Economic Impacts of Climate Change on Agriculture in Idaho

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Key Messages

- The agricultural sector comprises a substantial share of overall economic activity in Idaho, especially in the Magic Valley region of southern Idaho.
- Climate variables are inherently linked with agricultural production-related variables (e.g., yields).
- The Idaho climate is projected to change substantially under the business-as-usual (BAU) global CO_2 emissions scenario, RCP8.5, with projections of higher maximum and minimum temperatures, more frequent high precipitation events, and longer frost-free seasons.
- Findings in the existing peer-reviewed literature show that projected changes in climate variables will have effects of differing magnitudes on livestock and crop production; some crops (e.g., onions) are observed as more sensitive to changes in variables (e.g., temperature) than are grains.
- Changes in surface water and groundwater availability (as influenced by snowpack levels, associated runoff flows, and timing and water management decisions) and producer responses to shifting water availability will likely influence the performance of agriculture in Idaho over the next several decades.
- Idaho farmers and their stakeholder partners are already demonstrating ingenuity and leadership in experimenting with and adopting new practices and methods that may help mitigate some risks associated with the projected changing climate.

1. Introduction

The agricultural sector comprises an important part of the Idaho economy, with agriculture and food and beverage processing accounting for over 18% of total business sales (Idaho State Department of Agriculture (ISDA), 2020). Conditions in the sector influence the lives of all Idahoans to at least some degree through provision of food that fuels daily activities. The goal of this report is to describe the economic risks and opportunities for the Idaho agricultural sector in the context of climate change. The report describes current conditions in the Idaho agricultural sector, observed changes in Idaho's climate and trends in agricultural productivity over the past several decades, projected changes in Idaho's climate and agricultural productivity for key subsectors, specific effects of the changing climate on key agricultural subsectors as identified in the peer-reviewed research literature, the important linkages between water availability and agricultural sector performance, and existing evidence of adaptation strategy adoption by Idaho farmers.

Given the uncertainty regarding future conditions for the climate, environmental resource policy, agricultural markets, demographics, and general macroeconomic conditions, a numerical estimation of economy-wide variables was not calculated. However, the report provides stakeholders essential information that characterizes the linkages between climate and agricultural production and the risks and opportunities based on their location, current climate conditions, and projections for future climate and water availability. Additionally, many plausible adaptation strategies that Idaho farmers and ranchers may adopt in response to future changes in climate are provided. Such insights can be used by policymakers and stakeholders to consider potential impacts on their own institutions and businesses and plan appropriate responses. The interactions between adjustments in grower practices in the context of climate change, and especially the effects of such shifts on water availability, will be key to explaining the performance of the Idaho agricultural sector in the decades ahead.

2. Agriculture in Idaho

The agricultural sector is an important provider of goods and services and employment in Idaho (Eborn and Taylor, 2019). The agricultural sector share of state GDP is also higher in Idaho than for all neighboring states. For 2019, the share of agriculture in state GDP estimates for the neighboring states of Washington, Oregon, Nevada, Utah, Wyoming, and Montana ranged from 0.9% for Nevada to 5.2% for Montana, while that for Idaho was 8.9% (University of Arkansas, 2021).

Table 1 below includes cash receipts data from the United States Department of Agriculture (USDA) Economic Research Service (ERS) for 2019 and the average shares of total Idaho cash receipts for 2015-2019 for ten key agricultural commodities produced in Idaho. The data show that the Idaho agricultural sector is dominated by dairy and cattle industries. The importance of their shares on overall economic activity is even larger when considering that most hay and corn and some wheat and barley is used as cattle and milk cow feed. While not as large as livestock, crops, such as potatoes, hops, pulses, and onions combined, contribute over 25% of Idaho's agricultural cash receipts.

The main takeaways from Table 1 are that performance of the dairy and livestock industry has a substantial impact on the overall performance of Idaho's agricultural economy and the relative shares for each individual commodity can fluctuate from year-to-year as prices and production vary in response to changing market conditions.

Table 1. Estimates of cash receipts for 2019 and average shares for 2015-2019 for ten key commodities in Idaho

Commodity	2019 cash receipts (in millions)	Average share of total Idaho cash receipts for 2015-2019
Milk	$2,854	33.3%
Cattle and calves	$1,736	23.4%
Potatoes	$953	12.1%
Wheat and barley (combined)	$697	9.2%
Hay	$468	5.5%
Corn	$118	1.1%
Hops	$89	0.9%
Pulses (dry beans, lentils, and dry peas combined)	$69	1.3%
Onions	$66	0.8%
Trout	$37	0.6%

Source: Authors' calculations using data from USDA-ERS (2021).

Much like there is great diversity in climate throughout the state, as described by Abatzoglou et al. (2021) in the Climate Report of this assessment, the distribution of agricultural commodity production also varies across regions. For example, the vast majority of dairy cows and dairy processors are located in southern Idaho, especially in the Magic Valley of south-central Idaho. USDA National Agricultural Statistics Service (NASS) data for 2020 show that there were 635,000 milk cows in Idaho, and of those, over 400,000 (64%) were in the Magic Valley counties of Cassia, Gooding, Jerome, and Twin Falls. Due to grassland and rangeland pasture feeding (see Figure 1 for spatial distribution of grass/pasture throughout Idaho), beef cattle are more evenly distributed throughout Idaho. However, beef cattle populations are more predominant in southern Idaho relative to northern Idaho. The central mountain counties of Lemhi, Idaho, and Valley also have substantial beef cattle populations. The same data show that for 2020, the top five counties for number of beef cattle, with their respective regions per Figure 2 in parentheses, were Owyhee (West), Bingham (East), Cassia (Central), Twin Falls (Central), and Lemhi (East) (USDA-NASS, 2020a).

Crop production in Idaho is distributed across two principal areas: along the Snake River Plain that stretches across southern Idaho and the Columbia River aquifer region that covers much of northern Idaho. A more diverse set of crops, including potatoes, feed crops, hops, and onions are grown in southern Idaho than in northern Idaho where wheat, barley, and pulse crops predominate. This pattern of cropland spatial distribution can be observed in Figure 1 for which cropland area for 2020 is plotted using data from the USDA-NASS CropScape – Cropland Data Layer (USDA-NASS, 2020b). While the general distribution of cropland as concentrated along the Snake River in southern Idaho and in the Columbia River aquifer region in northern Idaho is clearer than the specific crop distribution due to the nature of the data, the more specific distribution can be observed in greater detail in Figure 1.

While trout production is somewhat small relative to other commodities in its share of overall cash receipts, the industry is concentrated in the Magic Valley; producers in this region of Idaho account for about 75% of trout consumed in the U.S. (Hines et al., 2018).

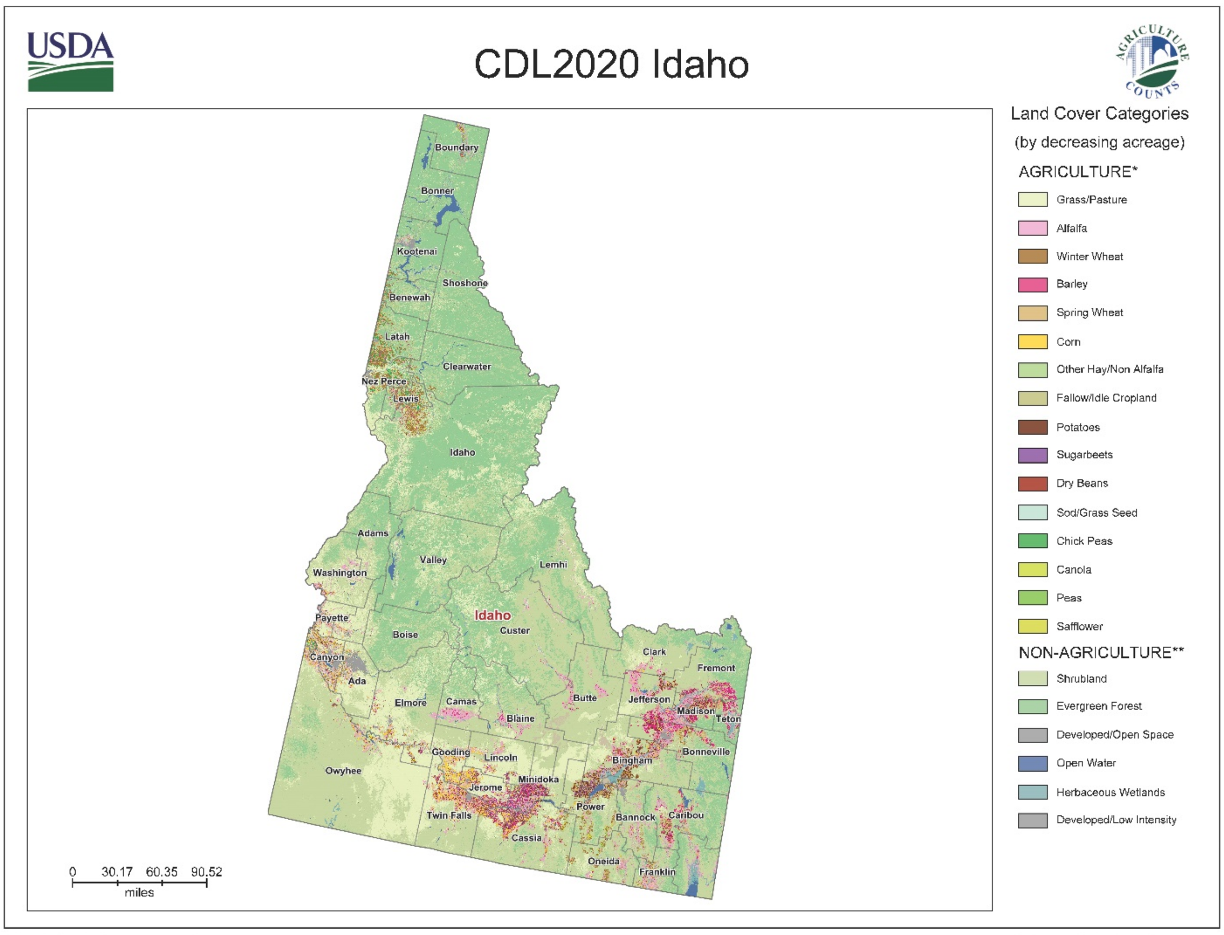
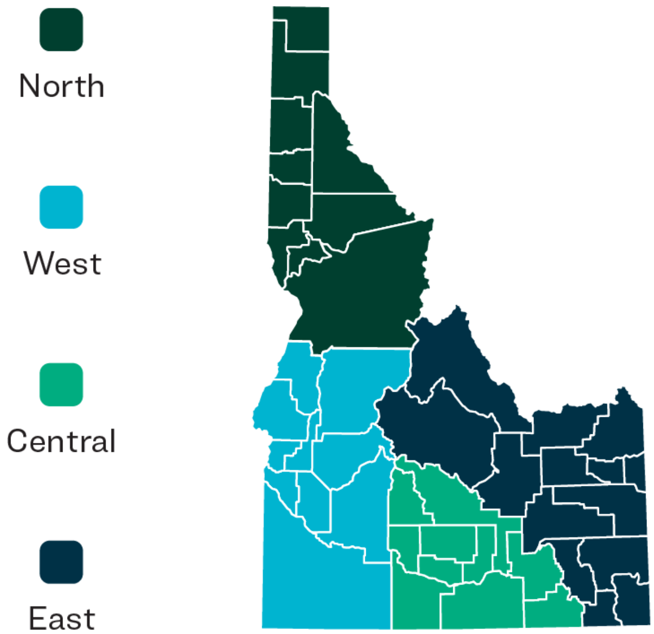


