Chapter 1

Climate Considerations

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Abstract

Agricultural systems in the inland Pacific Northwest (PNW) have evolved under a Mediterranean-type climate characterized by warm, dry summers and cool, wet winters. Precipitation is the primary limiting factor of production for most of the dryland wheat-growing region. The Cascade Mountain Range creates a rain shadow in its immediate lee that results in a considerable precipitation gradient: drier immediately east of the Cascades with wetter conditions further inland. While year-to-year variability in precipitation is considerable, the climate of the inland PNW has proven sufficiently stable to support dryland small grain production systems that rival the productivity of nearly every other rainfed cereal-producing region of the world. Production practices that enhance the dependability and sustainability of dryland cropping systems in the inland PNW are vitally important in the context of global climate change. Managing under observed and projected climate change impacts will require producers to develop their understanding of changing production uncertainties and risks. This chapter discusses how climatic factors influence regional agricultural systems, considers projected impacts of climate change on inland PNW dryland small grain production, and

Research results are coded by agroecological class, defined in the glossary, as follows:

● Annual Crop ▲ Annual Crop-Fallow Transition ■ Grain-Fallow explores how producers can learn from, and apply, information from models to a broad range of production management decisions.

Key Points

- Within the Pacific Northwest, local climate patterns and production practices are highly variable from one location to another. The region also has considerable inter-annual variability in precipitation and temperature.
- Regional models project that human-caused climate change will lead to an average annual temperature increase of 3–4°F by the 2050s and 4–6.5°F by 2100, with increased warming during the summer season. Annual precipitation is projected to increase by about 5–15% by 2050. However, summer precipitation is projected to decrease, resulting in reduced soil moisture during the late summer months. These projected shifts in average regional temperature and precipitation surpass current year-to-year climate variability. Climate change will also increase the frequency and severity of extreme weather events.
- Impacts of climate change on dryland wheat production may be variable throughout the region and variable at different time horizons. Increased atmospheric carbon dioxide may benefit yields by increasing energy and water use efficiencies. At the same time, changing temperature and precipitation regimes may also present new risks and challenges for producers.
- Opportunities exist for producers to alter practices to adapt to climate change impacts and reduce greenhouse gas emissions; these adaptation and mitigation strategies often have co-benefits for long-term sustainability.
- Climate models and decision support tools are rapidly evolving. New web-based resources are available to aid producers in obtaining climate information for specific agricultural management decisions.

Introduction

The PNW is characterized by a temperate, Mediterranean-type climate, typically with cool to cold, wet winters and warm to hot, dry summers.

The region's climate is highly variable over the seasons. At the same time, temperature and precipitation patterns in the PNW are also highly variable over space; topography has a strong influence on local climates. Diverse ecosystems within the PNW include old growth evergreen forests, shrub steppe rangelands, and agricultural zones suitable for a diverse array of crops including rainfed (dryland) grain and forage, irrigated grain and forage, wine grapes, vegetables, oilseeds, and tree fruits. This chapter begins with a description the PNW's historical climate, drivers of variability in temperature and precipitation and an overview of projected climate change impacts in the region. Next, climatic characteristics and diversity of the **inland PNW**'s dryland wheat production systems are discussed. We consider how these agricultural systems will be affected by climate change. Climate change impacts may require producers to consider **adaptation** measures in order to support the long-term sustainability of their operations, and there may be emerging incentives to invest in **mitigation** measures that enhance soil carbon storage and reduce greenhouse gas emissions associated with agricultural production. Finally, this chapter presents decision support tools that enable producers to learn about how climate change and variability may affect their operations. This growing array of informational resources for agricultural decision-makers can support identification of locally appropriate management strategies.

Overview of the Climate of the PNW

The Cascade Mountain Range divides the PNW into climatically distinct areas. The high elevation mountain range causes eastward-moving storms to lose their moisture as rain or snow when the storm systems move inland (cooler temperatures at high elevations mean that air is able to hold less moisture). There is a steep downward slope to low valleys east of the Cascades, and as air passes over the Cascades and warms as it descends, condensation and precipitation are even less likely. This process results in a "rain shadow" effect for much of the Columbia River Basin. Leeward of the Cascade Mountains, the maritime influence is limited and mean annual temperature is primarily influenced by elevation. The warmest locations are typically seen at lowest elevations of the Columbia River Basin. Average temperatures are cooler as the topography rises toward the Northern Rockies. Figure 1-1a shows historical (1981–2010) average annual maximum temperature across the PNW. Figure 1-1b shows historical

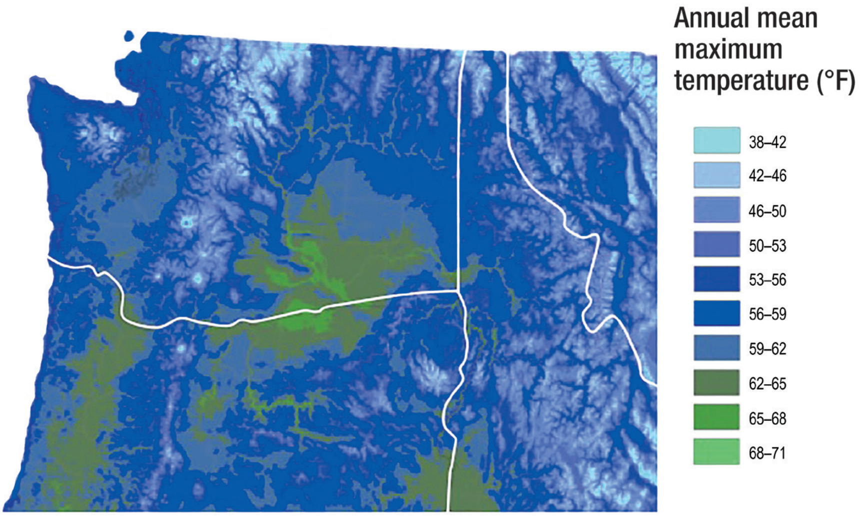

Figure 1-1a. Distribution of annual mean (1981–2010) maximum temperature. (Copyright 2016, PRISM Climate Group, Oregon State University.)

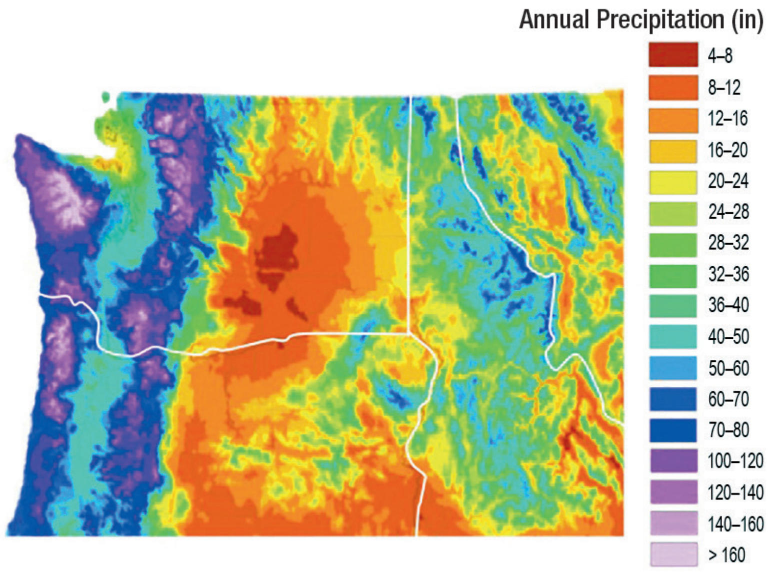

Figure 1-1b. Distribution of annual mean (1981–2010) precipitation. (Copyright 2016, PRISM Climate Group, Oregon State University.)

