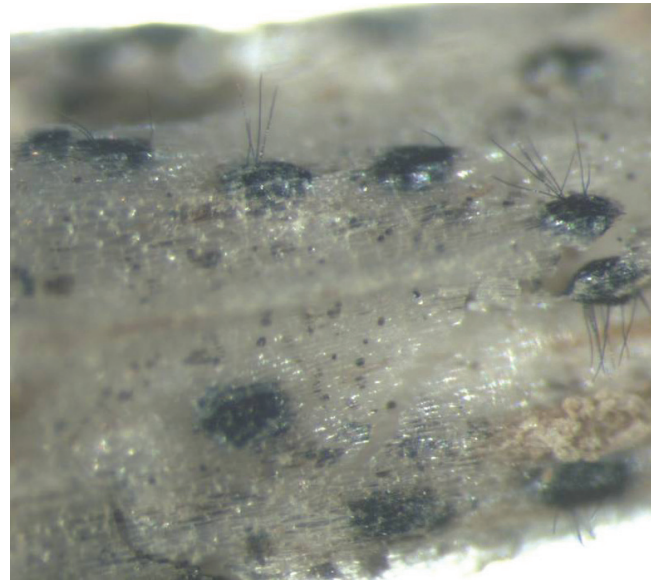


Field Flooding for Controlling Soilborne Potato Pathogens in Western Washington

WASHINGTON STATE UNIVERSITY EXTENSION • EM056E



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Introduction

Since 2006, The Nature Conservancy of Washington has funded research on how flooding agricultural fields may be used as an alternative crop rotation practice in western Washington to provide habitat for migratory shorebirds (Figure 1). This bulletin summarizes our work from 2009 to 2011, which examined the effects of flooding on the survival of certain soilborne fungal pathogens of potato, and may assist growers and agency personnel interested in or considering the practice.

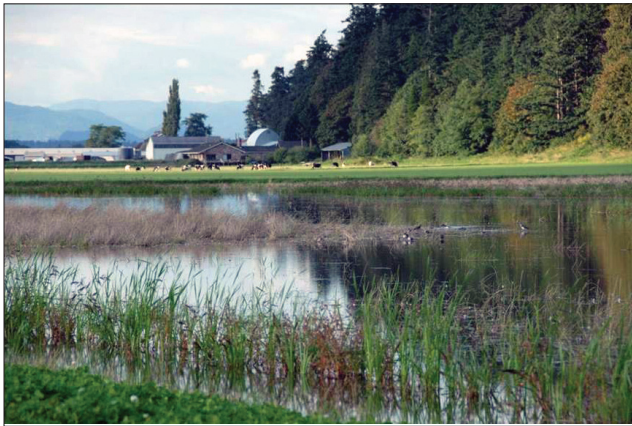


Figure 1. Flooded field site in Skagit County, WA, during summer. Photo courtesy of J. Morse.

To assess how field flooding has been used in the past and in other geographical locations, we conducted an extensive literature review. Examples of case studies that demonstrate both positive and negative effects are summarized below. Also, we examined the persistence of three soilborne pathogens of potato under flooded and non-flooded (fallowed) conditions. In the greenhouse, sclerotia (specialized survival structures) of *Colletotrichum coccodes*, the cause of black dot, did not persist past 3 months in flooded soil, and those of *Sclerotinia sclerotiorum*, the cause of white mold, were not recovered at 4.5 or 9 months in flooded soil, depending on temperature. In contrast, *Verticillium dahliae*, the cause of Verticillium wilt, was resistant to flooding under western Washington greenhouse and field conditions. We also participated in two small-scale (5 acres or less) on-farm trials with potato growers in Skagit County,

and found no obvious differences in emergence, plant health, tuber quality, or yield between potato crops that were planted one year before and one year after periodic fall/winter/spring flooding events. Flooding may be a viable crop rotation and an alternative to commonly-used methods for managing certain soilborne plant pathogens in western Washington, but care needs to be taken in planning and considering potential impacts apart from the survival of these three pathogens, and in regularly monitoring flooded field sites.

