Proposal to the USDA-CSREES Risk Assessment and Mitigation Program, 2009

Title: Area-wide Management of Potato Pests (AMPP) in the Pacific Northwest

Project Summary

We propose a comprehensive and integrated approach to managing aphid and leafhopper vectors of plant pathogens, and other insect pests, in inland Idaho, Oregon, and Washington potato crops. Potato is the #1 dollar-value vegetable crop in the region, contributing over $9 billion annually to the US economy. For decades growers have used frequent, prophylactic sprays of broad-spectrum insecticides to meet the very low damage thresholds mandated by potato processors. However, processors are now requiring growers to document their use of integrated pest management (IPM) schemes, and to justify each pesticide application. Unfortunately, we lack knowledge of the true disease-transmission risk posed by insect vectors and have yet to identify effective, targeted control options. This threatens the economic sustainability of regional potato production. We will fill these knowledge-gaps with three integrated research and extension components. The **First Component** develops a multi-state sampling network for aphids and leafhoppers and their associated plant pathogens, and effective reduced-spray management plans for these pests (and for the secondary pests likely to become more prevalent as spray frequency decreases). The **Second Component** develops a detailed understanding of the impacts of predators and pathogens on key pest species, so that biological control agents can be included in IPM decision making. This will be accomplished in part through the use of novel molecular gut-content analyses of key predator species. The **Third Component** develops an improved sociological understanding of how growers reach spray decisions, and creates the means for growers to analyze the economic effectiveness of new risk mitigation strategies given the uncertainty of vector and plant pathogen outbreaks. The principal investigators include entomologists, virologists, extension educators, economists and sociologists from the three regional land-grant universities and the USDA-ARS. Results and IPM recommendations will be disseminated through an innovative extension program that emphasizes hands-on learning and in-field demonstration, in addition to innovative web, instruction, and publication outlets. *The project directly addresses RAMP program goals to enhance the development and implementation of innovative, ecologically based sustainable IPM strategies and system(s) for a high value, major acreage food production system, at an area-wide scale.*

Roles of Key Personnel

Principal Investigators

William Snyder, the PI on the project, will Chair the annual meetings among researchers, extension specialists and the Grower Advisory Panel. Snyder will oversee collection of predators for molecular gut content analysis, and will guide (with the assistance of Pappu and Harwood) molecular identification of entomopathogens. He will serve on the committees of each of the PhD students on the project, as described below.

Juan Alvarez, Entomology, University of Idaho, will oversee the regional sampling effort in Idaho and the green peach aphid control trials located there, and will assist in the secondary pests-wireworm component. Alvarez will serve as the major advisory of the UI PhD student.

David Crowder, Entomology, Washington State (Postdoctoral scholar), has a mathematics/modeling background, and will oversee development of the wireworm predictive model. Similar work from his PhD is detailed in his Biographical Sketch. Dave has an extensive background in mathematical ecology/pest modeling.

Levan Elbakidze, Ag Economics, University of Idaho, will develop the economic risk assessment models. Previous experience in this area is detailed on his CV.

Jessica Goldberger, Rural Sociology, Washington State University, will oversee the grower survey component. Jessica has significant expertise in getting growers to return surveys at a high rate, as detailed in her Biographical Sketch (and discussed in the Narrative).

James Harwood, Entomology, University of Kentucky, is an expert on molecular gut-content analysis and has adopted the “DGGE” method to identify prey within predator guts without fore-knowledge of what prey relationships might be. James has published extensively on this topic, including several prominent review articles. James will oversee the molecular gut-content analyses, and will co-advise the U Kentucky PhD student with PI-Snyder. This student will visit Washington every summer to assist in field collections of predators.

David Horton, USDA-ARS Wapato, has been working for many years on wireworm pests in potato and other crops. Dave developed the wireworm baits that will be deployed to sample these pests, and will oversee this aspect of the project.

Randa Jabbour, Entomology, Washington State University (Postdoctoral scholar), completed her PhD in 2008 in the laboratory of Mary Barbercheck at Penn State, where she studied entomopathogens in the field. Randa will oversee the effort to field-sample entomopathogens.

Key Personnel

Andrew Jenson, Research Director, Washington State Potato Commission, has a PhD from Oregon State University (Entomology) and still regularly publishes on insect taxonomy as well as management of potato pests. Andy maintains the potatoes.com website, and will assist with our web design effort. Andy also will assist in lining up growers for the regional field sampling effort, and will Chair the Grower Advisory Panel.

Lerry Lacey, USDA-ARS Wapato, is an expert on entomopathogens and will assist with field collections and species identification.

Peter Landolt, USDA-ARS Wapato, is an expert on chemical communication in Lepidoptera. He will assist in identification of lepidopteran pests of potato, and in measuring damage thresholds for the caterpillars and potato beetle.

Joseph Munyaneza, USDA-ARS Wapato, has been working for many years on insect-vectored pathogens of several different types, across much of North America and the world. He was heavily involved in the original effort to identify the purple-top pathogen and vector. Joe will oversee the beet leafhopper control trials in Washington.

Hanu Pappu, Plant Pathology, Washington State University, will oversee the use of PCR to identify plant pathogens in vector insects and also plant tissue. Hanu has extensive experience in this area.

Keith Pike, Entomology, Washington State University-Prosser, has worked on aphids and aphid-vectored pathogens throughout much of his career, and will oversee the aphid-control trials in Washington.

Silvia Rondon, Crop and Soil Science, Oregon State University, has a research/extension split appointment, and will oversee both the green peach aphid and beet leafhopper control trials at the Hermiston, OR, field site.

Timothy Waters, Extension, Washington State University, will assist with regional sampling and in the organization and staffing of the field days.

Carrie Wohleb, Extension, Washington State University, has recently taken over Keith Pike's regional aphid monitoring network, and will oversee the regional sampling effort in WA and OR. She also will oversee development of the field day program.

Richard Zack, Entomology, Washington State University, has expertise in taxomomy of Lepidoptera, and will assist in identifying lepidopteran pests of potato and measuring their impacts on yields, and also those of the Colorado potato beetle.

PhD students

Five PhD students will be supported on this project. The first will be housed at the University of Kentucky and co-advised by PD-Snyder (Washington State University). This student will travel to the Pacific Northwest each summer for predator field collections, staying all summer, and in the winter will participate in molecular gut content analyses. The second will be housed at that University of Idaho Aberdeen station, working with co-PD Juan Alvarez as the major advisor, and will assist with green peach aphid control trials and the regional sampling network. Three students will be housed at Washington State University. RAMP support has been requested to support 2 students, and Richard Zack, Chair of the Entomology Department at WSU, has pledged a third graduate student research assistantship for the duration of the project (see attached letter of support). One student will be co-advised by co-PDs Alvarez, Pike and Rondon (Pike as graduate committee chair), with PD Snyder serving as the on-campus advisor, and will oversee the green peach aphid/PLRV component of the project. The second student will be co-advised by co-PDs Munyaneza and Rondon, with PD Snyder as the on-campus advisor (Snyder will be graduate Committee Chair), and will oversee the beet leafhopper/BLTVA component of the project. The third PhD student will be co-advised by co-PDs Alvarez, Zack and Horton (Zack will be committee Chair), and will oversee the “secondary pests” component of the project. To aid in project coordination PD Snyder will serve on the graduate committees of all of these students. We anticipate that this large number of graduate students working towards a common goal will achieve a “critical mass” where they can assist one another in their field and other work, and learn from one another.

1. Introduction

a. Long-term goals of the proposed project.

This proposal investigates reduced-insecticide management programs for insect vectors of plant pathogens, and other arthropod pests, of potato through the development of an Area-wide Management of Potato Pests (AMPP) program for the Inland Pacific Northwest. The long-term goals of the project are to 1) *give growers tools to accurately assess insect/disease risk, and to respond appropriately with targeted, economically efficient management plans*, 2) *develop the means to effectively include biological control in the management of each key pest*, and 3) *overcome sociological and economic barriers to the adoption of reduced-risk pest management*. All of our work is under the direction of an advisory panel of potato growers, field scouts, and processors, and addresses key challenges identified in the regional pest management plan.

b. Body of knowledge and past activities.

Potatoes are the #1 dollar-value vegetable crop across Idaho, Oregon and Washington (ISDA 2008, ODA 2008, WSDA 2008), accounting for > 50% of total US potato production (USDA-NASS). Potatoes anchor most crop rotations in the region by having significantly greater profit potential than any other crop in these series (USDA-NASS). **Thus, the economic viability of many regional growers is largely or entirely dependent on production of robust yields of consistently high-quality potato crops, every 3 or 4 years in a rotation.** Moderate summer temperatures, long sunny days, and relatively abundant irrigation water provide ideal conditions for potato production, and potato yields in the irrigated potato growing regions of central WA and OR, and southern ID, are among the highest in the world. The great majority (>85%) of these potatoes are placed into storage at harvest for eventual use in frozen potato products. End users include major restaurant and grocery chains, and important overseas markets in Asia and Europe. **It has been estimated that the economic impact of Inland Pacific Northwest (IPNW) potato production and processing exceeds $9 billion per year** (compiled estimates of the ID, OR and WA Potato Commissions; personal communication to co-PD A. Jensen).

Potato end users mandate a consistently high quality tuber, and in some cases processors will reject entire lots with as little as 5% damaged tubers. Because growers are dependent on profits from potatoes to support less-profitable crops in the rotation, rejection of a potato crop is financially devastating. Thus, IPNW potato growers can tolerate little risk of damage or of reduced yields, despite facing attack by a diverse community of arthropod pests and plant pathogens. Ultimately, nearly all insecticide application decisions on IPNW potatoes are driven by the need to control two insect vectors of plant pathogens: the green peach aphid (*Myzus persicae*), which transmits **potato leaf roll virus (PLRV)**, and the beet leafhopper (*Circulifer tenellus*), which transmits the **beet leafhopper-transmitted virescence agent (BLTVA)**, a phytoplasma. Both plant pathogens stunt plants and lower yields, and PLRV reduces the quality of stored potatoes (Nolte et al. 2003). Growers currently lack access to information on whether pest insects are carrying plant pathogens, and so insecticide sprays are made largely on a zero-tolerance basis once the vector is detected in a field or region. Initial sprays then are followed by continuing frequent (every 7 to 10 days) foliar applications of broad-spectrum organophosphate, neonicotinoid, carbamate or pyrethroid insecticides. **This chemically-intensive management plan is surprisingly ineffective at reducing vector densities, but nonetheless reports of insect-vectored disease symptoms in IPNW potatoes have been declining in recent years** (see below). One possible explanation is that the presence of particular vectors is not strongly indicative of plant-disease risk, because pathogen loads vary from year-to-year (although, this possibility has never been examined for our region).

