Executive Summary

1. **Title:** High-throughput Sensing for Potato Production and Breeding
2. **Type:** Research and Extension Planning Project
3. **Legislatively mandated focus areas**

Focus Area	**Percentage**
New innovations and technology	60%
Efforts to improve production efficiency, handling and processing, productivity and profitability over the long term	25%
Research in plant breeding, genetics, genomics, and other methods to improve crop characteristics, such as nutrient and pest management	15%

4. **Program Staff**

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5. Summary of stakeholder needs and goals

Potato growers and agronomists see an opportunity to use high-throughput sensing (HTS) for precision management of water, nutrients and crop protection chemicals. Our goal is to convene a planning meeting at which stakeholders will be asked how the public sector can best contribute to the development and implementation of HTS as a tool for potato production and breeding (more on p. 5).

6. Summary of outreach plan

An invitation to the planning meeting will be sent to the membership lists of state potato commissions. The one-day program will feature speakers from academia and industry in the morning, followed by small group discussion after lunch and a reconvening of everyone to establish priorities for research and extension (more on pp. 11-13).

7. Summary of potential benefits

Potato growers and crop management companies would benefit from using HTS to apply water, fertilizer, and pesticide inputs more precisely, leading to greater profitability and reduced environmental impacts. Furthermore, improvements in water quality and ecosystem services extend beyond rural communities and can benefit everyone.

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Introduction

1. Goals and context

Potato growers seek to manage the crop in ways that promote long-term sustainability for profitability, environmental stewardship, and socially responsible production. One way to achieve sustainability goals is through precision agriculture, which has been described as "doing the right management practice at the right place and right time" (Mulla 2013). Interest in precision agriculture is high among all farmers and of particular interest to potato growers because of the complexity of applying inputs to maximize potato yield, size, and quality (e.g., physical maturity of the skin, chemical maturity of carbohydrate metabolism).

A key driver of progress in precision agriculture has been advances in high-throughput (remote) sensing, particularly the use of reflectance spectroscopy to make inferences about crop physiology and stresses. Over the past two decades, imaging services from satellite and manned aircraft have improved in return frequency and spatial resolution, as well as spectral density and bandwidth (Mulla 2013). The use of low-altitude, unmanned aerial vehicles (UAVs) is rapidly expanding to address some of the limitations of high-altitude sensing, such as cloud cover, but UAVs have their own challenges, including aerodynamic stability and sensor payload (Sankaran et al. 2015).

Through formal and informal surveys, we know there is widespread experimentation among potato growers with high-throughput sensing (HTS) technologies, but there is also uncertainty as to how (or whether) it can be used to improve sustainability at the farm level. Considerable human resources are devoted every summer to scouting potato fields for insects and disease and to measuring crop development by harvesting small (~ 10 ft) strips, but the frequency and spatial extent of such monitoring is necessarily limited. There is also interest among U.S. public potato breeders (there are more than 10 across the U.S.) to use HTS techniques for variety development, particularly for traits that are impractical to measure in the early stages of clonal selection, such as tuber growth rate and water productivity (Passioura 2006; Blum 2009). However, adoption of the technology by breeders requires better “turn-key” solutions to translate HTS data into selectable phenotypes.

The goal of this planning grant is to develop a strategic plan for future research and extension on the use of HTS techniques in potato production and breeding. Toward this end, we propose to convene a meeting of potato industry stakeholders and researchers on November 14, 2017, in Madison, WI. After a series of presentations from leaders in this field, participants will be asked to identify how the public sector can best contribute to the development and implementation of HTS as a tool for potato production and breeding. We anticipate that the priorities established by the participants of the planning meeting will be the basis for an SCRI Standard Research & Extension Project proposal.

2. Background

A key challenge with high-throughput sensing (HTS) is to convert spectral reflectance measurements from aerial cameras into timely, geo-referenced, actionable data that informs management (crop production) or selection (breeding) decisions. This process begins with sensors capable of generating 2D images of reflected light intensity at different wavelengths, or spectral "bands." An ordinary camera is an example of such a sensor, which measures light intensity at three bands in the visible portion of the spectrum: red, green, and blue (RGB).