Background Information

The Greater Skagit Delta is one of the largest and most important coastal wetlands in Puget Sound, and provides essential habitat for wintering and migratory shorebirds (Figure 2; <http://www.whsrn.org/site-profile/greater-skagit-and>). The birds wade in shallow waters in search of the macro-invertebrates that provide them sustenance through the winter and during long migrations (Taft and Haig 2005). More than half of the shorebird populations in North America are in decline, presumably due, at least in part, to the loss of wetland habitats worldwide (Butler et al. 2004). Flooding fields can improve the habitat value of agricultural landscapes for shorebirds, and provide an alternative for farmers that is more economically viable than permanent land restoration.



Figure 2. Flooded field site in Skagit County, WA, during winter. Photo courtesy of J. Morse.

Field flooding is an ancient practice that developed hundreds of years ago in China. By growing crops in rotation with paddy rice, certain soilborne plant pathogens and pests could be eliminated (Palti, 1981). What happens in the soil under flooded conditions is not understood completely, but following is an excerpt from Stover (1979):

In flooded soil, the supply of oxygen is cut off and the oxygen concentration in the soil is reduced to practically zero within a few days by respiring soil microorganisms. Although it is unlikely that oxygen penetrates more than 0.4 inches deep in a flooded soil, if an oxygenated layer of soil even a few millimeters thick is present on the soil surface, algae may commonly be seen growing. Anaerobic (without oxygen) conditions thus are created under flooded (sometimes called submerged) soil. In this situation, carbon dioxide begins to build up. The concentration varies from 1 to 20% with a mean of about 5%. Soils with high organic matter content usually produce more carbon dioxide than those without it. Lack of oxygen then allows for anaerobic metabolism by soil microorganisms that benefit from the presence of easily decomposable organic matter. Ultimately, there is a decrease in the soil redox potential (the potential for ions and molecules to gain or lose electrons during chemical reactions), and an increase in pH. Some of the important chemical changes in flooded soils manifest as denitrification (reduction of nitrate by microorganisms, producing molecular nitrogen (N₂)); accumulation of ammonia; reduction of iron, manganese and sulphates; and the production of organic acids, methane and hydrogen sulphide.

Case Studies

Soilborne plant pathogens respond differently to soil flooding, and there can be both positive and negative effects of flooding in a soil environment. As a rule, populations of soil microorganisms like fungi, bacteria, and actinomycetes generally decline in flooded soils (Mitchell and Alexander 1962; Stover et al. 1953). Further, disease in host plants may be influenced by soil waterlogging depending on (i) the growth and ability of a pathogen to reach host tissues (if it is a motile propagule such as a zoospore); (ii) whether host resistance is altered; and/or (iii) if the activities of antagonistic microorganisms are changed (Drew and Lynch 1980). Direct digestion of fungal structures by microorganisms also has been proposed as one mechanism of inhibiting fungi through flooding (Mitchell and Alexander 1962).

There is always the danger of spreading soilborne pathogens via a flooding program, bringing risk to the practice. Hence, flooding might be able to con-

trol some diseases, but can also lead to the outbreak of others through pathogen spread.

One well-known example of a soilborne disease controlled by soil flooding is Panama disease, or Fusarium wilt, caused by *F. oxysporum* f. sp. *cubense*, on Gros Michel banana in the tropics. As summarized by Stover et al (1953), flooding in Honduras with 2 to 5 feet of water for up to 6 months resulted in 50% reduction of native soil fungi after 35 days, as well as nearly 85% reduction of native *Fusarium* species after 40 days. The Fusaria in submerged banana pseudostems appeared to be eradicated during the early stages of flooding, and microbial activities were probably greatest during this time. However, after draining the land of flood water, there was a six- to seven-fold increase in *Fusarium* species by 30 days, and an even greater increase by 60 days.

Stover (1961) postulated that, in order for soil flooding to succeed, a pathogen must not be able to survive in the deep layers of the soil profile, since plowing could eventually bring the pathogen to the surface. An integrated approach of post-flood fungicide applications and inter-flood plowing (that is, alternating cycles of flooding, draining, and plowing) reduced surviving *Fusarium* propagules in soil layers and increased the efficiency of flooding, as revealed by lowered disease incidence (Stover 1961 and 1979).