(1981–2010) average annual precipitation throughout the region.

Substantial year-to-year variability is evident in mean annual temperature (Figure 1-2a) and precipitation (Figure 1-2b) averaged across the PNW.

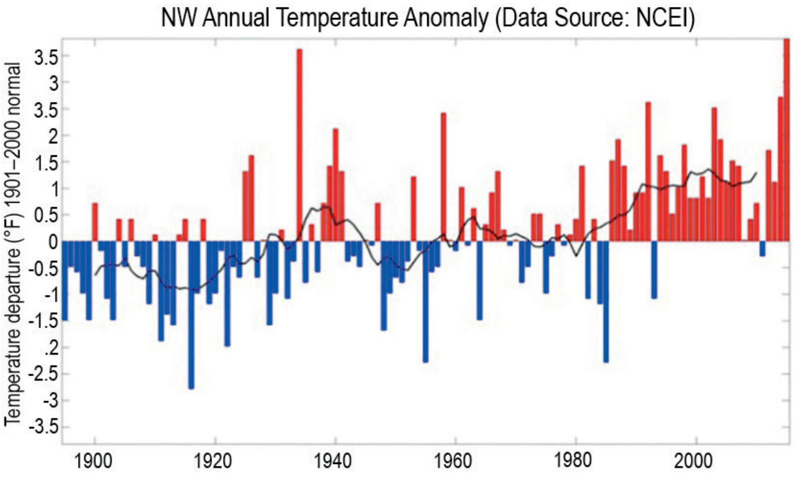

Figure 1-2a: Annual mean temperature anomaly for the National Centers for Environmental Information (NCEI) Northwest region (Washington, Oregon, and Idaho) dataset from 1900 to 2015. Anomalies are taken with respect to the 1900–2000 period. (Figure courtesy of John Abatzoglou.)

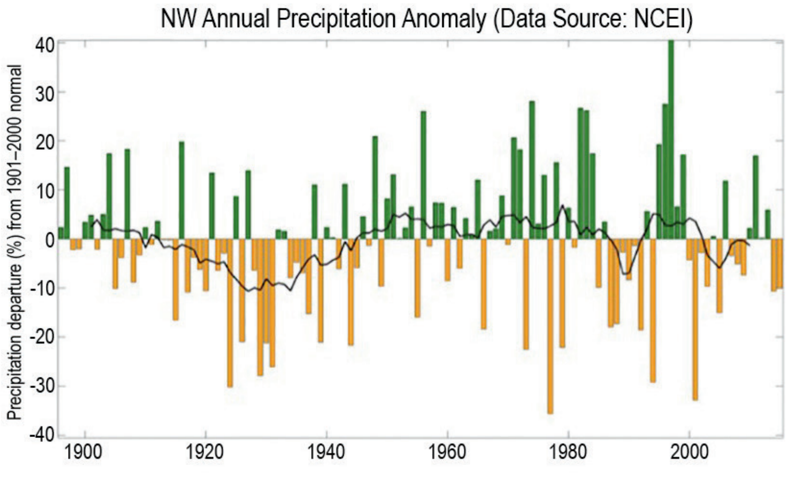

Figure 1-2b: Annual mean precipitation anomaly per water year for the National Centers for Environmental Information (NCEI) Northwest region (Washington, Oregon, and Idaho) dataset from 1900 to 2015. Anomalies are taken with respect to the 1900–2000 period. (Figure courtesy of John Abatzoglou.)

The two primary drivers of natural climate variability in the region are the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). These two cyclical patterns affect the climate of the region on annual to decadal timescales. In their warm phases (El Niño conditions for ENSO or positive phase PDO), the chance of a warmer than average PNW winter and spring increases. Cool phase conditions (La Niña conditions for ENSO and negative phase PDO) increase the odds that PNW winters will be cooler and wetter than an average year. For a detailed discussion of the link between ENSO and PDO cycles and regional temperature and precipitation variability, readers are encouraged to consult "Seasonal Climate Variability and Change in the Pacific Northwest of the United States" by Abatzoglou et al. 2014.

The warmest 10-year period since 1900 in the PNW occurred from 1998 to 2007, and very few years since 1980 have had below average annual mean temperatures. No long-term trends in precipitation are evident across the PNW except for an increase in spring precipitation (Abatzoglou et al. 2014). However, multi-decadal variability in annual precipitation is evident with protracted deficits in precipitation apparent in the 1920s and 1930s and relatively wetter conditions in the 1970s through the mid 1980s.

Earth's physical and biological systems are changing in many ways as a result of anthropogenic, or human-caused, greenhouse gas emissions. Observed and projected changes include rising sea levels, changes in ocean chemistry, warming oceans and air, and changing storm patterns. Consistent with a trend of global and national temperature increase throughout the 20th century, average annual temperatures in the PNW have increased (Abatzoglou et al. 2014). In general for the region, increasing temperatures are linked to longer frost-free seasons, decreased spring mountain snowpack, earlier peak stream flow, and decreased glacial area. Although mean annual temperature is the most frequently cited global indicator of climate change, seasonal temperature and precipitation at regional scales provide more salient links to climate impacts that may be otherwise masked in mean annual temperature (Abatzoglou et al. 2014). Current best estimates of global climate change impacts in the PNW indicate that annual average temperature increases of 3–4°F are expected by the 2050s, with annual average warming of 4–6.5°F projected by 2100 (Abatzoglou et al. 2014). Warming trends are projected to be greatest during the summer months. Annual precipitation is projected to increase 5–15% by the middle of the latter half of the 21st century (Vano et al. 2010). While total annual precipitation is projected to increase, summer season precipitation is expected to decrease and, combined with elevated summer temperatures, this could result in substantial reductions in late summer soil moisture (Vano et al. 2010).

Additional key impacts of forecasted climate change on agriculture in the inland PNW include increased frequency of temperature-induced drought conditions, greater temperature extremes (both minimum and maximum temperatures), and extreme precipitation events due to the fact that warmer air holds more moisture and is linked to more energetic storm events, which could lead to increased soil erosion and flooding (Binder et al. 2010). Warming leads to a longer available growing season, but can result in a shortened actual growth season for most crops due to accelerated growth. Later maturing crops may have reduced quality resulting from heat or inadequate moisture stressors during grain fill (Ortiz et al. 2008). Climate change may also affect the range and severity of agricultural **pests**, plant diseases, and invasive species. Anthropogenic greenhouse gas emissions also increase the concentration of carbon dioxide (CO_2) in the atmosphere, which impacts plant growth and water usage (Stöckle et al. 2010). Over the near-term in the inland PNW, increasing atmospheric CO_2 may offset the negative impacts of climate change on cereal production and may contribute to increased dryland yields because of increased **water use efficiency** in systems that are generally water-limited.

