Cohabitation of carabids, living in same burrows, was observed with no interference based on sex of beetles. We also observed that *Pterostichus melanarius* might have secreted fluids that helped to externally digest imbibed and/or slightly germinated Proso millet seeds previously cached.

The third experiment showed an obvious difference in the predation potential for male and female individuals of *Pterostichus melanarius*. On average, female's predated 10-redroot pigweed seeds/beetle/day compared to 6.5 seeds/beetle/day for males (Fig. 14). After feeding corn stamens containing pollen grains to carabids, it was observed that the entire stamen had been stripped clean. Using a dissecting microscope, we noted that a single beetle removed all of the pollen grains from stamens.



A media is needed to fill the Petri dishes used for seed predation stations to deter earthworms from taking weed seeds but without influencing carabid beetle seed predation rates. However, the mustard concentrations chosen as an amendment to the seed plate media (1g and 2g) were too potent, and subsequently had lethal effects on earthworms and deterred carabid predation of pigweed seeds. After a few days, the Petri dish media with mustard became moldy, and we hypothesized that the carabid beetles were avoiding the plates because of mold spores. The alternative hypothesis is that the mold spores interfered with the olfactory capabilities of the carabid beetles, thus preventing them from finding the weed seeds. *Pterostichus melanarius* preferred media which contained soil on top, incorporated, or none over platters with mustard ( $P < 0.001$ ) (table 5).

**Table 5.** ANOVA for effect of media, species of seed, and sex on seed predation rates of *Pterostichus melanarius*.

	Media Preference	Seed Preference	Male vs. female
<i>F</i>	10.31	11.02	20.88
<i>P-value</i>	<0.001	≤0.001	<0.0001

*Pterostichus melanarius* preferred certain weed seeds over others. Size, protein content of endosperm, and hardness of seed coat may have influenced predation preferences. The beetles displayed caching behavior that allowed access to the seeds at a later time, when the seeds had imbibed water and were softer. Imbibition hydrates the seed (endosperm) by softening hard seed coats, and creating greater access to the high protein content and nutrients of the endosperm.

There was a difference among *P. melanarius* seed preference ( $P \leq 0.001$ ) (table 5). This species of beetle may consume slug eggs as well. Slug eggs may contain a greater protein and nutrient content when compared to a seed. Given the abundance of slugs in vegetable cropping systems of the Willamette Valley, it may be essential that we find ways to exploit this characteristic of *P. melanarius*.

Corn pollen may be an alternate source of food for carabid beetles late in the summer. If this is the case, it is likely that weed seed predation rates would drop when corn begins to produce pollen. A closer look at corn pollen suggests that beetles would easily consume corn pollen, particularly when hydrated. This is a similar attribute of the seeds used (or predated on naturally), because a seed coat becomes quite soft when imbibed.

In the third study, we determined the difference in seed predation between female and male *Pterostichus melanarius*. A large part of predation potential was determined by sex ( $P < 0.0001$ ) (table 5). This study was conducted at the peak egg-laying season (late summer). We suspect that predation potential is greatest during these times due to the high nutrient demand of

gravid females during gestation. As with most species, when contributing to reproductive growth, a high demand of nutrition is needed.

## References

- AHLGREN, I. F. & AHLGREN, C. E. (1960). Ecological Effects of Forest Fires. *Botanical Review*, 26: 483-533.
- ALMENDROS, G., GONZÁLES-VILA, F. J. & MARTÍN, F. (1990). Fire-Induced Transformation of Soil Organic Matter From an Oak Forest: an Experimental Approach to the Effects of Fire on Humic Substances. *Soil Science*, 149: 158-168.
- ALMENDROS, G., GONZÁLES-VILA, F. J., MARTÍN, F., FRÜND, R. & LÜDEMANN, H.-D. (1992). Solid State NMR Studies of Fire-Induced Changes in the Structure of Humic Substances. *The Science of the Total Environment*, 117/118: 63-74.
- ASCARD J. (1995) Effects of Flame Weeding on Weed Species at Different Developmental Stages. *Weed Research*, 35: 397-411.
- AUSTIN, R. C. & BAISINGER, D. H. (1955). Some Effects of Burning on Forest Soils of Western Oregon and Washington. *Journal of Forestry*, 53: 275-280.
- BOGENHOLM, VANESSA (2004) The Use and Importance of Hand weeding in Organic Farming, California Certified Organic Farmers,

<http://www.croplifefoundation.org/Documents/Research%20Briefs/1%20handweeding%20report%20to%20Mr.Millan.pdf>

BOND, W.; DAVIES, G; TURNER, R.J. (2004, Nov.). A Review of Thermal Weed Control. Ryton Organic Gardens, Coventry, CV8 3LG, UK. *HDRA Organic Weed Management*.  
<http://www.gardenorganic.org.uk/organicweeds>.