The effectiveness of flooding for controlling Verticillium wilt on cotton in California has been demonstrated. As stated by Pullman and DeVay (1981), a single rotation of paddy rice production effectively controlled this disease in subsequent cotton crops for 2 to 3 years and increased the yield of cotton lint. Flooding for six weeks with or without paddy rice was required for population decline. The pathogen was no longer detected in the soil after 17 weeks of paddy rice, or with flooding alone only 9% of the initial population of *V. dahliae* remained. The addition of readily decomposable organic matter, such as root exudates to flooded soils, may have been important in eliminating *V. dahliae* by stimulating microbial activity, further decreasing soil oxygen, increasing CO₂, and decreasing the soil's redox potential. Although summer soil flooding with or without paddy rice culture helped to manage *Verticillium*, 12 weeks of soil flooding during the winter months and irrigating rice without flooding were shown to be ineffective. The duration of soil saturation proved important in both greenhouse and field experiments where populations of *V. dahliae* began to decline after 6 to 8 weeks of flooding. Anaerobic conditions and low redox potentials in flooded soils were likely responsible for eliminating *V. dahliae* (Pullman and DeVay 1981).

Brooks (1942) found that soil flooding in Florida controlled pink rot on celery caused by *S. sclerotiorum*. Treatment of muck soil with calcium cyanamide in conjunction with flooding proved very effective. This same result was obtained by Moore (1949) who reported that soil submerged under water caused sclerotia to decay within 25 to 45 days. Flooding at 3-day intervals with 2 inches of water and continuous flooding were equally effective, and sclerotia decayed as fast on the soil surface as at the 2-inch depth.

In another study, Stoner and Moore (1953) proposed that lowland rice farming could be used as a cultural control for *S. sclerotiorum* in the Everglades. Sclerotia rotted under the field soil conditions of summer lowland rice production there. In California, winter flooding to control stem rot of rice was investigated as an alternative to open-field burning of rice straw to minimize overwintering of *Sclerotium oryzae* (Cintas and Webster 2001). There, winter flooding resulted in a decrease in stem rot severity as well as an increase in rice yield. The average number of viable sclerotia recovered after burning was 0.33, down from an initial average of 1.43 viable sclerotia per gram of soil. In comparison, an initial average of 1.35 sclerotia was reduced to an average of 0.51 viable sclerotia per gram of soil when flooding was employed. The authors postulated that the total number of sclerotia recovered was lower in the winter-flooded treatments because high soil water content increased the rate at which sclerotia decomposed (Cintas and Webster 2001).

Strandberg (1984) reported that flooding organic soils in Florida during fallow periods reduced *Pythium* spp. capable of infecting carrot roots and other vegetables. Flooding the fields following harvest led to a rapid decline in soil populations of the pathogen, which then remained at low levels throughout the flooded period. When crops were planted after draining the fields, recovery of the pathogen was sufficiently slow to allow carrot roots to grow with only limited damage. Although not eradicated, the *Pythium* population was reduced with flooding, and the flooding effects were dependent mostly on temperatures above 68°F (Strandberg 1984).

Early studies on flooding for nematode control were summarized by Kincaid (1946). In delta soils of California, Brown (1933) suggested that larvae of *Heterodera marioni* were killed when flooding ensued for 4 months, but eggs of this nematode could only be eradicated when flooding was employed continuously for 2 years. Flooding interrupted by a 1-week period of drying and aeration during the hot summer months was found to be more effective in controlling *Meloidogyne incognita* and *M. javanica* than con-

tinuous flooding on muck soils in Florida (Rhoades 1964).

Hollis and Rodriguez-Kabana (1966) attributed the mortality of the rice nematode, *Tylenchorhynchus martini*, to the production of acetic, butyric, and propionic acids in flooded soil. These compounds can be produced by *Clostridium* spp., which are anaerobic spore-forming bacteria. Hollis (1967) reported that flooding could be utilized to address nematodes in Louisiana rice fields, and that ring and spiral nematodes present in many rice fields (*Criconemoides*, *Helicotylenchus*, and *Rotylenchus* species) could be controlled in this way.

Stover (1979) reported that the population of *Radopholus similis*, the causal nematode of a root rot in banana, was severely diminished by flooding 4 to 6 months. Control of stem nematode, *Ditylenchus dipsaci*, in sandy soils in the Netherlands by using flooding, was studied by Muller and van Aartrijk (1989). The nematode's elimination was observed after flooding for 10 weeks at a water temperature of 63°F and flooding was considered as a possible alternative to soil fumigation.