Diversity of Inland PNW Dryland Agricultural Systems

This section of Chapter 1 explores how variations in local climate and topography shape the characteristics of dryland agricultural systems in the inland PNW. The inland PNW's wheat production area corresponds approximately with the Columbia Plateau Ecoregion defined by the US Environmental Protection Agency (2011). This geographic area also parallels the study area for the Regional Approaches to Climate Change (REACCH) research effort, which focuses on dryland farming of the inland PNW where the predominant crops are small grains (wheat/barley), peas, and canola (Figure 1-3).

Throughout the inland PNW, winter weather is cool to cold with December and January mean daily temperature averaging 30°F and occasionally

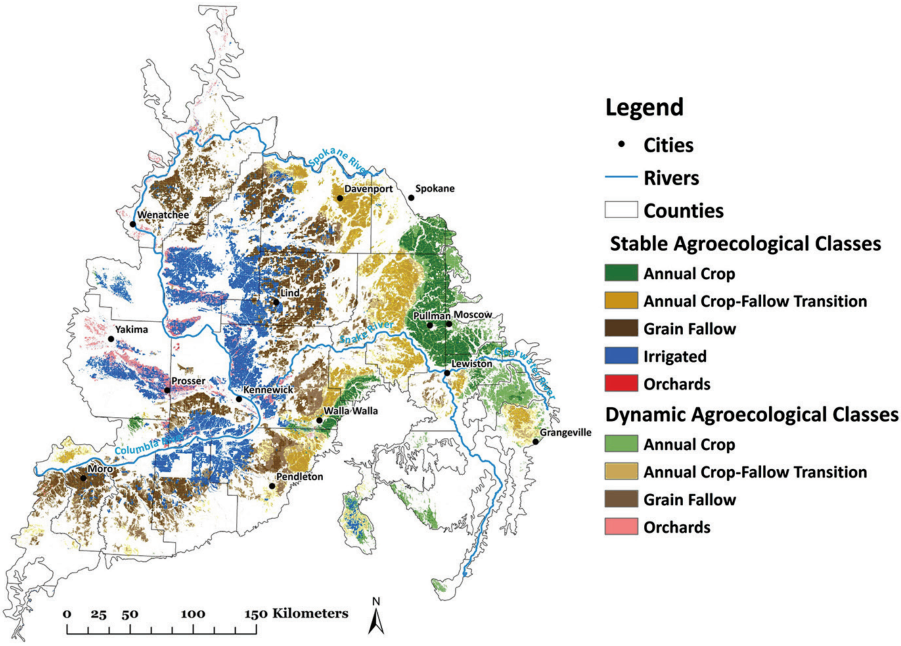

Figure 1-3. Agroecological classes (AECs) of the inland PNW based on 2007–2014 National Agricultural Statistics Service (NASS) Cropland Data Layer data. Much of the heterogeneity in cropping systems reflects climatic constraints, primarily temperature and precipitation regimes, and availability of water for irrigation. Production systems are diverse within each AEC as well. (Huggins et al. in preparation.)

dropping to 14°F or lower (Schillinger et al. 2010). In the summer months, high pressure systems lead to warm and dry conditions with low relative humidity. Across the region, average afternoon temperatures in the summer range between 68 and 95°F (Schillinger et al. 2010). The highest annual mean temperatures occur in the southwest portion of the inland PNW, with cooler annual average temperatures moving to the northeast (Figure 1-1a).

An estimated 70% of the inland PNW's precipitation occurs from October to March and 25% occurs during April to June. July through September are the driest months (Schillinger et al. 2010). As can be seen in Figure 1-1b, there is substantial variation in mean annual precipitation across the inland PNW. A gradient exists from the low precipitation zone in the western portion of the dryland wheat production area (average annual precipitation of 6") to the high precipitation zone in the eastern portion (average annual precipitation of 24") (Schillinger et al. 2010). Often,

Soil Orders of the Inland PNW

Alfisol. Leached basic or slightly acid soil with clay-rich subsurface layer. Alfisols have water available to vegetation for more than half the year or more than 3 consecutive months during a warm season. Alfisols are primarily formed under forest or mixed vegetative cover and are productive for most crops.

Andisol. Soil with high phosphorus retention, available water capacity, and cation exchange capacity. Andisols are most commonly formed from volcanic materials with high proportions of silica, aluminum, and iron-rich compounds. These soils are common in cool areas with moderate to high precipitation and are typically very productive.

Aridisol. Saline or alkaline soil with little organic matter. Aridisols have no available water during most of the time that the soils are warm enough for plant growth and occur in regions with less than 9" precipitation per year. The vegetation in many areas consists of scattered ephemeral grasses and shrubs. Some Aridisols support limited grazing. If irrigated, many aridisols are suitable for crops.

Entisol. Mineral soil that is not differentiated into distinct soil horizons. The absence of distinct soil horizons may be the result of an inert parent material, insufficient time for horizons to form, occurrence on steep slopes where erosion occurs more rapidly than soil horizon formation, or recent mixing of horizons.

Inceptisol. Freely draining soil that does not have sharply defined soil layers. Inceptisols have water available to plants for more than half the year or more than 3 consecutive months during a warm season and one or more distinct soil horizons. Inceptisols have a wide range of characteristics.

Mollisol. Soil with a dark surface layer rich in organic matter and containing high concentrations of calcium and magnesium. Mollisols characteristically form under grasslands in climates that have a moderate to pronounced seasonal moisture deficit or under forest ecosystems. These soils are very productive for crops.

studies of the region focus on mean annual precipitation as a distinguishing characteristic of different agricultural zones. Generalized precipitation classes for the dryland wheat production region are as follows: high (18”+); intermediate (12–18”); and low (less than 12”) mean annual precipitation (Schillinger and Papendick 2008). Roughly 50–60% of the inland PNW’s dryland crop production acres occur within the low precipitation zone (Schillinger et al. 2003; Schillinger and Papendick 2008).