The amount of radiation reflected from plants is inversely related to radiation absorbed by plant pigments and varies with the wavelength of incident radiation. Plant pigments such as chlorophyll absorb radiation strongly in the visible light spectrum from 400 to 700 nm, particularly near wavelengths such as 430 (blue) and 660 (red) nm for chlorophyll a and 450 and 650 nm for chlorophyll b (Pinter et al., 2003). In contrast, plant reflectance is high in the near infrared (NIR, 700–1300 nm) region as a result of leaf density and canopy structure effects (Figure 1).

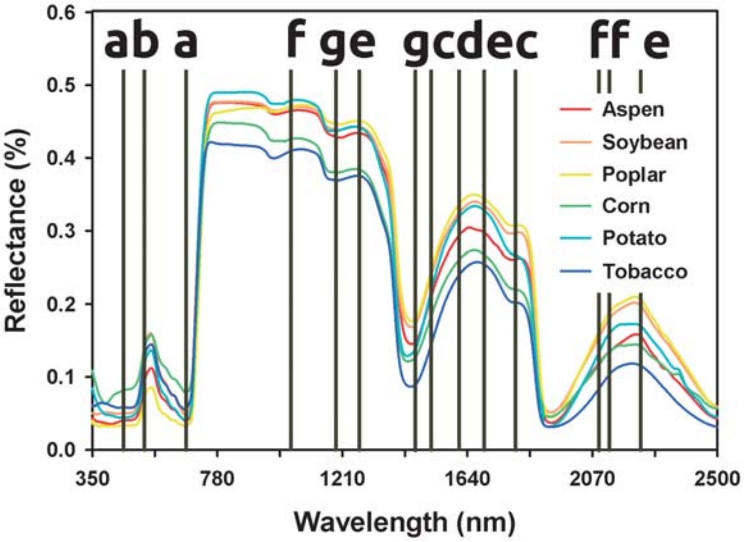

Fig. 1. Average reflectance spectra for several plant species. Vertical lines indicate spectral features associated with: a) chlorophyll, b) photosynthetic down-regulation, c) photosynthetic capacity associated with the enzyme RuBisCo, d) RuBP regeneration capacity, e) phenolics, f) nitrogen bonds and g) specific leaf area.

The sharp contrast in reflectance between the red and NIR portions of the spectrum has been used to develop spectral indices that are based on ratios of reflectance values in the visible and NIR regions. One of the earliest examples of a spectral index was NDVI (Normalized Difference Vegetation Index), which is calculated as (NIR – R)/(NIR + R) (Rouse et al. 1973). Cameras designed for NDVI measurements measure reflectance at one or more NIR bands in addition to visible light bands. Early demonstrations of the utility of NDVI for making inferences about plant vegetation followed the launch of the Landsat 1 satellite in 1972, which had a return frequency of 18 days and contained a multi-spectral camera with G, R and two NIR bands (Bauer and Cipra 1973). The utility of satellite-based, multi-spectral cameras for monitoring crops has improved dramatically since Landsat 1, with several systems offering close to 1 m spatial resolution and return frequencies of 1–3 days (e.g., GeoEye-1, WorldView-2, WorldView-3, RapidEye). RGB and NDVI images from these satellites, as well as from manned aircraft or UAVs carrying multi-spectral cameras, are readily available to growers and crop management consultants through technology service providers.

However, there is a lot of information about plants in the near and shortwave infrared portions of the spectrum (700–2500 nm; Figure 1) that the broadband, multi-spectral cameras in widespread commercial use do not capture. Hyperspectral imaging allows access to this information by measuring reflected light at hundreds of narrow bands. These rich datasets have facilitated the construction of more specific vegetation indices, targeting traits such as leaf area index (LAI), biomass, chlorophyll and nitrogen content (Thenkabail et al. 2010, Yao et al. 2010). There are currently two NASA-funded, airborne hyperspectral imaging instruments collecting data over the U.S.: AVIRIS-Classic, which has 10 nm bands and was first flown in 1987, and AVIRIS-Next Generation, which has 5 nm bands and has been flown since 2014 (http://aviris.jpl.nasa.gov). Co-Investigator Townsend has demonstrated that AVIRIS data can be used to estimate photosynthetic capacity, percent nitrogen, and other traits (Serbin et al. 2015; Singh et al. 2015), but the geographic coverage of these instruments is limited and intended primarily for research rather than commercial use. A hyperspectral instrument called Hyperion was lauched aboard the EO-1 satellite in 2000, but it also had limited coverage and spatial resolution and was recently decommissioned.

