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Northwest U.S. Agriculture in a Changing Climate: Collaboratively Defined Research and Extension Priorities

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In order for agricultural systems to successfully mitigate and adapt to climate change there is a need to coordinate and prioritize next steps for research and extension. This includes focusing on "win-win" management practices that simultaneously provide short-term benefits to farmers and improve the sustainability and resiliency of agricultural systems with respect to climate change. In the Northwest U.S., a collaborative process has been used to engage individuals spanning the research-practice continuum. This collaborative approach was utilized at a 2016 workshop titled "Agriculture in a Changing Climate," that included a broad range of participants including university faculty and students, crop and livestock producers, and individuals representing state, tribal and federal government agencies, industry, nonprofit organizations, and conservation districts. The Northwest U.S. encompasses a range of agro-ecological systems and diverse geographic and climatic contexts. Regional research and science communication efforts for climate change and agriculture have a strong history of engaging diverse stakeholders. These features of the Northwest U.S. provide a foundation for the collaborative research and extension prioritization presented here. We focus on identifying research and extension actions that can be taken over the next 5 years in four areas identified as important areas by conference organizers and participants: (1) cropping systems, (2) livestock systems, (3) decision support systems to support consideration of climate change in agricultural management decisions; and (4) partnerships among researchers and stakeholders. We couple insights from the workshop and a review of current literature to articulate current scientific understanding, and priorities recommended by workshop participants that target existing knowledge gaps, challenges, and opportunities. Priorities defined at the Agriculture in a Changing Climate workshop highlight the need for ongoing investment in interdisciplinary research integrating social, economic, and biophysical sciences, strategic collaborations, and knowledge sharing to develop actionable science that can support informed decision-making in the agriculture sector as the climate changes.

Keywords: actionable science, climate services, knowledge coproduction, climate change, mitigation, adaptation, agriculture, stakeholders

INTRODUCTION

Research at the nexus of climate change and agricultural production in the United States has focused on two distinct but related pathways of mitigation and adaptation. Mitigation efforts have attempted to quantify the impacts of agricultural production on climate change while also assessing practices that can be used to mitigate greenhouse gas (GHG) emissions associated with agricultural production. Adaptation research efforts have sought to explore the way adaptive practices can reduce the risks associated with climate change and build on opportunities. Research has been conducted for well over a decade on both mitigation and adaptation (e.g., Consortium for Agricultural Soils Mitigation of Greenhouse Gases, Washington State University Climate Friendly Farming Project, Southeast Climate Consortium). Recently, there has been increased emphasis on research focused on adapting agricultural systems to a changing climate, which coincides with a growing recognition in the land and resource management communities of the inevitability of an atmospheric doubling of carbon dioxide (CO_2) (IPCC, 2014a,b,c). Federal programmatic focal areas and funding for research in the past 5 years, exemplified by the United States Department of Agriculture (USDA) Regional Climate Hubs, reflect this intensified interest in agricultural adaptation (USDA NIFA, 2016; USDA, 2017). Additionally, there is increasing awareness that opportunities exist for "win-win" solutions that will improve farm economics while also making agricultural systems more resilient to a changing climate and lowering carbon footprints (Rosenzweig and Tubiello, 2007; Pretty, 2008; Power, 2010; Smith and Olesen, 2010; Duguma et al., 2014; Yorgey and Kruger, 2017).

The appeal of an approach that incorporates adaptation, mitigation, and profits is clear because it could provide a wealth of co-benefits to agriculture—and diverse stakeholders have articulated an interest in more research to evaluate the efficacy of potential management strategies across geographic regions and in multiple agroecosystems (Prokopy et al., 2015a; Allen et al., 2017). However, several intersecting factors make it difficult in practice to prioritize amongst management strategies across agro-ecosystems. First, many of these strategies have impacts that are spatially and temporally variable. This makes it difficult to make accurate projections of the costs and benefits for particular farmers. For example, building soil organic carbon (SOC) can enhance resilience by increasing soil water holding capacity, improving farmers' ability to withstand higher summer temperatures. It can also provide mitigation benefits by drawing carbon out of the atmosphere. However, the amount of SOC stored on an individual field or farm varies considerably. Factors including soil type and series, precipitation, and initial soil carbon levels can, in some cases, be even more important than management (e.g., reduction or elimination of tillage, cover crops, amendments) in determining the magnitude of soil carbon storage or loss (Paustian et al., 1997; Kemanian and Stöckle, 2010).

Second, the research and policy-making communities have limited understanding of how producers make management decisions, which makes it more difficult to identify and test realistic strategies that producers might choose to use. Agricultural producers must make resource management and investment decisions on the basis of highly complex and uncertain information from multiple sources. Thus, it is difficult to assess what information will be most relevant and useful to producers (Lemos et al., 2012; McNie, 2012; Weaver et al., 2013).

Third, there are limitations in climate scientists' ability to project the degree and rate of change of future climate, project impacts for specific cropping systems, and forecast the extent to which current crops and agroecosystems will be viable (Abatzoglou et al., 2014; Antle et al., 2016; Cammarano et al., 2016). For instance, to what extent can a producer increase soil carbon storage to retain more water within an existing crop or cropping system, before needing to change crops or fundamentally redesign the cropping system in response to climate change? Limitations in our ability to fully understand the nature of future climate change complicate efforts to evaluate agricultural adaptation and mitigation strategies, despite ongoing improvements in the usability of climate change projections for agricultural decision-makers (Antle et al., 2016; Parker and Abatzoglou, 2016; Rupp et al., 2016).

Given the potential for severe climate change impacts on agriculture and limits on time and financial resources, there is a need for a strategic approach to prioritizing near-term investments in research and extension to improve adaptive capacity, even in the face of these challenges and uncertainties. The Northwest United States is a good test-bed for evaluating opportunities for adaptation and mitigation, and is well-situated to test a collaborative approach to setting research and extension priorities.

From a biophysical perspective, the region is geographically and climatically heterogeneous, with a diversity of agro-ecological systems. Dryland and irrigated cropland produces over 250 commercially important crops, including nationally significant production of apples, pears, cherries, berries, and wheat (USDA NASS, 2015). The region encompasses a marked precipitation gradient with mean annual precipitation ranging from 150 mm to over 750 mm, leading to variation in grain crop varietals, cultivation strategies, and economic opportunities and challenges for farmers (Schillinger et al., 2010). Livestock are also important, with nationally significant production of milk, cheese, cattle and calves, and livestock forage (USDA ERS, 2015; USDA NASS, 2015). In 2012, the value of crop and livestock agricultural production in Washington, Oregon and Idaho was over $21.8 billion (USDA, 2012). The heterogeneity of the region's agricultural systems and ongoing work across the region has the potential to highlight key differences among systems, generating information that could provide a benchmark that is helpful to other agricultural production regions.

From a social perspective, the agricultural research and extension communities have long collaborated with farmer and industry networks and advisory groups, including in the realm of climate change. Comprehensive, interdisciplinary research and extension programming in the climate change and agriculture nexus has been occurring in the region for nearly 15 years, leading to substantial knowledge development, technology transfers and management adaptations (**Table 1**). In addition, the public sector has become increasingly vocal in supporting long-term investments in adaptation capacity and infrastructure, such as new irrigation water supply infrastructure, which is necessary to maintain a viable, if changing, agricultural resource base.

However, the level of complexity and uncertainty associated with climate change impacts and potential responses suggests the need for reinvigorating and advancing these long-standing partnerships in new ways. Important enhancements include the participation of a broad group of decision-makers at multiple organizational levels, such as crop advisors, irrigation districts, state and federal agencies, and private sector technology, and service providers (Bizikova et al., 2014; Prokopy et al., 2015b; Allen et al., 2017). There is also a need to more actively facilitate a feedback loop between researchers and stakeholders, as the applications of climate science to agricultural decision-making may not be as straight-forward as the application of new crop variety testing, innovations in machinery, or other similarly applied areas of science (Prokopy et al., 2015a).

In an effort to prioritize and catalyze future regional research and extension efforts, a workshop titled "Agriculture in a Changing Climate" was held on March 9–11, 2016 (AgCC, 2016), a first step toward reinvigorating those partnerships. The workshop's 82 participants spanned the research-practice continuum, including university faculty and students, crop and livestock producers, and individuals representing state, tribal, and federal government agencies, industry, nonprofit organizations, and conservation districts (**Figure 1**). They included many representatives of research teams and boundary entities involved in studies to inform adaptation and mitigation in agriculture in the region. Participants worked together to synthesize recent research findings and identify priorities related to climate mitigation and adaptation in the Northwest, with a particular focus on actions for the next 5 years (AgCC, 2016).