Along with precipitation, topography and soil characteristics play a central role in shaping agricultural production. The inland PNW ranges from more gently rolling topography in the west to steep rolling hills in the east. The predominant agricultural soils of the dryland wheat-producing region are silt loams, formed in windblown silt (loess) deposits of depths varying from 3–20 feet in the western portion of the inland PNW and up to 200 feet deep in the east (Douglas et al. 1992). These loess deposits occur over basalt bedrock or flood-deposited sediments (McClellan et al. 2012). Soils are dominated by Mollisol and Aridisol soil orders, but Entisols, Andisols, Alfisols, and Inceptisols are present in localized areas (USDA 1999). (See the Soil Orders of the Inland PNW sidebar for descriptions of these soil orders.) In the drier, warmer western region of the inland PNW, soils developed under steppe and shrub-steppe vegetation, dependent on precipitation (Schillinger et al. 2010). These dry zone soils are relatively low in organic matter, more sandy, and susceptible to wind erosion (Schillinger et al. 2010). Moving to the northeast, in the cooler, high precipitation zone of the inland PNW (including the Palouse Hills), the loess soils developed under native grasslands or forests (Schillinger et al. 2010). These soils are richer in organic matter and clay, and typically susceptible to water erosion when snowmelt or rain runs over recently thawed topsoil (Schillinger et al. 2010; McClellan et al. 2012). In the high precipitation zone, crops are often produced on slopes with an 8% to 30% grade, with some production on slopes as steep as 45% (Schillinger et al. 2003). Across the inland PNW, soil organic matter (SOM) ranges from more than 3% in the high precipitation zone to less than 1% in the low precipitation zone (Schillinger et al. 2006).

Numerous systems have been devised to subdivide the inland PNW into agricultural and ecological zones to communicate recommendations

Table 1-1. Agronomic zones.

Zone	Name	Mean Annual Precipitation	Soil Depth	Cumulative Growing Degree Days (1 Jan-31 May)	Average Winter Wheat Yields (bu/acre)	Soil Organic Matter (%)	Water Holding Capacity (in/ft)
1	Annual crop-wet-cold	Over 16"	—	Under 700; Cold	70–90	4+	2.2–2.6
2	Annual crop-wet-cool	Over 16"	—	700-1000; Cool	80–120	3–4	2.0–2.4
3	Annual crop-fallow - transition	14-16"	Over 40"; deep	700-1000; Cool	60–80	2–3	1.8–2.2
4	Annual crop-dry	10-16"	Under 40"; shallow	Under 1000; Cool	30–40	<1.5	1.6–2.0
5	Grain-fallow-dry	Under 14"	Over 40"; deep	—	40–60	<1.5	1.6–2.0
6	Irrigated	—	—	—	—	—	—

Adapted from Douglas et al. 1999, Table 5.2.

for management, model economic trends, and to study crops, pests and disease vulnerabilities. The low, intermediate, and high precipitation zones defined by Schillinger and Papendick (2008) and discussed earlier in this section are an example of one such classification system that is useful for producers and land managers. Many growers are also familiar with the six agronomic zones defined by Douglas et al. (1992) in which the following criteria are used to differentiate zones: mean annual precipitation, soil depth, and **growing degree days** (Table 1-1). Ranges of average winter wheat yields, soil organic matter, and soil **water holding capacity** have been specified for each of the agronomic zones (Douglas et al. 1999). Agronomic zones 2 through 5 make up the inland PNW's dryland wheat-producing region (Douglas et al. 1992).

Recently, three **agroecological classes** (AECs) have been defined using National Agricultural Statistics Service (NASS) cropland use data to characterize the diversity of agricultural practices in the inland PNW's dryland cereal production region (Kaur et al. 2015). These three classes are: (1) Annual Crop with less than 10% **fallow**, (2) Annual Crop-Fallow Transition with 10–40% fallow, and (3) Grain-Fallow with greater than 40% fallow (Table 1-2). The AEC classification system differs from other classification systems that have been applied in the region because

Table 1-2. Three agroecological classes (AECs) of the inland PNW.

Class	Percent Fallow	Common Grower Practices
Annual Crop ●	<10% fallow	3- or 4-year crop sequence; e.g., winter wheat-spring wheat, or barley-spring broadleaf, or winter wheat-spring grain-winter wheat-spring broadleaf.
Annual Crop-Fallow Transition ▲	10–40% fallow	2- or 3-year crop sequence; e.g., winter wheat-fallow or winter wheat-spring wheat-fallow. Crop choice is more limited by available water.
Grain-Fallow ■	>40% fallow	Typical 2-year crop sequence is winter wheat-fallow. Growers rely on fallow practices to store and retain winter precipitation in the soil profile to establish winter wheat.

distinctions among classes are based on actual land use rather than the biophysical characteristics that play a role in shaping those land-use practices.

The Annual Crop AEC is generally associated with high precipitation zones, while the Grain-Fallow AEC is associated with low precipitation zones. However, AECs are dynamic, changing as land use and land cover shift over time. Figure 1-3 displays the AECs in the inland PNW, including dynamic regions, which have recently transitioned from one use to another (Kaur et al. 2015). Focusing on distinctions among agricultural regions based upon actual land use allows researchers to analyze relationships among biophysical variables (e.g., climate, soils, terrain) and socioeconomic variables (e.g., land prices, commodities grown) (Huggins et al. in preparation). This framework for classification also enables researchers to predict changes in AECs linked to shifts in climate, markets, and management practices. Preliminary analyses of changing grower practices suggest that annual crop regions will decrease, being converted to annual crop-fallow transition systems—this would significantly reduce diversification and increase soil vulnerability to erosion due to increased fallowing (Kaur et al. 2015). Grain-fallow systems are less likely to be affected (Kaur et al. 2015). Figure 1-3 shows the AECs of the inland PNW in 2015, pale colors indicate that a particular area changed from a different prior use to the current AEC over the period of data collection (2007–2014).

Synthesis of Recent Research Developments

Modeling Climate Change

Global climate models (GCMs) simulate oceanic and atmospheric behavior at a coarse spatial resolution (grid cells of 4,000 square miles or more). There are many different GCMs, which differ in how they account for various climatic variables. While essential for understanding global patterns, GCMs have limited direct utility in regional studies because they do not include sufficient detail to capture local-scale spatial variability in climate. To address this limitation, projections of future climate are downscaled to a finer spatial scale. For example, adjustments are made to outputs from GCMs to better capture the rain shadow effect caused by the Cascade Mountains (Abatzoglou and Brown 2012; Mote and Salathe 2010).

It is important to run climate models based on a range of different storylines about future political, economic, technological, and social decisions, all of which affect greenhouse gas emissions. In order to make results from various GCM analyses comparable, the Intergovernmental Panel on Climate Change (IPCC) defined a standard set of possible greenhouse gas emissions pathways. The 5th IPCC Assessment Report compares four different Representative Concentration Pathways (RCPs), described in Table 1-3 (IPCC 2014). The RCPs considered in the IPCC 5th Assessment Report are named according to projected radiative forcing (sunlight absorption) values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 Watts per square meter). For reference, the additional radiative forcing in 2011 was estimated as +2.2 W/m^2. This simplistic approach gives researchers the ability to place boundaries on the conditions for forecasting while accounting for a range of possible greenhouse gas emissions scenarios and global economic growth trajectories.