3. Ongoing and recently completed work

Members of the planning committee have significant prior experience with high-throughput sensing, including for potato. Co-Investigators Rosen and Mulla from Minnesota have focused on nitrogen (N) management. In one study, data from an airborne, broad-band multispectral camera were used to compare the accuracy of four vegetation indices (GNDVI, GRVI, NDVI, NG) for predicting leaf N in potato. At 30 days after emergence, all four indices performed similarly, with root-mean squared errors of cross validation between 16 and 19% (expressed as a percentage of the range of predicted values) for both the Russet Burbank and Alpine Russet varieties (the former is the standard cultivar and the latter is a new release from 2011). At 56 days after emergence, however, NDVI did not perform as well as the other indices, having 5–7% higher error (Nigon et al. 2014). This is not unexpected as NDVI was developed primarily to detect the presence of vegetation and becomes less sensitive to changes in leaf chlorophyll content in mature canopies (Barnes et al. 2000; Thenkabail et al. 2000). In a companion study, Nigon et al. (2015) collected hyperspectral images for the same two potato varieties using an airborne AISA Eagle spectrometer and investigated how well various narrowband vegetation indices predicted nitrogen stress.

At Washington State University, co-Investigators Sankaran and Pavek have recently published on the use of HTS to detect hail damage in potato (Zhou et al. 2016). The effect of hail damage on the variety Russet Norkotah was simulated by mechanical defoliation of plants at three developmental stages: tuber initiation (45 days after planting, DAP), early bulking (75 DAP), and late bulking (93 DAP). At each time point, three levels of defoliation–33%, 66%, and 99%–were simulated and compared to the control treatment (0%). Multispectral images were taken once at 108 DAP in 2014 and 97 DAP in 2015, using a modified NiteCanon ELPH110 attached to a UAV. Because images were taken on only one day, the time lapse between canopy damage and imaging was different between the treatments. For the earliest treatment, the images were taken more than 50 days after damage, and there was no significant difference in the Green NDVI (GNDVI) index between treatments. For the early bulking and late bulking treatments, however, significant differences in GNDVI were detected, and the authors recommend collecting images no more than 10 days after a hailstorm to reliably estimate the damage. The correlation between GNDVI and total tuber yield was also significant when the damage occurred during early or late bulking, with *r* values between 0.74 and 0.88. Several additional studies on HTS for potato are ongoing at WSU, including for traits such as crop emergence, canopy closure, and late blight severity.

In Wisconsin, co-Investigators Townsend, Gevens, Jansky, and Bethke have several ongoing research projects utilizing reflectance spectroscopy in potato. The most comprehensive results thus far are from hyperspectral, leaf-level measurements of plants inoculated with potato virus Y (PVY), a ubiquitous disease vectored by aphids that reduces yield and is the primary cause of downgrading or rejection of foundation and certified seedlots (Gray et al. 2008). Figure 2A shows how well different combinations of wavelengths differentiated between infected vs. control plants; dark red indicates a correlation of 1, while dark blue is a correlation of 0. The results indicate that wavelengths in the shortwave infrared (SWIR) region, particularly 2300–2400 nm, were most effective. Figure 2B explores some of the physiological parameters that may be responsible for the discriminatory power of the spectra. Compared with the control, PVY-infected plants had lower foliar N, higher leaf mass per area (LMA) and lower photosynthetic capacity (Vcmax).

Another research focus for the Wisconsin group is early detection of late blight, which is arguably the most feared disease in potato because of its rapid spread and devastating effects. By the time visual symptoms appear and new spores are being produced on infected plant tissues, it can be too late to limit spore movement to surrounding fields. Thus, early detection by high-throughput sensing would be a major boon to potato growers. Results thus far indicate that hyperspectral data can be used to detect late blight with 25% accuracy within one day of inoculation, 55% accuracy after two days, and 70% accuracy after three days, whereas visual disease symptoms were not detected until 7–10 days after inoculation in the experiment.