This article documents insights and priorities from the workshop, and expands the synthesis of recent research findings through a more systematic review of the literature on agriculture and climate change in the Northwest U.S. The findings of the literature review summarize the state of the science on climate impacts and mitigation, vulnerabilities, and opportunities to adapt, and help articulate the knowledge gaps and challenges. The research and extension priorities proposed for the next 5 years are based on the outcomes of the workshop and target identified gaps, challenges, and opportunities. Priorities are discussed in four topic areas identified by conference organizers and participants: (1) cropping systems, (2) livestock systems, (3) decision support systems to help producers and others incorporate climate change considerations into longer-term decisions (e.g., land transactions, perennial crop plantings, irrigation system investments); and (4) efforts to foster effective partnerships and communication between researchers and stakeholders (AgCC, 2016). Effective, sustainable mitigation and adaptation solutions will require addressing these interrelated topic areas in coordination with one another.

While the priorities discussed here are specific to the tri-state region of Oregon, Washington, and Idaho, many of these recommendations are also relevant in other regions of

TABLE 1 | Major climate change and agriculture-related efforts in the Pacific Northwest from 2003 to 2016.

Project title	Description
Climate Friendly Farming Project (http://csanr.wsu.edu/program-areas/climate-friendly-farming/climate-friendly-farming-final-report/, Kruger et al., 2010)	Research and assessment of the potential for improved management and technology deployment to reduce agricultural greenhouse gas emissions in the Pacific Northwest
Regional Approaches to Climate Change for Pacific Northwest Agriculture (REACCH) (reacchpna.org)	Enhance sustainability of PNW cereal systems and contribute to climate change mitigation
BioEarth (http://bioearth.wsu.edu/, Adam et al., 2015)	Regional earth systems modeling to improve understanding of the interactions among carbon, nitrogen, and water at the regional scale, in the context of global change
OFoot (https://ofoot.wsu.edu/ and http://csanr.wsu.edu/organic-farming-footprints/)	Estimating carbon footprints for organic cropping systems
Site Specific Climate Friendly Farming Project (Brown et al., 2015)	Precision N use in dryland cropping systems
US Dairy Adoption of Anaerobic Digestion Systems Integrating Multiple Emerging Clean Technologies (http://csanr.wsu.edu/anaerobic-digestion-systems/)	Enhancing anaerobic digestion in dairy systems through advancement of add-on technologies
Animal Agriculture in a Changing Climate (national project with a western region) (http://articles.extension.org/pages/60702/animal-agriculture-and-climate-change)	Fosters animal production practices that are environmentally sound, economically viable, and that create resiliency for animal producers and their partners
Watershed Integrated Systems Dynamics Modeling (WISDM) (http://wisdm.wsu.edu/)	Improve understanding of interactions between water resources, water quality, climate change, and human behavior in agricultural and urban environments

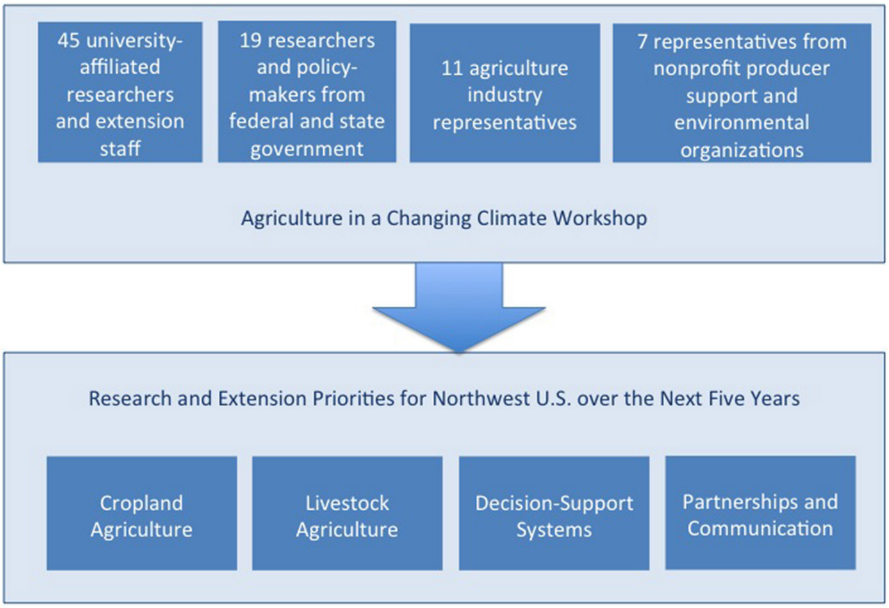

FIGURE 1 | During the "Agriculture in a Changing Climate Workshop," 82 participants from across the research-practice continuum worked collaboratively to identify priorities relating to climate change and Northwest U.S. agriculture in four focus areas: cropping systems, livestock systems, decision support systems, and partnerships and communication.

the U.S. with similar environmental conditions—for example, other irrigated cropping regions of the Western U.S. In addition, universal challenges are explored related to the development of climate-related decision support systems and effective partnerships along the full research-extension-practice continuum. Nationally, there has been a rise in the number and influence of institutions focused on coordinating efforts to support agricultural sustainability and resilience, such as the U.S. Department of Interior's Landscape Conservation Cooperatives and the U.S. Department of Agriculture's Climate Hubs. This article contributes to the ongoing discussion about how best to integrate mitigation and adaptation research and extension priorities, and demonstrates of the relevance of supporting researcher-stakeholder partnerships across the country.

CROPPING SYSTEMS IN A CHANGING CLIMATE

Climate Impacts and Vulnerabilities

Climate change in the Pacific Northwest is projected to lead to warmer temperatures, especially in summer; more frost-free days; wetter winters, and more variability in temperature and precipitation (Mote et al., 2013; Abatzoglou et al., 2014). Projected effects of climate change on agriculture in the temperate climate of the Northwest U.S., tend to be less severe than impacts projected for subtropical and tropical regions of the world (Parry et al., 2005; Schlenker and Roberts, 2009). The region's relatively cool climate also means that projected warming may be less detrimental than in other regions for some crops, and potentially beneficial for others. Because historical inter-annual variability is high, many cropping systems also have a significant amount of climate resilience built in, insulating them from some impacts of climate change. Taken in combination, these effects may lead to some benefits for the Northwest, when markets are national, or even global. However, projected climate change effects depend on the specific agricultural sector, geographic location, global climate models, and greenhouse gas concentration pathways considered (Eigenbrode et al., 2013).

Existing literature provides insights into crop yield and water availability vulnerabilities in multiple regional crop production systems. Increasing atmospheric CO_2 levels are expected to contribute to CO_2 fertilization and greater water use efficiency for dryland cereals, leading to stable or increased Northwest dryland wheat yields until mid-century (Tubiello et al., 2007; Hatfield et al., 2011; Karimi et al., 2017; Stöckle et al., 2017). By later in the century, projected further annual average warming of up to 3.3–4.4°C (6–8°F) in a high emission scenario may overwhelm the positive yield impacts of CO_2 fertilization by accelerating wheat senescence, reducing grain-filling, and grain shriveling (Ferris et al., 1998; Ortiz et al., 2008; Stöckle et al., 2010; Cammarano et al., 2016). Some recent research also indicates that warmer, drier summers may lead to increased fallowing throughout this century for rainfed areas that are currently cropped on an annual basis (Kaur et al., 2017). This could reduce overall yields, accelerate erosion, and decrease carbon sequestration compared to current conditions, increasing sustainability challenges.

For irrigated crops, a range of crop-specific impacts on potential yields are projected, assuming the absence of water, nutrient, or other stressors. Impacts depend on the relative importance of positive carbon dioxide effects and generally negative warming effects for each specific crop (Rajagopalan, 2016). Pastures and grasses are an important exception because these crops take advantage of a longer available growing season and are benefited by carbon dioxide fertilization, and thus see relatively larger increases in potential yields (Rajagopalan, 2016). Warming generally affects annuals negatively, as the positive carbon dioxide fertilization effects are outweighed by negative effects from a shortened growth season. In terms of irrigation demands, warming may allow for earlier planting (once spring soil wetness is considered) and accelerated crop development rates, leading to greater early irrigation demand for some crops (Rajagopalan, 2016).