Guerena (2006) wrote that at Tule Lake in California, where water is abundant and water pumping equipment and dikes exist, flooding for 7 to 9 months has been reported to control nematodes on potato, presumably because of the reduced amount of oxygen and the increased concentrations of organic acids, methane, and hydrogen sulfide. Two years may be required to kill nematode egg masses, however. Flooding works best near Tule Lake if both soil and air temperatures remain warm. An alternative to continuous flooding is several 2-week cycles of flooding alternated with 2 weeks of drying and disking. However, flooding can also be a means of dispersing nematodes, especially when flooding is poorly managed (Guerena 2006).

Concerns About Field Flooding

Soil water plays an important role in the motility of many plant pathogens. Zoospores of oomycetes like *Pythium* and *Phytophthora*, and the larvae of nematodes can move in water-filled pores (Palti 1981). Pathogens with high water potential requirements generally cause severe plant disease in wet soils, while pathogens with low water potential requirements can cause severe plant disease in dry soils (Cook and Papendick 1972). The germination of propagules of soilborne pathogens like *Fusarium*, *Pythium*, and *Verticillium* can be facilitated by high soil matric potentials where diffusion of exudates from roots and seeds into bulk soil is faster

(Drew and Lynch 1980). Also, soluble metabolites that leak from oxygen-stressed roots can stimulate chemotactic movement of mobile zoospores like *Phytophthora cinnamomi* along a concentration gradient near the root surface (Drew and Lynch 1980). As another example, water saturation of soil predisposed alfalfa roots to Phytophthora root rot (Kuan and Erwin 1930; Pratt and Mitchell 1976). Periodic flooding caused a greater incidence of disease in resistant and susceptible lines of alfalfa (Pratt and Mitchell 1976). Various factors, including chemotactic attraction of zoospores to roots grown in saturated soil, were associated with disease severity (Kuan and Erwin 1980). Mortality of pepper due to *Phy. capsici* increased as the number of 24-hr flooding periods at 10-day intervals increased; after three periodic floodings, 100% of the plants died (Bowers and Mitchell 1990). Pepper seedlings planted in soil infested with oospores of *Phy. capsici* became infected only after a saturation period was imposed (Hord and Ristaino 1992). After 2 or 24 hours saturation, high levels of infection occurred, but no plants were infected when held for 15 days without a saturation period.

The danger of plant pathogens surviving in irrigation water obtained from rivers, ponds, reservoirs, channels, etc. is an important consideration when using flooding as an irrigation method. Irrigation water may carry inoculum and can introduce nematodes and other pathogens into flooded fields (Palti 1981). For instance, flooding is a common disease control method practiced in cranberry beds and can minimize insecticide and fungicide inputs (Averill et al. 1997). But in a survey of commercial cranberry fields, *Phytophthora* spp. were revealed to have been introduced to 80% of the acreage (approximately 37% of New Jersey's production area) through application of infested water from irrigation reservoirs (Oudemans 1999).

WSU Flooding Studies

Greenhouse and field microplot studies were done at the WSU-Mount Vernon Northwestern Washington Research & Extension Center (NWREC) to investigate the effect of soil flooding on three pathogens sometimes present in potato production in western Washington: *Colletotrichum coccodes* (the cause of black dot), *Sclerotinia sclerotiorum* (the cause of white mold), and *Verticillium dahliae* (the cause of Verticillium wilt). All three pathogens form specialized structures called sclerotia which allow for long-term survival in soil. Sclerotia of the black dot fungus (Figure 3A) are small (0.02 inches); those of white mold (Figure 3B) are large (up to 0.5 inches long); those of *Verticillium* (Figure 3C) are very tiny (0.0012 to 0.004 inches) and are usually referred to as microsclerotia.



Figure 3A. Sclerotia formed on potato stems by the black dot fungus, *Colletotrichum coccodes*. Photo courtesy of B. Gundersen.



Figure 3B. Sclerotia on potato stems formed by the white mold fungus, *Sclerotinia sclerotiorum*. Photo courtesy of PNW-Veg Extension Group.