Figure 1. USDA-NASS CropScape for Idaho 2020 (USDA-NASS, 2020b).

Since a semi-arid climate, with low levels of overall annual and growing season precipitation, predominates in southern Idaho, investments in water storage infrastructure (dams and reservoirs) along the Snake River and its tributaries have allowed for agricultural production with irrigation since the early 20th century (Hansen et al., 2014). These dams and reservoirs and the underlying groundwater aquifers store water that is primarily supplied as melted snow runoff from winter snowpack in the central Idaho, southern Montana, and eastern Wyoming mountains during the spring and early summer months (Klos et al., 2015; Humes et al., 2021). Thus, performance of the Idaho agricultural sector is highly reliant on snowpack conditions that are observed in the winter months and springtime temperatures, since these climate variables are the driving factors for snow runoff volumes and streamflow characteristics.

To further examine the extent of regional heterogeneity for agricultural productivity and climate (section 3), the four University of Idaho Extension districts shown in Figure 2 were used for calculations of select agricultural production-related variables at the regional scale.



Source: University of Idaho Extension

Figure 2. Map of University of Idaho Extension districts.

The data in Table 2 are shares of total state production by region for several of Idaho's major agricultural crops and livestock. These data provide indications of the extent of regional sectoral concentration. The table is a "heat map," in which colors are used to indicate the differences in relative magnitudes of the presented data. In this case, the colors indicate relative shares that range from low (green) to high (red), with yellow and orange as intermediary indicators. The "heat map" format allows for easily identifying specific region and sector combinations that indicate substantial concentration (red) and qualitatively comparing those cases to region and sector combinations that are more evenly distributed (yellow or orange).

It is observed that there are several region and sector combinations that have substantial concentration. These are dairy in the central region (i.e., the Magic Valley), chickpeas in the northern region, and onions and hops in the western region. The concentration of these sectors in specific regions implies that climate change effects in the region of concentration may have relatively pronounced effects on the overall industry regarding its contribution to statewide agricultural production. Regarding practical implications of these data, one could suggest that stakeholders in the central region pay particular attention to adaptation plans for the dairy industry as climate projections are updated. The same applies for chickpeas in the northern and onions and hops in the northern and western regions, respectively.

Table 2. Heat map with shares of total state production by region for major crops and livestock Idaho

Region	**Dairy** (number of dairy cows, 2020)	**Cattle** (number of beef cows, 2020)	**Potatoes** (acres harvested, 2002)	**Hay** (production, 2018)	**Barley** (production, 2019)	**Wheat** (production, 2018)	**Dry beans** (production, 2018)	**Chickpeas** (production, 2018)	**Onions & Hops** (acres harvested, 2017)	**Trout** (number of aquaculture operations, 2017)
East	6%	43%	58%	42%	60%	43%	0%	1%	0%	22%
Central	74%	23%	35%	35%	33%	19%	30%	0%	0%	43%
West	21%	24%	8%	20%	1%	5%	10%	0%	100%	14%
North	0%	9%	0%	3%	5%	32%	59%	99%	0%	20%

Sources for production share data: USDA-NASS (2020a), USDA-NASS (2019), and USDA-NASS (2004).
Note: Data presented are shares of production and region. The colors indicate differences in relative production shares across regions. Green indicates low shares and red high shares, while yellow and orange are intermediary indicators.

There are several main takeaways from this section that describe current conditions in the agricultural sector in Idaho. First, the agricultural sector is an important source of economic output and employment in Idaho; performance of the sector has important implications for the livelihoods of many Idahoans. Second, the dairy and cattle industries comprised over half of agricultural cash receipts in the past decade; performance of these sectors is important for the broader agricultural industry. Third, crop production, including for crops used as livestock feed, is concentrated along the Snake River in southern Idaho, where surface water and groundwater irrigation are relied on as the primary source of growing season soil moisture. Lastly, several industries, and most notably the dairy industry in southern Idaho, currently have substantial regional concentration. Such industrial clustering can provide benefits, such as more efficient supply chain connections, and may offer an opportunity to readily share information on adaptation strategies for changes in climate.

3. Climate and Agriculture

Discussion of the general linkage between weather and agriculture may be stating the obvious; however, investigation of the relationships between individual weather-related variables (e.g., temperature) and agricultural production-related variables (e.g., yield) transitions quickly from general to complex. The many weather-related variables and crop and livestock species make for multiplicative numbers of variable combinations to examine. That these variables commonly interact with each other further exacerbates the convolution.

While acknowledging these complexities exist, the goal for this analysis is to describe key climate- and agricultural production-related variables in the context of current conditions in the Idaho agricultural economy and describe what climate change projections imply for impacts on future agricultural economic conditions.

Projecting the expected effects of climate on agricultural production into the future utilizes existing knowledge of weather variable effects on agricultural production and adjusts those weather variables to reflect their plausible level and variation in the future. While error exists in any projection of future conditions, scientists are increasingly more accurate in forecasting of both future weather and climate due to the improved availability of atmospheric data and sophisticated modeling to provide estimates of outcomes for future climate.

4. Observed and Projected Changes for Climate and Idaho Crop Productivity

With the basic linkages between agriculture and climate described, this report shifts focus toward current conditions regarding climate and agricultural productivity in Idaho. Focus is placed on crop productivity, as the linkages between climate and production are more observable in USDA-NASS production estimates for crops than livestock. On the global scale, Ortiz-Bobea et al. (2021) found that climate change has caused agricultural productivity to decline by an estimated 20.8% from 1961 to 2020. The extent of decline in productivity is heterogeneous across regions, with the largest declines observed in Africa and Latin America and the Caribbean. Productivity in North America was estimated to have dropped by about 12.5% over this period. However, Canada and Russia were observed to have increases in agricultural productivity and the extent of productivity losses were generally lower for higher latitude countries (Ortiz-Bobea et al., 2021).

Observed climatic changes in Idaho

The global average annual temperature has increased by 1ºC since 1960, on an average. A band of country-level changes extends from 0.5ºC to greater than 1.5ºC changes (Ortiz-Bobea et al., 2021). Klos et al. (2015) found that Idaho temperatures have increased by about 0.24ºC per decade from 1975 to 2010, which means that as of 2020, following the decadal average increase, Idaho's temperature increases have been near or slightly above the global average of 1ºC. The other main climate-related variable directly related to agriculture that was identified by Klos et al. (2015) to have changed significantly in Idaho from 1975 to 2010 was growing season length. Specifically, the growing season was estimated as being 3.9 days longer in 2010 than in 1975. While not statistically significant, snowpack levels as of April 1 were found as generally lower in 2010 compared to 1975. The combination of higher mean annual temperatures and longer growing season implies that there are greater risks for water availability for agriculture and other uses, but also opportunities to grow different crops today than existed decades ago.

Observed Idaho crop productivity trends

The evidence that increasing temperatures have had broadly negative but heterogeneous impacts on agricultural productivity globally implies that increasing temperatures in Idaho also plausibly have differential effects on productivity across crops. This is supported by additional findings that about 60% of global food production is rainfed and that irrigation expansion is a principal adaptation strategy in response to increasing temperatures and reducing heat stress in plants (Rosa et al., 2020). Actual agricultural productivity implications of climate change are influenced by producer decisions, including those pertaining to water, nutrient, and pest and weed management (Ward, 2014; Ortiz-Bobea et al., 2021).