Meanwhile, in Washington, some watersheds are expected to have reduced summer water supply (Hall et al., 2016). In combination with changes in demand, this creates an increase in the likelihood of water shortages (Hall et al., 2016) and curtailment of water use (Vano et al., 2010; Rajagopalan, 2016), but with reduced crop yields still within historical ranges (Rajagopalan, 2016). Because drought severity and frequency are expected to increase, drought will remain a key vulnerability for irrigated crops. More work is needed to identify the specific management challenges likely to arise for Northwest agricultural systems.

Climate change may also contribute to crop quality issues, particularly important for the many speciality crops produced in the Northwest. Warming trends could lead to insufficient chilling for some fruit and nut crops to develop, leading to reduced crop quality and yields (Luedeling et al., 2011). There are also indications that warming leads to decreased quality for potatoes (Alva et al., 2002; Timlin et al., 2006) and some current Northwest grape varieties (Jones, 2007; Diffenbaugh et al., 2011) and warming combined with drought stress may be implicated in the presence of diseases in vegetable seed crops. At the same time, warming trends may allow some species and varieties of tree fruit, nuts and grape varietals that are cold sensitive to be grown successfully in the region (Jones, 2007; Diffenbaugh et al., 2011; Luedeling et al., 2011; Parker and Abatzoglou, 2016). We do not yet know enough about the specific types of climate change impacts on crop quality to evaluate the usefulness of particular practices for diverse crops.

The same trends in climate will also contribute to changing ranges and behavior of plant pests (weeds, insects, and diseases), as well as beneficials (e.g., pollinators). Existing evidence suggests that individual pests, and the various biotic factors that regulate them, will respond differently to a changing climate, with both positive and negative impacts. As with the impacts on crop quality, we do not yet know enough about the impacts on specific pests and on particular crops to inform pest management practices, or to make projections of combined overall effects (Eigenbrode et al., 2017; Kirby et al., 2017). In addition, climate change and increased global commerce increase the possibility of invasive species, which can drastically change pest management regionally, nationally, or internationally (Lee et al., 2011; Leskey et al., 2012). Climate change is also projected to lead to warmer spring temperatures that will accelerate the timing of flowering, which could lead to a mismatch between flowering and availability of pollinators, thus impacting fruit setting (Houston et al., 2017).

Climate Mitigation Opportunities

Croplands emit and sequester multiple GHGs, including carbon dioxide (CO_2), nitrous oxide (N_2O), and small amounts of methane (CH_4). Soils across much of the region have lost carbon under cultivation. For example, dryland soils in the inland Northwest have lost an estimated 20–70% of their SOC since agricultural conversion (Puraskayastha et al., 2008; Brown and Huggins, 2012; Ghimire et al., 2015), a pattern seen elsewhere in the U.S. as well (Lal, 2004). The Columbia Basin is one important exception to this pattern, where irrigation and the associated increased plant productivity have contributed to higher total soil carbon under cultivation (Cochran et al., 2007). In both dryland and irrigated cropping systems, there is an opportunity for agricultural soils to sequester carbon by either reducing tillage or burning, or by increasing carbon inputs through crop residues, cover crops, or amendments (Paustian et al., 1997; Johnson et al., 2006).

Over the last 20 years, efforts to build SOC across much of the region have focused on encouraging the adoption of conservation tillage. These efforts have generated very important soil erosion reductions and soil health benefits (e.g., reduced bulk density, improved soil aggregation, water infiltration, and water holding capacity) over time, but experimental and modeling analyses suggest the potential climate mitigation impact is relatively modest (Brown and Huggins, 2012; Stöckle et al., 2012; Gollany et al., 2013; AgCC, 2016). Opportunities to store carbon are mostly from conversion to no-tillage in areas with greater precipitation, where productivity, and thus crop residue inputs, are higher. Stöckle et al. (2012) projected a change in SOC due to tillage of 0.26–0.49 Mg CO_2e ha^{-1} yr^{-1} over the first 30 years in the top 30 cm of soil from conversion to no-tillage in Pullman, Washington, an annual cropping area, with much smaller gains expected in drier and irrigated areas, or from conversion to reduced tillage.

In comparison, on a per-acre basis, the use of manures, biosolids, composts, and biochar may have greater potential for increasing SOC in the Northwest (Lazzeri et al., 2010; Cogger et al., 2013; AgCC, 2016), providing climate benefits as well as agronomic benefits. In a field experiment in eastern Washington State, biosolids application to a dryland grain-fallow system increased total soil carbon from 0.94 to 1.64% over 20 years (Cogger et al., 2013), while cover cropping in an irrigated system every other year raised soil organic matter from 0.6 to 1.2% over 13 years (Lazzeri et al., 2010). Biochar (a carbon-rich solid formed by pyrolysis of biomass) has garnered interest for a potential role in mitigating climate change (Woolf et al., 2010), and applications in corn in eastern Washington State have increased SOC (e.g., Bera et al., 2016), and raised pH (Streubel et al., 2011; Awale et al., 2017), an intriguing possibility given issues with soil acidification in some areas of the Northwest. However, costs, logistics of application, and other barriers such as pathogen concerns are sizeable (Galinato et al., 2011; AgCC, 2016), impacting the use of such soil amendments.

In addition to the carbon-based emissions, cropland soils (including those associated with livestock and poultry feed production) emit N_2O as a byproduct of the transformation of nitrogen carried out by soil microbes (Wrage et al., 2001; Zhu et al., 2013). Nitrous oxide emissions represent a significant challenge in the Northwest and elsewhere, as nitrogen is added to most cropland soils in fertilizers or manures, and negligible losses from an agronomic perspective can have a substantial impact from a GHG perspective (Post et al., 2012; Stöckle et al., 2012; Venterea et al., 2012). Because warmer, wetter soils are associated with high levels of N_2O emissions, there is a concern that emissions from agricultural soils may increase in the future (Venterea et al., 2012).

Despite ongoing advances (e.g., Waldo, 2016), measurement of N_2O emissions remains a methodological and scientific challenge (Henault et al., 2012; Venterea et al., 2012; Nicolini et al., 2013). Some existing experimental and modeling studies in eastern Washington State and southwest Montana have found N_2O emissions, as a percentage of nitrogen applied, that are lower than the current Intergovernmental Panel on Climate Change (IPCC) benchmark of 1% (0.1–0.9%; Cochran et al., 1981; Dusenbury et al., 2008; Haile-Mariam et al., 2008; Engel et al., 2010). However, other inland Northwest studies suggest emissions are more in line with, or even notably above, the IPCC benchmark (1.1–4.4%; Halvorson, 2010; Stöckle et al., 2012; Waldo, 2016).

Even with these methodological challenges, wider use of variable rate nitrogen application and of stabilized nitrogen fertilizers would likely reduce losses of reactive nitrogen, as existing research from other regions suggests that both can reduce N_2O emissions, including in semi-arid irrigated systems (Shoji et al., 2001; Sehy et al., 2003; Akiyama et al., 2010; Halvorson et al., 2011; Venterea et al., 2012). Both these practices aim to better match available nitrogen with crop needs, allowing for reductions in N-fertilizer inputs without negative impacts on crop yields. However, both practices tend to incur higher costs than traditional methods of nitrogen fertilization. Their broad-scale adoption, therefore, is dependent on the benefits to farmers outweighing increased costs.

Continuing improvements in process-based models (Stockle et al., 1994, 2003; Adam et al., 2015; Malek et al., 2016) and experimental work (Haile-Mariam et al., 2008; Brown and Huggins, 2012; Chi et al., 2016; Waldo et al., 2016) provide important insights and the capability to produce regionally-relevant estimates of mitigation potential of agricultural GHG reduction strategies. However, published estimates of the GHG reduction potential of the region are still incomplete due to the heterogeneity of the region's agroecosystems. For instance, there is very limited knowledge of the GHG impacts of the region's tree fruit, small fruit, and nursery, production systems; three cropping systems of significant geographic scale and economic impact.

Priorities for Adaptation and Mitigation in Cropland Agriculture

Based on the research and extension gaps that were identified during discussions at the Agriculture in a Changing Climate Workshop, the following priorities were identified for cropland agriculture in the Northwest U.S. over the next 5 years. These priorities are supported by a review of the current literature on remaining challenges and opportunities for climate change mitigation and adaptation in cropland agriculture. Each priority that emerged from the workshop is followed by a brief description of the supporting rationale and literature.