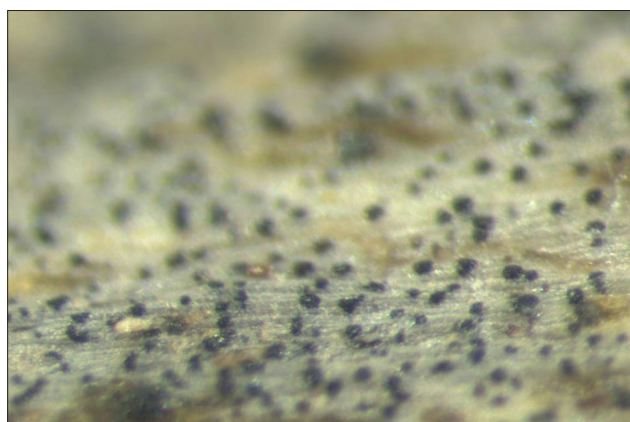


Figure 3C. Microsclerotia on potato stems formed by the *Verticillium* wilt fungus, *Verticillium dahliae*. Photo courtesy of B. Gundersen.

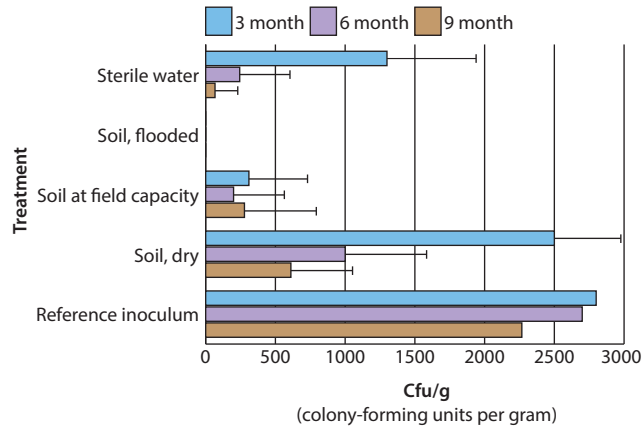


Figure 4. Recovery of sclerotia of *Colletotrichum coccodes* in a greenhouse study. Note: there was no recovery in the flooded soil after 3 months.

Sclerotia of *C. coccodes* were buried in flooded and fallowed soils in two greenhouse experiments at 68°F. At 3, 6, and 9 months there was no recovery of viable colonies of *C. coccodes* if the soil had been flooded (Figure 4) in either experiment. However, sclerotia of *S. sclerotiorum* buried in flooded soil at 62°F, showed a reduction of nearly 80% germination between 3 weeks and 3 months. It took between 3 and 6 months of flooding for *Sclerotinia* sclerotia to lose viability and decompose (Niem et al. 2013). Exposure to flooding at three soil temperatures (39°, 52°, and 68°F) resulted in sclerotia of *Sclerotinia* losing viability at 4.5 months, but only at the two higher temperatures. About 6% of sclerotia still retained viability after 4.5 months if at the cooler temperature. No sclerotia of *Sclerotinia* could be recovered at 9 months at any of the three temperatures (Niem et al. 2013).

Flooding for a sufficient time at adequate soil temperature is a potential method to eliminate *C. coccodes* and *S. sclerotiorum*, and could be used to control soilborne inoculum (sclerotia) of these pathogens in western



Figure 5. Microplot study in *Verticillium dahliae*-infested field. Plots were flooded or fallowed from April to October in 2009, kept over the winter, and then similarly cropped to potatoes during the 2010 growing season. A) Field set up, spring 2009; B) Flooded plot, spring 2009; C) Flooded plot, summer-fall 2009; D) Fallowed plot, summer-fall 2009; E) Plot left untreated, winter 2009-2010; and F) Potato plants, summer 2010. Photos courtesy of B. Gundersen.

Washington. It is important for growers to remember that for both pathogens, re-introduction of secondary inoculum (airborne conidia or ascospores from neighboring fields) would not be controlled by flooding, and could still lead to late-season outbreaks on above-ground foliage. Thus, this method would need to be part of an integrated disease management program.

In contrast, the microsclerotia of *V. dahliae* were resistant to flooding, especially when initial inoculum density was greater than 7 colony forming units per gram of soil. In greenhouse soil tests at 62°F, *V. dahliae* was readily recovered, even after 6 months of constant flooding (Niem et al. 2013). The same result was obtained in *Verticillium*-inoculated field microplots that were flooded or fallowed for about 6 months, between 24 April and 9 October in 2009 (Figure 5). The soil populations of *V. dahliae* as well of other species of *Verticillium* did not change for either treatment after one year (April 2009 to April 2010). Further, Russet Norkotah potatoes subsequently planted on 24 May 2010 into the previously flooded or fallowed microplot treatment areas did not reveal significant



Figure 6. *Verticillium* wilt on Russet Norkotah potato plants in the field microplot study was severe, and statistically the same. Microplot A was fallowed (A) and Microplot B was flooded (B) in 2009; both were planted to potatoes in 2010. There was 100% recovery of *V. dahliae* from all sampled stems at season end. Photo courtesy of B. Gundersen.