However, external socioeconomic forces are forcing IPNW potato growers to rethink their insect management practices. **In recent years several important end-users of frozen potato products (e.g., the Sysco and McDonald's corporations) have begun to require growers to develop "Sustainable Pest Management Plans"** that document and justify each insecticide application (example forms are attached; see also attached greenbiz.com article). Required information includes evidence that pest densities had reached damaging levels, and that insecticides were selected to minimize harm to beneficial insects and other aspects of environmental health. At the same time, **it has recently been announced that the organophosphate insecticide methamidophos (Monitor®, Bayer CropScience) has been withdrawn from the market** (see attached press release from Bayer). This insecticide has long been the backbone of insect pest management in IPNW potatoes due to its broad spectrum efficacy and low cost. Thus, growers are being forced to move rapidly from a pest management approach based largely on zero tolerance and calendar sprays, to a more nuanced risk-based mitigation approach where pest monitoring, carefully targeted sprays, and natural enemy conservation are the norm. Unfortunately, the industry is poorly prepared to make this transition.

Here, we propose a straightforward approach to helping growers transition to reduced-insecticide management of disease vectors and other pest insects in IPNW potatoes, while improving environmental health and maintaining high profitability, through the development of an Area-wide Management of Potato Pests (AMPP) program. **Our <u>First Objective</u> is to develop a tri-state sampling network for aphids and leafhoppers and their associated plant pathogens, and to develop effective reduced-spray management plans for these and other, secondary pests.** Unnecessary insecticide sprays could be avoided if growers were able to scale the intensity of their insecticide use to reflect true risk of disease transmission, while more effective targeted spray plans might pair tighter vector control with greater conservation of natural enemies. **Our <u>Second Objective</u> is to develop detailed information on the feeding relationships of predators and insect-attacking pathogens common in potato fields**, so that biological control can be considered in pest management decisions. Novel molecular gut-content analyses will allow us to identify, for the first time, which enemy species are attacking which pests under open-field conditions. **Our <u>Third Objective</u> is to develop an improved sociological understanding of how growers reach spray decisions, and to analyze the economic effectiveness of new risk mitigation strategies given the uncertainty of vector and plant pathogen outbreaks.** In this way we will ensure that growers can readily make a cost-benefit analysis when considering our low-input control tactics, and that our outreach programs are designed to effectively reach pest management decision makers.

Insect vectors of plant pathogens in IPNW potatoes, and the inefficiency of current controls

Green peach aphid and PLRV. – Green peach aphid is the most common aphid species in regional potato fields, accounting for 99% of all aphids present (Pike 2007). This species has a complex life cycle of 12 to 22 generations per year, with overwintering and early spring development occurring primarily on peach, nectarine and almond trees (Alvarez et al. 2003). Successive generations of green peach aphids then move to weedy hosts before moving to potato in mid-summer (Alvarez et al. 2003). Green peach aphids rarely cause measurable direct feeding damage to potato; instead, they are the most efficient vectors of the **<u>potato leaf roll virus (PLRV)</u>**. PLRV causes rolling of leaves, chlorosis, and stunting. The greatest economic damage

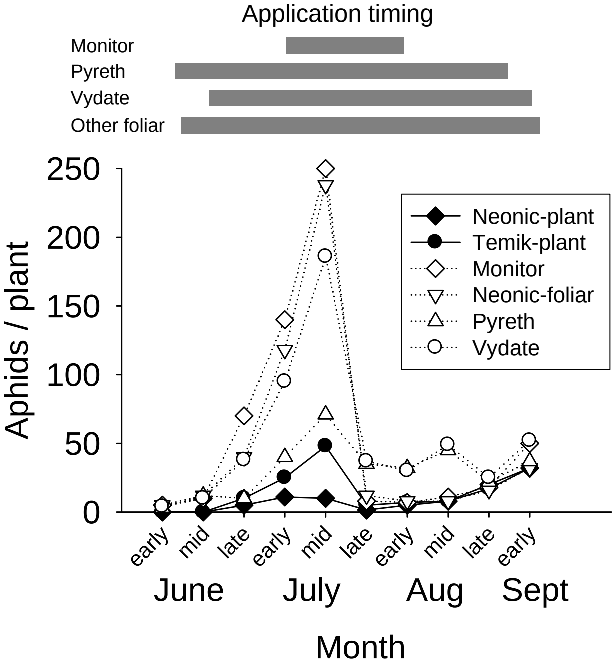

Fig. 1. *Green peach aphid densities in 159 commercial potato fields from 2004-2008 (pooled across years) in WA subject to various insecticide treatments. Gray bars indicate the main treatment period for selected chemicals.* ***Fields receiving a single neonicotinod treatment at planting exhibited low aphid densities all season.*** *Note however that each treatment represents fields that received that chemical at least once, but fields would always receive other chemicals as well.*

of PLRV results from induction of net necrosis in stored potato tubers, which lowers their aesthetic value by staining the potato flesh brown as phloem cells die (Nolte et al. 2003). Infected seed tubers and volunteer potatoes serve as the main primary sources of PLRV inoculum, although solanaceous weeds also act as virus reservoirs (Alvarez & Srinivasan 2005). A virus-free aphid must feed on the phloem tissue of a PLRV-infected plant for several hours before it can efficiently acquire and transmit the virus, but once acquired an aphid may retain the ability to infect healthy plants for the rest of its life (Mowry 2001).

Currently, growers utilize a vast array of control options in their attempts to prevent PLRV transmission (Fig. 1, Table 1). Perhaps most common is the foliar application of broad-spectrum organophosphate, carbamate, neonicotinoid and pyrethroid insecticides, applied as frequently as every 7-10 days on a calendar basis following the first detection of aphids in a field or region (Ruffle & Miller 2002). These sprays are costly to growers (ca. $7-30/acre/spray) and decimate natural enemy populations (Koss et al. 2005). Since 2005 Co-PD Pike has intensively sampled aphid densities in WA potato fields,

Table 1. *Most frequently used insecticides, miticides and nematicides, WA potato fields 2004-2007 (from Pike 2008); a total of 159 fields were studied. Abbreviations: CA, carbamate; CZ, carbazate; OC, organochloride; NE, neonicotinoid; OP, organophosphate; OS, organosulfur; PA, pyridine azomethine; PY, synthetic pyrethroid; SP, spinosyn; TE, tetronic acid.*

Chemical name	Trade name	Chemical class	%fields treated	Applications/ treated field	% of all products used	Key pest targeted
oxamyl	Vydate	CA	42.8	2.9	19.5	nematodes
esfenvalerate	Asana	PY	48.4	1.7	13.3	Beet leafhopper, potato beetle, looper
methamidophos	Monitor	OP	49.7	1.6	12.5	Beet leafhopper, aphids
cylfuthrin-imidacloprid	Leverage	PY-NE	42.8	1.5	9.9	Beet leafhopper, potato beetle, looper, aphids
dimethoate	Dimethoate	OP	21.4	2.0	6.7	aphids
spiromesifen	Oberon	TE	34.0	1.2	6.3	mites
propargite	Comite, Omite	OS	28.3	1.1	5.1	mites
aldicarb	Temik	CA	30.2	1.0	4.8	aphids, nematodes
cylfuthrin	Bay-throid	PY	11.3	2.4	4.4	Leafhopper, looper
thiamethoxam	e.g, Actara	NE	16.4	1.2	3.0	aphids, potato beetle
imidacloprid	e.g., Admire	NE	6.9	1.0	1.1	aphids, potato beetle

while also collecting insecticide-use records from each field (Pike 2008). **Surprisingly, these data reveal that green peach aphid densities peak as high as 250 aphids per plant in fields treated with the typical regime of frequent foliar sprays** (Fig. 1). At-planting treatments of neonicotinoid insecticides appear to prevent aphid outbreaks (Fig. 1), but this approach was used on < 25% of potato fields in the survey (Pike 2008). Anecdotal reports from growers suggest they are leery of the high cost of at-planting neonicotinoid treatments ($70/acre) when there is the perceived need in any case for later-season foliar sprays to combat other pests. **However, it appears that growers avoid the cost, in losses to PLRV, of poor aphid control because PLRV inoculum is no longer widely available.** Trials in WA and ID have recorded steadily declining rates of PLRV infection in seed potato (Fig. 2), perhaps reflecting tighter aphid control in seed growing areas (Pavek & Holden 2008). Unfortunately, our current aphid sampling regimen does not include tests for virus levels in aphids, thus we have no information on historical trends in virus levels in regional aphid populations.

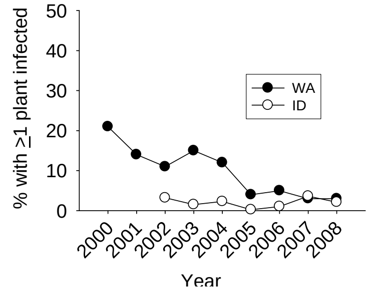

__Fig. 2__. The percentage of seed lots in trials from WA and ID with $\geq$1 PLRV infected plant. Note that the percentage of all __plants__ infected would be far lower.

Beet leafhopper and BLTVA. **–** In 2002, potato growers in WA and OR reported widespread outbreaks of potato "purple top" disease, causing significant yield losses (Munyaneza & Upton 2005, Munyaneza et al. 2006a,b, 2007, 2008). In a few cases entire fields were lost to this disease, resulting in a devastating financial loss to these growers. Purple top symptoms include a rolling upward of the top leaves with purplish discoloration, moderate proliferation of buds, shortened internodes, swollen nodes, aerial tubers, leaf scorching, and early plant decline (Lee et al. 2004, Crosslin et al. 2005, Munyaneza et al. 2006a,b, 2007, 2008). In response to these outbreaks the WA and OR Potato Commissions jointly funded a multi-disciplinary team of entomologists and plant pathologists to investigate causal agents, insect vectors, and disease epidemiology. It was determined that the **__beet leafhopper-transmitted virescence agent (BLTVA)__** phytoplasma is the causal agent of purple top disease in the Columbia Basin (Lee et al. 2004, Crosslin et al. 2005, 2006, Munyaneza et al. 2006a), and that this pathogen is transmitted by the beet leafhopper, *Circulifer tenellus* (Lee et al. 2004, Crosslin et al. 2005, 2006, Munyaneza et al. 2006a, 2008, 2009).

Since the original outbreak, a flurry of research into the leafhopper-BLTVA complex has made progress in understanding this disease. BLTVA infection rate in beet leafhoppers in and adjacent to potato fields is often high (5-30%), and because beet leafhoppers are in potato fields throughout the growing season conditions appear conducive to disease transmission (Munyaneza et al. 2009). In response to this threat growers generally treat beet leafhoppers with repeated foliar sprays of broad-spectrum insecticides throughout the growing season. However, co-PDs Munyaneza and Rondon have collected preliminary data suggesting that May and early-June sprays could be enough to provide season-long BLTVA control (Fig. 3), because potato may be susceptible to BLTVA only early in development: in field-cage studies, **potatoes were no longer**

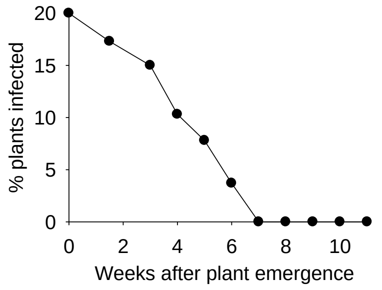

__Fig. 3__. In a field-cage trial, potato plants greater than 6wk post emergence did not develop disease symptoms after feeding by leafhoppers carrying BLTVA.

susceptible to BLTVA infection beyond 6 weeks post-emergence. A sampling program in WA, under the direction of co-PD Jensen, has revealed no clear correlation between beet leafhopper densities and the incidence of purple-top symptoms in adjacent potato crops (Jensen 2008). **Likely this is because BLTVA titers in beet leafhoppers vary from year to year**, although unfortunately the trapping effort has not included quantification of BLTVA in these vectors. Were growers to have information both on plant stages susceptible to BLTVA and the levels of BLTVA in the vector population, many mid- to late-season sprays could be avoided.