Figure 3 includes a set of plots of yield data from USDA-NASS (2021c) for select Idaho crops for 1960 to 2020 (for some crops the observation period is shorter due to data availability). These plots are provided to examine the trends in crop productivity over the period in which annual average temperatures in Idaho were, based on estimates in Klos et al. (2015), to have increased by over 1ºC. There are several main observations from the yield plots in Figure 3. First, Idaho crop yields have trended upward for most examined crops. This implies that productivity has increased on average over the observation period. Second, in Idaho, yields of non-irrigated crops (alfalfa hay, chickpeas, wheat, and barley) are substantially more variable than those for irrigated crops.

The Idaho crop production data plotted in Figure 3 are also presented in Table 3 as averages in growth rates for individual decades within the observation period. These average growth rate data provide an alternative measure for the trends in productivity over the observation period of 1960 to 2020 (shorter observation period for some crops). The data show that average growth rates in the state were positive over most of the observation period. However, fluctuations in yield growth rates were generally larger for non-irrigated than irrigated crops.

There are two main takeaways from the data in Figure 3 and Table 3. First, there have been lower relative changes in yields from year-to-year for irrigated versus non-irrigated crops in Idaho. This observation of lower production risk due to use of irrigation in the Idaho context provides insights into why farmers elsewhere in the U.S. and world adopt irrigation as a primary strategy to reduce production risk from factors, such as increasing temperatures. Second, productivity has generally increased for most of Idaho's main crops over the past several decades. However, the upward trends are steeper for irrigated crops and non-irrigated crop yields have much wider variability. The next subsections describe the projected changes in climate and productivity trends for several major Idaho crops in the upcoming decades.

Figure 3. Observed yields for select Idaho crops for years spanning from 1960 to 2020 (USDA-NASS, 2021c).

Note: Data were not available for the full period for all crops. The associated data periods for the crops for which data were incomplete are as follows: irrigated and non-irrigated wheat and irrigated and non-irrigated barley: 1960-2008, irrigated and non-irrigated alfalfa hay: 1988-2008, chickpeas: 1992-2020, and onions: 2015-2020.

Table 3. Average annual growth rates for major crops grown in Idaho for decades spanning from 1960 to 2020

Years	Potatoes	All wheat	Irrigated wheat	Non-irrigated wheat	All barley	Irrigated barley	Non-irrigated barley
1960 – 1969	3.63%	3.77%	2.58%	5.11%	7.87%	3.93%	7.60%
1970 – 1979	2.08%	2.01%	2.47%	0.84%	1.80%	1.93%	2.66%
1980 – 1989	0.94%	3.71%	1.32%	6.60%	2.63%	2.07%	5.94%
1990 – 1999	1.64%	1.74%	1.85%	1.20%	1.23%	0.72%	2.02%
2000 – 2009	2.19%	0.60%	0.67%	-0.66%	2.86%	1.83%	6.44%
2010 – 2020	0.83%	2.15%	…	…	1.50%	…	…

Years	All hay	Irrigated alfalfa hay	Non-irrigated alfalfa hay	Chickpeas	Hops	Onions
1960 – 1969	1.99%	…	…	…	0.96%	…
1970 – 1979	0.72%	…	…	…	-0.60%	…
1980 – 1989	1.94%	2.45%	44.88%	…	-0.68%	…
1990 – 1999	0.03%	0.03%	6.45%	43.73%	0.21%	…
2000 – 2009	0.39%	1.35%	0.42%	1.68%	4.01%	…
2010 – 2020	1.02%	…	…	2.88%	0.26%	3.24%

Source: USDA-NASS (2021c).
Note: Data were not available for the full period for all crops. The associated data periods for the crops for which data were incomplete are as follows: irrigated and non-irrigated wheat and irrigated and non-irrigated barley: 1960-2008, irrigated and non-irrigated alfalfa hay: 1988-2008, chickpeas: 1992-2020, and onions: 2015-2020.

Projected climatic changes in Idaho

This subsection focuses on climate projections for Idaho through the mid-21st century. Several key sources were consulted to identify the expected impactful factors related to climate change on agriculture in Idaho. The first key source is the USDA-ARS report from 2013, led by Dr. Charles Walthall, the National Program Leader for the USDA-ARS Climate Change, Soils and Air Quality Research Program, which is a comprehensive investigation into the effects of climate change on agriculture in the U.S. This report characterizes abiotic, or direct, effects from changes to atmospheric conditions on processes, such as plant photosynthesis, and biotic, or indirect, effects from adjustments in pest pressures and other ecosystem characteristics associated with the changing climate (Walthall et al., 2013). The second key source is a similar report by Bowling et al. (2018) with a focus on such effects on agriculture in Indiana. The third key source is the Climate Report of this assessment, which describes future climate projections for Idaho.

A synthesis of the climate-related variables of focus in Walthall et al. (2013), Bowling et al. (2018), and the Climate Report is included in Table 4. It is observed that the climate variables of focus for each report fall under three main categories: atmospheric composition, temperature, and precipitation. Within these sets are individual variables, such as higher CO_2 levels and growing season temperatures.

Table 4. Synthesis of climate change-related variables identified as impacting agriculture in three key reports

	Walthall et al. (2013) – U.S.	**Bowling et al. (2018) – Indiana**	**Abatzoglou et al. (2021) - Idaho**
Atmosphere	• Higher CO_2 levels • Potentially lower solar radiation due to increased cloud cover	• Higher CO_2 levels	• Higher CO_2 and other greenhouse gases
Precipitation	• Higher likelihood of extreme precipitation events	• Increased annual, winter, and spring precipitation • Increased frequency of high precipitation events	• Increased winter/spring precipitation • Greater precipitation intensity
Temperature	• Higher temperatures during growing season and pollination • Increased nighttime temperatures	• Warmer annual, seasonal, and growing season temperatures • Longer frost-free periods • Increased frequency and magnitude of extreme heat events	• Warmer temperatures in all seasons • Warmer, drier summers and more heat stress days • Significant warming of coldest night of the year and minimum daily temperatures • Longer freeze-free season
Interaction between changes in atmosphere, precipitation, and temperature		• Reduced plant-available water due to longer periods between precipitation and higher plant water demand due to higher temperatures	• Increased temperature and higher evaporative demand may increase demand for irrigation

Due to the regional variation in agricultural production across the state, projections for two key climate variables that are highlighted in the Climate Report and important for agriculture, frost-free season lengths and "heat stress" days with greater than or equal to 100°F temperatures, were examined at a regional scale. These variables are more specific measures of increased temperatures. Such calculations allow for comparison of regional differences regarding annual heat stress days and frost-free period lengths for the historical period of 1971-2000 (late 20th century) and the future period of 2040-2069 under the greenhouse gas emissions scenario of Representative Concentration Pathway (RCP) 8.5 (also referred to as the Business-as-Usual (BAU) CO_2 emissions scenario). Mid-century projections are less sensitive to choice of RCP; differences between RCP4.5 and RCP8.5 are most important for late century projections. The primary data source is the Climate Toolbox developed by Hegewisch et al. (2021), which relies on gridMET (i.e., METDATA) data (Abatzoglou, 2013). Regional estimates of the climate measures were obtained for Idaho and then each of the University of Idaho Extension districts (Figure 2). With these gridded climate datasets, each pixel contains information on modelled climate variables (e.g., minimum temperature, maximum temperature). To illustrate the calculations for the case of average annual heat stress days during the period 1971-2000, a pixel representing a specific location had an associated value of 5. This means that this location had an annual average of 5 days over 100°F from 1971 to 2000. Such values for every pixel in each region were grouped together to obtain regionally estimated ranges.

The regionally aggregated data for annual average heat stress days are displayed in Table 5. It is observed that for the historical period 1971-2000, the share of area in Idaho with 1 or more heat stress days was 6.9% and the maximum value was 5 days for a location in western Idaho. The projections for the period 2040-2069 under the BAU emissions scenario show nearly the same percentage of area (5.4%) will experience an annual average of 25 or more heat stress days. While all regions are expected to have an increased percentage of area that experiences heat stress conditions under the BAU scenario, the projected changes in the central and western regions are above the statewide averages, while those in the eastern and northern regions are below the statewide averages. The extent of heat risk is expected to increase more in central and western Idaho than eastern and northern Idaho under the BAU CO_2 emissions scenario.

Table 5. Estimates of annual heat stress days for Idaho by region

	Annual heat stress days					
	Historical for 1971-2000		Projected for 2040-2069 under business-as-usual greenhouse gas emission scenario			
	Percentage of area with 1 or more heat stress day	Max value	Percentage of area with 1 or more heat stress day	Percentage of area with 10 or more heat stress days	Percentage of area with 25 or more heat stress days	Max value
Idaho	6.9%	5	61.8%	18.5%	5.4%	45
East	0	0	47.1%	2.7%	0	19
Central	2.4%	2	81.8%	34.3%	3.3%	37
West	21.6%	5	70.5%	35.3%	17.5%	45
North	3.3%	4	58.3%	10.7%	1.0%	37

Source: Authors' calculations using data from Hegewisch et al. (2021).