CHANDLER, C.; CHENEY, P.; TRABAUD, L.; WILLIAMS, D. (1983). Forest Fire Behavior and Effects, Wiley and Sons New York. *Fire in Forestry*.

Davis, F.S.; Wayland, J.R.; Merkle, M.G. (1973). Phytotoxicity of a UHF Electromagnetic Field. *Nature*, 241: 291-292.

DEBANO L.F.; SAVAGE S.M.; HAMILTON, D.A. (1976). The Transfer of Heat and Hydrophobic Substances During Burning. *Soil Science Society of America Journal*, 40: 779-782.

DIERAUER, H.U. & PFIFFNER L. (1993). Effects of Flame Weeding in Organic Vegetable Growing on Ground Beetles (*Col. Carabidae*). *Communications of the 4<sup>th</sup> International Conference I.F.O.A.M. Non Chemical Weed Control*, Dijon, France, 137-140.

DIPROSE M.F.; BENSON F.A.; WILLIS, A.J. (1984). The Effect of Externally Applied Electrostatic Fields, Microwave Radiation and Electric Currents on Plants and Other Organisms with Special Reference to Weed Control. *The Botanical Review* 50 (2), 171-223.

DOERR, STEFAN H.; AND CERDA, ARTEMI (2005). Fire Effects on Soil System Functioning: New Insights and Future Challenges. *International Journal of Wildland Fire*, 14: 339-342  
CSIRO publishing, [www.publish.csiro.au/journals/ijwlf](http://www.publish.csiro.au/journals/ijwlf).

- FITZPATRICK, GREG (2005). The Nature Conservancy. gfitzpatrick@tnc.org.
- FORCELLA, F.; & BURNSIDE, O.C. (1994). Pest Management - Weeds. *Sustainable Agriculture Systems*, (eds J.L. Hatfield & D.L. Karlen), CRC Press, Florida, USA, 157-197.
- GONZALEZ-PEREZ, J.A.; GONZALEZ-VILA, F.J.; ALAMENDROS, G; KNICKER, H. (2004). The Effect of Fire on Soil Organic Matter. *Environmental International* 30: 855-870.
- HARWOOD, C.E. & JACKSON, W.D. (1975). Atmospheric Losses of Four Plant Nutrients During a Forest Fire. *Australian Forestry* 38: 92-99.
- HAUSER, S.; NORRGROVE, L.; NYOBE, T. (2002). Crop Rotation and Farming Systems: Small Holder Farming Systems and Agroforestry Systems. *Encyclopedia of Soil Science*, 243-246.
- HILHORST, H.W.M. & KARSEN, C.M. (1992, August). Seed Dormancy and Germination: the Role of Absciscic Acid and Gibberellins and the Importance of Hormone Mutants. *Plant Growth and Regulation*, 11 (3): 225-238.
- HOPKINS, C.Y. (1936). Thermal Death Point of Certain Weed Seeds. *Canadian Journal of Research*, 14: 178-183.
- HOSKING, J. S. (1938). The Ignition at Low Temperatures of the Organic Matter in Soils. *Journal of Agricultural Science* 28: 393-400.
- KHANNA, A.S. (2002). High Temperature Oxidation and Corrosion, *ASM International Typeset* in Replika Press Pvt Ltd, Delhi 110 040, India