Opportunities to improve vector control in IPNW potatoes

Altogether, current knowledge suggests several avenues to improve vector control in IPNW potatoes. First, the most commonly used approach to vector control, calendar-based foliar sprays of broad-spectrum insecticides, is largely ineffective and/or unnecessary (as for aphids; Fig. 1, 2), or largely comes after potato plants are no longer susceptible to the pathogen (as for beet leafhopper; Fig. 3). It may well be that many sprays are made when the pathogen is not common in the vector population, although we know little about pathogen levels in these vectors. Frequent foliar sprays decimate natural enemy populations (Koss et al. 2005), and likely contribute to outbreaks of later-season secondary pests such as spider mites. It appears that a single at-planting application of neonicotinoids provides effective season-long control of aphids (Fig. 1), which could also help conserve beneficial predators. Control options for beet leafhopper are less clear, but early-season treatments may be the only control necessary given that the potato plant becomes resistant to BLTVA by June (Fig. 3). What is needed is a means to deliver information to growers on both vector abundance and plant-pathogen incidence in these vectors. Also, effective management plans must be developed that target the most vulnerable points in the transmission cycle, with intervention intensity scaled to reflect both vector and pathogen incidence. Currently, growers often are treating for vectors when pathogen levels are exceedingly low in these populations, and/or at times of the year when disease transmission is unlikely.

Secondary pests

Frequent applications of broad-spectrum insecticides targeting aphids and leafhoppers (Fig. 1, Table 1) probably mask the activity of species that would otherwise rise to pest status (e.g., Koss et al. 2005). Key among these are wireworms, the subterranean larval stages of *Limonius* click beetles (Coleoptera: Elateridae; two species, *L. canus* and *L. californicus* are common), which damage potato tubers by drilling into them while feeding (Jansson & Seal 1994, Parker & Howard 2001, Alvarez 2004). The larval stage lasts 2-5 years such that one generation may span several crops in a rotation. For this reason wireworm densities are thought in part to reflect a field's rotational history, with potato crops following such preferred crops as grains or clover most likely to experience high wireworm pressure (Lane 1941). Chemical controls are rarely effective against wireworm because the larvae are often deep enough in the soil (up to 1 m) that pre- or at-planting chemical drenches or soil fumigation does not reliably reach them. Movement through different soil depths also makes sampling of wireworm quite difficult (Gibson 1939, Jones & Shirck 1942, Parker & Howard 2001, Horton & Landolt 2001, Horton 2006). **Thus, the best approach to managing risk of wireworm attack may be to develop a predictive model, so that growers can avoid planting in fields likely to have high wireworm pressure.** Anecdotal evidence suggests that field management history and a wide variety of environmental variables (e.g., soil moisture, composition) are predictive of wireworm pressure. Unfortunately, these data have never been collected across a range of fields/regions, and integrated into a statistically rigorous predictive model.

Other key secondary pests in IPNW potatoes include a poorly known complex of lepidopteran larvae, and the Colorado potato beetle. In a preliminary 2008 survey of 10 fields two species, cabbage looper (*Trichoplusia ni*) and spotted cutworm (*Xestia c-nigrum*) accounted for 93% of all caterpillars collected from IPNW potato fields (Zack et al. 2008). Anecdotal reports from growers suggest that caterpillars are a growing problem, although underlying causes are unclear, and we have little or no information on the abundance, diversity, and economic thresholds of these emerging pests. It is unclear whether lepidopteran pests even reach sufficient densities to impact potato yields. Similarly, in our region Colorado potato beetle (*Leptinotarsa decemlineata*) generally does not reach the devastating densities seen in the eastern US (Walsh & Riley 1868, Hare 1980), even when insecticide applications are infrequent/ineffective (Koss et al. 2005). Furthermore, at-planting neonicotinoid applications to treat aphids appear also to delay the build-up of potato beetle populations (Table 1; Pike 2008). What is desperately needed for these secondary pests is a calculation of damage thresholds at densities, and under field conditions, typical of this region (e.g., Ferro et al. 1983 for Massachusetts). It may well be that neither pest commonly reaches densities where chemical control makes economic sense, in particular when the harm of these sprays to beneficial insects is also considered.

The impact of natural enemies in IPNW potato crops

Under current pest management schemes in regional potatoes, centered on frequent calendar sprays of broad-spectrum insecticides, the impact of natural enemies on pests likely is quite low (Koss & Snyder 2005). However, reducing the intensity of broad-spectrum insecticide applications can trigger a ca. 10-fold increase in the densities of generalist predators in WA potato fields (Koss et al. 2005). Predators at these densities are capable of reducing green peach aphids by 99%, while also significantly reducing densities of Colorado potato beetle eggs and larvae (Chang & Snyder 2004, Koss & Snyder 2005).The generalist predator community is dominated by a diverse group of linyphiid spiders (Araneae), predatory *Geocoris* and *Nabis* bugs (Hemiptera), and predatory lady (primarily *Hippodamia convergens*) and ground (primarily *Bembidion lampros* and *Pterostichus melanarius*) beetles (Tamaki & Weeks 1972a,b, Lacey et al. 1999, Alvarez et al. 2003, Koss et al. 2005). All of the common generalist predator species readily feed on green peach aphid and Colorado potato beetle in simple laboratory or field arenas where no other prey are provided (Koss et al. 2004, 2005, Chang & Snyder 2004, Koss & Snyder 2005, Straub & Snyder 2006, 2008). However, we have no information on feeding relationships among these species under open-field conditions, and no knowledge of whether the predators feed significantly on beet leafhopper or potato caterpillars under any conditions. This knowledge gap is unfortunate, because growers are unable to include predators in their pest management decisions.

These predators are often small, wary or nocturnal, and this in conjunction with dense potato foliage makes direct observation of predation events difficult. Furthermore, the two most common predator species, *Nabis alternatus* and *Geocoris bullatus* (Snyder et al. 2006), feed using piercing-sucking mouthparts such that gut dissection, were it practical, would not yield identifiable prey remains. Fortunately, recent advances in molecular techniques to identify the prey within predator guts present the opportunity to learn a great deal about feeding relationships under open-field conditions (e.g., Hagler & Naranjo 1994, 2005, Symondson et al. 1996, Bohan et al. 2000, Harwood et al. 2007, Juen & Traugott 2007, Chacón et al. 2008, Unruh et al. 2008). Here we propose to use PCR-based approaches to identify (1) which predator species are feeding on which of the key pests in a broadly qualitative way, and (2) to quantitatively describe the full range of pest and non-pest species consumed by each of the key predator species. This information will provide growers, for the first time, with the means to relate the number of predators discovered during scouting to the number of pests these enemies will kill.

In contrast to predators, parasitoids appear to be relatively unimportant in IPNW potatoes, with percentage parasitism of aphids, beet leafhoppers and potato beetles generally < 1% in most commercial fields (Koss 2003; personal obs. W. Snyder and A. Jensen). However, belowground insect stages (e.g., wireworm larvae, caterpillar and potato beetle pupae) are attacked by a diverse community of pathogenic nematodes and fungi (Liu & Berry 1995, Berry et al. 1997, Armer et al. 2004, Ramirez et al. 2009). Entomopathogenic nematodes in the genera *Heterorhabditis* and *Steinernema* occur in regional potato fields, but have not yet been identified to species (Ramirez et al. 2009). Endemic fungal pathogens are less studied, but in one field survey *Beauveria* spp. dominated (Ramirez et al. 2009). Infection rates on sentinel waxworm hosts placed into WA potato fields reach as high as 50%, but almost nothing is known of infection rates on potato pests (Ramirez et al. 2009). This ignorance hinders our ability to consider entomopathogens as a component of the natural enemy community, a knowledge gap we propose to fill through a regional survey of entomopathogen populations and extensive host range testing on key potato pests (described in *Methods*, below).

Socio-economic challenges to IPM adoption in IPNW potatoes

To our knowledge, no formal sociological study of pest management decision-making has ever been attempted for Inland Pacific Northwest potatoes. However, we suspect that sociological factors may slow the move to new, reduced-input pest management practices. First, it is our impression that crop consultants make many pest management decisions on the basis of limited (at best) scouting. Because these consultants usually work for companies that sell pesticides, a clear conflict of interest may arise where IPM implementation is concerned. At the same time, from the spray record data collected by co-PD Pike (and the experiences of others on the team), we know that some growers spray far less than the community average, and that effective IPM techniques (e.g., at-plant neonicotinoid applications against aphids) have been adopted by some growers. This suggests that different decision-makers view control options quite differently. Therefore, we propose to include in our project an intensive survey effort, directed by co-PD Goldberger, targeting all levels of pest management decision-makers in the industry – growers, processors, and field scouts – to learn more about where they get their spray information, and to identify characteristics (whether ground is rented or owned, farm size, presence of organic acreage on the farm, employer, etc.) likely to influence the decision to spray more or less often, or to adopt or reject IPM practices (e.g., scouting for pests and/or beneficials). With this information, extension programs can be better tailored to reach each population. Survey work, conducted both early and late in the project, will also serve as a quantitative measure of the program's success in changing pest management practices.

Economic concerns form an additional barrier to IPM implementation. For example, pyrethroids can be bought and applied via chemigation for ca. $4 per acre, which limits incentives for growers to change their ways. Because end-users mandate nearly blemish-free potatoes, growers are understandably risk averse. Potatoes anchor many crop rotations by providing relatively high profit potential, and growers cannot remain in business without consistently high yields of high quality potatoes. Cost-benefit analysis is currently difficult because growers lack information on pathogen levels in vectors, forcing them to be overly conservative in their risk estimates. The withdrawal of methamidophos from the market, and new requirements by end-users to justify each insecticide application, provide counteracting economic incentives to reduce insecticide use. The balance of these competing economic factors will likely determine the success or failure of any new IPM tactics. To provide decision-makers with complete cost/benefit analysis to guide their spray choices, co-PD Elbakidze will construct a profit-optimization model that includes data generated by this project on pest management costs and effectiveness, disease risk as measured by the regional sampling network, and expected efficiency of natural enemies against particular pests. New IPM approaches will never be adopted if they do not carry obvious economic benefits that decision-makers can clearly see.

c. Stakeholder involvement

Potato growers in the three states are represented by grower-controlled and funded potato commissions, and it was Commission representatives that initiated this project. However, successful implementation must also involve other segments of the potato industry. Because the market demands high-quality finished products, processing companies exert strong influence on growers' production practices, dictating such things as variety choice and planting and harvesting dates. Processors have also recently started implementing grower-level Sustainable Agriculture/IPM audits, mandated by major buyers such as Sysco and McDonald's (representative audit paperwork is attached). Additionally, crop consultants provide pest management advice to growers, who are often overburdened with other demands of their businesses. So that all of these pest decision-makers are intimately involved, our project will be overseen by an Area-wide Management of Potato Pests Advisory Panel (AMPPAP). The panel has been constructed to include growers, processing companies, and crop consultants (***letters of cooperation from panel members are attached***) that together represent all three states. The advisory panel consists of representatives of 3 major potato producers, 3 scientists with broad expertise who work closely with the commissions in coordinating their research, and representatives from two processed foods companies, including an organic food company:

Table 2. Inaugural members of the Area-wide Mangement of Potato Pests Advisory Panel (AMPPAP).