Cropping Priority A. Quantify vulnerabilities associated with the timing, amount, and inter-annual variability in water supply to support water-management decisions at multiple spatial and time scales.

Climate change is projected to lead to reduced snowpack and changes in timing of water availability, and is also expected to increase drought frequency, increasing water-related vulnerabilities. While changes in temperatures could also lead to new opportunities for individual farmers who have secure (senior) water rights, farmers' and water managers' water use decisions will affect junior water-right holders in the context of increased scarcity (Dang et al., 2016; Konar et al., 2016). In the Columbia River Basin, water use for pastures and hay has a large impact on aggregate water use and thus on shaping patterns of, and responses to, shortages (Rajagopalan, 2016). Development of adaptation strategies that can be used by individuals or irrigation districts is likely to be important. Such strategies may include improved irrigation efficiency, managed aquifer recharge and storage, micro-storage of irrigation water, use of reclaimed wastewater, and structures that facilitate water transfers to highest value uses during times of shortages. The effectiveness of different approaches may depend on the magnitude and timing of water supply vulnerabilities. As their implementation will require multiple years in some cases, quantifying potential water deficiencies and savings is an urgent need. Research and extension can also support development or improvement of tools that provide specific data and information for water-related decision-making, helping to promote more cost-efficient allocation of water (Dang et al., 2016).

Adaptations to climate change may also affect water demand through shifts in the crops and varieties grown, or through cover cropping or double cropping that takes advantage of lengthened growing seasons (Hall et al., 2016; Parker and Abatzoglou, 2016; Rajagopalan, 2016). Improved understanding of the effect these strategies have on water-related climate vulnerabilities will be important for the long-term profitability of irrigated crops—generally the higher-value products—in the region.

Cropping Priority B. Quantify expected climate change impacts on crop quality and crop pests (weeds, diseases, and insects), and evaluate strategies to address them, to support efforts to maintain quality of production.

To date, agricultural climate impact assessment research in the region has primarily focused on yield (quantity) effects. Workshop participants recognized a need to complement this with more information regarding the implications of climate change for crop quality (AgCC, 2016). Climate-related thresholds (e.g., consecutive days above important heat thresholds, accumulated chilling degree days, first and last frost dates) affect crop quality, either through direct impacts on the crop itself, or indirectly through influence on pests. These crop quality impacts should be investigated.

A need exists to assess climate change effects on pest pressure and to test control strategies for diverse locations throughout the Northwest. This will be challenging because species-specific pest and disease responses must be assessed for each crop of interest (AgCC, 2016). This need is particularly pressing for specialty crops, where crop protection costs are high and thresholds for effects are low.

Cropping Priority C. Establish credible estimates of carbon and nitrogen fluxes for Northwest agricultural systems to support innovation in and adoption of GHG reduction strategies.

Understanding current carbon and nitrogen fluxes and their variability can support GHG emissions reductions strategies. For example, in the Northwest, an extension of an analysis by Brown (2015) indicates that quantifying N_2O emissions is important to determining whether or not mitigation efforts could be accelerated through incentive mechanisms. The monetary incentive provided through existing GHG offset protocols is likely to not be large enough to induce changes in management if the lower end of the range of experimental emissions rates is used. However, if higher experimental measurements are used the incentive increases (e.g., \$0.42–0.96 per hectare at an emissions factor of 0.2% vs. \$2.50–5.89 per hectare at 2.9%, at a price of \$50 per Mg CO_2 equivalent), especially when viewed in combination with the savings from reduced fertilizer expenses (Brown et al., this issue).

Cropping Priority D. Develop technical or other approaches to overcome existing barriers to increasing organic inputs in cropping systems, to support adoption of practices with substantial potential to increase carbon sequestration across the region.

Organic inputs to cropping systems can be increased through a variety of strategies, including increasing residues through choice of crop or variety, use of organic amendments, and integration of grazing livestock into cropping systems. Better understanding of the barriers that limit the use of organic soil amendments in different locations and types of cropping systems in the Northwest, and development of strategies to overcome these barriers (e.g., engineering biochar to add value through nutrients) could lead to more widespread use, increasing soil carbon sequestration and providing additional soil health benefits, even in the absence of a carbon market. Meanwhile, while integration of cropping and grazing systems is currently limited in the Northwest, an increasing number of innovative producers are grazing cover crops in both irrigated and dryland systems (Yorgey et al., 2017a,b).

Efforts to quantify the benefits provided by amendments through improved SOC (e.g., in the form of improved water holding capacity) could address these adoption barriers by providing motivation to farmers to invest in SOC-building strategies, especially in light of the recent emphasis on soil health by NRCS and other public and private agricultural advisors (AgCC, 2016). Understanding whether and under what conditions amendments may increase N_2O emissions is also a need as existing data have shown that this may sometimes occur (Collins et al., 2011; AgCC, 2016).

Cropping Priority E. Quantify under what conditions variable rate application and stabilized nitrogen fertilizers are most likely to decrease overall nitrogen use, and where that reduction is enough to offset increased costs, to support adoption of effective nitrogen management practices.

Variable rate nitrogen application and the use of stabilized nitrogen fertilizers were identified as priorities because of the likelihood that in some cases they can also provide short-term financial benefits to farmers, thus representing a win-win strategy. Variable rate nitrogen application, which aims to match fertilizer application to crop nitrogen needs as they vary within fields, has had variable impacts on overall nitrogen use. Based on experimental data (Mulla et al., 1992; Fiez et al., 1994; Huggins, 2010; Taylor, 2016) researchers have suggested that reductions of 10–35 kg ha^{-1} are achievable in low yielding areas of some but not all dryland cropping systems depending on the type of wheat grown, with low yielding areas varying, but in some cases representing 30% of field area (Brown et al., this issue). In addition to further research, extension efforts are also needed to support management of these technologies and assist farmers in evaluating performance (AgCC, 2016).

Enhanced efficiency nitrogen fertilizers reduce nutrient losses and better match availability with plant needs either by slowing release or by including additives that affect soil enzymatic or microbial processes. Price premiums (in the range of 10–40% in the late 2000s, Olson-Rutz et al., 2011) have been an important barrier to use of advanced fertilizer formulations in the Northwest and elsewhere. Prices had dropped significantly by early 2016, due to expiring patents and other factors, a change that makes these technologies more likely to be economically beneficial to producers (AgCC, 2016). Anecdotal evidence suggests that there is a need for decision-support to help farmers use them effectively (AgCC, 2016).

LIVESTOCK SYSTEMS IN A CHANGING CLIMATE

Climate Impacts and Vulnerabilities

While there have not been as many regional analyses of likely climate change-related impacts on livestock as for crops, existing studies suggest that higher temperatures projected for the twenty-first century are likely to cause heat stress for livestock, which will affect reproductive health, milk production, and can cause mortality (Key et al., 2014; Mauger et al., 2015). However, climate change impacts in the Northwest may be less detrimental than other regions of the country. Thus there are reasons to expect that the region may produce an increasing proportion of the nation's dairy and beef products in the future. For example, an economic analysis of the effects of climate change on milk production estimated that Washington State would experience a 0.4% loss in milk production from climate change by the end of the century, compared to Florida's projected 25% loss (Mauger et al., 2015). There may be opportunities to expand use of many heat stress reduction practices that are already implemented in the Northwest U.S. and other regions (e.g., Pressman, 2010; Brush et al., 2011; Key et al., 2014).

Historically, livestock production in the Northwest has benefited from a diversity of alternative forage resources, and from fewer and less severe droughts than other rangeland regions in the United States. However, it is important to recognize that drought risks may change in the future (Luce et al., 2016). Rangelands are particularly vulnerable to climate change because of their large land extent, sensitive ecology, inaccessibility to mechanical equipment, and relative low economic value. Climate change affects forage growth cycles and is likely to make spring grass available for grazing earlier in the season and ending earlier. Recent analysis suggests that Washington, Oregon, and Idaho are all likely to exhibit higher levels of rangelands vulnerability by 2060 (and beyond), among the higher for rangeland areas of the United States (Reeves et al., 2017). In addition, increased variability is expected to add significant challenges to implementing responsive grazing management plans and adapting effectively (Neibergs et al., 2017). Such planning could be important because, though strategies exist for coping with expected impacts and taking advantage of potential opportunities, their relative effectiveness in Northwest livestock systems will likely be system specific.