Future Climate Projections for the Inland PNW

Understanding the interactions of anthropogenic climate change and natural drivers of climate variability is a key area of research. As described in the introduction to this chapter, climate change is occurring against a background of ongoing year-to-year climate variability. We expect significant regional climate variability to continue in the future even under climate change, with the magnitude of the climate change signal equaling and surpassing the historical climate variability signal for mean annual temperature in the latter half of the 21st century

Table 1-3. Representative concentration pathways used in IPCC Assessment Report 5.

IPCC Representative Concentration Pathways (RCPs) and generalized emissions scenarios	
RCP 2.6	Global annual greenhouse gas emissions (measured in CO_2 equivalents) peak between 2010–2020, with emissions declining substantially thereafter
RCP 4.5	Emissions peak around 2040, then decline
RCP 6	Emissions peak around 2080, then decline
RCP 8.5	Emissions continue to rise throughout the 21st century

(Abatzoglou et al. 2014). The most apparent warming trend in the PNW is for the coldest night of the year, which has warmed significantly in recent decades (Abatzoglou et al. 2014). The only cooling trend observed in the region was for spring temperatures over the last three decades, and this trend is tied to climate variability (Abatzoglou et al. 2014). Future climate projections consistently forecast that the annual maximum temperatures will increase. There will still be cool years, but the frequency at which they occur is expected to dwindle. Figure 1-4 shows projections of future mean annual temperature and precipitation in southeast Washington for two different RCPs. Even under a scenario of moderate global greenhouse gas emissions that peak in 2040 and decline thereafter, substantial temperature and precipitation shifts are projected for the region by mid-century.

Growing degree days are a measure of heat accumulation used by crop models to project plant development rates and determine when crops will reach maturity. Under a scenario of greenhouse gas emissions continuing to increase throughout the 21st century, planting dates, crop maturity dates, feasibility of double cropping systems, and pest and disease pressures may be dramatically affected by warming (Figure 1-5).

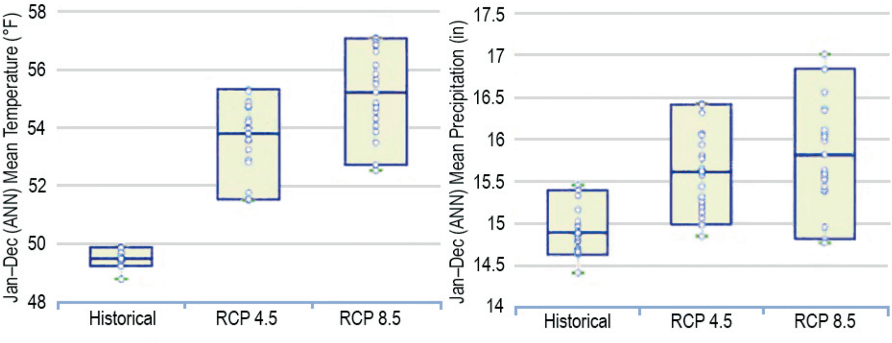

Figure 1-4. Projected changes in mean annual temperature (left) and precipitation (right) for southeastern Washington (45.6-47.8N, 117-120.5W). Historical mean annual temperature and precipitation (1971–2000) are compared with projected annual means for 2040–2060 under two different representative concentration pathways (RCPs). (RCP 4.5 indicates greenhouse gas emissions peaking in 2040 then declining, RCP 8.5 indicates emissions continuing to rise in the 21st century. Figure courtesy of John Abatzoglou.)

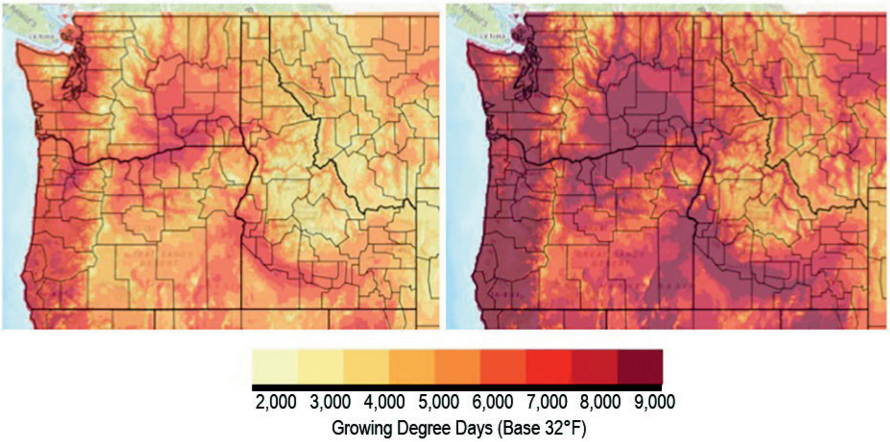

Figure 1-5. Cumulative growing degree days (base 32°F) 1971–2000 (left) and 2040–2069 representative concentration pathway (RCP) 8.5 (right), projections obtained from the AgClimate atlas. See the section about decision support tools at the end of this chapter for more information on how to access and interpret projections such as this. (Figure courtesy of John Abatzoglou.)

Impacts of Climate Change on Small Grains

Dryland small grain production regions are vulnerable to projected reductions in summer precipitation, decreases in summer soil moisture and extended warm weather episodes, which potentially reduce yields or exacerbate production challenges on marginal lands. Wheat and alternative crops are vulnerable to heat stress that can accelerate wheat senescence (the period between maturity and death of a plant) and reduce photosynthesis, which causes shriveling and negatively affects grain quality (Ferris et al. 1998; Ortiz et al. 2008). Warmer, drier conditions are also expected to exacerbate wind-caused soil erosion and reduce early stand establishment of winter wheat on summer fallow (Eigenbrode et al. 2013). Winter wheat could benefit from warmer winters, but may be challenged if drier summers impede late summer and fall planting of these crops, reducing germination and stand establishment. Pest and disease phenology shifts, or changes in the timing of emergence and species ranges, are also projected to impact inland PNW small grain production systems (Eigenbrode et al. 2013). (See Chapter 10: Disease Management for Wheat and Barley and Chapter 11: Insect Management Strategies.)

Projected changes to precipitation patterns in the PNW under climate change are highly variable and more difficult to project than changes in temperature. Cool season (October-March) precipitation is generally projected to increase in the region (Vano et al. 2010). Depending on the timing of precipitation, planting of spring wheat could become more challenging, reducing yields or causing a shift toward more winter cropping (Stöckle et al. 2010). At the same time, increased soil moisture early in the growing season may mitigate the effects of projected reductions in summer precipitation (Stöckle et al. 2010).

Based on crop models, potential yield losses from projected climate change impacts alone would be severe by the end of the 21st century (Stöckle et al. 2010). However, increased atmospheric CO_2 that contributes to more rapid plant development and growth (called **CO_2 fertilization**) and agronomic adaptation are expected to offset the negative effects of climate change on small grain crop yields in the inland PNW. Tubiello et al. (2002) projected US West Coast non-irrigated winter wheat production to increase 10–30% by 2030, relative to baseline climate (1951–1994).

