Agriculture in a Changing Climate

Research and Extension Priorities in the Northwest

A white paper articulating recommendations for climate change mitigation and adaptation research and extension, initiated at the 2016 Agriculture in a Changing Climate Workshop

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ABSTRACT

Encompassing a range of agro-ecological systems and diverse geographic and climatic contexts, the Northwest region provides a unique opportunity to test a collaborative approach to assessing and prioritizing climate change mitigation and adaptation opportunities. At a 2016 workshop titled “Agriculture in a Changing Climate”, university faculty and students, crop and livestock producers, and individuals representing state, tribal and federal government agencies, industry, nonprofit organizations, and conservation districts worked together to define research and extension priorities for the future. Insights and priorities related to climate change mitigation and adaptation in the Northwest were defined at the workshop. In this white paper, we synthesize those priorities, coupling recommendations from participants with a review of current literature. The focus is on identifying research and extension actions that can be taken over the next five years. We review current scientific understanding of climate impacts and mitigation, vulnerabilities, and opportunities to adapt, and enumerate research and extension priorities in four areas: (1) cropping systems, (2) livestock systems, (3) decision support systems to help producers and others incorporate climate change considerations into longer-term decisions; and (4) partnerships and communication between researchers and stakeholders. Priorities articulated in this white paper highlight the need for ongoing investment and strategic collaboration and knowledge sharing to develop actionable science. Actionable science will be more effective if integrated with regional extension efforts, facilitating utilization of scientific knowledge by the agricultural industry as the climate changes.

1 INTRODUCTION

In the 21st century, human-caused (anthropogenic) climate change presents new and complex challenges to agricultural systems that have evolved to take advantage of unique local climate conditions. Adaptive practices that increase agricultural systems' resilience and mitigate agriculture's contribution to climate change are being developed and tested at a variety of scales and locations across the United States in response to these new challenges.

Adaptation entails making changes to social and ecological systems in response to current and expected climate change impacts (Moser and Ekstrom, 2010; IPCC, 2014a). This includes short-term "coping" actions, such as responding to seasonal variability, and longer-term "purposeful" adaptation (Moser and Ekstrom, 2010). Mitigation involves deliberate human intervention to reduce the sources and enhance the sinks of greenhouse gases (GHGs) that contribute to global climate change (IPCC, 2014b). For agriculture, mitigation has largely focused on carbon sequestration and reductions in methane (CH_4) and nitrous oxide (N_2O) emissions (USDA, 2016).

Decades of research indicate that climate change will present new challenges for producers in the Northwest United States (hereafter called Northwest) resulting from changes in growing seasons, increased heat and drought stress, changes to irrigation water supply and changing pest and disease pressures (Kruger, *et al.*, 2010; Dalton, *et al.*, 2013, Hall, *et al.*, 2016). At the same time, this region may become an increasingly important center for U.S. food production as other agricultural areas experience greater negative effects on production due to climate change. There is a need to build on existing research efforts to better understand high-priority climate-related vulnerabilities, along with other future environmental and socioeconomic changes. In order for Northwest agricultural systems to achieve increased production while ensuring sustainability, producers will need to both understand and manage emerging challenges and opportunities.

In an effort to build on existing knowledge and to catalyze future regional research and extension efforts, a workshop entitled "Agriculture in a Changing Climate" was held on March 9-11, 2016 (AgCC, 2016). 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. The goal of this workshop was to bring stakeholders together to plan a coordinated approach to meet needs related to climate mitigation and adaptation in the Northwest, with a particular focus on actions for the next five years (AgCC, 2016).

In addition to a core focus on adaptation and mitigation, the workshop considered two areas of special interest in bridging the gap between climate change-related research and agricultural management: 1) the potential for 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 2) efforts to foster effective partnerships and communication between researchers and stakeholders (Lemos, *et al.,* 2012; Weaver, *et al*., 2013; McNie, 2013; AgCC, 2016).

This paper documents insights and priorities from the workshop, builds on them through a review of knowledge relating to agriculture and climate change for the Northwest, and places priorities in the context of the complexities that can be expected to impact agriculture's sustainability. We briefly review the state of the science, and enumerate research and extension priorities for four areas: cropping systems, livestock systems, decision support tools, and partnerships between researchers and stakeholders. While each of these topics is discussed separately, we recognize that they are interrelated in important ways. For example, achieving priorities for partnership is important to achieving the success of crop and livestock systems individually, as well as for adaptation and mitigation as a whole.