Mitigation Opportunities

In 2014, enteric fermentation in domestic livestock accounted for 22.5% of total U.S. CH_4 emissions, while manure management accounted for 8.4% of CH_4 emissions and 4.4% of N_2O emissions (EPA, 2014). Global research suggests that production system characteristics may affect GHG emissions (Eckard et al., 2010; Cottle et al., 2011; Smith et al., 2014), but the potential for such reductions in the Northwest remain uncertain.

Regular collection of manure prevents the significant GHG emissions that can result from anaerobic conditions developing within piles in the barn or feedlot pad (Sommer et al., 2007, 2013). However, only limited research has sought to quantify such GHG emissions in the Northwest (e.g., Brown et al., 2008). A review by Brown et al. (2008) suggested that improving manure management technology through improved composting, lagooning (manure storage in lagoons), and anaerobic digestion has significant potential to reduce livestock emissions. Composting can reduce GHG emissions, odors, and other air quality issues (Pattey et al., 2005). Liquid storage with a covered or aerated lagoon can have similar reductions in GHGs (Westerman and Zhang, 1997; VanderZaag et al., 2008). Application of manure to fields that is timed to coincide with crop or grass growth under mild temperatures and with minimum precipitation reduces GHG emissions and other air and water quality impacts (Ribaudo et al., 2003; Webb et al., 2010). Livestock producers adopting these and other mitigation practices to reduce emissions face challenges associated with determining which strategies are most effective for their unique system and are most likely to lead to net economic benefits over the long term.

Anaerobic digestion of livestock manure reduces GHG emissions and generates renewable energy by capturing CH_4 and CO_2 (Clemens et al., 2006; Holm-Nielsen et al., 2009; Mitchell et al., 2015). Recovery of nutrients from the resulting effluent further reduces the potential for nitrogen release as N_2O when applying the liquid to fields (Zeng and Li, 2006; Greaves et al., 2010), as well as for nitrogen (and other nutrients) to be released into water bodies. However, adoption of anaerobic digestion technologies has been slow across the U.S., despite their benefits. Contributing factors include unfavorable economics in light of current energy prices, ongoing regulatory uncertainty, and the fact that anaerobic digestion technology alone does not successfully alleviate nutrient-related concerns which are a higher priority for most dairies.

Follett et al. (2001) estimated that as much as 110 million metric tons of carbon could be sequestered per year on designated grazing land in the United States. Although, inland Northwest rangelands are generally arid, with low productivity, and susceptible to disturbance (and associated carbon loss) particularly as the climate changes (DiTomaso, 2000; Bradley et al., 2006; Neibergs et al., 2017), small changes to improve grazing management across millions of acres have the potential to increase or decrease total stored carbon in the region (Follett et al., 2001; Schuman et al., 2002; Booker et al., 2013; AgCC, 2016; Teague et al., 2016). In addition, applications of soil amendments (as discussed earlier in cropping systems) could increase carbon storage (Brown and Kurtz, 2010; Ryals and Silver, 2013), though questions remain about the economic feasibility of using soil amendments to increase SOC on Northwest rangelands. Experimental research on carbon sequestration in rangelands has been limited in the region (Briske et al., 2008), and the potential that such changes have to impact carbon sequestration in Northwest rangelands has yet to be quantified.

Priorities for Mitigation and Adaptation in Livestock Systems

Livestock Priority A. Share information on flexible drought management planning and on the effectiveness and cost of short- and long-term strategies for coping with heat and water stress to support adaptation.

Adapting livestock production to future climatic conditions will likely result from a combination of changes in planning (long-term) and changes in specific practices (both short- and long-term). Drought management plans may become increasingly important. This may entail a planned grazing process with high-density, short-duration grazing. This approach would allow for additional forage production during dry periods and would help producers to decide earlier whether they will need to sell animals if feed supply is insufficient (Kachergis et al., 2014). Selecting drought-tolerant feed species may also be an important adaptation strategy to reduce the impact of drought.

Short term adaptation strategies for heat stress include carefully monitoring ventilation systems, monitoring animal behavior for signs of heat stress, improving protocols for feeding animals in extreme weather, and adding more watering locations, shade structures, or other heat abatement systems (Pressman, 2010; Brush et al., 2011; Key et al., 2014). Many of these short-term adaptation strategies mentioned are already implemented on farms. Some producers are also making long-term investments in animal genetics, selecting breeds that respond relatively well to the dry and hot conditions, which are projected by climate models to occur more frequently (Place and Mitloehner, 2010).

Livestock Priority B. Increase adoption of strategies that build soil health and maintain ecosystem resilience to support adaptation of rangelands and other livestock systems to a changing climate.

Improved soil health across rangeland regions is critical to successful adaptation, and would also provide a mitigation benefit, even in the absence of incentive mechanisms. Current research suggests that much of the rangeland forage use in the Northwest is sub-optimal because of fixed turn-out and grazing end dates required by state and federal leases, leading to an inability to change grazing prescriptions in response to dynamic rangeland conditions (Neibergs et al., 2017). Thus, there is an opportunity to improve carbon storage and ecosystem function through improved technology-assisted matching of grazing to available forage resources (AgCC, 2016). Better matching of grazing management to forage resources in a dynamic planned grazing system could reduce the degradation of forage resources—associated with increased disturbance and carbon loss—increase productivity, and sequester carbon. The development and implementation of such strategies is critical given expected increases in rangeland vulnerability in the future.

The development of additional economically feasible models for integrated cropping and grazing systems provide another opportunity to support soil health in the region, with combined benefits for adaptation and mitigation. In integrated systems, ruminants increase SOC, biodiversity, and soil quality, which improves soil resilience during extreme wet and dry periods (Teague et al., 2016). In the areas of Washington and Oregon west of the Cascade mountains, growing cover crops for feed in rotation with annual crops such as corn silage (currently done on less than half of the acres in western Washington State), may significantly boost both local feed production and carbon sequestration (Olson et al., 2014; Poeplau and Don, 2015). Research to better understand barriers to integrating cropping and livestock systems in the Northwest, and collaborative efforts to develop practical integrated systems that overcome those barriers, would be beneficial (AgCC, 2016).

Livestock Priority C. Quantify GHG emissions associated with specific types of livestock operations, and evaluate animal production system characteristics that lead to reduced emissions in the Northwest, to facilitate their adoption.

Some of the most effective strategies for reducing the GHG emissions of livestock agriculture involve changes to the characteristics of animal production systems. Current research efforts are investigating choice of species and species mixing, and genetically-determined feed conversion and animal fertility rates (Eckard et al., 2010; Cottle et al., 2011; Smith et al., 2014) but there is a need to evaluate which of these strategies may be most relevant and feasible for the Northwest U.S. There is also potential for productivity improvements based on diet by switching to feed crops grown with minimal agricultural inputs (and therefore a smaller carbon footprint) and harvested in a manner that supports soil carbon storage (Beauchemin et al., 2009; Martin et al., 2010; Grainger and Beauchemin, 2011). Such strategies are likely to provide cost reductions for producers and facilitate adoption, even in the absence of carbon incentives.

Livestock Priority D. Update and share regional recommendations and decision support tools that support the appropriate use of existing technologies to plan and manage manure nutrients, reduce GHG emissions, and limit nutrient losses to soil, water, and air.

Limiting nutrient release from livestock systems, and the resulting negative soil, water and air quality impacts is a priority in several local areas of the Northwest with high concentrations of livestock (Mitchell et al., 2005; Baldwin et al., 2006; Leytem and Bjorneberg, 2009; USEPA, 2012). A robust manure nutrient management plan is an essential first step to reducing nutrient releases, and simultaneously reducing GHG emissions (Steed and Hashimoto, 1994; Van Horn et al., 1994; Rico et al., 2007; AgCC, 2016). In addition, manure management for intensive livestock systems will need to adapt to climate change in several ways. Adaptations to projected changes in timing, intensity, and frequency of rainfall events include increasing manure storage capacity and adjusting the timing of manure application (AgCC, 2016). Application setback distances may also play a role, though understanding is currently poor (e.g., Giddings, 1993). Timing of manure or fertilizer application may need to be adjusted to accommodate changes in timing of crop growth resulting from climate change. This points to a need for flexible regulation of the timing of manure application. Producers also require up-to-date recommendations about agronomic rates, potential risks and advantages of building new manure or water storage vessels, and redesigning outdoor pens to handle wetter early spring conditions.