Name	Title	Employer	State	Notes
Phil Hamm	Plant Pathologist, Director	OSU Hermiston Res. Center	OR	Main liaison to OR Pot. Comm., research
Greg Harris	Farm Manager/Agronomist	R.D. Offcutt Co. NW	OR/WA	Manages several thousand potato acres
Andy Jensen	Research Director	WA Potato Commission	WA	Oversees commission-funded research
Todd Jones	Senior Director-Operations	AgriNorthwest	WA/OR	Manages thousands of potato acres
Kalvin Keys	Area Manager-Operations	Con-Agra Foods/Lamb Weston	Regional	Processor; contact on sustainability issues
Kamren Koompin	Potato grower	Self employed	ID	Independent grower
Alec McErlich	Ag Res Development Mngr.	Small Planet Foods	Regional	Organic div. of General Mills (processor)
Allen Smith	Certified Crop Advisor	Wilbur-Ellis	WA	Crop advisor; chem. dealer
Mike Thornton	Director	ID Center Potato Research	ID	Main liaison to ID Potato Comm., research

d. Suitability of the project for Risk Assessment and Mitigation program

Our project was initiated by the potato industry in response to the *loss of a critical tactic in a management program due to the manufacturer's marketing decision* (methamidophos has been withdrawn from the market). Our project is focused on the *development and implementation of innovative IPM systems on an area-wide/landscape basis, which reduces reliance on single pest management tactics and potential risks to human health and the environment* resulting from calendar-based insecticide sprays, and demonstrates *the benefits of adopting IPM practices* through detailed economic analysis of alternative IPM systems. Innovative outreach components are explicitly tied to each research objective, and the project is overseen by a grower-advisory panel. Potato is one of the most valuable crops in the region, anchoring common crop rotations through its high profit potential. Our project addresses key goals of the National IPM Roadmap by "keeping a step ahead" of the *phase-out of certain insecticides* in response to *environmental* *concerns, consumer demands, and public opinion*; *developing alternative tactics that have major economic benefits as well as protect public health and the environment*; and *promoting a healthy within crop environment by conserving natural enemies*. Our project involves broad collaboration between University and Federal scientists, and the private sector. **Most importantly, we address the top two research priorities of the Pacific Northwest Potato Pest Management Strategic plan** (Hirnyck et al. 2007) by (1) developing comprehensive pest prediction models, reliable sampling methods and accurate thresholds, and (2) Developing pest management strategies that lower inputs/costs for growers while maintaining sustainability; we also address the priority to determine pesticide impacts on beneficials. **Finally, we address the #1 education priority** by providing accessible, web-based pest management information in one online clearinghouse; and additional outreach priorities by educating growers about interdisciplinary pest management and the proper use of pesticides (e.g., timing, pest ID).

2. OBJECTIVES

Table 3 below summarizes project objectives, key personnel, and outreach foci:

Objective	Problem	Solution	Personnel	Outreach Focus
I. Develop more effective and economically sound pest management practices				
1) Insect vectors of plant disease				
i. Integrated vector sampling	Separate sampling networks exist for each pest/state; none measure plant pathogen levels in vectors	Develop a single sampling network, use PCR to measure pathogen prevalence in vectors	Jensen &Wohleb (Chairs), Pappu, Alvarez, Pike Rondon, Munyaneza	Create integrated website for entire region; develop practical sampling plans
ii. Reduced-input vector controls	Spray intensity currently not correlated with control, not scaled to transmission risk	Demonstrate targeted, reduced-input controls in each state	Munyaneza & Pike (WA), Rondon (OR), Alvarez (ID)	Field tours of each state's demonstration site
2) Secondary insect pests				
i. Predictive wireworm model	No effective chemical controls; growers unable to predict risk	Create risk model using rotation & other variables	Horton (Chair), Alvarez, Crowder	Create easy-to-use model interface, on web site
ii. Caterpillars, potato beetle	Little information on damage thresholds	ID lep species, calculate thresholds	Landolt (Chair), Zack	Prepare color guide to pest species
II. Include natural enemy impacts in pest management decision making				
1) Generalist predators	Growers cannot calculate natural enemy impacts	PCR-based gut content analysis to delineate interactions	Harwood (Chair), Snyder	Hands-on training in predator identification at field days
2) Pathogens	Entomopathogen activity is high, but impact not known	Collect & ID species; define host ranges	Lacey (Chair), Jabbour, Harwood	Create web and print guides to entomopathogens
III. Overcome socio-economic barriers to adoption of new pest management approaches				
1) Sociology of pest control	Unclear how pest management decisions are reached	Survey decision makers pre- and post-program	Goldberger (Chair), Jensen	Shapes outreach efforts, assesses project success
2) Economics	Growers must weigh costs/ benefits before adoption	Develop a profit optimization model	Elbakidze (Chair), Crowder	Create web-based economics worksheet

3. METHODS

I. Develop more effective and economically sound pest management practices

1) Better manage insect vectors of potato disease

i. Integrated vector sampling plan for ID, OR and WA.

Separate sampling programs for green peach aphid and beet leafhopper are maintained in some of the 3 states, but this information is only available to growers spread across at least 6 different web sites. **Critically, none of the current sampling programs also measure pathogen loads in these vectors, and a single clearinghouse for this information does not currently exist.** Thus, it is impossible for growers to accurately assess disease risk, leading to overly conservative, and chemical-intensive, vector management (Fig. 1). Most commonly, once aphids or beet leafhoppers are detected in a given region, growers commence calendar sprays. This is unfortunate, because some evidence (e.g., Fig. 2) suggests that aphids and beet leafhoppers often do not carry, or only carry at low levels, the pathogens that growers are ultimately trying to manage. For beet leafhopper, damaging transmission might only be possible early in the season, with later season BLTVA loads in vectors of much less concern (Fig. 3). Many insecticide applications could be avoided, particularly in the early and late season, if growers could target their sprays to times when vectors are dangerous and plants susceptible.

Objectives: (1) Develop a single, tri-state sampling network for green peach aphid and beet leafhopper, (2) Use PCR to measure pathogen prevalence in these vectors, and **(3) Transmit this information to growers through a single website.**

Sampling methodology: Our sampling regime will expand upon the sampling networks currently in existence by (1) including simultaneous aphid and beet leafhopper sampling, and (2) testing a subsample of insects for plant pathogens. Vector populations will be monitored along two routes, one in the Columbia Basin of WA and adjacent OR (totaling 30 fields), and the second running through southern ID (totaling 15 fields). Fields will be located with the help of each state's Potato Commission, and will be chosen to span the irrigated potato growing areas of each region. Fields will be chosen to represent a range of pest management approaches, from organic to standard chemical control (as in Koss et al. 2005). Each field will be visited weekly between plant emergence and vine kill. Arthropods will be sampled using a 1'X1' beating sheet, slipped under the vegetation in the between-rows furrow; plants will be sharply struck three times over the sheet, and arthropods will be counted immediately focusing first on fast moving species. **Note that we will collect not just aphids and leafhoppers during this sampling effort, but also secondary pests (caterpillars, potato beetles) and natural enemies**; these data will guide work described below that addresses secondary pests and predators. Twenty beat sheet samples will be collected per field. Beet leafhopper populations will also be monitored using yellow sticky cards (5.25 x 3.75 inches). The cards will be mounted on small stakes and placed about 10 cm above the soil surface, with 10 cards placed around the perimeter of each field sampled. Cards will be collected and replaced weekly. For each field and season, with the help of the Potato Commissions, processors, and other industry collaborators **following harvest we will compile detailed spray records for each field, potato yield, and the incidence of any insect-vectored pathogens and/or direct insect feeding damage to tubers.** Co-PDs Alvarez and Pike have extensive experience sampling green peach aphids in potato, and find these insects to be difficult to count accurately. To assess the methodology above, in 10 fields we will also census aphids by turning 10 leaflets on each of 50 plants per field, and collecting aphids using a camel-hair brush. We then will use regression to compare these absolute counts to the beat sheet counts, and will adjust our sampling regime if beat-sheeting is found to be inaccurate.

PCR analysis of pathogen loads: During each field visit, a subsample of vector insects will be collected for pathogen testing. Depending on pest numbers on a given sampling date, we will start by randomly selecting 10% of the aphid and leafhoppers collected (testing individual insects) per sampling date to get an estimate of PLRV/BLTVA prevalence; we will adjust the number of insects sampled based on the results of this initial screening. Aphids will be collected as described above, while beet leafhoppers will be collected using gentle sweep net passes. Insects will be transferred immediately to 95% EtOH, and placed on dry ice for transport to the laboratory. For detecting PLRV in aphids, total RNA will be extracted from single aphids using RNAeasy Kit (Qiagen) and will be used as the template for amplifying PLRV RNA using RT-PCR. Complete genomic sequence of PLRV is available in GenBank, and based on consensus sequences, PLRV-specific primers will be designed and used. Protocols have been developed that facilitate the detection of PLRV in a single aphid (Singh et al. 1995). PCR products will be visualized by agarose gel electrophoresis. To ensure the specificity of the primers, amplicons obtained from aphids will initially be cloned and sequenced, and the identity of the amplicon will be established by comparison with available PLRV sequences. While testing field-collected aphids for PLRV, aphids from a 'healthy', virus-free aphid colony and viruliferous aphids (carrying PLRV) will be included as negative and positive controls, respectively. Beet leafhoppers will also be tested for BLTVA by PCR, using methods described by Crosslin et al. (2005, 2006). Briefly, total nucleic acids will be extracted from individual insects using the CTAB method as modified by Crosslin et al. (2005, 2006). Two rounds of PCR will be performed amplifying conserved regions of phytoplasma 16S-23S rRNA genes. Primary amplification reactions will be done with primer pair P1 and P7 using reaction conditions described previously (Crosslin et al. 2005, 2006). Nested PCR reactions will be conducted using primer pair fU5 and BLTVA-int and reaction conditions (see Crosslin et al. 2005, 2006). Amplification products will be separated on 1.5% agarose gels, stained with ethidium bromide and visualized on a UV transilluminator. Samples are considered positive for BLTVA if the expected amplification product of ≈1.2 kbp is amplified by the PCR reactions.