Using the crop model CropSyst, four GCMs, and assuming a scenario of rapid economic growth and technological development with a balanced reliance on fossil fuel-based and renewable energy sources, Stöckle et al. (2010) projected dryland winter wheat yield increases of 13–15% by the 2020s, 13–25% by the 2040s, and 23–35% by the 2080s for a range of locations across Washington state relative to baseline climate (1975–2005) when warming and CO_2 fertilization were included (Stöckle et al. 2010). Dryland spring wheat yields for a range of locations across Washington were projected to change by +7% to +8% by the 2020s, –7% to +2% by the 2040s, and –11% to +0% by the 2080s (Stöckle et al. 2010). The range of values obtained depend upon the production zone and planting date, with lower increases or deficits in lower precipitation zones and better performance occurring if planting is adjusted earlier in the season, avoiding higher temperatures during vulnerable stages (Stöckle et al. 2010). These projections are based on changes in mean temperatures and do not consider the frequency of extreme heat events, which could negatively affect yields, but for which projections are less certain.

Grower Considerations

Recent sociological research suggests that the general public of the inland PNW is increasingly concerned about climate change and that there may be growing public interest in regulation of agricultural practices to support climate change adaptation and mitigation (Wulfhorst et al. 2015). An increasing number of growers expect that future climate change will create conditions that necessitate modifying their agricultural management practices (Bernacchi et al. 2015). This section begins with a discussion of various approaches to climate forecasting at different temporal and spatial scales. Appropriate modeling tools with respect to specific kinds of decisions are described. Next, we outline emerging research about production practices to mitigate and adapt to climate change. Finally, we consider the potential for future economic and regulatory changes linked to climate change impacts.

Climate Forecasting

Producers are accustomed to looking at 7–10 day weather forecasts to make many decisions about planting, fertilizer application, and harvesting. While the limitations of such forecasts are well documented, their utility is indisputable. Making projections about the future climate, however, depends on a different set of modeling tools. Here we'll explore the differences among weather forecasts, seasonal climate forecasting, and longer term climate projections.

Numerical weather forecasts are designed to provide information on what the weather is likely to be like for a specific location and time. These forecasts rely on numerical weather models that are based on the laws of atmospheric physics and thermodynamics. Numerical weather models are initialized and run forward through time starting with initial conditions that are based on measured observations from weather balloons, satellites, and surface weather stations. The simplest forecast to make is for conditions 15-minutes from now, as current observations serve as a guide. Such numerical weather forecasts tend to degrade with time due to errors in initial observations and modeling inaccuracies and typically have limited utility beyond 10 days. Numerical weather models used by the National Weather Service have contributed to an estimated $31.5 billion dollar a year benefit to the US (Lazo et al. 2009).

Seasonal climate forecasts are designed to provide information on climate variability over the next several months. Unlike weather forecasts, they are not intended to provide forecasts for specific dates, but estimates of temperature and precipitation anomalies for the upcoming month of December or December-February, for example. Seasonal climate forecasts take various approaches, but generally rely on linkages between boundary conditions such as ocean temperatures, soil moisture, ice coverage and climate, in addition to the initial conditions that numerical weather forecasts rely on. Seasonal climate forecasts have demonstrated utility for certain seasons and geographic areas; however, they have generally been underutilized in seasonal decision-making. At the same time, the misuse of seasonal forecasts can be detrimental and may limit users' future trust and reliance on seasonal forecasts as guides for decision-making (Hartmann et al. 2002). For example, a water resource manager should not base their decision about how to manage a reservoir exclusively on a seasonal forecast, but information from a seasonal forecast could help them put strategies in place to prepare for a drier than average year (Hartmann et al. 2002).

Climate change projections are designed to provide information on climate statistics over multi-decadal time periods. Unlike weather and seasonal climate forecasts, climate change projections are not designed to yield skillful information about a specific day or month, but rather statistical generalizations about climate over longer term horizons. Climate change projections utilize the same numerical procedures used in numerical weather models and dynamic seasonal forecast models, but also include processes related to integrative aspects of the climate systems including the carbon cycle, vegetation dynamics, and sea-ice dynamics. Individual modeling centers across the world have developed GCMs to conduct such climate experiments. More than 40 models were used in the 5th assessment report of the IPCC, with each modeling group running the same set of experiments with their model to produce a cohesive set of results for comparison. Each modeling group uses different model configurations, including different horizontal resolutions, processes, and feedbacks. The result is a diversity of models that simulate the climate system's response to anthropogenic emissions in various slightly different manners. While this diversity of responses yields "uncertainty" in terms of regional changes in climate, it may be preferable to have a large set of forecasts to draw upon rather than rely on a single or limited set of forecasts (Walker et al. 2003; Hawkins and Sutton 2011).

Selecting the Right Model for the Decision at Hand

Farmers constantly negotiate a wide variety of decisions related to planting and harvesting dates, fertilizer application, financing and insurance, crop varietals and rotations, machinery acquisition, implementing new technology, land use, and more. The range of decisions that dryland small grain producers make require consideration of a variety of different climate-forecasting models. Acquiring and using climate projections has been a challenge for many researchers, let alone agricultural decision-makers. Challenges associated with using outputs from climate model simulations arise for the following reasons: (1) model results are typically stored in formats that require familiarity with computer programming, (2) outputs may be formidably large to download and analyze without high-performance computing, and (3) outputs are often not refined to reflect conditions specific to a location of interest for individual users. These issues create a substantial barrier between data producers and consumers, inhibiting stakeholders' ability to use model outputs to plan for, cope with, or try to optimize climate impacts that may arise in a changing climate (Allen et al. 2015). Fortunately, progress continues to be made in producing, synthesizing, and interpreting climate model projections in a manner that is relevant to agricultural decision-makers.

Researchers are expanding efforts to supply agricultural decision-makers with appropriate tools for specific decisions. It is important to develop an understanding of how to select the right model forecasts for different kinds of decisions. For example, if you were choosing an optimal day for planting within a less-than-10-day range, you would rely on a weather forecast. If, however, you were deciding between planting winter wheat or spring wheat for the upcoming season, you would need a seasonal climate forecast. If you are considering a land acquisition, you would need to review longer term climate change projections to estimate return on investment. There are gaps in this suite of tools: limited information exists for 10–30 day bands and near-term decadal forecasts (next 10–20 years), although these are areas where climate science is rapidly advancing. Emerging research will also support growers in learning from other regions that serve as examples of the future climate of the inland PNW. Such climate analogues can be powerful tools for decision support.

Production Practices for Adaptation and Mitigation

Climate change may exacerbate existing challenges and create new management challenges for inland PNW growers. At the same time, there are likely opportunities associated with a changing climate as other regions increasingly rely on the inland PNW for small grain production, and warmer temperatures and CO_2 fertilization may increase yields for some crops in some locations. Ensuring sustainable small grain production into the future will require growers, policymakers, agriculture industry professionals, and researchers to be familiar with emerging challenges and opportunities. Dryland farmers in the inland PNW have strategies available to them to adapt to changing conditions and, in some cases, work toward climate change mitigation.