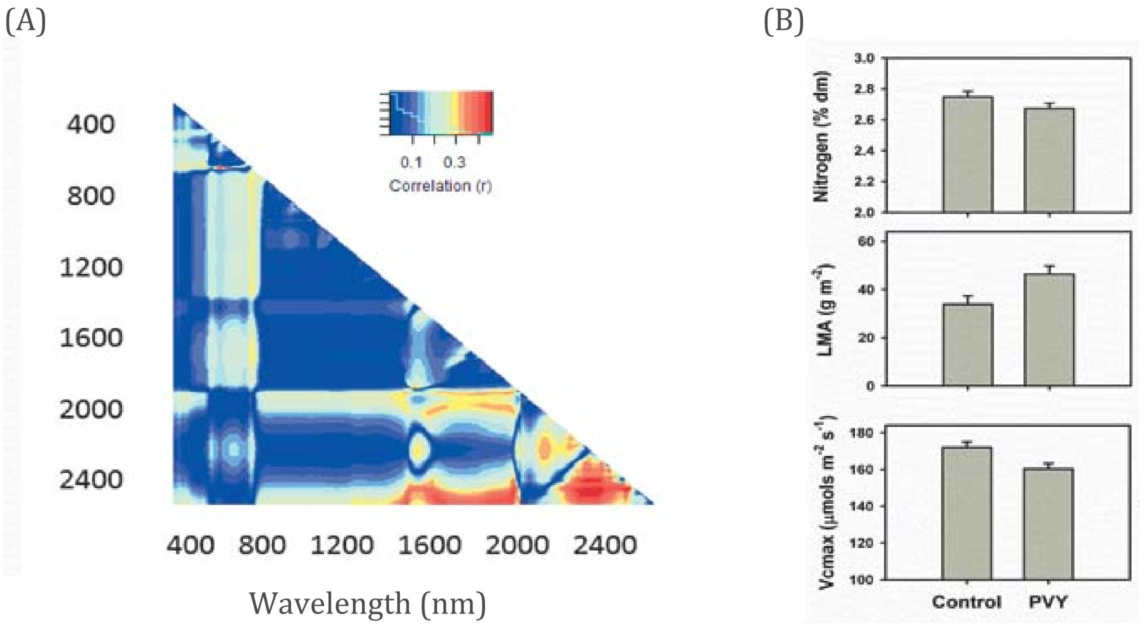

Fig. 2. Hyperspectral (400–2400 nm) measurements of potato leaves from plants infected with potato virus Y. (A) Heatmap showing the predictive ability of different combinations of wavelenths. (B) Potential physiological bases for discriminating infected vs. uninfected plants (LMA = leaf mass per area, Vcmax = photosynthetic capacity).

4. Preliminary results related to strategic planning

Each winter, states with significant potato production hold conferences featuring presentations by university researchers and extension personnel. In recent years, remote sensing has been a frequent topic of discussion. At the 2017 conference in Wisconsin (held Feb. 7–9 in Stevens Point), co-Investigators Bethke and Jansky moderated a one-hour session that combined presentations and discussion about remote sensing for potato. A paper questionnaire was distributed to 60 participants and returned by 32 people by the end of the session, for a response rate of 53%.

Twenty people (62%) indicated they had previously used remote sensing, and the number planning to use the technology in 2017 was even higher (68%). Satellites (25%), aircraft (31%), and UAVs (41%) had all been used. The most common types of spectral images were those based on visible light (44%) or NDVI (47%), although 20% indicated they had used thermal cameras or other systems. When asked about the purpose of the remote sensing, responses included disease monitoring (22%), nutrient management (38%), water management (28%), and tracking emergence or canopy development (25%). Participants were also asked, "What bottlenecks do you see of remote sensing on your farm?" The most common themes in the responses were managing and interpreting the images (34%) and the return on investment (31%).

Rationale and Significance

It is widely appreciated within academia and industry that high-throughput sensing (HTS) technologies have the potential to improve crop production and breeding, but there are complex challenges to realizing these benefits. Many growers already have access to NDVI and RGB imagery through crop management and other technology companies, but preliminary stakeholder engagement suggests a continuing need for research and extension activities related to the interpretation and utilization of such images for timely management decisions. The development of extension guidelines on this topic requires the kind of trans-disciplinary expertise represented by the co-Investigators on this proposal (engineering, biology, economics). Our team is also uniquely qualified to deliver practical outcomes for the next generation of remote sensing cameras, known as hyperspectral imaging, which offer exciting new possibilities compared to NDVI for assessing the disease and physiological status of potato. Our proposed planning activities will bring together many different actors in academia and industry to develop a set of research and extension priorities for leveraging HTS to improve the sustainability of potato agriculture.

Of the five legislatively mandated focus areas for SCRI, our proposal is clearly linked to topic #4 on new innovations and technology. However, the goal is not technology development as an end unto itself but as a means to (i) improve production efficiency and ultimately profitability (topic #3), and (ii) improve breeding efficiency for traits that are impractical to directly measure in the early stages of clonal selection, such as yield components related to water- and N-use productivity (topic #1).