"Ground truthing" of simple sampling techniques likely to be adopted by decision makers: In our field sampling we will make use of a variety of sampling methods catered to locating particular pest or natural enemy species (described throughout Methods). However, in our experience field scouts and other decision-makers will only adopt sampling routines that can be completed quickly (minutes per field), such as collecting several beat-sheet or sweep net samples. Our extensive beat-sheet sampling effort provides us with the opportunity to calculate how many such samples are necessary to achieve an accurate estimate of true arthropod densites. Briefly, to accomplish this we will estimate the mean (arithmetic mean) and variance (sample variance, s^2) of a given number of samples, calculated using random-draws of particular beat-sheet samples collecting during Regional Vector Sampling. Using this information, we will calculate the number of samples needed (n) to gain a range of precision (p) and a 1-α (100%) confidence level, based on the t-distribution as follows:

$n = (2t_{\alpha/2}*s/mp)$ (Southwood and Henderson 2000) where $t_{\alpha/2}$ is the α/2 quantile of Student's t-distribution. This information will then be used to make sampling-plan recommendations to growers.

Integrated outreach components: Unified potato pest management web site: In all of our outreach work we will take full advantage of the many regional potato newsletters published by each state's Potato Commission, and the full range of regional potato meetings and field days in and out of the field season, which provide opportunities for traditional presentations and interaction with industry. However, a key focus of our outreach will address the **#1 Education Priority outlined in the recently updated Pest Management Strategic Plan for Pacific Northwest Potato Production** (Hirnyk et al. 2007), **by creating a one-stop-shopping clearinghouse for potato pest management at the address: http://www.potatoes.com/IPM.** The "potatoes.com" site is maintained under the direction of co-PD Jensen, who will oversee development of the new clearinghouse site (funds are budgeted for additional web development contracting).

This site will be used to disseminate information generated under all project objectives. Most relevant to the objective discussed here, for each vector-pathogen association a detailed report will be provided on the website using a map format. These maps will indicate the number of aphids and beet leafhoppers caught at each of the trap sites, and their pathogen loads, updated weekly. Critically, the economic risk-assessment modeling described under Objective 3, will allow us to provide control recommendations for particular regions, with these recommendations formulated as described in that section. The maps will also include notes about other pest species and natural enemies found at the sites. The website will also include instruction on insect identification, trapping and scouting procedures, information on insect biology and movement, and recommended strategies for controlling the pests, developed as described below.

ii. Reduced insecticide control programs for aphids and beet leafhopper

Although foliar, calendar-based sprays with a zero-tolerance threshold are the most common approaches to managing aphid and leafhopper vectors, we know that these sprays can be ineffective in reducing aphid densities (Fig. 1) and suspect that many are made past the time that potato plants are susceptible to infection by BLTVA (Fig. 3). This suggests that the deployment of more effective and/or properly timed sprays could greatly reduce overall spray intensity. Here, we propose to investigate reduced-input control strategies for both aphid and leafhopper vectors.

Objectives: At sites located in different states (1) Demonstrate the efficacy of at-planting neonicotinoid sprays for green peach aphid control, (2) Determine potato growth stages susceptible to BLTVA infection, (3) Examine the relationship between spray timing and beet leafhopper densities, and **(4) Transmit information on vector control to decision makers through field days with opportunities for hands-on learning.**

Alternative controls for green peach aphid. – Field data collected by co-PD Pike suggest that a single at-planting treatment of a neonicotinoid insecticide might provide effective, season-long aphid control (Fig. 1). However, this has not been experimentally demonstrated in our region within replicated plots, or directly compared to replicate plots treated with the conventional calendar-based foliar sprays (or a non-treated control). Note also that in Pike's data all fields received both at-planting and foliar insecticide sprays, such that independent effectiveness of at-planting neonicotinoid application cannot be fully evaluated. Here, we propose to compare chemical treatment options at university research farms in Aberdeen ID (Univ. of Idaho), Hermiston OR (Oregon State Univ.), and Prosser WA (Washington State

Univ.). Experimental design and procedures will be identical at each location, so that the regions can be considered blocks and the entire dataset analyzed together within a single ANOVA (or repeated measures MANOVA for response variables repeatedly measured throughout the season [von Ende 1993]). These regionally-replicated demonstration plots will also serve as the sites for farm walks and grower field days. Finally, data collected from this sub-objective will contribute to the formulation of an economic cost-benefit model as described in *Objective 3* below.

Our experiments will be conducted within a standard ANOVA design, with site (ID, OR, WA) as a blocking factor, and pest management treatment (STANDARD, NEONIC-PLANT, CONTROL) as factors nested within each block. At each site, treatments will be applied within a completely randomized design, with 10 replicates per treatment. Replicate plots will be 10 x 20 meters, separated by 10-m of bare ground on all sides, with potatoes established and managed following typical industry practices as described below. **STANDARD** plots will be treated with oxamyl (Vydate®) applied at-plant, in-furrow and at the label rate, followed by 6-10 (as needed to hold aphid densities at < 1 / leaflet) foliar treatments that rotate through the five most common foliar-applied insecticides as outlined in Table 1 (applied following label instructions), initiated when aphids are first detected in the region by our area-wide sampling network. **NEONIC-PLANT** plots will be treated with an at-plant treatment of the neonicotinoid insecticide imidacloprid, chosen because this chemical is now available in a generic version such that application cost is falling. Foliar applications of the selective aphicide pymetrozine will be made in late summer if warranted, only if GPA reaches an average level ≥ 1 / leaflet at 3 weeks or longer preceding harvest. **CONTROL** plots will not be treated with any insecticides, but will otherwise be managed for fertility, weeds and fungal pathogens. Management of the experimental plots will follow practices typical for long-season potatoes in the region: Plots will be planted with Russet Burbank potatoes, as this variety remains the dominant long-season potato variety (NASS 2008). Potatoes will be planted in May for harvest in September, at industry-standard row spacing (34” between rows). Fertilizers will be applied as necessary pending the result of soil tests, at levels standardized to typical IPNW grower practices (Lang et al. 1999). Weed and fungal control will follow practices standard to each region.

In each plot we will determine the number of aphids per leaflet through weekly aphid sampling, starting 30 days post-emergence and continued through to harvest. Aphid densities will be determined by visual counts (based on 10 randomly-selected sites/plot, and 5 leaflets examined at each site). Percentage PLRV and BLTVA infection will be determined 3 times during the season at 40 day intervals starting 30 days post-emergence (For PLRV using a commercially available ELISA kit [Agdia Inc., Elkhart, IN] and/or RT-PCR using PLRV-specific primers and total plant RNA preparation as a template (Russo et al. 1999); for BLTVA using PCR on 50 leaflets / plot, using methods in Crosslin et al. 2006). Finally, at maturity potato plots will be harvested to determine yield, graded, and then evaluated for bulk density and fry color. A subset of tubers will be held for net necrosis assessment in storage by separately bagging tubers collected from 10 different plants in each plot, storing them at 7^{o} C for 90 d and then at room temperature for 2 d, and then cutting each tuber open to score for net necrosis.

To complement our secondary pest and generalist predator studies, described below, these same plots will also be sampled every 2 weeks for other pests and predators, using a D-vac suction sampler. Four plants will be randomly selected in each plot, with the D-vac held over each plant for 30 seconds (see Koss et al. 2005). Samples will be frozen for later sorting. **To complement our economic risk/benefit model** (also described below) **throughout the course of the experiment we will keep detailed records of input costs**, and these along with yield and quality metrics will be used to inform the development of the economic models. This experiment will be repeated each of the first two years of the project; a smaller number of demonstration plots will be maintained in years 3 and 4 to support the field days described below.

Controls for beet leafhopper. –To provide the most effective control, timing of insecticide applications should be correlated with both local beet leafhopper densities and BLTVA infectivity, and the susceptibility of plants to infection. We propose to conduct studies under field conditions to gain a greater understanding of when to initiate and end insecticide sprays targeted against the beet leafhopper, to develop treatment recommendations for this vector. Detailed information on plant stages susceptible to BLTVA infection, and on the number of sprays needed to maintain sufficiently low beet leafhopper densities, would allow growers to avoid wasteful late-season insecticide applications. BLTVA is not a problem in ID, and for this reason these experiments will be conducted only in OR and WA.

Experiment 1: Determine plant stages susceptible to BLTVA infection, and the relationship between beet leafhopper density and the likelihood of transmission. Infection of plants with BLTVA is likely dependent on both the density of pathogen-carrying leafhopper vectors and the susceptibility of the potato plant. Indeed, these two factors might interact in a non-linear fashion, with susceptible plants requiring very low levels of feeding for transmission to occur, but older plants requiring attack by very large numbers of infected vectors for any disease symptoms to be manifest. Here, we propose to investigate the roles of two factors, vector density and plant age, on production of BLTVA-caused symptoms in potatoes.

Experimental replicates will be 8-m^3 mesh field cages each housing 8 potato plants (cages are described in Straub & Snyder 2006). The study will be conducted as a fully-factorial manipulation of beet leafhopper density (0, 1, 2, 4, or 16 vectors per cage) crossed with plant age (2, 4, 8, 12, 16 weeks post emergence), generating a response-surface design. This approach sacrifices replication of particular treatment combinations for greater coverage of the total response space (Inouye 2001, Gotelli & Ellison 2004). Response-surface methods are powerful tools for detecting interactions when (as in this case) a large range of variable combinations occur in the field (e.g., beet leafhopper densities vary greatly while long-season potatoes are in the field for several months, so that a range of leafhopper densities may feed on plants of many different ages). The experiment will be done at the USDA-ARS laboratory in Yakima, WA, and also at the Oregon State University Research Station in Hermiston, OR, with these two sites serving as blocks in the statistical analyses. Our design creates 25 unique treatment combinations (5 vector densities x 5 plant ages = 25), and each of these will be replicated twice for a total of 50 cages at each location. The experiment will be conducted in years 1 and 3 of the project. Certified clean potato seed (cv. Russet Burbank) will be used. The potatoes will be hand-planted in pots in the greenhouse, with separate groups of potatoes started at different times to yield simultaneously the potato age classifications described above. Plants will be allowed to harden-off and then transplanted into the field cages (Straub & Snyder 2006). Irrigation will be done using drip lines. Plants will be allowed 1 week to recover from transplant shock, and then vector insects will be released. Leafhoppers will be infected with the pathogen by allowing the insects to feed upon BLTVA-infected potato plants for 1 week; a subset of leafhoppers will be collected and tested for BLTVA incidence using PCR before the start of the experiment. The plants in the cages will be monitored for purple top disease symptoms and later tested for BLTVA by PCR to confirm disease infection, developed by co-PD Munyaneza and colleagues (Crosslin et al. 2006).

Potatoes will be harvested and yield estimated. Tuber processing quality will be assessed; the tubers will be checked for internal defects, measured for solids (specific gravity), and fried to test for high sugars. The data will be analyzed through a combination of multi-factorial ANOVA and maximum likelihood estimation to model-fit the data (Inouye 2001, Gotelli & Ellison 2004).