The data for historical and projected annual average of frost-free season lengths are shown in Table 6. These data are presented with various ranges of the annual average of frost-free season in days with an associated area. For the historical period of 1971-2000, most of Idaho had an annual average frost-free season ranging between 101 and 250 days. Under the BAU CO_2 emissions scenario, it is projected that in 2040-2069, most of Idaho will have longer frost-free seasons. Specifically, the associated frost-free season range is projected to shift to between 151 and 300 days. However, as was observed with annual heat stress days, there are regional differences with respect to the extent of changes. The percentage of area with a projected annual average frost-free season length of more than 200 days under the BAU CO_2 emissions scenario exceeds 50% for all regions except eastern Idaho.

Table 6. Estimates of frost-free season length for Idaho and by region

	Frost-free season length			
	Historical for 1971-2000		Projected for 2040-2069 under business-as-usual greenhouse gas emission scenario	
	Range of frost-free season (in days)	Percentage of region within range	Range of frost-free season (in days)	Percentage of region within range
Idaho	54 to 100	1.9%	108 to 150	2.3%
	101 to 150	25.0%	151 to 200	27.9%
	151 to 200	48.7%	201 to 250	38.2%
	201 to 250	23.6%	251 to 300	29.4%
	251 to 296	0.8%	301 to 342	2.2%
East	77 to 100	0.9%	125 to 150	1.6%
	101 to 150	45.0%	151 to 200	52.3%
	151 to 200	53.6%	201 to 250	45.1%
	201 to 209	0.4%	251 to 264	1.0%
Central	76 to 100	0.6%	119 to 150	1.0%
	101 to 150	9.5%	151 to 200	11.8%
	151 to 200	62.0%	201 to 250	49.7%
	201 to 232	27.8%	251 to 293	37.4%
West	60 to 100	2.3%	114 to 150	2.8%
	101 to 150	19.6%	151 to 200	20.5%
	151 to 200	38.5%	201 to 250	34.5%
	201 to 250	39.3%	251 to 300	41.0%
	251 to 255	0.3%	301 to 310	1.2%
North	54 to 100	3.4%	108 to 150	3.5%
	101 to 150	16.5%	151 to 200	16.4%
	151 to 200	44.7%	201 to 250	26.6%
	201 to 250	32.6%	251 to 300	46.2%
	251 to 296	2.8%	301 to 342	7.4%

Source: Authors' calculations using data from Hegewisch et al. (2021).

Projected productivity changes for Idaho crops under higher temperatures and CO_2 levels

Rajagopalan et al. (2018) estimated the yield impacts for several key crops grown under irrigation in the Columbia River Basin from projected higher temperatures and CO_2 emissions through 2030 under climate scenarios similar to the BAU scenario. The examined crops that overlap with those of focus in this report include hay, hops, potatoes, and wheat. It is important to note that all of these projections are for crops grown under irrigation and assume there is no heat stress (Rajagopalan et al., 2018).

Rajagopalan et al. (2018) made several key observations regarding changing climate effects on growing season characteristics that underly their yield projections. First, the growing seasons for most evaluated annual crops grown under irrigation are expected to both start and end earlier. Growing seasons for annual crops are expected to be shorter and perhaps upwards of 20 days shorter for potatoes. Second, irrigation demand is projected to be greater overall and especially early in the growing season. Summer irrigation demand is projected as higher overall, but lower in the late summer due to the shift to an earlier and shorter growing season. Temperature is the main driving factor of these projected increases in irrigation demand.

Regarding projections for specific crops and those of focus in this report, for potatoes and wheat, increases in CO_2 are projected as positively related to irrigated yields, while temperatures are negatively related to yields. Increases in CO_2 and temperature are both projected to increase yields for hay and hops. The net effect of increased temperature and CO_2 on irrigated yields is positive for hay, hops, and wheat, but negative for potatoes (Rajagopalan et al., 2018).[1]

Although Rajagopalan et al. (2018) provided estimates of projected productivity effects for many of the main crops grown in Idaho through the 2030s in the context of increasing temperatures and CO_2, consultation of findings in peer-reviewed research is needed to provide a more thorough description of the mechanisms through which climate change affects agricultural production. Thus, several experts in their respective sectors provide such a peer-reviewed research approach in the next section. Focus was placed on describing expected risks and opportunities that may arise due to the changing climate regarding production, storage, and/or processing by livestock or crop type. The next section starts with a more general review of expected impacts on soil and weeds, since they are influential for performance of the overall agricultural sector.

5. Effects of Climate Change and Economic Impacts by Agricultural Sector Effects and Other Resource Constraints

Soil

Contributor: Linda Schott

Soil is composed of biotic (e.g., plants and insects) and abiotic (air, minerals, and water) matter and the interaction among the components adjusts in response to environmental change. Although it only makes up between 1-5% of soil by volume, one of the most important elements of soil is organic matter. Soils that have increasing or sustained concentrations of soil organic matter are often labeled as 'healthy' or 'sustainable.' Key services that healthy soil provide

[1] See Figure 4 on p. 2162 in Rajagopalan et al. (2018) for a visual summary of these results.

include anchoring plant roots; providing air, water, and nutrients for plants to grow; serving as a suitable habitat for soil fauna; acting as a water filtration system; and supporting buildings, roads, and other structures (Kibblewhite et al., 2008).

Bowling et al. (2018) described how the principal effect of increasing air temperatures on soils is the increased rate of decomposition of soil organic matter. Depending upon soil texture and other inherent properties, a reduction of soil organic matter can lead to a reduction of both soil water holding capacity and a soil's ability to infiltrate water (Bowling et al., 2018). Changes in water filtration can also be impacted by the extension of the frost-free season. When soil freezes, compaction is reduced, since the freezing expands the soil minerals. By extending the frost-free season, water filtration can be reduced because compacted soil is less effective at filtering water, especially in the absence of other materials that can reduce soil compaction (e.g., plant roots) (Martin, 2021).

The increased likelihood of abnormally high precipitation events in combination with more compacted soil can increase the risk of water-related erosion. The risk of such nutrient losses due to water runoff varies by soil type and its inherent ability to infiltrate water. Soil compaction can also limit plant growth and the observation that soil compaction is greater under dry soils implies that there is a critical compounding negative effect on plant growth with increasing temperatures and associated evapotranspiration (Magdoff and Van Es, 2009).

One of the main ways to reduce the risk of soil compaction, increase infiltration, and build organic matter is to plant cover crops. However, there is a fundamental issue in that these benefits from cover crops can only be realized if the cover crop can be successfully established, which is often difficult in semi-arid climates. Since establishing a cover crop influences all components of the soil, including moisture availability for cash crop production, the decision to grow cover crops is complex (Idowu and Grover, 2014). The consideration of planting cover crops in Idaho may, however, become increasingly important with the prospects for increasing temperatures and associated decomposition of soil organic matter in the future. Other practices, such as reducing tilling, can add similar soil attribute benefits to cover crops, but mainly lessen organic matter decomposition rather than promoting accumulation associated with the presence of living roots.

Weeds

Contributor: Albert Adjesiwor

Various climate change forecasts have predicted increased atmospheric CO_2 concentrations with a concomitant increase in global temperatures. Precipitation has also been predicted to be more erratic with frequent drought spells. All these would be consequential for weed management in crop production systems.

The concentration of CO_2 in the atmosphere has a profound effect on photosynthesis. Theoretically, as the atmospheric CO_2 concentration increases, net photosynthesis is expected to increase because of reduced photorespiration (Lara and Andero, 2011). It is generally expected that the rising CO_2 concentration in the atmosphere will increase photosynthesis in C3 plants (e.g., wheat and barley) more than in C4 plants (e.g., corn) (Lara and Andreo, 2011). The extent of this stimulation will vary with temperature and among species (Allen and Prasad, 2004). The Weed Science Society of America's composite list of weeds is comprised of nearly 2000 weed species in 500 genera and 125 families. Out of this number, 146 species in 53 genera and 10 families exhibit the C4 photosynthetic pathway (Elmore and Paul, 1983). Thus, the majority of the weed species are likely to benefit and become even more competitive in cropping systems under rising CO_2 levels.

Increases in atmospheric temperatures would result in significant weed shifts in agricultural productions systems. Ramesh et al. (2017) described how increasing temperatures would allow weed species to expand their geographic coverage. Weeds that are adapted to dry and hot conditions in the southern states are likely to expand northern states. For example, Ward et. al. (2013) noted that "In little over 20 years, Palmer amaranth has risen from relative obscurity to its current status as one of the most widespread, troublesome, and economically damaging agronomic weeds." Palmer amaranth, a weed that is native to southern U.S., is now one of the most troublesome weeds in more northern states like North Dakota. In addition to appearance of weeds that did not previously grow in certain locations, existing weeds are expected to emerge earlier than normal in the growing season. Lee (2011) observed that a 4°C increase in temperature could advance the emergence timing of *Chenopodium album* and *Setaria viridis* by 26 and 35 days, respectively. Earlier emergence would affect the timing of preemergence herbicide applications. The greatest yield loss occurs when weeds emerge with or before the crop. Thus, adjusting herbicide application schedules to earlier than the previous normal time in the cropping season will be important to prevent yield loss.