It is important to note that this paper focuses primarily on management and agronomic adaptation and mitigation efforts within existing agricultural systems. Additional topics such as production of biofuel crops (an important issue related to croplands mitigation) and energy conservation strategies (particularly in energy-intensive livestock production systems; see for example ATTRA, 2010, and Berkeley Lab, 2011), while identified in the workshop, will require additional development beyond the scope of this paper.

1.1 Overview of Northwest Agriculture

Encompassing great climatic and environmental heterogeneity, the Northwest supports diverse agricultural systems that are a vital component of the region's culture and economy. Dryland and irrigated cropland produces over 250 commercially important crops, including nationally significant production of apples, pears, cherries, berries, wheat, pulses, multiple vegetables, nuts and condiments, as well as nursery and greenhouse production, and Christmas trees (USDA NASS, 2015). Livestock are also important, with nationally significant production of milk, cheese, cattle and calves, and livestock forage (USDA NASS, 2015; USDA ERS, 2015). In 2012, the value of crop and livestock agricultural production in the three states was over $21.8 billion (USDA, 2012).

2 CROPPING SYSTEMS IN A CHANGING CLIMATE

2.1 Climate Impacts and Vulnerabilities

Existing literature provides insights into crop yield and water availability vulnerabilities on as many as 40 specific crops and multiple regional crop production systems. Projected effects of climate change on agriculture in the temperate climate of the Northwest U.S., dominated by winter precipitation, 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 resilience built in, insulating them from some effects of climate change. This may lead to some benefits for the Northwest, where markets are national, or even global. However, projected climate change effects depend on the specific agricultural sector, geographic location, global climate models, and emission scenarios considered.

Climate change may allow earlier spring planting dates for some crops (Eigenbrode, *et al.*, 2013). Although increased incidence of extreme weather events such a late spring freezes potentially expose crops to greater risks of frost injury, models project a continued decrease in the frequency of freeze events in the Northwest (Eigenbrode, *et al.*, 2013). Warmer, wetter winters may benefit dryland cereals (Stöckle, *et al.*, 2010). Increasing atmospheric carbon dioxide (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 through the 2050s (Tubiello, *et al.*, 2007; Stöckle, *et al.*, 2010; Hatfield, *et al.*, 2011). By later in the century, projected further annual average warming of up to 3.3 to 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).

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.*, 2015). This could reduce yields, accelerate erosion, and decrease carbon sequestration, increasing sustainability challenges. Meanwhile, for irrigated crops, changes in crop development rates due to spring warming may lead to greater early irrigation demand and water shortages in some parts of the region (Vano, *et al.*, 2010; Yorgey, *et al.*, 2011; Hall, *et al.*, 2016).

Climate change may also contribute to crop quality issues, particularly important for the many specialty[1] 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; Luedeling, *et al.*, 2011; Diffenbaugh, *et al.*, 2011; Parker and Abatzoglou, 2016).

The same trends will also contribute to changing ranges and behavior of plant pests (weeds, insects and diseases) (Eigenbrode, *et al.*, 2013). 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, making the projection of overall effects difficult (Eigenbrode, *et al.*, 2013; Eigenbrode, 2016). In addition, climate change and increased global commerce increase the possibility of invasive species, which can

[1] Specialty crops are defined by the U.S. Department of Agriculture's National Institute of Food and Agriculture to include fruits and vegetables, tree nuts, dried fruits, and horticulture and nursery crops (including floriculture). See for example: https://nifa.usda.gov/sites/default/files/grant/FY16 SCRI RFPA.pdf

drastically change pest management not only on a single crop, but also regionally, nationally, or internationally (Lee, *et al.*, 2011; Leskey, *et al.*, 2012).

2.2 Climate Mitigation Opportunities

Croplands emit and sequester multiple GHGs, including CO_2, nitrous oxide (N_2O), and small amounts of methane (CH_4). Soils across much of the region have lost carbon under cultivation, following a pattern that has occurred across the U.S. For example, dryland soils in the inland Northwest have lost an estimated 20-70% of their soil organic carbon (SOC) since agricultural conversion (Puraskastha, *et al.*, 2008; Brown and Huggins, 2012; Ghimire, *et al.*, 2015), a pattern seen elsewhere in the U.S. as well (Lal, 2004). Thus, there is an opportunity for agricultural soils to sequester carbon by either increasing carbon inputs through crop residues, cover crops, or amendments; or by reducing tillage or burning (Paustian, *et al.*, 1997; Johnson, *et al.*, 2006). 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 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 thirteen years. 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; Machado and Pritchett, 2014; Awale, *et al.*, in press); an intriguing possibility given issues with soil acidification in some areas of the Northwest.