<u>Experiment 2: Spray timing and resulting beet leafhopper densities</u>. A randomized complete block design with 14 treatments and 4 replications per treatment will be established, with Russet Burbank potatoes, at both the WA and OR sites. Both locations are known to support robust beet leafhopper populations that carry BLTVA (Munyuneza and Rondon, unpublished data). Plots will be 4 rows wide and 50 feet long. Treatments will consist of 1) untreated control (no insecticides all season long), 2) treated weekly with a rotation of methamidophos, esfenvalerate and Leverage (cyfluthrin + imidicloprid) all season long starting at emergence (these are the most commonly used beet leafhopper insecticides, see Table 1), 3) insecticide rotation stopped 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, or 12 weeks after plant emergence. Beet leafhoppers will be monitored with sweep nets. A subsample of beet leafhoppers will be tested for BLTVA using PCR to measure the infection rate. Plants will be examined visually for purple top disease symptoms and tested for BLTVA using PCR. Tubers from clean and BLTVA-infected plants will be stored at commercial conditions and processed for tuber quality at desired intervals (0, 30, 60, and 120 days after harvest). To assess tuber quality, samples of tubers from phytoplasma free and infected plants for each exposure time will be used at each processing date; the tubers will be measured for solids (specific gravity), fried to test for high sugars and sugar ends, and checked for internal defects. This experiment will be conducted in years 2 and 4 of the project.

<u>Integrated extension component: experimental plots used for demonstration and hands-on learning</u>: Here, our extension effort will focus on a series of field days hosted at demonstration sites in each of the three states (one each year at each location). In our experience most pest managers are comfortable dealing with chemically-based control options, and the opportunity to see our spray demonstration plots and learn more about these strategies may be the key draw to attend the field days. However, we intend to take advantage of this audience by providing hands-on learning opportunities catered to educate about each objective of this project. Growers and other pest managers will rotate through a series of stations: (1) Guests will visit the spray-treatment demonstration plots, where we will demonstrate scouting for aphids and leafhoppers, and also secondary pests and beneficials. Guests will be given a beat sheet and allowed to collect samples from potato plots planted for this purpose. Educators will assist in identification of arthropods collected in this way, taking care to point out differences between pest and non-pest species, and identifying beneficial predators. Each attendee will be given a full-color, flip card guide to pest and beneficial potato arthropods, and these guides will be used to assist in basic identification training. (2) A station will be prepared where microscopes are available, with entomopathogen-infected insects placed in focus so that attendees can learn more about the diversity of beneficial, insect-killing pathogens in their fields. (3) A final station with several computers will be established indoors, allowing educators to give a guided tour of the potatoes.com/IPM web site, pointing out tools available on that site on the economics of new pest management options and how the vector/pathogen sampling network data can inform decisions, arthropod identification, etc. While the field days will be focal points, our outreach effort will also include the full range of regional newsletters, other field days, and grower meetings as additional outlets for project-generated information.

2. Managing secondary insect pests

Reduced-input management plans for plant-disease vectors will fail if other, secondary pests rise in importance, and cannot also be managed. Pests in three major taxa are of particular concern: wireworms, caterpillars and potato beetles. Wireworms are difficult to treat or even sample, so avoiding infested fields may be the best approach to managing the risk of attack by these pests. We know almost nothing about lepidopteran pests of potato, although anecdotal reports from growers suggest that injury from these pests is becoming more common. Here, we address research and extension needs for these key secondary pests.

Objectives: (1) Create a predictive model of the risk of wireworm attack based on regional field data, (2) Describe key species of lepidopteran pests and develop damage thresholds for caterpillars and potato beetles, and **(3) Make this information available to growers.**

i. Developing predictive models for wireworm

As discussed previously, the seasonal movement of wireworm larvae up and down in the soil profile makes pre- or at-planting treatment with soil fumigants or insecticides unreliable control tactics. Sampling for wireworms often fails to provide useful estimates of wireworm pressure (Parker & Howard 2001, Horton 2006). What growers need is a means to assess before planting the risk of economically-significant damage, so that treatments can be applied or high-risk sites can be avoided. Lists of field traits that predict wireworm risk are available (e.g., Andrews et al. 2008), but these assessments appear often to be based upon educated guesses rather than quantitative data. We propose to develop a formal, quantitative listing of environmental factors and field-associated traits that predict damage potential. We will conduct an intensive sampling program over an extensive geographic area, to develop this risk assessment.

This work will be conducted in the same 45 potato fields, spread over the three states, described above in the "Regional Vector Sampling" objective. Each circle will receive 30 wireworm baits (oatmeal baits described in Horton 2006) set out in a grid to include the entire circle, with baits buried using a battery- or gasoline-powered soil auger (each will be flagged to allow easy retrieval). After 4 days in the field, baits will be retrieved and examined for wireworms. A subsample of wireworms will be examined to determine species' composition, using available keys (Lanchester 1946) or by comparison with vouchers in co-PD Horton's laboratory. We will bait each field twice, with the two baiting periods scheduled to be completed before the field is planted to potatoes in early spring. Tubers will be examined at harvest for wireworm damage. A random sample of 2000 tubers per circle will be examined, and we will record percentage of

***Table 4*: Model parameters**	**Information source**
Cumulative water ((rainfall + irrigation)/acre))	Weather stations, grower
Degree days above 3°C (Parker & Howard 2001)	Weather stations
Cultivar susceptibility	Andrews et al. (2008)
% planted with grain/clover within 500 m of potato field	Grower, GIS
% of potato field planted with grain or clover previous 2 yr	Grower
Fumigant intensity (gal/acre)	Grower
Insecticide before/at planting (lb/acre)	Grower
Cultivation depth	Grower
Soil nitrogen (ppm)	Soil samples, grower
Soil phosphorous (ppm)	Soil samples, grower
Soil potassium (ppm)	Soil samples, grower
% organic matter	Soil samples, grower
% sand	Soil samples, grower
% clay	Soil samples, grower
Soil pH	Soil samples, grower

tubers showing damage and numbers of feeding holes per tuber (Horton 2006). Soil characteristics (% organic matter, pH, etc.) will be determined at each field by analysis of soil cores or discussion with the grower.

Next, we will develop a multiple regression model incorporating data on 15 environmental and operational factors (explanatory variables) (Table 4) by looking for correlations with wireworm densities and tuber damage. We will use step-wise linear regression and AIC values (Sokal & Rohlf 1995) to develop the "best-fit" model using data collected at all sites over the first 3 years (135 data points total). The r-squared value of this model will provide a measure of the model's ability to predict tuber damage. To validate the model, we will incorporate data collected in the fourth year into the model to predict damage in each field. These predictions will be compared to the observed damage in each field using a paired t-test. A lack of statistical difference between the observed and expected values would indicate the model accurately predicted damage caused by wireworms. Once validated, this model would allow growers to predict whether wireworm-induced damage will exceed economic thresholds in their fields without having to scout for wireworms (which is unreliable anyway). In turn this will allow growers to assess whether to treat for wireworms or to avoid planting potatoes at a site altogether.

<u>Integrated extension component: make the predictive wireworm model available to decision makers</u>: Our objective is to create an easy-to-use, web-based interface on the project website, wherein growers may enter the variables (or subsets of the variables) in Table 4 for a given field, and obtain an estimate of wireworm risk for that field. This page will link to information on wireworm biology, sampling and control, and will be housed on the potaoes.com/IPM web site and promoted through the full range of print and presentation outlets that reach the potato industry (newsletters, field days, grower meetings). These data will also be used to hone the profit maximization model described below.

ii. Assessing risks posed by lepidopteran pests and Colorado potato beetle

As described above, during our "Regional Vector Sampling" we will also collect caterpillars, and these will be returned to co-PDs Zack and Landolt to be identified to species. Of these a subsample will be kept alive and reared to adulthood to assist in species verification. When caterpillars are detected in a field, additional sampling will be initiated to determine density through a more refined sampling approach: 100 plants will be randomly identified and hand-searched for 2 minutes/plant, and caterpillars counted and collected for identification. Colorado potato beetle will also be counted as part of the regional sampling network. However, detailed density counts are not needed for this species as an extensive, region-wide dataset is already available for potatoes under a variety of pest management regimes (Koss 2003, Koss et al. 2005).

Next, we will assess the impact on potato yields from the most common Lepidoptera species and Colorado potato beetle, across the range of densities seen in our surveys of production potato fields. We will place large field cages (8 m^3, described in Straub & Snyder 2006) over patches of 8 potato plants, grown at the ID, OR and WA field locations used for the aphid-control experiments, and maintained using the standard industry practices as described previously. Experiments with each pest species will include 50 replicates, with 5 serving as "no pest" controls and the remaining 45 stocked with caterpillar or beetle pests at a range of densities, with these densities scaled to reflect the range of real-world densities found during current and previous sampling efforts. Insects will be allowed to complete one entire generation, and then tubers will be harvested and weighed. Experiments with each pest species will be repeated for potato plants at 1 and then 2 months post emergence. These data will allow us to determine the relationship between pest density and resulting damage to potato yields, and how this changes with plant age. In turn, these data will be used to create economic-risk models (see Objective 3), allowing growers to make economically-rational spray treatment decisions. Our suspicion is that caterpillars and potato beetles rarely reach densities where treatment is justified.

Integrated extension component: create web and print-based guide to caterpillars in IPNW potatoes: From these data online and simple, full-color flip card guides will be prepared describing identification of each pest species, basic biology, and treatment options. All information will be made available on the potatoes.com/IPM site, and will be used to develop the profit maximization model described below.

II. Include natural enemies in IPM decision-making

Long-term reliance of IPNW potato producers on calendar sprays of broad-spectrum insecticides has led to a paucity of information on natural enemies in potatoes. However, we know that once spray intensity is reduced, natural enemy populations can be quite large (Koss et al. 2005). Moreover, as we transition from insecticidal controls of primary pests, secondary pests such as potato beetles and caterpillars are likely to become more important, and natural enemies in reduced-insecticide fields are likely to provide some control of these secondary pests. Indeed, growers are being required, through "Sustainable Pest Management Plans" now mandated by end users, to consider biological control when making spray decisions. Insect-attacking pathogens appear to be common, but their biodiversity and pest host ranges are unknown. Here, we propose to investigate the roles of two important classes of natural enemies, generalist predators and entomopathogens, in natural control of potato pests. These data will then be used to provide growers with the tools to calculate natural enemy benefits when making spray decisions.

Objectives: (1) Delineate the full web of feeding relations for important predator species, (2) Survey entomopathogen biodiversity and document the host ranges of key species, and (3) Conduct field days to give growers hands-on experience in natural enemy ID.