Water is arguably the most important resource to competing plants, especially in dryland conditions. Aside from the effect of lack of rainfall on plant growth, drought increases leaf pubescence and leaf cuticle thickness, both of which reduce herbicide entry into plants (Patterson, 1995). Thus, drought stress reduces herbicide efficacy and crop recovery from herbicide injury. In addition, drought can prolong herbicide carryover. Most herbicides are broken down by soil microbes and various soil property-related chemical processes. These processes all require soil moisture to occur. Under drought, these processes would either be slowed down or brought to an immediate halt. For example, *imazamox*, an herbicide used in Clearfield wheat, could have up to 36 months plant-back restriction to barley (an important crop in Idaho) if there is less than 406 mm of moisture (precipitation + irrigation) following application. However, if there is more moisture (more than 406 mm), the plant-back restriction to barley could be cut back to just 9 months. Similarly, if *pendimethalin* (an herbicide labeled for use in multiple crops in Idaho) is applied in the spring at 4.7 L/ha and there is more than 305 mm of moisture (precipitation + irrigation), the plant-back restriction to sugar beet is 12 months. However, if there is less moisture (less than 305 mm), plant-back restriction is about 18 months. A few inches of moisture can make a sizable difference in the persistence of herbicides in soils.

Dairy

Contributor: Mario de Haro-Martí[2]

As of 2021, Idaho is the third milk producer state in the U.S. (ISDA), with top-quality milk and high production efficiency. Southern Idaho provides exceptional climatic conditions for thriving modern dairy production. Irrigated agriculture and low urbanization provide ample space and locally-grown feed. Relatively cold but mild winters, coupled with dry, desert conditions and mild summers with warm days and cool nights, are ideal for dairy cattle. Dairy cows thrive under

[2] A more comprehensive discussion of climate change effects on dairy production is available upon request from the contributing author.

cooler climates compared to hotter ones (West, 2003; USDA Northeast Climate Hub, 2018). Heat stress is a significant factor in cows' loss of productivity. Extremely cold climates are counterproductive, too, since the animals need to be protected from severe and sustained cold. Dry climates dramatically reduce the pressure of pests and diseases transmitted by microorganisms for both livestock and the crops they consume. These Idaho climate conditions – ample land and water, an agricultural-based economy, and receptive communities – drove the dairy industry's sustained growth from the mid-1980s to the mid-2000s (Brown, 2012).

Higher temperatures in winter and summer can translate into higher pest and disease pressure for both crops and livestock. In addition, increased overall summer and night temperatures increase heat stress in dairy cattle and workers. Failure to mitigate increased heat stress can result in lower milk production, lower conception rates, lower feed efficiency, and an increase in cow diseases and metabolic disorders. Water consumption by cattle for drinking and cooling also increases. Idaho, and most of the Pacific Northwest, is expected to experience lower increases in temperature and, therefore, smaller losses of milk production than southern U.S. states. Mauger et al. (2015) estimated the loss of milk production in areas of Washington (the closest to Idaho) to be between 0.7 to 1.1 lbs/day between the 2050s to 2080s due to the expected changes in temperature and humidity attributable to climate change.

Dairy feeding rations are adjusted based on many factors, including ambient temperature and cattle energy demands, crops available to provide proper nutrition, stage of growth of the cow, etc. Adjustments in feed would be necessary if ambient temperatures increase and heat stress is more prevalent.

Increased heat stress would also affect dairy workers, potentially leading to heat exhaustion and other adverse effects. Early adoption of mitigation strategies applied to crop and livestock production could help Idaho producers increase their share of U.S. national milk production, considering that other states likely face much higher milk production losses due to climate change effects (Yorgey et al., 2017; Mauger et al., 2015).

A change in precipitation patterns could increase early spring flows and reduce water infiltration in soils due to lower snow accumulation and increased early melting. Besides its effects on water availability to irrigate crops, these two associated effects can extend the period where rain and melted snow generate muddy conditions on dairies. This is a common occurrence at the beginning of fall and spring. Still, longer periods of muddy corrals and movement areas can result in increased work to maintain and drain such surfaces and workers' efforts to attend to the cows at milking time (Prante, 2020; Ade 2010). Diseases like mastitis can increase during this transition season, especially from the frozen winter until the late spring-summer dry time. Augmented wastewater storage capacity may be needed to absorb the increased water runoff from corrals and other surfaces, absorb increased water use in parlors, and accommodate possible flooding. Increased extreme weather events that can affect dairy production include extended drought, increased flooding events due to changes in precipitation patterns, and snow cover melting over frozen soils (USDA Northeast Climate Hub, 2018; Romero-Lankao, et al. 2014; Dalton et al., 2013).

Climate change is associated with an increment in the occurrence of thermal inversions (Hou and Wu, 2016). Thermal inversions are common in southern Idaho, but an increase in number and intensity can negatively affect the dairy production areas' communities. Emissions related to dairy production that can concentrate during inversions include ammonia; hydrogen sulfide;

odors; particulate matter from dust, feed, and other activities; and volatile organic compounds (VOCs) from internal combustion engines (Rogge et al., 2006). They can mix with other anthropogenic emissions, including NOx, VOCs, soot, and low-level ozone, all products of human activities in cities and industrial areas (National Research Council, 2003). At present, odor (and occasionally dust) are the most noticeable emissions from dairies directly affecting surrounding communities (Ndegwa and Harrison, 2016; Sheffield, et al., 2008). This could change if stronger and longer inversions occur, especially if cities grow, adding their pollutants near dairy production areas. Under this scenario, inversions could bring acute respiratory issues for humans (Loftus et al., 2020) and livestock (Urban-Chmiel and Grooms, 2012) alike.

Potential adaptation strategies include dairy livestock housing that incorporates enhanced climate control, such as cross-ventilated barns, free-stall barns with enhanced cooling systems, shading with cooling systems at open lots and feeding areas, and increasing the number and size of waterers (Gaughan, et al., 2019; West, 2003). Cropping systems related to dairy cattle feeding is another area where adaptation may be needed. In years with extended cropping seasons, choosing the varieties of crops carefully and using dual crops, including cover crops mixes and others, would need to be explored. In years with extended or intensive drought, crops may need to be switched to drought-resistant or less water demanding crops like sorghums, hay/pasture mixes, and short-season corn, among others (Golden et al., 2016; Janowiak, 2016). Long-term integrated systemic approaches would be necessary to have effective disease and pest control. Air emissions control techniques and technologies to reduce emissions that can be affected by climate change will become more prevalent due to local impacts like inversions and potential climate change mitigation requirements.

Cattle

Contributor: J. Benton Glaze, Jr.

The cattle industry contributes to Idaho's agricultural economy. In 2019, cash receipts from Idaho's cattle and calves sector totaled approximately $1.7 billion. Idaho's cattle and calves' inventory of approximately 2.5 million animals positioned the state at the rank of 12th in the U.S. (USDA-NASS, 2020a). Beef cattle operations are in all counties of Idaho and represent all segments of the beef industry (e.g., commercial cow-calf, seedstock, stocker, backgrounder, feedlot, packer). To reach optimal levels of production and economic efficiency, the vast majority of beef cattle operations utilize rangeland and forage resources during various periods of the production cycle. Idaho cow-calf operations routinely graze their cattle on private and public rangelands throughout the growing season and utilize standing forages and crop aftermath as far beyond the growing season as possible.

Beef cattle have access to a diversity of forage plants that vary in nutritional quality. These animals get the nutrients (e.g., energy, protein, vitamins, minerals) needed for maintenance, growth, reproduction, and milk production from the available forage resources. The nutritional quality of these forages is affected by several factors, including plant part, plant age, plant group, season of growth, soils, stocking rates, and climatic conditions. The efficient use of rangeland and forage resources by beef cattle operations is dependent upon how well nutrient availability is matched with animal nutrient requirements. Climate change, including the factors of increased temperatures and changes in precipitation patterns (as noted previously), has the potential to upset the match between animals and their environment.

To gain an understanding of the potential climate change effects on beef cattle production in Idaho, consider the work by Neibergs et al. (2018). The projected climate change effects in the Pacific Northwest include increases in temperatures and variable precipitation patterns. The increased temperatures are expected in the summer months, which will extend the growing season for pasture grasses and supplemental feed crops and lead to increases in water demands for irrigated pasture and supplemental feed crops. Shifts in precipitation patterns will lead to drier summers and wetter falls and winters. Snowpack accumulations are expected to decline due to the increased temperatures, which can negatively impact irrigation water supplies. Increases in wildfire risk and severity on pasture and rangelands are projected with these temperature and precipitation changes.

The main effects of climate change on livestock largely pertain to increases in surface temperatures, which can impact livestock production via changes in the production and quality of feeds and forages, water availability, and animal growth, reproduction, and milk production (Rojas-Downing et al., 2017). An example of how climate variables impact forage production in the Northern Great Basin is provided by DelCurto et al. (2000). In the study, wide ranges of crop year precipitation (range 158 mm to 524 mm) resulted in extreme ranges in forage protein content and available forage (range 240 kg/ha to 580 kg/ha). As the quantity and quality of feed resources change due to changes in climatic conditions, beef cattle producers should be prepared to make changes in their management protocols to keep animals performing at optimal levels.

The beef cattle production and environmental conditions that are represented across the state of Idaho are quite varied and climatic changes will impact each differently. Cattle producers should be aware of the impending climatic changes and implement strategies to maintain a balance between the cattle and the conditions in which they are expected to perform. Some of the strategies that beef cattle producers may consider in dealing with climatic change include monitoring range and forage resources; adjusting herd size; altering stocking rates; leasing/buying additional range, forage, and/or crop resources; sourcing and purchasing supplemental feeds; maintaining water supplies; and developing new, efficient water supply options.