In contrast, a combination of experimental and modeling analyses have consistently shown a modest potential for carbon sequestration across the Northwest from reductions in tillage (Brown and Huggins, 2012; Stockle, *et al.*, 2012; Gollany, *et al.*, 2013). Opportunities are mostly from conversion to no-tillage in areas with greater precipitation, where productivity, and thus crop residue inputs, are higher. Stockle, *et al.* (2012) projected a change in SOC due to tillage of 0.26 to 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 areas, or from conversion to reduced tillage (including in irrigated areas).

Cropland soils (including those associated with livestock and poultry feed production) emit N_2O as a byproduct of the transformation of nitrogen (added as fertilizer or manures) carried out by soil microbes (Wrage, *et al.*, 2011; Zhu, *et al.*, 2013). Nitrous oxide emissions represent a significant challenge in the Northwest and elsewhere, as negligible losses from an agronomic perspective can have a substantial impact from a GHG perspective (Post, *et al.*, 2012; Venterea, *et al.*, 2012; Stockle, *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 (Waldo, 2016; AgCC, 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 (N) 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%; Smith, 2010, as cited in Halvorsen, 2010; Stockle, *et al.*, 2012; Waldo, 2016).

2.3 Priorities for Mitigation and Adaptation in Cropland Agriculture

Based on discussions at the Agriculture in a Changing Climate Workshop, the following priorities were identified for the Northwest U.S. region over the next five years:

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

Improvements in process-based models (Stockle, *et al.*, 1994; Stockle, *et al.*, 2003; Adam, *et al.*, 2015; Malek, *et al.*, 2016) and experimental work (Haile-Mariam, *et al.*, 2008; Brown and Huggins, 2012; Waldo, *et al.*, 2016; Chi, *et al.*, 2016) provides 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, nursery and rangeland livestock production systems; four systems of significant geographic scale and economic impact.

There is an ongoing need for improved understanding and measurements of N_2O and CO_2 emissions from major agricultural systems under different management strategies both within and outside the Northwest. In the Northwest, an analysis by Brown (2015) indicates that quantifying N_2O emissions can support mitigation efforts. 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, it may be large enough to lead to changes in management if higher experimental measurements are used (e.g. $10.42 versus $64.03 per acre at $50 per metric ton of CO_2 equivalent).

Cropping Priority B. 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.

Wider use of precision agriculture tools for nitrogen application and use of stabilized nitrogen fertilizers is likely to reduce losses of reactive nitrogen in multiple forms, including as N_2O. Both practices aim to better match available nitrogen with crop needs, allowing for reductions in N-fertilizer inputs without negative impacts on crop yields. Existing, but limited, research suggests that both can reduce N_2O emissions, including in semi-arid irrigated systems (Sehy, *et al.*, 2003; Akiyama, *et al.*, 2010; Shoji, *et al.*, 2011; Halvorson, *et al.*, 2011; Venterea, *et al.*, 2012).

At a very basic level, Global Positioning Systems (GPS) are a precision agriculture tool that reduces nitrogen fertilizer application overlap, with savings in the form of reduced fertilizer needs of roughly 5%, and up to 11% for irregularly shaped fields. Survey data suggest that an estimated 65-70% of dryland grain farmers utilized GPS in 2012 (Gantla, *et al.*, 2015), thus leaving some room for expanded adoption of a technology generally regarded as cost-effective.

Variable rate nitrogen application, which aims to match fertilizer application to crop nitrogen needs as they vary within fields, has had more variable impact. In some specific locations, production systems, and crop rotations, reductions of 30-40% in overall nitrogen application rate with equal or higher yields have been achieved under experimental conditions (Fiez, *et al.*, 1994; Brown and Huggins, 2011), but this is not seen in all crop rotations or locations, or on commercial farms (Young, *et al.*, 2013). Ongoing needs also include extension efforts 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 (AgCC, 2016). Anecdotal evidence suggests that there is a need for decision-support to help producers use them effectively (AgCC, 2016).