1) Quantify the impacts of generalist predators

In the absence of frequent, broad-spectrum insecticide applications, densities of natural enemies, primarily a diverse group of predatory *Geocoris* and *Nabis* bugs, lady and ground beetles, and linyphiid spiders, increase dramatically in regional potato fields (Koss et al. 2005). These natural enemies have the potential to consume large numbers of potato pests (Koss et al. 2004, Chang & Snyder 2004, Koss & Snyder 2005, Snyder & Straub 2006, 2008, Ramirez & Snyder 2009), but feeding relationships under open-field conditions are almost entirely unknown. These are broad generalists that may feed on any of the numerous non-pest species present in potato fields. We know that all common predator species will feed on aphids and potato beetles when in no-choice situations (Koss et al. 2004), and we have also observed many of these species feeding on pests in the open-field (Chang & Snyder 2004). However, growers need a much more specific, quantitative calculation that links a particular number of predators of a given species discovered during scouting, to the number of pests the predators will kill. With this information growers could decide to postpone sprays when biological control is likely to keep pest densities below damaging levels. Here, we propose to fill this knowledge gap through the use of molecular gut content analysis to define feeding relationships in our potato fields, under natural conditions. Due to cost limitations we will focus this effort on 10 fields in WA and OR.

i. Use molecular gut-content analysis to determine real-world feeding relationships

Study 1. Determine which predator species are feeding on which pest species: Here, we will conduct a broadly qualitative, multiplex PCR-based screening (after Harper et al. 2005) of a broad range of generalist predator species, looking for evidence that each has fed on one of the key vectors or secondary pests (green peach aphid, beet leafhopper, cabbage looper, striped cutworm, and Colorado potato beetle). The goal is to verify the predator species that we think are most important, based on their high abundance (Koss et al. 2005), are in fact regularly feeding on these pests. As mentioned above, all are generalists that might be feeding on other, non-pest prey and thus choosing to avoid attacking pests (Koss et al. 2004, Koss & Snyder 2005, Snyder & Straub 2005). On the other hand, sometimes molecular gut-content analyses have uncovered evidence that predators not previously considered important, were in fact major predators (e.g., the case of *Orius* attacking soybean aphid in the Midwest, Harwood et al. 2007, 2009; and linyphiid spiders attacking English grain aphids in winter wheat, Harwood et al. 2004).

Two organic fields, which generally have higher pest incidence than conventionally-managed fields (Koss et al. 2005), will be used in this first study to identify trophic connections between the key pests listed above and the community of generalist predators (< 15 predator species are collected with any regularity; Koss 2003, Alvarez et al. 2003, Chang & Snyder 2004, Koss et al. 2005). In each field we will first collect predators using sets of 5 gentle sweeps with a standard sweep net, pausing then to individually collect each predator captured into chilled 95% EtOH. Carabid beetles will be trapped in pitfall traps filled with ethylene glycol, which preserves prey DNA. We intend, where possible, to collect a minimum of 25 predators of each common species per field every two weeks for 3 months (June, July & August). Sufficient funds have been budgeted to allow the multiplex screening of these predators against target pests collected from open-field plots, and therefore identify the major components of the pest food web in the region. These insects and spiders will then be immediately transferred to dry ice for transport to the laboratory, where they will be stored at -80ºC. We will use pest-species-specific primers, already developed by co-PD Harwood to the key pests listed above, and multiplex PCR to identify pest remains in these predators. Harwood has extensive experience with work of this type, and our methodology will follow procedures developed in his laboratory (see Harwood et al. 2007, 2009; reviewed by Sheppard & Harwood 2005, Harwood & Greenstone 2008). Briefly, DNA will be extracted from samples using a Qiagen DNeasy Tissue Extraction Kit following manufacturer's guidelines with modifications for gut-content analysis. Extraction and PCR analysis of predator gut contents will follow comprehensively documented protocols and will follow those approaches used widely during whole-body maceration (or gut-extraction) of predators (see Harwood et al. 2007, 2009). This study will be completed in the first year of the project.

Study 2. Develop complete feeding webs for the key predator species identified in the above study, including both pest and non-pest prey: A key limitation of traditional PCR approaches (as used in the previous objective), and other similar techniques such as monoclonal antibodies, is that these approaches can only detect prey for which a specific primer has been developed (e.g., Read et al. 2006, Harwood et al. 2007, 2009, Juen & Traugott 2007, Fournier et al. 2008). The limitation of this approach is that no "unexpected" feeding relationships can be detected. This problem is of particular concern in a crop like potato, where pest species are just a small fraction of all prey available to predators (Koss et al. 2005, Snyder & Straub 2005). Most useful to pest managers would be to know how densities of non-pest prey can affect the per-capita impacts of

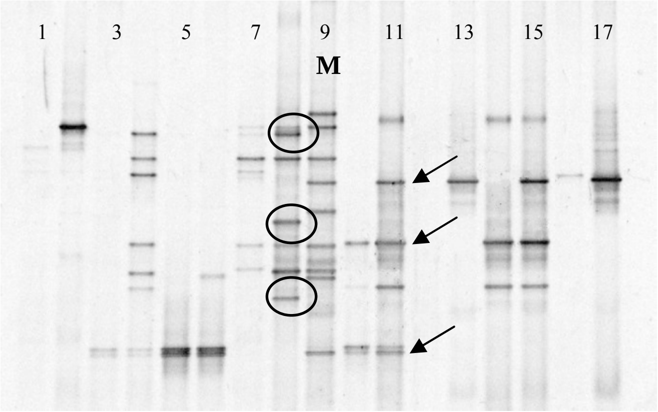

Fig. 4. *DGGE gel showing COI DNA bands for multiple prey DNA. Lane 9 = marker (M) of known targets. Results clearly differentiate multiple targets that can be aligned to targets on the marker lane (e.g. sample in lane 11 contains many "common" targets as indicated by arrows). Those that do not align (e.g. those in lane 8 are circled) with the standard can therefore be sequenced directly to confirm species identification.*

predators on targeted pests. Also, generalist predators often feed on one another (Rosenheim 1998), and it would be useful to also know the identities of such "intra-guild predators" that might be disruptive to overall pest control.

Co-PD Harwood has adopted an approach commonly used in bacterial biodiversity studies (where there is no preconceived notion of which bacteria species might be present) that will allow us to overcome these shortcomings of the more traditional molecular approaches. Briefly, we will amplify all DNA within predators' digestive tracts using universal primers. These multiple PCR products then are separated utilizing denaturing gradient gel electrophoresis (DGGE), a technique that separates identically-sized products based on nucleotide content (Fig. 4). This technique has long been used to quantify bacterial biodiversity in environmental samples (Muyzer et al. 1993, Schabereiter-Gurtner et al. 2003), but has not been applied to studies of predator-prey interactions (until now). **However, DGGE offers tremendous potential for studying these interactions because it enables identification of every prey item present in the digestive tract, without a predetermined notion of what the whole range of prey might be.** We have budgeted sufficient funds to allow the screening of the gut contents of 6,000-10,000 predators per year (for two years). Precise numbers of predators to be screened cannot be pre-determined because of the temporal variability in predator abundance. On each sampling date we will collect predators as described above, focusing on the 5 species determined in the study described just above to have the greatest impact on pests. Although sweep-netting could contaminate samples for molecular gut analysis (King et al. 2008), experimental data suggest the likelihood for error is negligible (Harwood 2008). However, to ensure reliability, in year 1 a sweep netting versus hand-collection protocol (after Harwood 2008) will be undertaken to examine this likelihood using DGGE techniques. Carabid beetles (and other ground-active predators) will be collected in pitfall traps filled with ethylene glycol, which preserves prey DNA in predator guts. The level of replication here is sufficient to provide an accurate estimation of food web interactions using molecular gut-content analysis (Harwood et al. 2007). The extraction procedure will follow protocols already optimized for use with DGGE-based gut-content analysis in the laboratory of the Harwood (described in detail in above). Briefly, sequences of the cytochrome oxidase I (COI) gene region will be obtained from predators and prey to produce a reference data set. Predator gut contents will be PCR amplified, the products separated via DGGE and **prey identified either by direct comparison to known PCR products on a denaturing gel or by sequencing if the PCR product does not match any known standard (e.g., Fig. 4).** Although not a new technique *per se*, DGGE has not been used in terrestrial food web studies thus far. However, extensive (>12 months) research has optimized a series of protocols that allow for the identification of prey DNA (example shown in Fig. 4). Crucially, there is a need to ensure the gels are not "overloaded" with predator DNA – therefore where possible predator guts will be extracted by simple dissection or whole-body manipulation minimizing the amount of predator DNA in the sample. It is also conceivable that too many fragments of prey DNA will be present in the predator gut (although this is unlikely given that many predators are food-limited in the field). However, during development and manipulation of DGGE conditions, bands have always successfully separated in laboratory and field-collected specimens. Thus we do not envision this as a problem in the research. Insects used in this study will be collected in years 2 and 3 of the project, and analyzed in years 2-4.

Defining predator and prey communities in these potato fields: A central goal of our work is to relate what the predators are actually eating to the full variety of prey that they have available to them. So, at the same time that we are sampling each potato field for predators as described in the two studies above, we will also collect a more general measure of which insects and spiders are in the fields, using the intensive arthropod-sampling regime devised by Koss et al. (2005). This will have three parts: 1) suction sampling 2) visual sampling, and 3) pitfall trapping. We will D-vac 100 randomly selected potato plants per field (10 plants per collecting bag), visually count all insects per plant on 30 plants per field (2 minute search each), and place 20 pitfall traps per field (open for 24 hours) to collect ground-active predators. Samples will be returned to Snyder's laboratory on ice, and then frozen for later identification. After predator gut contents have been determined, and the insect community samples have been sorted and counted, we will have information on what the predators are actually eating versus what prey are available to them, both pest and non-pest. We then will use regression analysis to correlate predator feeding behavior to the availability of different prey types; "field" will be the unit of replication.

Determination of DNA detection periods: Different predators digest their prey at different rates (Greenstone et al. 2007), potentially impacting the detection time of prey remains within the gut. The detection of prey remains by molecular gut-content analysis has indicated that this material is sometimes (Symondson & Liddell 1993, Chen et al., 2000), but not always (Harwood et al. 2004, 2007), influenced by the predator and/or prey combinations examined. Therefore in order to reliably interpret field-collected data, it is imperative that predator-prey feeding trials are undertaken in the laboratory to enable between-species comparisons. Feeding trials will be conducted by feeding green peach aphids (the most common potato pest) to the 5 key predator species (identified in Study 1) to determine the decay rate of prey DNA in each predatory species' digestive tract. Initially, a ~658 bp fragment of COI will be bi-directionally sequenced for the predators and prey using the universal LCO-1490 and HCO-2198 primers (i.e., those used in most animal DNA barcoding studies; Folmer et al. 1994). From these larger sequences, prey-specific COI primers will be designed to amplify a similar-sized fragment of COI to that amplified by the general primers utilized in the DGGE studies (above). The prey-specific primers will be used to amplify COI from extractions of starved predators that have been fed prey and preserved 0, 2, 4, 6, 8, 12, 16, and 24 h post feeding (n=10 predators per time period). Regression analysis (or probit models) will be fitted to determine the detection period of prey DNA following consumption.

2) Assessing biodiversity and impacts of insect-attacking pathogens.

Endemic entomopathogens are common in IPNW potato fields (Ramirez et al. 2009), and their potential impact is great (Lacey et al. 1999, Armer et al. 2004, Ramirez et al. 2009, Ramirez and Snyder 2009). However, species identities and host range have yet to be determined. Here, we propose to fill this knowledge gap, allowing growers to begin to consider the impacts of insect-attacking pathogens in regional pest management.