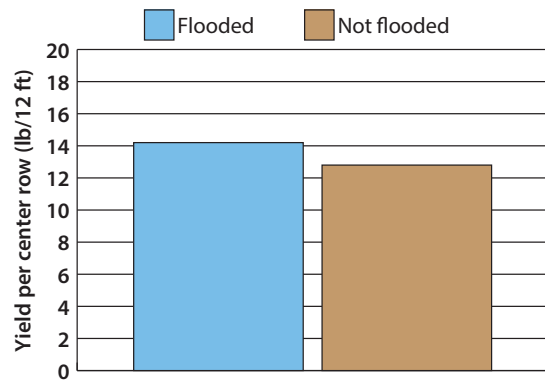


Figure 7. Yield of Russet Norkotah potato tubers from the field microplot study was statistically the same for flooded and not flooded (fallowed) plots.

differences in incidence of plants with *Verticillium* wilt (95.6 and 90.8%), recovery of *V. dahliae* from sampled potato stems (100% for both flooded and fallowed areas; Figure 6), or total tuber yield (14.2 and 12.8 lb per row, respectively; Figure 7). Flooding is not a recommended measure for controlling *Verticillium* in western Washington (Niem et al., 2013).

TNC On-Farm Trials

In 2009, *The Nature Conservancy* arranged for two small-scale cooperator field sites in the Skagit Valley as part of their *Farming for Wildlife* program. These fields (approximately 5 acres each) were planted to potatoes and harvested in 2009, and then divided in half, with each half designated either for flooding or fallowing in 2010. Potatoes were replanted in 2011 on the entire field which was surveyed to ascertain possible differences in disease, tuber quality, and yield between the flooded and fallowed areas. Figure 8 shows photos of each field site. It is important to note that this study did not have true replication, so only general comments can be made.

Baseline soil samples from both sites were collected in April of 2009 from assigned quadrants in each designated flooded and fallowed treatment area. General plant health was monitored over the summer, and potato tuber quality and yield were ascertained at the end of the growing season.

Soil populations of *Fusarium*, *Pythium/Phytophthora*, and *Verticillium* were estimated, fell within typical ranges, and found to be similar across field quadrants. There were no remarkable potato disease problems at emergence or during the growing season and these three pathogens caused no disease problems. Tuber quality was very high. In 2009, WSU-estimated yields averaged 40 and 38 lb per 100 tubers for previ-



Figure 8. Photos of Cooperator Field Sites A and B.

ously flooded and fallowed areas, respectively, at Field A, and 24 and 22 lb per 100 tubers for previously flooded and fallowed areas, respectively, at Field B (Niem et al. 2013).

In October of 2009, flooding was employed. Unfortunately, in winter of 2010, there was loss in the integrity of the flooding treatment at both locations. At Site A, the cooperator had difficulty in maintaining standing water in spite of nearly daily pumping. At Site B, there was uncontrollable water entry into fallowed areas. During our field survey summer visits in 2011, when potatoes had been re-planted, we attempted to adjust for loss of treatment integrity at Site B by avoiding areas where unwanted water intrusion occurred. We assumed, though, that all areas of the flooded half at Site A received approximately equivalent water volume even without sustained standing water. It is important to note that, for the purpose of this study, we are using the term "flooded" as an indication of both "submerged" and "saturated" soil conditions. There are physical and chemical differences, and possibly biological differences, between submerged and saturated soils, however.