Cropping Priority C. Develop technical or other approaches to overcome existing barriers to integrating organic soil amendments more broadly in cropping systems, to support adoption of practices with substantial potential to increase carbon sequestration across the region.

Over the last twenty 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 research suggests the potential climate mitigation impact is relatively modest (AgCC, 2016). 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. However, costs, logistics of application, and other barriers such as pathogen concerns are sizeable (Galinato, *et al.*, 2011; AgCC, 2016). Better understanding of the barriers, and development of strategies to overcome these barriers (e.g. engineering biochar to add value through nutrients) may provide avenues to overcome them in the absence of a carbon market. Understanding whether and under what conditions amendments may increase N_2O emissions is also a need as existing data indicate this may sometimes occur (Collins, *et al.*, 2011; AgCC, 2016).

Efforts to quantify the benefits provided by amendments through improved SOC (e.g., in the form of improved water holding capacity) could also address 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).

Cropping Priority D. Quantify vulnerabilities associated with water supply—including drought frequency and severity, reductions in availability, and changes in crop water demand—to support water-management decisions at multiple spatial and time scales.

Given that climate change is projected to increase water-related vulnerabilities while potentially leading to new opportunities for individual farmers who have secure (senior) water rights, it is essential to understand how farmers' and water managers' water use decisions will affect junior water-right holders in the context of increased scarcity (Konar *et al.*, 2016; Dang *et al.*, 2016). Development of adaptation strategies that can be used by individuals or irrigation districts may also be important. Such strategies include improved irrigation efficiency, managed aquifer recharge and storage, micro-storage of irrigation water, or use of reclaimed livestock wastewater. 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 to take advantage of altered growing seasons (Parker and Abatzoglou, 2016). Improved understanding of the effect these strategies have on water-related climate vulnerabilities will be critical for the long-term profitability of irrigated crops in the region.

Cropping Priority E. 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 for more information regarding the implications of climate change for crop quality (AgCC, 2016). Impacts of associated climatic variables (e.g., consecutive days above important heat thresholds, accumulated chilling degree days, first and last frost dates) on crop quality 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 effect are low.

3 LIVESTOCK SYSTEMS IN A CHANGING CLIMATE

3.1 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 21st century are likely to cause heat stress for livestock, which will affect reproductive health, milk production, and can cause mortality (Mauger, *et al.*, 2013; Key, *et al.*, 2014). However, climate change impacts in the Northwest may be less detrimental than in 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).

Historically, the Northwest has benefited from a diversity of alternative forage resources, and fewer and less severe droughts than other rangeland regions in the United States. Though drought risks may change in the future, and increased drought could affect hay production (Adam *et al*., 2012; Luce, *et al.*, 2016), strategic planning could make Northwest range and pastureland resources more valuable assets for both grazing and providing ecosystem services such as carbon storage (AgCC, 2016; Neibergs, *et al.*, in press).

However, inland Northwest rangelands are also highly susceptible to disturbance, including non-native species invasion and fire, and existing research suggests some potential for increased wildfire as the climate changes (Abatzoglou and Kolden, 2011; Luce, *et al.*, 2016; Neibergs, *et al.*, submitted). These disturbances may impact grazing productivity and carbon storage (DiTomaso, 2000; Bradley, *et al.*, 2006).

3.2 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). Only limited research has sought to quantify GHG emissions from livestock in the Northwest, focusing mainly on manure management (e.g. Brown, *et al.*, 2008; Carlson, *et al.*, 2016). 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.

Anaerobic digestion of livestock manure reduces GHG emissions from manure 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 nitrogen 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).

To date, experimental research on carbon sequestration in rangelands is limited in the region (Briske, *et al.*, 2008). Approaches using balanced applications of manure show significant potential to increase carbon storage region wide (Brown and Kurtz, 2010), though there remain questions about the economic feasibility of using soil amendments to increase SOC on Northwest rangelands. Management of such applications to soils is important, as under some circumstances it can lead to fugitive emissions of other GHGs such as N_2O (Collins, *et al.*, 2011; see the Cropping Systems in a Changing Climate section, above).

Better matching of grazing management to forage resources in a dynamic planned grazing system could reduce the degradation of forage resources, increase productivity, and sequester carbon. 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.

2.3 Priorities for Mitigation and Adaptation in Livestock Systems

Livestock Priority A. Develop regional recommendations and decision support tools, and support ongoing educational efforts to encourage appropriate use of existing technologies to plan and manage manure nutrients, reduce GHG emissions, and limit nutrient losses to soil, water, and air.