To survey for entomopathogens, on each of the 45 farms in our sampling network we will bury 10 mesh bags, each containing 5 waxworm larvae (*Galleria mellonella*, which are very susceptible to entomopathogenic infection) 10–15 cm under the soil (Ramirez et al. 2009). After 48 h, we will retrieve the sentinel hosts and place them individually onto modified White traps (Kaya & Stock 1997) for 3 wk to collect emerging entomopathogens. The placement of sentinel hosts underestimates densities of pathogens such as fungal spores, which insects contact only by moving freely through the soil. Thus, we will also collect 50 soil cores (2.54 cm X 15.25 cm) at each site and use the *Galleria* baiting technique (Kaya & Stock 1997) to estimate the relative abundance and diversity of entompathogenic nematodes and fungi. EPN strains will be stored as aqueous solutions in tissue culture flasks and cultured using wax worms (Kaya & Stock 1997); pathogens will be identified to species using PCR, in PD Snyder's laboratory under the guidance of co-PDs Harwood and Pappu. Following pathogen identification, we will test each pathogen species against the two wireworm species (*L. canus*, *L. californicus*), and Colorado potato beetles and cutworm pupae; these are subterranean stages most likely to be attacked by these pathogens. Insect larvae/pupae will be placed singly in 2-oz plastic cups filled with 15 g sterilized field soil, and then pathogen species will be applied at the rates of 50 nematodes or 100 fungal conidia per larva (replicated 20 times for each pest species). After 7 days, we will record the number of larvae killed by each pathogen.

III. Overcome socio-economic barriers to adoption of new pest management approaches

IPNW potato growers face intense economic pressure to develop a blemish-free potato crop, while at the same time they are losing important insecticides and being asked to document reductions in overall insecticide use. Currently, many pest management decisions are made by pesticide company representatives. Thus socioeconomic factors are likely to affect the success or failure of our project. Here, we propose two objectives:

Objectives: (1) Reach a better understanding of the sociology of pest management decision making through an extensive survey effort, 2) Develop economic models that growers can use to weigh the advantages of changing their pest management practices, and **3) Use the sociological study to hone our extension efforts and assess project success, and present the economic analyses in a form useful to growers on the potatoes.com/IPM website.**

1) Understand the sociology of pest management decisions.

We will conduct sociological analyses of growers' awareness and adoption of IPM practices, and assess growers' preferences for different types of outreach (e.g., workshops, online modules, print media). Findings will guide our efforts to encourage use of new monitoring tools and pest control approaches. We will develop an assessment and evaluation of both successes achieved and obstacles faced by growers in incorporating IPM practices into their pest management programs. These evaluations will be used to direct future education and outreach efforts, guide future research, and serve as a model for increasing sustainability in other cropping sectors. Our overall goal is to ensure that technology transfer of IPM is as effective as possible.

Co-PD Goldberger will attempt to survey ***all*** potato pest management decision-makers in the 3 states, located with the help of the Potato Commissions and our Advisory Panel. These include growers, processors and field scouts, and we estimate their numbers as: Washington (*N*=200), Idaho (*N*=300), and Oregon (*N*=50). This population will first be surveyed before the project is initiated in year 1, and then again at the project's conclusion in year 4. **By generating survey data both pre- and post-project, this component will allow an accurate assessment of how effective our project has been in changing grower practices.** The late-project survey will include questions asking specifically about knowledge of our project, and specifically how our project has changed IPM practices. Goldberger will collaborate with WSU's Social and Economic Sciences Research Center (SESRC) during all stages of survey design, testing, and implementation. She will use the survey procedures known as the "Tailored Design Method" (Dillman 2007) for the proposed surveys. Proven to produce high quality information and high response rates, the Tailored Design Method includes personalized correspondence, a user-friendly questionnaire, multiple contacts by First-Class mail, and stamped return envelopes. To further boost response rates, responders will be able to complete surveys on paper or online. Surveys will include questions about (a) responder demographics, (b) farm characteristics, (c) experiences with potato pests, (d) use of conventional pesticides and alternative approaches, (e) sources of information for making pest control decisions, (f) pest management challenges, and (g) research and outreach needs. We know from Pike's insecticide-use survey (Fig. 1, Table 1) that managers vary widely in the intensity of their insecticide use, and we hope this sociological study will provide insight into factors correlated with different patterns of input-intensity. Survey data will be analyzed using bivariate and multivariate techniques. Survey results will be used to inform outreach efforts and assess project impacts. Moreover, our grower surveys combined with our outreach efforts will provide us with substantial insight into the practical issues of pest management that are of concern to the potato farming community.

<u>Integrated outreach component</u>: Survey results will be used to better focus our outreach efforts as the project develops, by revealing decision-maker needs and where they are obtaining information on pest management. The surveys also provide the key means by which we will assess our project's success in changing pest management practices.

2) Provide growers with tools to assess economic viability of pest management alternatives.

If producers knew in advance when severe epidemics of PLRV and BLTVA were likely to occur, and whether their fields were susceptible to infection, they could be forewarned of the need to apply recommended vector control measures. The ***objective*** of the economic analysis is to quantify the economic benefits of aphid and leafhopper control strategies conditioned on virus incidence estimates. Co-PD Elbakidze will construct a regional economic model to quantify the monetary value of the probabilistic estimates of PLRV and BLTVA densities in aphid and leafhopper vectors. The analysis will incorporate a full range of variables measured as part of this project, including entomological factors harmful to production (pest densities, disease prevalence in vectors, potential for damage by secondary pests), entomological factors beneficial to production (densities of natural enemies and their impacts on particular pests), and agronomic productivity indicators (costs of various pest management options) as part of the overall revenue maximization model. Critically, negative effects of sprays on natural enemies will be included in these analyses of when treatment is warranted. A stochastic economic profit maximization model will incorporate numerous issues pertaining to the economics of pest management including value of information, risk management, economic interrelationships in production input usage, pest dynamics, and externalities of pest management options (McCarl 1981). The model will be based on a stochastic mathematical programming approach with recourse within the framework of producer profit maximization (Cocks 1968). Risk assessment will incorporate assumptions and sensitivity analysis pertaining to the degree of risk aversion (Meyer 1977).

Economics of production under risk has been the topic of many previous studies (Collender & Zilberman 1985, Garoian et al. 1987). In this project a profit maximization model will be built for potato producers facing the risk of aphid/leafhopper spread of plant pathogens, and also varying risks of attack by secondary pests based on decisions made for the control of primary pests. The model will maximize the profits of producers while minimizing variance of profits at various levels of risk aversion (Elbakidze et al. 2008, McCarl 1990, Machina 1987, Meyer 1977, Lambert & McCarl 1985). Stochastic mathematical programming is a widely accepted tool to address uncertainties related to objective function coefficients, input-output coefficients and right hand sides of the constraints (Dantzig 1955, Cocks 1968, Boisvert & McCarl 1990). In this study we will use discrete stochastic programming with recourse to model decision making of the producers contingent on the availability of forecast information about potential outbreaks of PLRV and BLTVA. Disease risk forecasting paired with reduced-spray management plans for aphid and leafhopper pests may foster higher densities of biological control agents in potato fields and thus more intense natural control, which will be incorporated into our modeling effort. Economic analyses of cost-savings from our new approaches, along with a greater understanding of sociological forces shaping grower spray decisions, will speed adoption of new, more environmentally-friendly pest control approaches.

Integrated outreach component: Region-specific risk-assessment recommendations to growers. The key outcome of our economic modeling objective will be the ability to provide region-specific recommendations to growers on what pest management options to pursue. This will weigh risks of damage by vector-pathogen complexes and secondary pests, versus costs to buy/apply insecticides and in lost biological control when more intensive spray plans are implemented. For example, in years where PLRV and BLTVA incidence is low, the recommendation may be to treat with neonicotinoids at planting only, and then scout for secondary pests using monitoring procedures, informed by damage threshold calculations for secondary pests, all created during this project. In contrast, for example when BLTVA incidence is high, it may be recommended to maintain foliar sprays through the six-week window when potatoes are susceptible to this pathogen. With no data in hand it is difficult to predict precisely the form that these recommendation will take, but one possibility is that separate risk levels will be assigned to particular sub-regions (e.g., the south, central and northern Columbia Basin), based on data from the regional sampling network. Thus, the economic modeling effort will unite all research components of this project, and exploit this information to make simple, clear recommendations to growers on appropriate control efforts for their particular region. This information will be transmitted to growers on potatoes.com/IPM through regionally-focused pest management alerts & recommendations, and through an easy-to-use web interface where growers can input costs of particular control decisions and simulate the economic consequences.

4. Project Management Plan

PDs and the advisory panel will meet twice per year, once in mid-fall semester to discuss the previous year's data, and once in the mid-spring to finalize plans for the upcoming field season. Project personnel roles were mentioned briefly in Table 3, and are discussed in detail in the Key Personnel appendix, but are mentioned here along with a project timeline and indicators and milestones:

Objectives & activity	Years	Personnel & roles	Indicators
I. Improve management of insect pests			
1. Improve insect-vector management			
i. develop regional sampling network	1-4	Sampling will be led by Wohleb (WSU extension) in WA and OR, and Alvarez (UI entomology research/extension) in ID	Both vector densities and pathogen loads are measured regionally
ii. Examine alternatives for aphid control	1-2	Pike (WSU entomology) will lead research in WA, Rondon (OSU crop & soil science) will lead in OR, Alvarez will lead in ID	Reduced-input management is demonstrated
iii. Examine alternatives for beat leafhopper control	1-4	Munyaneza (USDA-ARS) will lead in WA, Rondon will lead in OR	Correct spray timing, period plant susceptible demonstrated
iv. present data in single clearinghouse web site	1-4	Jensen (WSPC) has web development experience and will lead this effort	Web site is posted and publicized
v. involve decision makers in field days with hands-on learning opportunities	1-4	Coordinated by Pike (WA), Rondon (OR), and Alvarez in (ID)	Attendees receive hands-on training in use of project materials
2. Improve management of secondary pests			
i. develop predictive wireworm model	1-4	Horton (USDA-ARS), Wohleb and Alvarez will lead field sampling, and Crowder (WSU entomology, modeling background) will lead model development	Predictive model is validated and made available to decision makers
ii. develop damage thresholds for caterpillars and potato beetles	1-4	Zack (WSU Entomology) and Landolt (USDA-ARS) will identify lep species, and oversee damage measures for both pests	Damage thresholds are available, delivered to pest managers
II. Include natural enemy impacts in pest management decision making			
i. determine which generalists feed upon which pests	1	Snyder (WSU entomology, PD) will direct collection of predators, Harwood (UK entomology) will lead gut-content analysis	Top five predator species will be identified
ii. measure feeding rates of key predators on key pests	2-4	As above, Snyder will direct predator collections and characterization of prey communities, Harwood examines gut contents	Feeding relations of top 5 predator species will be delineated
iii. survey entomopathogens and measure host range	1-4	Jabbour (WSU entomology) will lead collections and run host-range tests, Snyder, Harwood and Lacey (USDA-ARS) will lead species identifications	A list of common species, and their host ranges, will be prepared and distributed
III. Overcome socio-economic barriers to adoption of new IPM approaches			
i. understand sociology of pest management decision making	1, 4	Goldberger (WSU rural sociology) will survey pest managers located with assistance from advisory panel	Survey results are compiled/analysed, project successes documented
ii. understand economics of adoption	1-4	Elbakidze (UI ag economics) will develop economic risk model	Model is used to inform pest management recommendations

Institution abbreviations: University of Idaho (UI), Washington State University (WSU), Washington State Potato Commission (WSPC), USDA-ARS in Wapato, WA (USDA-ARS). States: Washington (WA), Oregon (OR), Idaho (ID).

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