Critically important strategies for adapting to increased extreme weather events include improving **soil health** (see Chapter 2: Soil Health), protecting soils from erosion (see Chapter 4: Crop Residue Management), diversifying annual cropping systems (see Chapter 5: Rotational Diversification and Intensification), and monitoring and managing for changing weed, disease, and insect pest pressures (see Chapter 9: Integrated Weed Management, Chapter 10: Disease Management for Wheat and Barley, and Chapter 11: Insect Management Strategies). Ongoing research is investigating the potential benefits of shifting to earlier planting dates and adopting new varieties suited to changing precipitation and temperature regimes.

On-farm climate change mitigation strategies work to reduce greenhouse gas emissions from agriculture while often bringing co-benefits that support long-term sustainability and productivity of farmland. Strategies for mitigation which are applicable to dryland growers include: improving water use efficiency and **nitrogen use efficiency**, reduced tillage or "improved fallow" practices to increase net carbon sequestration (Chapter 3: Conservation Tillage Systems), utilizing organic soil amendments (Chapter 7: Soil Amendments) and using site-specific management to ensure precise application of inputs and reduce greenhouse gas emissions (Chapter 8: Precision Agriculture).

Economic Considerations

Agricultural decision-makers are accustomed to making decisions in the context of multiple uncertainties. Understanding vulnerabilities and risks under future climate conditions is key. For instance, if you are considering land acquisition with a 20–30 year amortization of costs, how should you value—or discount—expected earnings for that period given the range of possible climate futures? Land transactions may be an under-appreciated decision point for farm management because we should no longer assume static climatic conditions (e.g., yield projections or income generation potential) for any given piece of land. A person making a land acquisition decision needs to be able to hedge the investment decision in the context of their relative risk portfolio.

Climate change impacts are likely to change the regulatory context in which producers are operating. Envisioning the future of dryland small grain farming, it is plausible that federal, state, and county programs designed to support farmers and incentivize sustainable farming practices may require increased levels of climate change resilience planning. For more in-depth discussion of changing agricultural policies, see Chapter 12: Farm Policies and the Role for Decision Support Tools.

Previous widely used scenarios describing future social and economic conditions largely neglect to consider agricultural innovations specifically, causing them to be viewed as unrealistic and overly pessimistic by most agricultural analysts. In reality, farming practices are continually developing: practices to manage and monitor the application of fertilizers and pesticides continue to be developed and improved, more energy-efficient machinery is being used on farms, and crops are being developed with new genetic characteristics. Scenarios that account for these various developments in technology, as well as in agricultural trade and policy, enable us to explore specific relationships between global food production and climate (Jones et al. 2016).

Tools and Resources for Growers

The science of climate change impacts on small grain production systems in the inland PNW is rapidly evolving. The authors of this report encourage regional small grain producers to join the community of university-based researchers, Extension professionals, and growers at www.agclimate.net and stay informed about current research and opportunities for continuing education. The informational resources and links to tools listed in this section will be continually updated at on the AgClimate Network website. The following resources will assist growers in accessing: (1) educational material about climate modeling and climate change impacts on inland PNW agricultural systems, (2) locally specific weather and climate data, and (3) decision support tools for agricultural management.

Educational Resources about Climate Modeling and Climate Change Impacts

A Changing Climate for Agriculture: Tools for Kick-Starting Adaptation

https://www.youtube.com/watch?v=7Yc2yPri2hE

Watch this webinar for an up-to-date discussion of how current downscaled climate data can be used to support decision-making in agriculture. This Climate Learning Network webinar presentation by the University of Idaho's John Abatzoglou introduces viewers to several of the climate data resources and decision support tools discussed in this chapter.

What Do We Currently Know about the Impacts of Climate Change on Pacific Northwest Cropland Agriculture?

https://www.surveymonkey.com/r/XFPHB96?sm=RN4RdLEnTR08hZ8awmGxHQ%3d%3d

An accessible webinar presented by Chad Kruger, director of Washington State University's Center for Sustaining Agriculture and Natural Resources. This is a helpful resource for producers looking to get up to speed on the basics of climate change impacts.

Modeling Environmental Change: A Guide to Understanding Results from Models

http://cru.cahe.wsu.edu/CEPublications/FS159E/FS159E.pdf

Written to orient readers from diverse backgrounds to the basics of how environmental models are developed, this Extension publication covers the kinds of input data that go into climate change impact models and considers approaches to defining future scenarios, communicating model outputs, and representing uncertainty.

Assessment of Climate Change Impact on Eastern Washington Agriculture

http://link.springer.com/article/10.1007/s10584-010-9851-4

This is a peer-reviewed analysis of climate change impacts on multiple crops, including dryland wheat, potatoes, and apples in the PNW authored by crop and climate scientists. You can expect to see an updated version of this analysis based on the latest climate model projections in the near future.

Agriculture: Impacts, Adaptation, and Mitigation

http://cses.washington.edu/db/pdf/daltonetal678.pdf

A chapter in the 2013 publication Climate Change in the Northwest, this resource outlines the wide range of projected climate change effects on agriculture in the Northwest US. This is an accessible yet relatively in-depth discussion of the state of current scientific knowledge.

Weather and Climate Data

Climate Engine

http://climateengine.org

A number of spatially and temporally complete historical and current near-surface climate and weather datasets now exist. These data are based on a vast network of place-based observations and overcome some flaws in earlier datasets linked to gaps in observations, sparseness of stations in some regions, and inconsistent variables that were recorded. Abatzoglou (2013) developed a gridded surface meteorological dataset that includes temperature, humidity, winds, solar radiation, and precipitation (***http://metdata.northwestknowledge.net***). To make these data more accessible, the University of Idaho and the Desert Research Institute developed Climate Engine, which lets users analyze maps, examine time series, and download digital data without needing to process the entire data archive.

Office of the Washington State Climatologist

http://www.climate.washington.edu

The Washington State Climatologist collects, shares, and interprets climate data from various sources. The website distributes peer-reviewed climate and weather information for governmental and private decision-makers working on drought, flooding, climate change, and related issues.

National Oceanic and Atmospheric Administration Climate Data Online

https://www.ncdc.noaa.gov/cdo-web/

The Climate Data Online website provides access to the National Climate Data Center's archive of global historical weather and climate data, as well as weather station history information. These data include daily, monthly, seasonal, and yearly measurements of temperature, precipitation, wind, and growing degree days as well as radar data and 30-year climate averages.

AgWeatherNet

http://weather.wsu.edu

Washington State University's AgWeatherNet provides current and historical weather data from WSU's network of 178 automated weather stations. The weather network is managed by the AgWeatherNet team, located at the WSU Irrigated Agriculture Research and Extension Center in Prosser, Washington. WSU's automated weather stations are located primarily in the irrigated regions of eastern Washington. Variables tracked by AgWeatherNet include air temperature, relative humidity, dew point temperature, soil temperature at 8 inches, precipitation, wind speed, wind direction, solar radiation, and leaf wetness. Some stations also measure atmospheric pressure. These variables are recorded every 5 seconds and summarized every 15 minutes by a data logger. The website also connects users with models and decision aid tools.