Approach

1. Justification for the meeting

At the time of pre-proposal submission, our main focus was on assembling a team of researchers and industry advisors for the purpose of developing an SCRI Standard Research & Extension Project proposal. While that is still an expected outcome of the proposed planning grant, it is now apparent that an essential near-term for the potato industry is the development of a strategic plan on how the public sector can best contribute to the development and implementation of HTS as a tool for potato production and breeding. This determination is based on extensive conversations with a geographically diverse set of stakeholders, many of who wrote letters of support for the pre-proposal (four additional letters are attached as an appendix to this narrative). At both the national and state level, there are potato research advisory committees composed of growers, processors, and other stakeholders, who are either directly (state level) or indirectly (federal level) responsible for selecting research proposals for funding. At all levels we have seen tremendous support for this planning grant, but a common refrain from industry stakeholders has been the need to clarify how the public sector should structure its research and extension activities to complement, rather than duplicate, the growing role of the private sector in this arena. This planning grant will help address this question and establish the priorities for future grant proposals to SCRI and other programs.

2. Recent meetings on the same subject

We are unaware of any prior meeting of national scope on the topic of high-throughput sensing (HTS) for potato production and breeding. However, in 2015 a USDA-NIFA AFRI grant was awarded to co-Investigator Sankaran to hold a conference on ‘Advances in Field-Based High-throughput Phenotyping and Data Management: Grains and Specialty Crops,’ which was held Nov. 9–10, 2015, in Spokane, WA (https://labs.wsu.edu/sankaran-phenomics/phenomics-conf/). The principal audience for the meeting was academic researchers, and the 69 on-site participants came from diverse backgrounds (35% Genetics and breeding, 28% Engineering, 23% Plant biology and physiology, and 14% Bioinformatics). The outcomes of this conference strongly indicated the need for research to advance high-throughput phenotyping technologies as a tool to assist and accelerate plant breeding mainly by (i) increasing the efficiency in which current phenotypes are measured and (ii) measuring new phenotypes that cannot be assessed otherwise. More details can be found in Sankaran et al. (2016). Earlier in 2015, a similarly themed ‘Workshop in Field-Based, High-Throughput Phenotyping’ was held March 16–19 in Maricopa, AZ (http://www.fieldphenomics.org/workshops/2015-htp-workshop), as part of an NSF-funded project.

Unlike our proposed meeting, these prior meetings were not focused on the biology and management of potato, and another key difference is that our primary focus is on the application of HTS to commercial potato production, not small-plot research trials. As indicated by the title of this proposal, breeding applications will be considered during the strategic planning but are of secondary importance, and this is reflected in the schedule of the proposed planning meeting.

3. Members of the organizing committee

The planning conference will be co-chaired by PD Endelman and co-Investigator Andrew Jensen, who, as a manager of the Northwest Potato Research Consortium, brings a critical, non-academic perspective to the strategic planning process. The other members of the organizing committee are listed as Key Personnel on pp. 2–3 of the Narrative and represent a truly transdisciplinary group of scientists. There are three experts on the technology of high-throughput sensing (Sankaran, Townsend, Mulla), who have come to this area of research from different academic traditions (Engineering, Geography, Soil Science). There are six biological scientists with a range of expertise including potato genetics (Jansky), physiology (Bethke), agronomy (Thornton, Pavek), soil fertility (Rosen), and pathology (Gevens), and one expert in agricultural economics (Mitchell).

4. Proposed program

A one-day meeting is proposed that will bring together researchers, growers, agronomists, technology service providers, and representatives of state potato commissions. All speakers listed on the schedule below have agreed to speak at the conference, which is tentatively planned for November 14, 2017, in Madison, WI.

The first part of the morning will feature presentations from the members of the planning committee who are nationally recognized experts on remote sensing: Sindhuja Sankaran, Phil Townsend, and David Mulla. Recent work by these co-Investigators was reviewed in section 3 of the Introduction. All three are involved in remote sensing projects for several crops, which allows us to draw on technological advances that cut across species. To focus more specifically on the needs of the potato community, there will be presentations by four potato scientists who are collaborating with the remote sensing experts: Paul Bethke (physiology), Amanda Gevens (pathology), Carl Rosen (soil fertility), and Sagar Sathuvalli (breeding). After the morning break, we will hear from two agronomists working in industry—Jeremy Buchman from Black Gold Farms and Mike Larsen from Mart Produce—about their experiences with remote sensing in potato production and outlook for the future.