Livestock Priority E. Develop cost reduction strategies and added value products that improve the economics for anaerobic digestion and manure nutrient recovery systems to support their adoption.

Continued research efforts are needed to improve the economic viability of anaerobic digestion systems by reducing costs and developing added-value products (Nasir et al., 2012; Mitchell et al., 2015; AgCC, 2016). Further development of emerging add-on technologies may also increase adoption rates by addressing producers' high priority concerns, such as nutrient recovery technologies that reduce impacts of high nutrient loads on water, air and other resources (Chen et al., 2005; Yorgey et al., 2014). Research should assess economic and non-economic benefits and challenges of these technologies at different scales across the Northwest. Improved, un-biased extension information about emerging technologies will also support industry and producer decision-making as external pressures change over time (AgCC, 2016).

DECISION SUPPORT SYSTEMS

Existing Use of Decision Support Systems and Their Potential

Agricultural decision-makers need targeted cropping and livestock system information that is easily integrated at the appropriate time and location to be useful. Decision support systems (DSS) are becoming a vehicle of choice to provide information in complex situations (Magarey et al., 2002; Samietz et al., 2007; Jones et al., 2010). Many existing agricultural decision support systems are aimed at dealing with time-sensitive information—such as forecasting when pests and diseases require various management interventions to prevent crop loss—and are often paired with short-range weather forecasts to enable users to respond. Data visualization tools can complement these DSS, allowing users to peruse weather and climate information, and in some cases also include derivative variables of particular importance to agriculture (e.g., growing degree days, chilling hours).

With this ongoing attention to DSS, there has been interest in using decision support systems to help producers adapt to climate change (**Table 2**). For the purpose of this paper, we refer to such DSS as climate change-related DSS. Climate change-related DSS need to incorporate insights learned from other types of DSS in order to be successful. For example, investing in validation of DSS outputs through testing model projections against empirical data is critical to ensuring credibility of results. This is important because producers have a long memory, and lack of validation and subsequent model failure would set back adoption of the system dramatically (AgCC, 2016).

Like non-climate related DSS, climate change-related DSS requires a collaborative and interdisciplinary approach to account for the complexity of solutions and to provide a suite of options. Non-climate related DSS are often developed for a relatively narrow purpose; for example, forecasting some part of the life history of an insect important for management, or predicting an epizootic for a particular plant disease. The users of these DSS are generally trying to deal with a complex set of problems that may occur at similar or different times of the year. Therefore, from the user perspective, it is important for the models included in the DSS to interact in some fashion. Experience has shown that for a DSS to be deemed usable and adopted by decision-makers, it must incorporate a significant number of models so that users come to the DSS over a significant fraction of the growing season (Jones et al., 2010). This sort of DSS essentially opens a new communication channel that allows a more efficient transfer of general (e.g., pest management guidance) as well as specific (model-based) information.

Development of climate change-related DSS has some distinct challenges. While many non-climate related DSS use information from weather forecasts, most ignore the inherent uncertainty and focus on a single result (e.g., forecasted high for tomorrow of 72°F). By contrast, seasonal climate forecasts (e.g., outlooks for the next several months) often involve a range of possible outcomes and uncertainty that a user of the climate change-related DSS may incorporate into their decision-making process. Likewise, longer-term climate change projections involve a large amount of data that should not be distilled into a single result, but instead should be viewed probabilistically, with uncertainties relating to climate change projections clearly communicated to the user (Wright-Morton et al., 2017). The construction of these tools is made more complex due to the greater diversity of potential clientele, ranging from agricultural producers to government agency users and researchers, as well as the varied time-scales of user interest.

Ongoing maintenance is essential to the long-term success of any DSS, including climate change-related DSS. This challenge requires creative and intentional planning to be successful. Funding agencies are generally eager to fund tool development, but much less willing to fund the maintenance of a tool or system. Existing successful DSS in the Northwest such as WSU-DAS or AIRPACT (Air-quality forecasting for the Pacific Northwest, lar.wsu.edu/airpact) have generally relied on multiple funding sources for ongoing programming and maintenance, including institutional support (e.g., from the hosting university or agency users), user fees, and support of the existing system made possible through ongoing expansion (AgCC, 2016). Other approaches that have been taken include voluntary support from users (so far unsuccessful to our knowledge), and selling advertising space (so far unsuccessful, but with potential). Partnerships with industry may also be relevant for accessing data and ensuring financial

TABLE 2 | Examples of existing and developing DSS relevant to the Northwest that include a climate or climate change aspect or have potential to include these aspects.

Tool	Description
COMET-Farm (http://cometfarm.nrel.colostate.edu/) and COMET-Planner (http://www.comet-planner.com/)	A carbon and GHG accounting system for whole farms and ranches in the US. Planner enables users to evaluate potential carbon sequestration and greenhouse gas reductions from adopting NRCS conservation practices
AgBiz Climate and suite of AgBizLogic tools (http://www.agbizlogic.com)	Economic, financial, and environmental decision tools for businesses that grow, harvest, package, add value, and sell agricultural products
WSU-Decision Aid System (DAS) for tree fruits (http://www.decisionaid.systems)	Integrates horticultural, insect and disease models to provide current management recommendations to Washington State tree fruit growers
Northwest Climate Toolbox (https://climatetoolbox.org/)	Synthesizes agriculturally relevant recent and projected climate information, allows users to query specific locations, climate scenarios, models and time horizons
Cattle heat stress alert and forecast (https://www.ars.usda.gov/plains-area/clay-center-ne/marc/docs/heat-stress/cattle-heat-stress-forecast/)	Uses National Weather Service 7-day forecast information to forecast animal heat stress
Dairy CropSyst (http://modeling.bsyse.wsu.edu/rnelson/Dairy-CropSyst/index.html)	A whole farm emissions and nutrient fate modeling tool that can support dairy decision making, with a focus on manure management
OFoot (https://ofoot.wsu.edu/)	A calculator for estimating the carbon footprint of organic farms

Some are developed specifically for the Northwest, while others are national in scope. The USDA Northwest Climate Hub (https://www.climatehubs.oce.usda.gov/northwest), provides links to many of these tools, and will be updated over time.

sustainability, though issues related to proprietary information and transparency of data collection and use need to be addressed. Diversifying and customizing the DSS to a range of end-users may be an important strategy, as it opens up the potential for multiple complimentary revenue streams.

Depending on their purposes, specific tools within a DSS may require weather or climate data at various spatial and temporal resolutions. Existing climate and non-climate related DSS cope with a variety of challenges related to use of individual datasets (including data quality, spatial and temporal coverage, resolution, and data biases). Implementing quality control procedures and managing these challenges is a key ongoing cost of managing DSS over time. Even with recent improvements, there are challenges in maintaining seamless flow of real-time data and forecasts, and some level of continual maintenance is required.

For this and other reasons, collaboration and centralized infrastructure may also be a key strategy for keeping development and maintenance costs low over time. Expansion to new geographic areas or commodities would be most cost-effective if it takes advantage of a wide variety of existing infrastructure, including environmental/forecasting subsystems, routines for setting up user profiles, data display and manipulation, access to management recommendations, and ancillary databases for miscellaneous purposes. Successful collaboration and maintenance lowers programming costs, allowing for more efficient focus on development of specific models that provide the decision-support outputs.

Priorities for Decision Support Systems to Inform Climate Change Mitigation and Adaptation

As described above, lessons learned in developing and using traditional decision support systems must be incorporated into the development of climate change-related DSS to be successful. The priorities for such development described below arose from discussions of those lessons in the literature and during the Agriculture in a Changing Climate Workshop.

DSS Priority A. Integrate climate change-related DSS with existing DSS tools and integrate financial planning components, so producers can evaluate the economics of potential management actions and investments.