A robust manure nutrient management plan is an essential first step to reducing GHG emissions and the negative soil, water, and air quality impacts of nutrient release (Van Horn, *et al.*, 1994; Steed and Hashimoto, 1994; Rico, *et al.*, 2007; AgCC, 2016). 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; Sommer, *et al.*, 2013). 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 (Zhang and Westerman, 1997; VanderZaag, *et al.*, 2008). Application of manure to fields should be timed to coincide with crop or grass growth under mild temperatures and with minimum precipitation to reduce GHG emissions and other sources of reduced air and water quality (Ribaudo, *et al.*, 2003; Webb, *et al.*, 2010).

Livestock systems will need to adapt to projected changes in timing, intensity, and frequency of rainfall events by 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 B. Develop cost reduction strategies and added value products that improve the economics for anaerobic digestion and manure nutrient recovery systems to support their adoption.

Adoption of anaerobic digestion technologies has been slow across the U.S., despite their benefits for GHG reduction and renewable energy generation. Contributing factors include unfavorable economics in light of current energy prices, ongoing regulatory uncertainty for dairies, and the fact that anaerobic digestion (AD) technology alone does not successfully alleviate nutrient-related concerns. 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 to support industry and producer decision-making as external pressures change over time (AgCC, 2016).

Livestock Priority C. Quantify the carbon storage potential of rangeland and pastureland soils, and evaluate best practices for enhancing soil carbon, to support adoption of carbon sequestration strategies.

Although Northwest rangelands are generally arid with low productivity, small changes in grazing management across millions of acres have significant potential to increase or decrease total stored carbon in the region (Follett, *et al.*, 2001; Schuman, *et al.*, 2002; Booker, *et al.*, 2013; Teague, *et al.*, 2016; AgCC, 2016;). 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.*, in press). Thus, there is an opportunity to improve carbon storage and ecosystem function through improved and technology-assisted matching of grazing to available forage resources (AgCC, 2016). An example of this was provided by Ryals and Silver (2013), who demonstrated that one application of composted organic matter on annual ranging grassland in California sequestered significantly more carbon and yielded more forage than a grassland without the amendment.

In integrated cropping and grazing systems, ruminants increase SOC, biodiversity, and soil quality, which improves soil resilience during extreme wet and dry periods (Teague, *et al.*, 2016). While integration of cropping and grazing systems is currently limited in the Northwest, some innovative producers are grazing cover crops in both irrigated and dryland systems (Yorgey, *et al.*, 2017a, 2017b). 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), may significantly boost both local feed production and boost 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 D. 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). 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 E. Share information on the effectiveness and cost of short- and long-term strategies for coping with heat and water stress, as well as drought management planning, to support adaptation.

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).

Drought management plans may become increasingly important. This may entail a planned grazing process with high-density, short-duration grazing. This plan would allow for additional forage production during dry periods and would allow producers to identify at an early stage whether they may 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. Developing technologies to recover and re-use water for irrigation or animal drinking may also have a future role.

4 DECISION SUPPORT SYSTEMS

4.1 Existing Use of Decision Support Systems and Their Potential

Agricultural decision-makers need targeted crop and livestock system information that is easily digestible 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 allow users a chance to respond. In addition, data visualization tools can complement these DSS, allowing users to peruse weather and climate information, in some cases also including 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 1). For the purpose of this paper, we refer to such DSS as climate change-related DSS. Climate change-related DSS will need to incorporate insights learned from other types of DSS in order to be successful. For example, investing in validation of DSS outputs, or testing of 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.

At the same time, climate change-related decision support systems will have some distinct challenges. While many 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 information or 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.*, in press). The construction of these tools is made more complex due to the greater diversity of potential clientele ranging from stakeholders to researchers as well as varied time-scales of user interest.

Table 1. Examples of existing and developing DSS relevant to the Northwest that include a climate or climate change aspect or has potential to include these aspects. 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/tools-agriculture) provides links to many of these tools, and will be updated over time.