Potato production

Contributor: Joseph Sagers

Potato yields are determined by water and nutrient availability and photosynthesis, especially via captured sunlight during the longest days of the potato growing season (Thornton, 2017). Changes toward higher atmospheric temperatures and CO_2 will have impacts on potato yields through their effects on plant growth and soil conditions, including water availability.

Potatoes are a heavy water using crop. Hot, dry summers will cause soil moisture evaporation and plant evapotranspiration, which will result in an increase in demand for soil moisture supplied via irrigation. Even small deviations from optimal soil moisture, either too little or too much, during the growing season, can have substantial effects on potato yields (Shock et al., 1998). Management of the timing of water for irrigation will be critical for reducing water stress on plant and tuber growth, as temperatures will be higher on average, but fluctuate throughout the growing season (Shock et al., 2007).

Other effects of higher temperatures on potato yields pertain to soil-related characteristics. Many potato diseases thrive in cool wet conditions and when temperatures are above 50°F; there is less pressure from fungus and disease and the plant can develop properly. The risks that diseases will impact potato growth are lower with later planting (Thornton and Nolte, 2011), which may be more feasible under longer frost-free seasons. Decreased disease pressures will reduce the need for fungicide applications. Under higher temperatures, there is greater risk of Pythium leak and pink rot at harvest, which cause severe decay and losses in storage. Some diseases, such as verticillium, may increase from the lengthened growing season, as well as nematodes, insects, and other invertebrate pests.

Estimates by Rajagopalan et al. (2018) showed that increased CO_2 levels will have a positive effect while increases in temperatures are expected to have a negative effect on irrigated potato yields in the Pacific Northwest, with the overall effect of increased CO_2 and temperatures expected as negative. Importantly, these projections do not account for adaptation and adjustment of grower practices in response to changing growing conditions. Despite all the soil-related variables mentioned above that also could impact potato plant and tuber growth, actual observed yields will depend greatly on grower management decisions.

Some management practices that potato producers could consider for mitigating the most detrimental effects of increased CO_2 and temperatures include updating irrigation management schedules and planting new seed varieties that are better suited for growth under warmer temperatures.

Potato storage

Contributors: Brandy Wilson and Nora Olsen

For decades, potato storage facilities have relied on Idaho's cool nights to keep potatoes at an optimum storage temperature. This use of available cooling air allows Idaho's potato processing facilities to operate year-round, meeting demand for fresh potatoes, French fries, chips, and other products. This historical annual average frost-free season, which ranged from 101 to 250 days, could expand to a range of 151 to 300 days (Table 6). Without proper cooling and temperature control, stored potatoes are at greater risk of respiration and evaporation weight loss, sprouting, and disease development (Olsen, 2014). Conditions in storage can also influence the ratio of starches to sugars (Winkler et al., 2018). These quality changes can make processing potatoes less desirable and marketable.

Winkler et al. (2018) described how and why higher temperatures influence potato quality throughout the potato production and storage cycle. In addition, projections by Winkler et al. (2018) showed the most likely changes in storage management practices that would occur so that potatoes in the historically cold state of Michigan could continue to be marketable for potato chip processing. As Winkler et al. (2018) explained, "the projected shorter period of reliable cold temperatures for storage has implications for…the larger national industry." Such implications include the "likely need to switch from ventilation only to more costly refrigeration," leading to an "increased cooling demand and cost of production." While it is hoped that variety development will lead to better tuber performance in storage, developing new varieties that gain market acceptance—particularly for processing—can take years. There would also be more demand for new sprout and disease control methods.

Building on the Winkler et al. (2018) study, Forbush (2021) applied engineering principles for storage design and ventilation to examine the potential impacts of climate change on potato storage. A comparison by Forbush (2021) showed the average airflow rates for potato storage in regions around the world (France, Germany, Netherlands, Poland, United Kingdom, and three regions in the United States) and the average weather data during harvest months, when the potatoes are brought into storage and initially cooled.

In Bremen, Germany, where the average minimum temperature is 6.3ºC (43.3ºF), the airflow range required to achieve an appropriate cooling rate is 150 cubic meters per metric ton of potatoes, per hour (m^3/mT-hr; Forbush, 2021). In Boise, Idaho, the average minimum temperature is 2ºC lower, at 4.3ºC (39.7ºF), and the airflow range required to achieve an appropriate cooling rate is 30 to 56 m^3/mT-hr (Forbush, 2021). By looking at the systems required to cool potatoes today in warmer regions like Germany, people who design potato storage facilities can project which types of ventilation systems and refrigeration could be required in Idaho in the future in a climate change scenario. The warmer regions in France, Germany, and the Netherlands require ventilation systems that can handle nearly three times the airflow of what is currently used in Boise, Idaho and those larger systems typically use mechanical refrigeration to make up for the loss of ambient cooling availability (Forbush, 2021). Other factors come into play with airflow rates, including differences in humidity and precipitation among the regions. For example, it is easier to keep potatoes dry in storage in Boise, Idaho than in the other locations compared in the Forbush study. However, any requirement to increase airflow, which is anticipated to be necessary in the absence of natural cooling, would increase the cost of potato production. Producers and packers that update storage facilities would incur higher initial construction costs—as well as operational cost increases because of additional energy demand—to add mechanical refrigeration systems, more robust fans and ventilation equipment, and other mechanical systems needed to compensate for the lack of natural cooling (Forbush, 2021). Further analysis that combined the data sets from assessment's Climate Report, the Michigan potato storage study (Winkler et al., 2018), and the engineering projections comparing the temperatures of other regions around the world (Forbush, 2021) would be needed to draw conclusions about the projected ventilation and refrigeration needs under different climate models and the resulting costs associated with building design and operation.

Hay

Contributor: J. Reed Findlay

Hay is a valuable and important crop in Idaho. As of 2020, Idaho was ranked third nationally in alfalfa hay production, with hay being grown on 1.30 million acres and total production of 5.27 million tons of forage (USDA-NASS, 2021a). Alfalfa and forage grasses are the major hay crop species grown in Idaho.

Alfalfa and grasses are forage crops that employ growing degree days (heat units provided by solar radiation) as an energy source for the chemical reaction of photosynthesis to produce dry matter. Increases in heat units during the growing season can increase the energy available for photosynthesis in forage crops, with resultant increases in yield. Heat unit effects can vary over the growing season. Thivierge et al. (2016) found that cooler regions in Canada will benefit the most from an increase in climatic heat units. They also found that first crop hay had higher yields, while the regrowth stages of the crop could suffer due to temperature stress. They also showed that when harvest timing and number of cuttings were modified, both yield and forage nutritive value could be maintained.

Carbon is one of the main nutrients used in the previously mentioned photosynthetic reaction. While forage crops obtain many of their nutrients from the soil solution, they obtain carbon, hydrogen, and oxygen from the atmosphere. Any nutrient that is limited can reduce crop yields. Conversely, increasing the concentration and its availability can increase yields. Thivierge et al. (2016) found that, in isolation, elevated CO_2 levels resulted in elevated alfalfa yields according to climate change models. There are, however, possible negative effects predicted by climate change models that account for both CO_2 and temperature. Sanz-Sáez et al. (2012) used a climate change model that assumed elevated CO_2 in combination with increased temperatures and found that digestible dry matter, as well as crude protein, were reduced and that the fiber content of the harvested forage was increased. Such studies, however, do not account for producer adoption of mitigating practices.

Forage management will play a crucial role in mitigating any effects resulting from climate change. Time of planting, number and timing of cuttings, irrigation scheduling, and crop fertility will need increased management skills in the future to deal with any future climatic perturbations. Wentian et al. (2019) found that early planting coupled with increased harvests could increase yields using their climate model. They did, however, find that the model predicted an increase in winter-kill at some locations due to reduced snow cover. Reduced snow cover can lead to cooler soil temperatures and expose the alfalfa crowns to killing frost. It was felt by the researchers that management skills will be critical in reducing the effect of winter-kill. They stated that use of readily available winter hardy cultivars could mitigate winter-kill.

Changing CO_2 levels and climatic temperatures could cause Idaho hay producers to respond through adjustments in current input usage and management decisions; doing so would have production cost implications. Costs associated with alfalfa hay production include fertilizer, pesticide, custom operations, irrigation, labor, and machinery inputs. The value of these costs in Idaho as of 2019 on a per acre basis are as follows: fertilizer $73.78, pesticides and chemicals $17.25, planting and harvesting operations $212.35, irrigation $88.44, labor $43.54, and machinery $9.12. These production costs are used to estimate a cost for alfalfa of $76.05 per ton (Eborn et al., 2019). These costs are dependent on future energy costs, infrastructure, and government regulation.

Barley, wheat, and pulses

Contributor: Patrick Hatzenbuehler

Grain production is an important component of the Idaho agricultural economy. Since 2013, Idaho has led the nation in annual barley production among U.S. states, producing about a third of the national total (Ellis, 2020a). Wheat is grown in 42 of 44 Idaho counties and about half of the wheat produced in the state is processed domestically while the other half is exported, primarily to countries in Asia and Latin America (Idaho Wheat Commission, 2021). Pulses (chickpeas, beans, lentils, and dry peas) are an important crop in many crop rotations for growers in both northern and southern Idaho, although chickpea, lentil, and dry pea production occurs almost exclusively in northern Idaho (see Table 2).