A holistic approach is vitally important when developing climate change-related DSS. Developers of climate change-related decision support systems should consider incorporating multiple models to improve the tool's ability to walk producers through a variety of factors that may be affected by climate change (e.g., crop phenology, insect maturation, disease risk). Developers of climate change-related DSS should consider collaborating with providers of traditional DSS that producers already know and use. There is value in providing users with climate change-related information at online locations where they already go for decision support, such as pest management DSS (McNie, 2012; Kirchhoff et al., 2013). Integrating climate change-related DSS with other agricultural DSS creates opportunities to engage users who may not seek out climate change-related tools on their own, or who are skeptical about climate change (Feldman and Ingram, 2009; Akerlof et al., 2012). Integrated tools enable producers to consider climate as one of many risks that they need to plan for and manage (Howden et al., 2007; McNie, 2012; Kirchhoff et al., 2013).

The utility of climate change-related DSS would be enhanced by including models that evaluate the economics of different management strategies in addition to modeling agronomic impacts. Climate change-related DSS could thereby help producers incorporate climate change considerations into investment decisions, such as perennial crop plantings, equipment purchases, land purchases, and long-term leases (Allen et al., 2017; Capalbo et al., 2017; Kanter et al., in press), by helping them analyze costs, outcomes, and tradeoffs of alternative decisions. It is important that producers have access to climate-related DSS that allow them to make more efficient use of capital as well as inputs, as in many cases investment decisions have longer-term outcomes, and thus incorporating climate considerations is likely to improve readiness for future changes.

DSS Priority B. Develop multi-scale climate change-related decision support systems that focus on aggregate-scale as well as individual (farm-scale) decision-making, to help decision-makers at broader scales incorporate climate change.

Many of the available agricultural DSS are focused on individual producer-level decisions. These systems generally need data that have the highest spatial resolution and relatively short forecast duration (e.g., 2–4 weeks) to help make decisions regarding different management options. However, decisions are also made at larger scales, including irrigation district, watershed, or other political boundaries. Decisions made at each scale are conditional on those made at other scales and affect each other through feedbacks.

There are considerably fewer users at the aggregate scales, primarily regulators, or policy makers. However, the effects of poor decisions by this group can be extensive, and may result in serious economic impacts to individual producers or managers. There will also likely be higher development and support costs per user for aggregate-scale DSS, both because of fewer users, and because of the higher complexity of aggregate models. Yet these users tend to have access to more significant financial resources. Targeting these aggregate-scale decision-makers as users of climate-related DSS could lead to broader incorporation of climate change considerations in larger scale planning activities. Multi-scale tools may also help the aggregate-scale decision-makers visualize and evaluate the farm-scale impacts of their broader scale decisions (and vice versa).

DSS Priority C. Develop a centralized, quality-controlled source of input weather and climate data at multiple temporal scales so DSS developers can focus on the decision support aspect to directly inform adaptation decisions.

The majority of currently available climate projections are aggregated to a time-scale that has limited utility for supporting farm management decisions (Lemos et al., 2012; Weaver et al., 2013; Newsom et al., 2016). Many climate change projections are focused on a 20–30 year time-scale that are useful for policy and infrastructural investment purposes, but not for most farm management and investment decisions, which typically require shorter (2–10 year, or even seasonal) forecasts (Allen et al., 2017). In addition, climate change projections often focus on changes in average conditions, rather than extremes (e.g., heat waves, drought) that tend to more directly impact agricultural production (Lemos et al., 2012; Kirchhoff et al., 2013; Weaver et al., 2013). If ongoing scientific advances enable reliable seasonal forecasts and decadal climate prediction, as well as projections of changes in the frequency and intensity of extreme events, then their incorporation into climate-related DSS would likely make them more valuable to producers for farm-level planning and management (AgCC, 2016), especially if climate change makes it more difficult for producers to rely on experience to inform their expectations.

The development of climate change-related DSS would be greatly accelerated and considerably cheaper if there were a centralized source of quality-controlled weather data and climate forecasts. A central repository would also improve DSS quality by improving access to independent datasets for filling in missing data and for validation efforts. To illustrate the potential cost savings, it is estimated that 70% of the effort required to expand the Washington State University-Decision Aid System (WSU-DAS) for tree fruits from Washington State to British Columbia will be the development of the environmental monitoring/forecast system, with only 30% of effort for adapting the DSS to the management differences (AgCC, 2016). Achieving consistency and integration between one or more weather and climate datasets that are of interest within a climate change-related DSS can add to these challenges, as datasets will likely combine historical observations and multiple climate change projections.

Data should be available with a simple interface that would allow users to quickly access the desired climatic parameters for a particular location and time period (both historical and forecast), as well as automated collection of the data by web-based DSS. Users (DSS developers) should also be provided with explanations that would help them understand the limitations of the data and assumptions. For example, in climate projection data sets, changes in temperature are typically more pronounced than changes in precipitation, which needs to be considered when DSS developers are using the data as inputs to run biological models, or for deriving other variables.

PARTNERSHIPS AND COMMUNICATION AMONG RESEARCHERS AND DECISION-MAKERS

Existing Partnerships and Their Value

Recent decades have seen rapidly expanding efforts to conduct research that directly informs policies and the decisions made by agricultural producers, yet significant barriers remain in the pursuit of usable science focused on climate change and agriculture (Lemos et al., 2012; Kirchhoff et al., 2013; Wibeck, 2014). Active partnerships already exist in the Northwest U.S. among individuals working at many points along the research-extension-practice continuum on specific topics, in particular geographies, or on specific crops or production systems (AgCC, 2016). There is a need for the research and extension community to continue developing strategies for effective collaboration and communication with stakeholders, who have diverse needs and expertise (Moser and Ekstrom, 2010; Akerlof et al., 2012; Wibeck, 2014; AgCC, 2016). Existing literature suggests effective mechanisms for researchers to engage with agricultural decision-makers, and for building the necessary extension capacity—including that of conservation district staff, private-sector technical service providers, and others—to deliver actionable climate change information (McNie, 2012; Kirchhoff et al., 2013; Wibeck, 2014; Prokopy et al., 2015a; Roesch-McNally et al., 2017). In order to produce relevant tools and research, scientists need to be well-versed in the concerns and challenges that regional producers are facing and how those producers make decisions (McNie, 2012; Kirchhoff et al., 2013; Weaver et al., 2013; Allen et al., 2017).

Agricultural producers already manage multiple risks—economic, production-based, environmental, weather—however, managing for climate change-related risks is uniquely challenging because impacts are uncertain, variable over space and time, and often perceived as being only of concern in the distant future (Moser and Ekstrom, 2010; Leiserowitz et al., 2011; Akerlof et al., 2012). In some cases, discussions of climate change with agricultural producers has been complicated both by the politicized nature of the discussion (McCright and Dunlap, 2011), and because decision-makers may discount climate science as political rhetoric (Leiserowitz et al., 2011). These complications pose added obstacles for moving toward proactive, purposeful responses to long-term climate change risks, balancing the trade-offs and finding approaches for which the benefits outweigh the costs, for both individual producers and society.

Fortunately, there are increasing opportunities in the Northwest for effective collaboration among climate and agriculture researchers, agricultural professionals, producers, and other decision-makers who can use research results and decision support systems to inform their decisions. Northwest agricultural professionals recognize the effects of climate change as a priority research area (Zimmerman et al., 2014; AgCC, 2016). Interest in the results of agriculture and climate change research may also be growing in response to unprecedented regional climate patterns from 2014 through 2016 (AgCC, 2016). Workshop participants from different backgrounds—including researchers, agricultural professionals, industry representatives, and producers—voiced a sense of readiness in the Northwest to communicate openly to address climate change impacts through science, management, and policy channels (AgCC, 2016). There is also clear interest among scientists, producers and policy makers in working collaboratively across institutions to develop new technologies to monitor and manage agricultural systems (AgCC, 2016). Regional priorities for research and extension partnerships and communication in the Northwest U.S. are consistent with a nationwide trend to increasingly value and emphasize knowledge co-production and actionable climate science for natural resource decision-makers (Sarewitz and Pielke, 2007; McNie, 2012; Kirchhoff et al., 2013; Weaver et al., 2013).

Priorities for Partnerships and Communication Among Researchers and Decision-Makers

Specific recommendations for fostering the necessary collaboration and co-production of agriculture and climate change research in the Northwest U.S. emerged from discussions at the Agriculture in a Changing Climate Workshop, and are articulated in the following priorities.

Partnerships Priority A. Continue to build a robust network of diverse agriculture professionals and researchers that collaboratively identify research priorities and management-relevant questions, and integrate results into useful decision support systems.