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
AgClimate Atlas (http://climate.nkn.uidaho.edu/HUB/)	Synthesizes agriculturally relevant downscaled climate information, allows users to query specific locations, climate scenarios, models and time horizons
REACCH climate visualization tools (http://climate.nkn.uidaho.edu/REACCH/decisionTools.php and https://www.reacchpna.org/toolshttps://www.reacchpna.org/tools)	Provides visualizations of projected future climate, and tools that support decisions such as scheduling fertilizer application and pest management practices
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/CS_Suite_4/)	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

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

DSS Priority A. Holistically integrate decision support tools into climate change-related decision support systems so users can gain insights on multiple aspects of decision-making and to open the door for increased overall use of these systems.

The development of most climate change-related decision support systems (DSS) requires an interdisciplinary approach to account for the complexity of solutions and to provide a suite of options. Existing non-climate related DSS are often developed for a specific purpose – for example, forecasting some part of the life history of an insect important for management, or prediction of a particular plant disease. However, users of 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.

A holistic approach is likely even more important—and useful—when developing climate change-related DSS. Developers of climate change-related decision support systems should consider incorporating multiple models to improve the DSS'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).

In addition, 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 for climate change-tool developers 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).

DSS Priority B. Integrate economic and financial components into climate change-related decision support systems, so producers can evaluate the economics of potential management actions and investments.

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. In particular, climate change-related DSS may help producers to incorporate climate change considerations into investment decisions, such as perennial crop plantings, equipment purchases, land purchases and long-term leases (Allen, *et al*., in press; Kanter, *et al*., in press). It is important that producers have access to decision support systems that allow them to make more efficient use of capital as well as inputs, by helping them analyze costs, outcomes, and tradeoffs of alternative decisions.

In theory, carbon markets and other environmental credit or incentive programs could become alternative sources of revenue for agricultural producers, though regional experiences with these types of credit-based incentive programs are quite limited. It may therefore be useful for producers to have access to DSS that allow them to consider revenues from environmental or other benefits, in addition to traditional revenue sources. There is a growing interest from federal funding agencies in providing producers with tools that assess the economic and environmental tradeoffs of management decisions (U.S. GAO, 2014). These could allow producers to evaluate benefits such as soil carbon, environmental footprints, or other sustainability or risk-management attributes within a DSS they may already be familiar with.

DSS Priority C. 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—mostly regulators or policy makers—at the aggregate scales. 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 level 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 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 D. Develop a centralized, quality-controlled source of input weather and climate data at multiple spatial and temporal scales so DSS developers can focus on the decision support aspect.

Depending on their purposes, specific tools within a DSS may require weather or climate data at various spatial and temporal resolutions. Existing 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. The development of 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 the challenges discussed above, as datasets come in various forms, including both station-based (mesonet) and gridded datasets, and may combine historical observations and 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 should also be provided with explanations that would help DSS developers 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.

DSS Priority E. Collaborate on the development of sustainable funding models to ensure long-term sustained operations of climate change-related decision support systems.

Ongoing maintenance is essential to the long-term success of climate change-related decision support systems, and 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, including institutional support for ongoing programming and maintenance needs (e.g. from the hosting university or agency users), user fees, and maintenance 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 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.

Collaboration and centralized infrastructure may also be a key strategy for keeping development and maintenance costs low over time. Expansion to new 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.

DSS Priority F. Focus DSS and modeling efforts on producing outputs that are relevant and useful to decision-makers, to directly inform adaptation decisions.

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; Weaver, *et al*., 2013; Kirchhoff, *et al*., 2013). The ability to project changes in the frequency and intensity of extreme events and incorporate them into climate change-related DSS would be extremely useful for farm-level planning and management (AgCC, 2016).

The majority of currently available climate projections is 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*., in press). If ongoing scientific advances enable reliable seasonal forecasts and decadal climate prediction, these would likely be valuable to producers in the future, especially if climate change makes it more difficult for producers to rely on experience to inform their seasonal expectations.

5 PARTNERSHIPS AMONG RESEARCHERS AND DECISION-MAKERS

5.1 Existing Partnerships Related to Climate Change and Agriculture

Discussions of climate change with agricultural producers has at times been complicated by the politicized nature of the discussion (McCright and Dunlap, 2011). However, there are increasing opportunities for effective collaboration between climate and agriculture researchers, agricultural professionals, producers, and other decision-makers who can use research results and decision support tools or systems to inform their decisions. Among Northwest agricultural professionals, the effects of climate change are recognized as a priority research area (Zimmerman, *et al*., 2014). 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. 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 was also clear interest voiced among scientists, producers and policy makers for working collaboratively across institutions to develop new technologies to monitor and manage agricultural systems (AgCC, 2016).