- KITUR, B.K. & FRYE, W.W. (1983). Effects of Heating on Soil Chemical Properties and Growth and Nutrient Composition of Corn and Millet. *Soil Science Society of America Journal* 47: 91-94.
- KUTIEL, P. & NAVEH, Z. (1987). The Effect of Fire on Nutrients in a Pine Forest Soil. *Plant and Soil* 104: 269-274.
- LANDIS, D.A. (1996). Biological Control: Approaches and Application. *Radcliffe's IPM World Textbook*. University of Minnesota, Department of Entomology and Pesticide Research Center.
- MELANDER, B.; HEISEL, T; JØRGENSEN, M.H. (2002). Aspects of steaming the soil to reduce weed seedling emergence. *Proceedings 12th EWRS Symposium 2002*, 236-237.
- MOHLER, C.L. & GALFORD, A.E. (1997, June). Weed Seedling Emergence and Seed Survival: Separating the Effects of Seed Position and Soil Modification by Tillage. *Weed Research* 37 (3): Page 147.
- NEARY, D.G.; KLOPATEK, C.C.; DEBANO, L.F.; FFOLLIATE, P.F. (1999). Fire Effects on Below Ground Sustainability: A Review and Synthesis. *Forest Ecology and Management* 122, 51-71.
- ODEGARD, KYLE; WIGGENS, SCOBEL (2007, April 20). Soft Soils Aid Invasive-Plant Removal. *Gazette Times*, A1 and A6.

- PEACHEY, ED (2001). Effect of Soil Solarization, Cover Crops, and Metham on Field Emergence and Survival of Buried Annual Bluegrass (*Poa annua*) Seeds. *Weed Technology*, 15: 81-88.
- PIETIKÄINEN, JANNA (1999, NOVEMBER 12). Soil Microbes in Boreal Forest Humus After Fire, Finnish Forest Research Institute Vantaa Research Centre.
- PURELL, GREG (2006) -IPM: Integrated Pest Management.
- RICE, R.P.; PUTNAM, A.R. (1977). Some Factors Which Influence the Toxicity of UHF Energy to Weed Seeds. *Weed Science* 25 (2), 179-183.
- SCOPEL, A.L.; BALLAREÂ, C.L.; RADOSEVICH, S.R. (1994). Photostimulation of Seed Germination During Soil Tillage. *New Phytol.* 126,145±152.
- SERTSU, S.M. & SÁNCHEZ, P.A. (1978). Effects of Heating on Some Changes in Soil Properties in Relation to an Ethiopian Land Management Practice. *Soil Science Society of America Journal* 42: 940-944.
- SMITH, D.W. & JAMES, T.D. (1978). Characteristics of Prescribed Burns and Resultant Short-Term Environmental Changes in *Populus tremuloides* Woodland in Southern Ontario. *Canadian Journal of Botany* 56: 1782-1791.
- STANDIFER, L.C.; WILSON, W. & PORCHE-SORBET, R. (1984). Effects of solarization on soil weed populations. *Weed Science*. 32: 569-573.

UNKNOWN AUTHOR (1999, April). Something for Strawberry Growers to Get Steamed up About. *The Fruit Grower* 11-12.

VAN ESSO, M.; GHERSA, C.; SORIANO, A. (1986). Cultivation Effects on the Dynamics of a Johnson Grass Seed Population in the Soil Profile. *Soil Till.* 6: 325±335.

VDL CULTIVIT (2005). [www.cultivit.com/downloadCultivit.pdf](http://www.cultivit.com/downloadCultivit.pdf).

WAYLAND, J.; MERKLE, M.; DAVIS, F.; MENGES, R.M.; ROBINSON, R. (1975). Control of Weeds With UHF Electromagnetic Fields. *Weed Research* 15, 1-5.

WESSON, G.; WAREING, P.F. (1969). The Induction of Light Sensitivity in Weed Seeds by Burial. *Botany* 20, 414±425.

WHITE, G.; BOND, B. & PINEL, M. (2000a). Steaming Ahead. *Grower*, Nexus Horticulture, Swanley, UK, 134 (5), 19-20.

WILLIAMS, MIKE (1999). Direct Heat Treatment Kills Soil Borne Disease. *Farmer's Weekly* 131: 70.

WOLF, D.C. & SKIPPER, H.D. (1994). Soil Sterilization. In: Weaver, R. W. et al. (eds). Methods of Soil Analysis. Part 2, Microbiological and Biochemical Properties. *Soil Science Society of America*, Book Series. Soil Science Society of America, Inc., Madison, Wisconsin, USA. 41-51.

YENISH, J.P.; DOLL, J.D.; BUHLER, D.D. (1992). Effects of Tillage on Vertical Distribution and Viability of Weed Seed in Soil. *Weed Science* 40: 429±433.