The state of knowledge about climate change impacts and mitigation is rapidly evolving, and new concerns and information needs continue to emerge among agricultural decision-makers. In addition, producers' trusted sources of information are rapidly diversifying, including family, friends, neighbors, crop consultants, and input suppliers (Haigh et al., 2015; Prokopy et al., 2015a; Wright-Morton et al., 2016), as well as a growing use of web-based resources. Ongoing collaborations among researchers and stakeholders are therefore essential in order to (a) conduct relevant research and to develop effective climate change-related decision support systems, and (b) to make them available to users through the right channels, and (c) with appropriate training and support to facilitate their effective use. A clearinghouse for agriculture and climate change research, tools, and news would meet the need for such ongoing collaboration. The growing Agriculture Climate Network and its cornerstone website (www.agclimate.net) that shares and discusses agriculture and climate change research topics and resources in the Northwest U.S. represents one effort to foster such a robust network. This network is supported by organizations and programs that also provide additional climate science and tools, such as the Northwest Climate Hub (https://www.climatehubs.oce.usda.gov/northwest) and the Pacific Northwest Climate Impacts Research Consortium (http://pnwcirc.org/circ).

Partnerships Priority B. Partner along the research-extension-practice continuum to demonstrate the overall economic and environmental costs and benefits of climate change adaptation and mitigation strategies, to accurately inform individual adoption decisions.

Agricultural systems are complex, and producers are generally experienced in integrating many different considerations into a single decision (Mase and Prokopy, 2014). Often, a focus on short-term improvements and regulatory actions can have unintended negative impacts on other parts of the production system or the environment. Quantifying a holistic array of environmental and economic costs and benefits (which requires better incorporation of economic and social sciences) is one important strategy for improving research at the intersection of management and decision-making.

It is not realistic to expect producers to be motivated by mitigation strategies that have an overall cost. Costs and benefits of adaptation and mitigation strategies should be assessed and demonstrated at short-, mid-, and long-term time scales, and across the diverse agricultural systems of the Northwest. This will allow stakeholders to identify and consider those strategies that will be beneficial to them. In addition, producers may decide not to follow an adaptation or mitigation approach not because of a lack of scientific support, but because they are uncertain about the economic implications or the logistical burden of changing their operations. Ultimately, on-the ground demonstration of practice effectiveness is often needed before a producer is willing risk new methods or make significant investments on their farm (AgCC, 2016).

Partnerships Priority C. Communicate the limits of farm-level adaptation strategies, as well as important thresholds or tipping points at which climate change impacts may become more detrimental, to help decision-makers understand vulnerabilities.

A balanced approach is needed in communicating the potential effects of climate change. This approach should acknowledge the potential for opportunities for Northwest agricultural producers, and research indicating that individual farm-level adaptation may be adequate for many crops. However, it should also acknowledge that uncertainty still exists in terms of the magnitude of change in climatic variables, and that climate change may proceed more quickly than indicated by the scenarios currently used in many existing climate impacts studies for agriculture. In addition, vulnerabilities still exist, particularly due to impact of extreme events such as droughts, floods, and heat waves.

There are few published studies that examine the effectiveness and limits of individual farm-level adaptation strategies, such as changing varieties, selecting alternative crops, or building soil carbon storage (Stöckle et al., 2010). For some climate change-related risks (e.g., water shortages, flooding), effective responses may be required beyond the farm level. There is a need to ensure that—at a minimum—management and policy decisions implemented in the near term do not undermine farmers' ability to cope with more severe climate change impacts in the future (Howden et al., 2007; Roesch-McNally et al., 2017).

CONCLUSION

Climate change impacts on agriculture in the Northwest are projected to be generally milder than in many other agricultural regions of the country and the world given that the region's historical climate is relatively cool. Thus for some crops, moderate warming may be beneficial. Additionally, the region's cropping systems have a significant amount of resiliency built in to address historical inter-annual climate variability. This relative level of "regional climate change insulation" may lead to improved global market opportunities for some Northwest producers in the future.

Climate change, however, will likely create additional sustainability challenges for agriculture in the Northwest. For example, increased reliance on Northwest dairies for the United States' national milk production could exacerbate issues of water availability and manure management in some areas of the region. It could also increase the need to import feed, with associated import of nutrients to the region, contributing further to nutrient-related air and water quality concerns. Another significant concern is that climate change may cause farmers to increase fallowing as a risk mitigation strategy in the dryland crop production areas of the inland Northwest. This could threaten decades of progress made in reducing soil erosion, and make maintaining SOC more challenging (Kaur et al., 2017; Morrow et al., 2017). Similarly, some strategies to limit emissions of N_2O could increase losses of nitrogen as ammonia or nitrate. Investing in the necessary research and extension to understand these sustainability challenges, quantify trade-offs, and test and evaluate the cost and effectiveness of potential responses will provide the scientific foundation to inform producer responses as well as policies and incentives that support sustainable agricultural production over the long term.

Other agricultural regions in the United States may face more severe impacts from a changing climate, which may pose different challenges and raise different environmental concerns to those that are the focus in the Northwest. However, as climate change progresses, it is important to understand thresholds in environmental sustainability, the limits of farm-level adaptation, and the points beyond which easily accessible adaptation strategies will no longer be effective in each production region. Building from the example above on soil erosion, previously effective strategies in the Northwest and elsewhere—such as adoption of no-till farming—may not be sufficient to overcome the new challenges posed by a changing climate, requiring transformative thinking and the development of new management approaches or genetic improvements not yet envisioned.

We have synthesized the perspectives shared at the Agriculture in a Changing Climate Workshop (AgCC, 2016) and have provided specifics about research and extension priorities based on a review of agriculture and climate change-focused literature. Knowledge gaps, remaining challenges, and existing opportunities have guided the definition of research and extension priorities that are expected to help the Northwest's agricultural sector adapt to current and future climate change and contribute to mitigation efforts.

Multiple, interrelated challenges exist for funding entities, researchers, extension professionals, and agricultural advisors pursuing these priorities. Agricultural systems in the region are highly variable, so adaptation or mitigation practices that are successful for one location or production system may not be successful in another. Different decision-makers—from policy-makers to producers—require information at different scales. Also, efforts to address these priorities require an understanding of the complexity and interconnected nature of climate systems, agroecosystems, and society. Where possible, this article anticipates these challenges and suggests effective strategies that would lead to research that informs agricultural decision-making at multiple levels. The specific research results obtained by pursuing these priorities will be most directly informative within the Northwest region and its specific production systems, however, there are many lessons that can be applied elsewhere related to effective approaches to inform climate change adaptation and mitigation in agricultural systems.

There are many challenges to the viability and sustainability of agricultural systems in the Northwest U.S., including changing national and global trade opportunities, labor issues, and competing land use priorities (Allen et al., 2017). Climate change impacts intersect with these existing challenges in multiple ways. Managing agricultural systems to mitigate and adapt to climate change presents new and complex issues for agricultural decision-makers, yet there are good reasons to be cautiously optimistic about the potential for increasingly sustainable and resilient agricultural systems in this region. The agricultural industry is experienced at adapting to climatic variability and managing multiple risks. This experience in risk management, coupled with the relatively moderate impacts expected in the Northwest, suggest that proactive and informed producers can likely adapt to future changes and continue to sustainably provide agricultural products to the region and the country. The efforts of producers must be supported by the work of agriculture and climate change researchers from diverse disciplines (and their supporting and funding institutions). These research and extension priorities provide a roadmap for continuing to invest strategically in collaboration and knowledge-sharing designed to produce actionable science, to build capacity and facilitate the use of such science. By pursuing these priorities we can move toward implementing key adaptation and mitigation strategies appropriate to the unique production systems of the Northwest.

AUTHOR CONTRIBUTIONS

GY: Lead author responsible for conference planning/design of collaborative process, major text outline and writing, coordination and editing of manuscript. SH: condensing cropping systems contributions, major manuscript editing. EA: Partnerships contributions, coordination of livestock systems section, major manuscript editing. EW and NE: Conference planning committee, livestock contributions. VJ: Key conference planner decision support systems contributions. BS: Primary conference organizer and coordinator, key conference planner/design of collaborative process, text contributions. KR and JA: Decision support systems contributions. GR: partnerships contributions. BV: Conference planning committee. HC: Conference planning committee, cropping systems contributions. LH: Conference planning committee, economics/decision support contributions. TE: Livestock contributions. CK: Key conference planner/design of collaborative process, major manuscript editing. All: manuscript review and editing.

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