The effects of increased temperature on wheat are first discussed in relation to the planting of winter versus spring wheat. In 2020, 660,000 acres (~57%) of winter wheat and 495,000 acres (~43%) of spring wheat were harvested in Idaho (USDA-NASS, 2021a). For winter wheat (most barley in Idaho is spring planted (Olson et al., 2003)), increased winter temperatures can reduce snow levels in regions that are typically covered in snow during winter months. Snow provides several benefits to fall planted crops. First, a coverage of a few inches of snow blocks the plants from fluctuating temperatures (Karki, 2021; Martin, 2021) and increases soil temperatures by up to 30°F (DeDecker, 2021). This insulation reduces the risk of winter-kill in fall planted wheat. Ice damage is also more likely when temperatures fluctuate from warm-to-cold in the absence of snow insulation. Planting of cold tolerant seed varieties may help reduce yield losses due to cold temperature exposure (Karki, 2021). Lengthening of the frost-free seasons may also increase pest pressure in grain cropping systems, since there is greater emergence of insect pests and soil diseases, such as rusts, as soil temperatures increase (Martin, 2021). The increased potential pest pressure would have effects on spring planted crops inclusive of wheat, barley, and pulses.

The increased photosynthetic effects of increased temperatures and CO_2 and potential higher yields for some types of plants may not be as large for grains due to their relatively smaller leaves (Backlund et al., 2008). Under dry conditions, heat stress on wheat plants can cause reductions in grain fill (Keeling et al., 1994). Yield effects from high temperatures on barley plants are particularly important during the reproductive stage (Cammarano et al., 2019). Peer-reviewed research is not as extensive on pulses, but the plant growth effects from heat stress are likely like those observed with grains.

Adaptation strategies among Idaho wheat, barley, and pulse producers will likely include adoption of improved varieties that are more tolerant of disease and temperature effects; adjustment of planting timing, such as fewer winter wheat acres and more spring wheat acres; and increased usage of inputs (labor, machinery, and chemicals) used to manage pests and diseases.

Onions

Contributor: Olga Walsh[3]

Idaho ranks 5th in the nation in onion production. Southwest Idaho is famous for Giant Spanish sweet onions. Twenty-five percent of all U.S. onions are produced in the Snake River Valley of southwest Idaho and eastern Oregon (Idaho Preferred, 2021). The marketable yield of many horticultural crops, including onions, is likely to be more sensitive to climate change compared to grain and oilseed crops (Backlund et al., 2008).

Although bulbing is primarily a photoperiodic response, it is also influenced by temperature, light intensity, nitrogen (N), and irrigation (Coolong, 2003). The day length initiates bulbing; the higher the temperature, the earlier bulbing will occur (Sullivan et al., 2001). Bulbing increases with temperature; however, bulb yields typically decline at temperatures nearing 85ºF (Coolong, 2003). Temperature increases above 40°C (104°F) reduced the bulb size; an increase of about 3.5°C above 38ºC (from 100.4°F to about 106.7°F) reduced onion yield (Lawande, 2010). With appropriate photoperiod and temperature, onion leaves change from photosynthetic to storage units (Bachie et al., 2019). Later planting days expose onion plants to higher growing daylength and temperature during early growth stages. However, heat stress results in physiological shut down of onion plants. When onions are exposed to temperatures greater than 85°F, the plants' physiological activity is dramatically reduced. The heat stress is associated with lower water uptake, slower leaf growth, and death of newly emerging leaves (du Toit et al., 2016). Modeling

[3] A more comprehensive discussion of climate change effects on onion production is available from the contributing author upon request.

has indicated that all onion growth stages will arrive earlier in future due to shortening of each growth stage length. This temporal shift is expected to be more prominent in the future (Schmidt and Zinkernagel, 2017). The duration of onion crop from emergence to maturity will be shortened due to higher temperatures, resulting in reduced yields (Daymond et al., 1997). Some heat stress issues may be mitigated by irrigation management.

Onion plants grown under elevated CO_2 had an increased photosynthesis rate (by 22%) and produced over 40% greater biomass, compared to ambient CO_2 (Jasoni et al., 2004). Onion yields were increased by 25-30%, primarily due to greater bulb size at elevated CO_2 levels (Daymond et al., 1997). The positive effect of elevated CO_2 on onion yield was found to be negated due to progressively warmer temperatures, resulting in lower onion bulb yield. Although the elevated CO_2 may have a positive effect on onion growth, the anticipated temperature effects will be more substantial (Schmidt and Zinkernagel, 2017).

For quality considerations, flavor intensity due to sulfur (S) accumulation and pyruvic acid content increased linearly with an increase in temperature during the growing season (Coolong and Randle, 2003). As onions mature, their dry matter content increases, resulting in greater storage potential. Onions must be cured soon after harvest to optimize storage quality. Ideal conditions for onion bulb curing are 68-86°F and 70% relative humidity for at least 12 to 24 hours. In Idaho, most onions are cured in the field. Temperatures in the 80°F range tend to enhance the bronze onion skin color. Temperatures greater than 90°F result in sunscald (Howell et al., 2021). Heat stress is the primary cause of internal dry scale and bulb rots in onions (du Toit et al., 2016).

Regarding pest management issues, root-lesion nematode is a major pest affecting onions in Idaho, with most damage done by fourth-stage juveniles and adults. The life cycle on root-lesion nematode depends on temperature and is shortest at 86°F. Root-knot nematode is another key pest for onions in Idaho. Warm soil temperatures at planting can lead to severe damage early in the season. Damage may be most severe during years with warm spring temperatures (Hafez and Palanisamy, 2016).

Adequate nutrition is important for optimizing onion production. The changing climate is directly linked with growth and metabolism in plants and is likely to change N uptake from applied fertilizers. Despite decreases in nutrient concentrations in plants, the greater biomass production under elevated CO_2 could lead to increased nutrient demand (Tausz-Posch et al., 2014). This highlights the complexity of future fertilizer management decisions associated with intricate interactions among nutrients.

Since higher N fertilizer rates resulted in a more pronounced positive effect on crop growth parameters and yields at elevated CO_2 and higher temperatures (Ramanan, 2019), applying sufficient soil nutrients will be important. For most efficient nutrient uptake and minimized loss to the environment, fertilizers should be applied at the time the crop's demand for nutrition is greatest.

Hops

Contributors: Ritika Lamichhane and Emmanuella Owusu Ansah[4]

Idaho accounts for 17% of the total U.S. hop crop production, making it the second largest hop producing state after Washington (USDA-NASS, 2020c). Idaho produced 17.2 million pounds of hops, with an average yield of 1,855 pounds per acre in 2020 (Ellis, 2020b).

Hop productivity and quality are sensitive to temperature and water availability, among other factors (Morton et al., 2017). Hops have been identified to undergo an interesting phenomenon called vernalization, a process in which plants endure a prolonged period of cold temperatures, usually winter, which causes changes in the plant and initiates the plant's ability to flower in springtime. Incomplete vernalization affects cone-set, yield, and maturity dates of hops (Crain, 2011). Hop yield decreased by more than 28% in dry-cool conditions, while in dry-hot conditions, the yield dropped by 35-68%. However, high temperatures in April-May can sometimes improve yields by increasing evaporative demand and reducing soil moisture to more optimal conditions (Potopova et al., 2021).

Hops require large amounts of water due to their high leaf surface and this requirement cannot be supplied only by rainfall; it must be supplemented by the application of efficient irrigation systems (Hāpi Research, 2019). Water stress capacity varies with the cultivar grown; some are more tolerant, whereas others, less (Lattak, 2017). The quantity of irrigation needed is dependent on the local climate area and timing of irrigation. Hop irrigation requirements range from 700 to 800 mm per season in the arid-regions from mid-spring to shortly before harvest (Turner et al., 2011). Several reports have concluded that irrigation systems in hop fields improve yields without altering alpha and beta acids concentrations (Turner et al., 2011).

For nutrient needs, hop yield is directly proportional to the N uptake by the plant. This uptake pattern helps in determining its N requirement. During its initial growth in early June, little N is taken up, which increases sharply by the end of June and remains constant the following month. A large amount of N is accumulated in the hop's cones; N application should be manipulated based on its yield (Gingrich et al., 1994). Intense rainfall/irrigation causes the need for multiple applications, as it may wash the chemicals away (Rhodes and McCarl, 2020). The literature on response of hops to atmospheric CO_2 is not extensive. However, hops is a C3 plant species and Long et al. (2006) reported that C3 species produced an average 16% more biomass and 13% greater yield at 550μmol CO_2 mol^{-1} when compared with ambient CO_2 concentrations.

Regarding pest management, the lack of freezing temperatures allows hop fungal diseases to survive as living mycelium in the dormant plants (Great Lakes Hops, 2020). Due to the spacing in hops, irrigation system type has been shown to be associated with disease infestation, especially for powdery mildew, an important disease in hop production (Jackson et al., 2019).

While much research is needed regarding hop production response to climate variables, the above cited literature implies that varietal development and selection, irrigation availability and monitoring, and pest management will be important for continued successful hop production in Idaho.

[4] A more comprehensive discussion of climate change effects on hop production is available from the contributing authors upon request.

Trout

Contributor: Matt Powell

Idaho's aquaculture production is centered in, but not exclusive to, the Magic Valley, encompassing over 70 farms, five processing plants, and two feed mills and providing more than 800 jobs.

Rainbow trout are the most prevalent aquaculture product grown in the valley and represent approximately 70% of U.S. production (USDA-NASS, 2021b). White sturgeon and tilapia are produced in Idaho as well.