In 2011, potatoes were planted again at both field sites. The field flooding that was done in 2010 did not seem to affect emergence, plant health, or yield because the values for flooded and fallowed

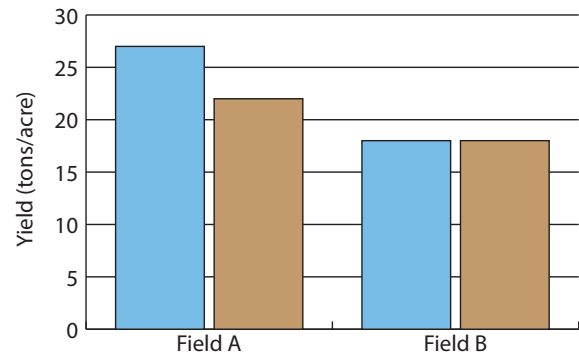
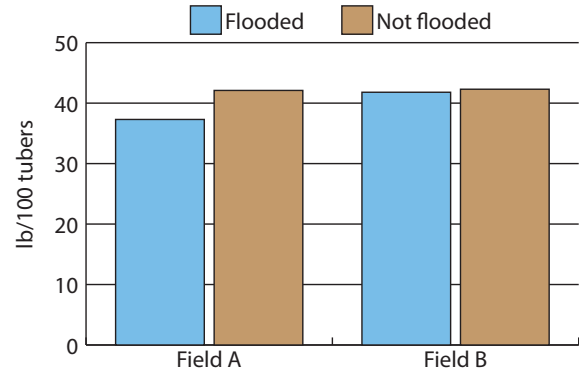


Figure 9. 2011 Yield estimates for The Nature Conservancy on-farm field trials that were planted to potatoes in 2009, partially flooded in 2009–2010, and replanted to potatoes in 2011. WSU estimated average yield (top); Cooperators' estimated yield (bottom).

areas were mostly similar at both field sites. WSU-estimated yields (based on 1,000 total tubers per site) averaged 37 and 42 lb per 100 tubers for flooded and fallowed areas at Field A and, unexpectedly, 42 lb per 100 tubers for both areas at Field B. The estimates provided by the cooperators were 27 and 23.5 tons/acre for flooded and fallowed areas at Field A and 18 tons/acre for each area at Field B (Niem et al. 2013; Figure 9). Because there was no evidence of potato diseases caused by *Fusarium*, *Pythium/Phytophthora* and *Verticillium*, tuber quality again was especially high, and because the actual flooding that was employed was inconsistent at both sites, follow-up estimates on changes in soil populations of *Fusarium*, *Pythium/Phytophthora* and *Verticillium* could not be determined simply. However, at harvest, there was less evidence of *Rhizoctonia* black scurf on tubers produced in flooded areas than in fallowed quadrants at both field sites, making the potato pathogen, *R. solani*, a good candidate for future studies on flooding for possible *Rhizoctonia* control.

Although data on bird use are not included in this report, flooded on-farm field sites in western Washington have provided substantial habitat value for

over 18 species of shorebirds and thousands of overwintering waterfowl (reports on bird use and other project components are available at: <http://waconservation.org/projects/puget/>).

Summary

These studies showed that flooding may be useful in western Washington for eliminating some soil-borne pathogens, but not all. In WSU greenhouse and microplot experiments, flooding under certain soil temperature conditions eliminated the survival structures of the potato black dot and white mold pathogens, but not those causing Verticillium wilt. Moreover, flooding needs to be part of an integrated disease management program since both *C. coccodes* and *S. sclerotiorum* produce airborne spores that can be potentially re-introduced from infected neighboring fields. Although soil fumigation is not often used in the region's potato production (unlike in many other potato growing areas), the same principle would apply. However, soil flooding is considered more environmentally sound than soil fumigation.

Flooding is not without drawbacks, given that it can be difficult and sometimes expensive to maintain standing water continuously at a field site. Even within the small-scale on-farm trials, spatial variation existed in depth of water and duration of flooding causing saturated conditions rather than continuous submersion to exist in some parts of a field and not others. The variation was due, presumably to micro-topography and differences in the underlying soil structure. Soil saturation rather than submersion could have influenced our finding of no obvious differences in plant emergence and health, or in tuber quality and yield, between flooded and fallowed field areas. Any effects that flooding conditions might have had in altering the populations of other organisms (insects, nematodes, soil microorganisms, weeds, etc.), or on the chemical and physical characteristics of the soil, were not part of this study.

Although flooding introduces the risk of spreading soil and soilborne organisms from one part of a field to another, or creating conditions that can even be favorable for some diseases and pests, such did not appear to be the case for the three potato pathogens we examined. However, before flooding any site, careful planning should be done to assess site history, soil structure, and water quality, as well as the potential impacts on plant diseases and pest populations. Additionally, as with any novel farming practice, careful field monitoring should be practiced whenever flooding is done, and small-scale rather than large-scale implementation is best, initially.

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