The final three talks before lunch will focus on topics that have been identified as key bottlenecks to more widespread adoption of the technology. The first two feature Craig Poling (Sentek Systems) and Keith Tinsey (CropTrak) from technology service companies, who will discuss the challenges of extracting useful information from images and its translation into timely management decisions. Then economist Paul Mitchell (UW-Madison) will talk about the return on investment (ROI) for remote sensing at the farm level.

After lunch we will split into six groups for one hour. For the first 20 minutes, participants will be given an opportunity to introduce themselves and share their experiences with HTS. For the next 20 minutes, each group will reflect on the presentations from the morning, compiling a list of comments and questions. For the final 20 minutes, each group will be asked to consider two related questions:

1) What is role of the public sector in developing HTS as a tool for potato production?
2) What research and extension topics should be prioritized for an SCRI Standard Research & Extension Project?

Time	Topic	Speakers
8:30a	Welcome	Jeff Endelman (Univ. Wisconsin) Andy Jensen (Northwest Potato Research Consortium)
8:45	Envisioning the future of high-throughput sensing for potato production & breeding	Sindhuja Sankaran (Washington State Univ)
9:00	Reflectance spectroscopy for measuring water stress	Paul Bethke (USDA-ARS, Wisconsin)
9:15	Disease detection and management	Amanda Gevens (Univ. Wisconsin)
9:30	Hyperspectral imaging of potato physiology and performance	Phil Townsend (Univ. Wisconsin)
9:45	Using remote sensing to manage nitrogen in irrigated potato production	David Mulla (Univ. Minnesota) Carl Rosen (Univ. Minnesota)
10:15	Screening germplasm for Verticillium wilt resistance	Sagar Sathuvalli (Oregon State Univ.)
10:30	Break	
10:45	Optimizing field sampling	Jeremy Buchman (Black Gold Farms, ND)
11:00	Experiences with remote sensing	Mike Larsen (Mart Produce, Idaho)
11:15	Sensors and image processing	Craig Poling (Sentek Systems, Minnesota)
11:30	Decision support systems	Keith Tinsey (CropTrak, Michigan)
11:45	Farm economics of remote sensing	Paul Mitchell (Univ. Wisconsin)
12:00	LUNCH	
1:00	Small Groups – Developing a strategic plan	
2:00	Group presentations & Discussion	Jeff Endelman Andy Jensen
3:30	Adjourn	
4:00	Meeting of the organizing committee	

After one hour of small group discussion, we will reconvene as a full conference and hear from the designated spokesperson for each group. The conference co-chairs will facilitate the discussion and record the results on a laptop that is projected onto the screen for everyone to see. We will adjourn by 3:30, anticipating that some participants will opt to return home that afternoon. Informal, small group dinners will be organized for participants staying in Madison. After a short break, the organizing committee will meet at 4 pm to reflect on the conference and discuss preparations for writing the strategic plan and future proposals.

5. Expected outcomes

The notes taken during the afternoon session of the conference will contain recommendations for future research and extension priorities from a geographically diverse group of stakeholders. PD Endelman will compile the initial synthesis of those comments and then share the draft strategic plan with the rest of the planning committee and other invited speakers for comment and further development. After this stage, the document will be shared with all conference participants for feedback before it is finalized.

The outcomes of the planning meeting will be shared with stakeholders and the general public in several ways. The conference summary and strategic plan will be publicly available on the website of the project director and also shared with Potatoes USA (formerly the US Potato Board) for dissemination. Members of the planning committee will also give presentations about the project outcomes at the 2018 winter extension conferences held annually in each state.

By the end of the planning meeting or soon thereafter, we expect to identify a core team of scientists who will develop an SCRI SREP proposal to accomplish the research and extension objectives prioritized by the stakeholders.

6. Method of announcement

As documented by the letters of support, we can expect the cooperation of the state and national potato groups in advertising the planning meeting. An email will be sent to their membership lists with a short description of the meeting and link to the conference website, which will contain an agenda along with logistical and registration information. The presentations and final group discussion will be recorded and archived online for the benefit of stakeholders who could not attend in person.

Appendix

Additional letters of support from stakeholders