Active partnerships already exist 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, however, to foster and connect such partnerships along the full continuum. This aligns with a need numerous stakeholders have in the past voiced for a clearinghouse for agriculture and climate change research, tools, and news. The growing Agriculture Climate Network (agclimate.net) and its cornerstone website sharing and discussing agriculture and climate change research topics and resources represent one valuable resource that can be used to support progress towards priorities. Additional climate science and tools are available through the Pacific Northwest Climate Impacts Research Consortium's webpage (http://pnwcirc.org/circ).

5.2 Priorities for Partnerships and Communication among Researchers and Decision-Makers

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

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; Lemos, *et al.*, 2012; Kirchhoff, *et al.*, 2013; Weaver, *et al.*, 2013). 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.

There is important work to be done, therefore, to identify the most 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 (AgCC, 2016). Ongoing collaborations among researchers and stakeholders are 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, with the appropriate training and support to facilitate their effective use.

Partnerships Priority B. Partner to demonstrate the economic and environmental costs and benefits of climate change adaptation and mitigation strategies for specific production systems and locations in the Northwest, to accurately inform decision-makers.

Climate change information shared with producers has often focused on the mitigation and adaptation potential of specific management strategies, rather than focusing on the role of these management strategies more holistically. This approach often leads to emphasis on a single benefit without giving sufficient consideration to the interdependency of the full production system (AgCC, 2016). 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. This is particularly concerning in the context of efforts to reduce GHG emissions that may increase other environmental impacts, or may require producers to incur costs without clear returns (AgCC, 2016).

Better incorporation of economic and social sciences is one important strategy for improving research at the intersection of management and decision-making, as highlighted by Cropping Priority C, Livestock Priority B, and DSS Priority B, above. It is not realistic to expect producers to be motivated by mitigation benefits 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.

Workshop participants were interested in research that accounts for the economic value of environmental services and factors that producers value (for example, soil moisture, soil quality, or crop resilience) (AgCC, 2016). 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).

Producers already manage multiple risks—economic, production-based, environmental, weather—and climate change is just one additional risk. 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. And in some cases, decision-makers may mistakenly discount climate science as political rhetoric. These perceptions pose added obstacles for moving towards 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.

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 (Stockle, *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.*, 2016).

6 CONCLUSION

Climate change impacts in the Northwest may be milder than in many other agricultural regions of the country and the world that are projected to see greater warming or are more vulnerable to drought. This could open future market opportunities for Northwest producers, but will not come without additional sustainability challenges. For example, increased reliance on Northwest dairies for the United States' national milk production could exacerbate issues of water availability and manure management in the region. It could also increase the need to import feed, with its transportation-related carbon emissions and import of nutrients to the region, contributing further to nutrient-related air and water quality concerns.

Climate change impacts and the strategies implemented to combat them could also exacerbate other environmental concerns. For example, if climate change leads to increased fallowing in dryland areas, this could threaten decades of progress made in reducing soil erosion and will also make maintaining soil organic carbon more challenging. Similarly, strategies to limit emissions of nitrous oxide could increase losses of nitrogen as ammonia or nitrate. Investing in the necessary research and extension to understand these challenges, quantify these 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.

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. Building from the example above on soil erosion, previously effective strategies such as no-till may not be enough to overcome the new challenges posed by a changing climate, requiring transformative thinking and the development of new management approaches.

The Agriculture in a Changing Climate Workshop (AgCC, 2016) and the review of existing science highlighted specific research and extension priorities that would help the 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. These priorities are system-specific and location-specific, within a region of diverse conditions and production systems. The results obtained by pursuing these priorities must provide information at a useful scale, and different decision-makers—from policy-makers to producers—require information at different scales. And finally, these priorities must be addressed with an understanding of the complexity and interconnectedness of climate systems, agricultural systems, ecosystems, and society.

There is reason for hope in the face of these challenges. The agricultural industry is experienced at adapting to climatic variability and managing multiple risks. Coupled with the relatively moderate impacts expected in the Northwest, such experience suggests that producers can 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). By continuing to invest strategically in collaboration and knowledge-sharing designed to produce actionable science, coupled with extension efforts to build capacity and facilitate the use of such science, we can move forward in implementing key adaptation and mitigation strategies appropriate to the unique production systems of the Northwest.

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IMAGE CREDITS

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