REACCH Climate and Weather Tools

http://climate.nkn.uidaho.edu/REACCH/climateTools.php

Researchers involved with the Regional Approaches to Climate Change (REACCH) project developed a web tool for agricultural decision makers to get information about location-specific historical climate, current weather, seasonal forecasts and future projections. An example summary table of a number of climate metrics that could be important for agriculture is shown in Figure 1-6. The user can select a location and obtain a summary of contemporary climate normals and projected changes for different time periods.

Decision Support Tools for Agricultural Management

REACCH Decision Support Tools

http://climate.nkn.uidaho.edu/REACCH/decisionTools.php

Related to REACCH's climate and weather tools discussed above, REACCH scientists developed a suite of web-based decision support tools. These tools focus on decision-making issues specific to the crops in the inland PNW. Both short-term decisions, such as scheduling fertilizer application and pest management practices, as well as long-term decisions, such as assessing specific locations for crop suitability, are supported.

AgClimate Atlas

http://climate.nkn.uidaho.edu/NWTOOLBOX/mapping.php

The AgClimate Atlas is a web-based application developed by University of Idaho researchers with support from the USDA NW Climate Hub. The atlas provides downscaled climate data and derived climate metrics including cold hardiness, growing degree days, and reference evapotranspiration that

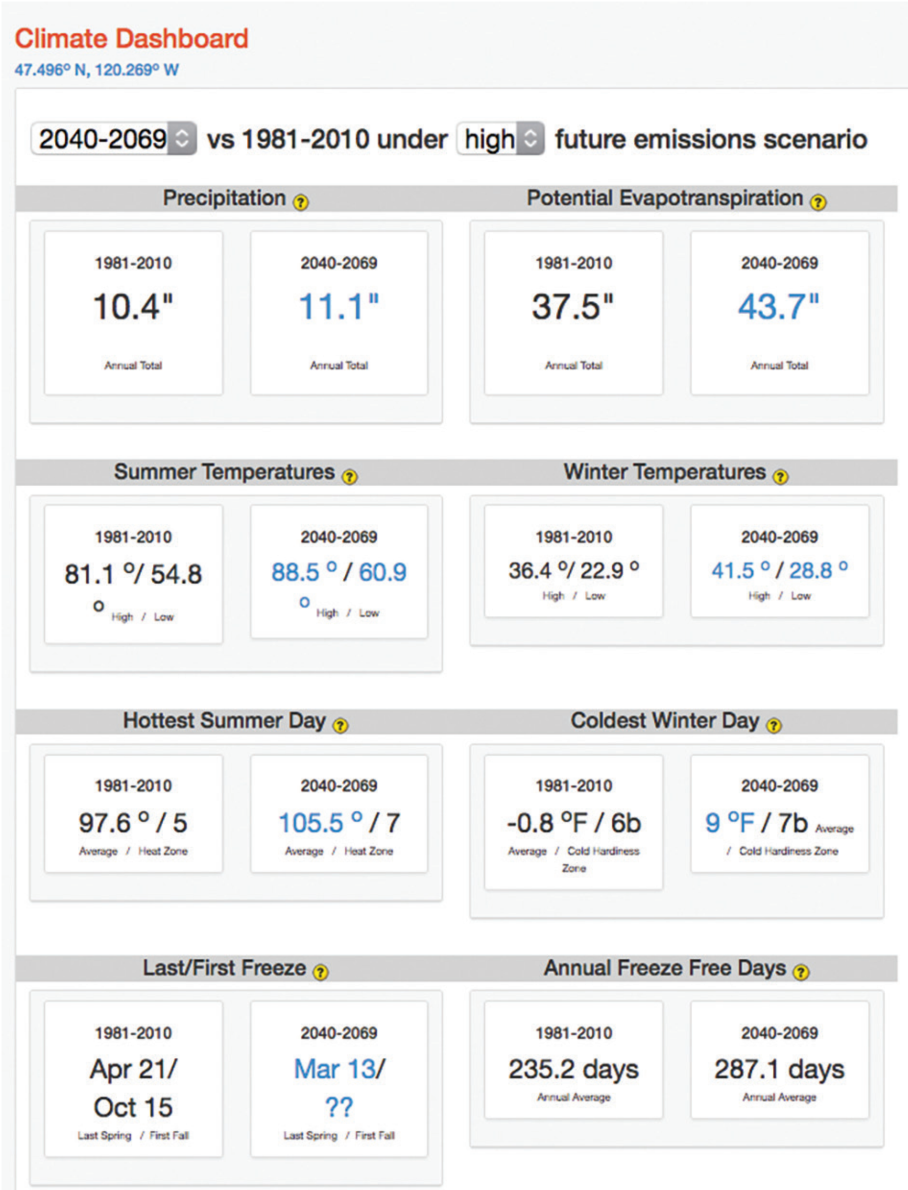

Figure 1-6. Regional Approaches to Climate Change (REACCH) climate and weather tools sample summary table.

may be useful for agricultural decision making. For example, certain wine grape varietals have growing degree day requirements (base 50°F) that are not currently met across much of the Northwest, providing one limitation on cultivation. However, by the mid-21st century, additional warming is projected to result in a large increase in accumulated heat that may allow for those varietals to reach maturation in the region. Users can select from a variety of metrics, climate scenarios, models, and time horizons (for example, early, mid, or late 21st century). Users can also “mouse” over to extract information for a specific pixel, or download these maps in a format that can be used in ArcGIS or equivalent GIS software.

Integrated Scenario Tools

http://climate.nkn.uidaho.edu/IntegratedScenarios/index.php

The Northwest Climate Science Center funded a project to create a coordinated set of climate, hydrology, and vegetation scenarios called Integrated Scenarios of the Future Northwest Environment. Researchers at the University of Idaho developed tools to visualize data from that project. For example, for irrigated crops in the Northwest, the amount of water storage in the mountain snowpack and the timing of streamflows are key factors. Using the streamflow web tool (***http://climate.nkn.uidaho.edu/IntegratedScenarios/vis_streamflows.php***) users can see graphs that project substantial drops in streamflow during June-August when irrigation demand peaks.

Conclusion

Consistent with global trends, the PNW is projected to experience substantial shifts from historical climate patterns in the coming century. The specific effects of climate change on dryland cropping systems in the inland PNW are expected to be variable over time and variable from one location to another. In the near term, longer growing seasons and increased CO_2 fertilization may lead to increasing yields for dryland cereals in the region. However, later in the 21st century, projections suggest that heat and drought stress and changing pest and disease pressures along with increased incidences of extreme weather events will likely pose new challenges for inland PNW producers. It is hoped that this guide will be informative for regional growers operating under diverse local conditions and utilizing a range of production strategies. This guide, and the tools and resources discussed within, are intended to support producers in identifying appropriate management strategies to ensure the long-term profitability and sustainability of dryland small grain production in the inland PNW.

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