Potential effects to aquaculture production from climatic changes in Idaho would involve fluctuations in water temperatures and water availability. Overall impacts to freshwater fisheries from climactic changes have been the subject of extensive review and primarily forecast water temperature increases, decreased dissolved oxygen levels, and increased toxicity of pollutants (Galappaththi et al., 2020; Ficke et al., 2007).

Fish farms within Idaho rely on spring water that does not require energy inputs (pumping or treatment) prior to use in flow through raceway systems. Natural spring water temperatures remain within an optimal range (13-18ºC), conducive to efficient growth and food conversion in trout (Myrick and Cech, 2000). Rainbow trout have been successfully introduced to a variety of habitats worldwide and there is evidence that natural populations can undergo selection for increased water temperatures (Chen et al., 2015). There is abundant observational and experimental evidence that increasing water temperature negatively impacts commercial fish production (Ficke et al., 2007). Increasing water temperatures are concomitant with decreased dissolved oxygen levels and both result in lower fish growth rates and less efficient feed conversion in cool water species like trout (Westers, 2001; Wurtsbaugh and Davis, 1977). The farther from temperature and dissolved oxygen optima spring water becomes, the less efficient the system becomes, which, in turn, significantly raises the cost of production.

Water availability and fluctuations in water flow are products of local hydrology in Idaho. Trout production in this state is largely "downstream" of potential climatic changes that would affect land use, precipitation, soil moisture content, and evapotranspiration in this region. Thus, human responses to climate change involving increased groundwater pumping, increased water diversions, etc. will further tax current water use strategies and likely reduce spring flows upon which the Idaho trout production relies. Decreasing spring water flows will impact aquaculture production in Idaho where water use is already adjudicated among competing agricultural interests.

The magnitude of potential climate change impacts to Idaho aquaculture is dependent on a number of variables. Measurable change in temperatures or spring flows will directly and indirectly increase complexity and uncertainty at all levels of current aquaculture production.

6. Risks of Reduced Surface Water and Groundwater Availability

Main messages from the preceding sections are: (1) that there is substantial heterogeneity regarding the degree of the expected climate effects on productivity across crops and livestock sectors and (2) that the availability of surface water and groundwater for irrigation is a fundamental factor for Idaho agricultural productivity in the coming decades.

Considering the projections by Rajagopalan et al. (2018) for increases in demand for irrigation, such that higher annual irrigation is expected, but the timing will shift toward earlier in the growing season, the assessment's Water Report was consulted to determine the prospects for overall water availability in the context of climate change. The Water Report describes how Idaho consistently ranks near the top of U.S. states for annual surface water and groundwater withdrawals and agriculture is by far the largest user of water in Idaho (comprising more than 80% of total use). Regarding projections for the effects of increased temperature on surface water availability, the Water Report identified two main mechanisms through which temperature impacts water supply. First, increased air temperatures cause plants to uptake a greater amount of water during the photosynthesis process. This effect translates into an increase in overall demand for water by crops planted in Idaho. Second, a shift is expected towards a greater proportion of precipitation falling as rain rather than snow, which will change streamflow dynamics, including timing. Specifically, higher streamflow is expected in spring, with lower streamflow expected in summer. The projections of Rajagopalan et al. (2018) discussed earlier encompass such adjustments in stream water supply to reflect the likelihood of both greater water availability and demand on average during the earlier part of the growing season.

The other important variables for irrigated crop production pertain to decisions made by water supply management institutions and producers. The number of acres of irrigated crops is a key metric for irrigation water demand. Table 7 includes trends for irrigated cropland acreage over the most recent USDA Agricultural Census, implemented every five years from 1997 to 2017. The data show that overall cropland acreage has declined by over 820,000 acres over the full period. Irrigated cropland acreage declined between 1997 and 2017 by over 140,000 acres, but after an initial decline between 1997 and 2002, irrigated acreage increased between each Census from 2002 to 2017. Decisions by water supply institutions and producers will determine whether the longer trend of overall declines in irrigated acreage or the more recent micro-trend of acreage increases will predominate in the years ahead.

Table 7. Observed changes in Idaho all cropland harvested and irrigated cropland harvested acreage from 1997 to 2017

Year	Area all cropland harvested (acres)	Area irrigated cropland harvested (acres)
1997	9,878,666	3,426,626
2002	9,305,068	3,136,644
2007	8,877,039	3,158,591
2012	9,350,365	3,269,921
2017	9,057,378	3,286,347
Change from 1997 to 2017	-821,288	-140,279

Source: USDA-NASS (2021c).

7. Resilience and Ingenuity among Idaho Agricultural Producers

How are agricultural stakeholders in Idaho responding to climate change? In this section, three case studies are shared that demonstrate current adaptation and experimentation in different agricultural sectors that may provide lessons or insights for future adaptation.

Case study 1: Eastern Snake Plain farmers' adaptations to reduced groundwater

Contributors: Chloe Wardropper and Katrina Running

The sustainability of agriculture in Idaho depends on the capacity of farmers to adapt to future water resource constraints. Climate change, coupled with land use changes and a growing population, is expected to alter the timing and amount of water available for agriculture in the coming years (Humes et al., 2021).

This case study describes how Idaho farmers have adapted to reduced groundwater availability. While a policy decision was the cause of reduced groundwater availability in this case, it simulates a future scenario in which climate change-caused drought leads to lower groundwater levels.

Idaho's Eastern Snake Plain Aquifer (ESPA) region covers most of southern Idaho and contributes substantially to agricultural production in the state, producing potatoes, sugar beets, and wheat (USDA-NASS, 2014). Income from agricultural activities accounts for almost two-thirds of the median household income in the region (Watson and Ringwood, 2016). In 2015, negotiations between representatives of surface water and groundwater users culminated in an overhaul of existing water policy. The new water management agreement requires groundwater irrigators in the ESPA's eight groundwater districts to reduce total irrigation water consumption by an average of 13% (du Bray et al., 2018).

Our team conducted a survey in 2018 to understand how farmers in this region adapted to reduced groundwater availability (Running et al., 2019). Our survey included a list of 27 possible adaptation actions farmers could have implemented to reduce water use after the settlement agreement and mitigate the impacts and risk the settlement agreement posed to their farm. Of the 265 farmer respondents, the majority had undertaken at least one adaptation action, and on average, farmers reported nine distinct adaptations. The two most commonly reported adaptations were improving irrigation system efficiency (77%) and reducing spending on farm inputs or equipment (67%). Irrigating less frequently (59%), changing crop rotation (53%), and switching to a more efficient irrigation system (53%) were also actions taken by more than half of respondents. The least commonly adopted adaptation actions (with fewer than 10% of respondents reporting their use) included selling land (8%), joining a co-op (8%), and the most extreme strategy available, exiting farming altogether (6%). Many of these adaptations reflect efforts to operate as efficiently as possible while maintaining existing crops and operational structure. That said, adaptations were varied and contextual to the operation. It is important to incentivize agricultural adaptation to future climate change impacts, like reduced groundwater, and understand a diversity of possible approaches to address changing conditions. Additionally, working in collaboration with local farmers will help ensure adaptations are compatible with local farming practices.

Center pivot irrigation in southeast Idaho, a water-conserving system, compared to flood irrigation. Photo credit: Natural Resources Conservation Service (NRCS).

Case study 2: Climate adaptation with a rangeland decision-support tool

Contributors: Chloe Wardropper, Vincent Jansen, Roger Lew, Jen Hinds, and Jason Karl

Rangelands provide many ecosystem services that are impacted by climate change, including forage production for livestock, water quality and quantity, biodiversity conservation, and carbon sequestration (Sala et al., 2017). U.S. rangelands support multiple activities, including livestock grazing, recreation, and resource extraction (Reid et al. 2014; and Winford et al. 2021(assessment's Rangelands Report)).

Decision-support tools that tailor information on weather and forage for rangeland users have the potential to help ranchers and others adapt to climate change (Wardropper et al., 2021). This case study describes the potential opportunities afforded by one such tool developed by University of Idaho researchers and The Nature Conservancy (TNC) in collaboration with ranchers in Oregon and Idaho.

RangeSAT is a web-based rangeland climate tool created to provide near-real time estimates of biomass using Landsat satellite surface reflectance products for adaptive grazing management. It allows each end-user to view pasture- and ranch-specific maps and graphs of above-ground biomass at single dates or averages across time, from 1984 to the present. Climate variables can be viewed alongside graphs of the vegetation metrics, such as the normalized difference vegetation index (NDVI) and biomass (Figure 4). Development of RangeSAT was initiated by Oregon TNC, ranchers, and university scientists in Oregon and Idaho seeking more precise ways to plan and understand the impact of grazing and climate at the pasture to landscape scale. Currently, RangeSAT biomass models have been created for the Pacific Northwest bunchgrass prairie (Jansen et al., 2018) and select sagebrush steppe locations in southern Idaho. Ranchers in the study regions graze livestock on their privately-owned land and on rangeland and pastures owned and managed by TNC, the University of Idaho, and federal and state governments.

RangeSAT can be used by ranchers to plan livestock movements within seasons, assess the effects of past management decisions, and visualize how vegetation amounts across their pastures or ranch change over time. For example, TNC in Oregon is currently developing a framework to use RangeSAT to help monitor end-of-season vegetation amounts to adaptively manage their lands. RangeSAT and other decision-support tools on vegetation and climate continue to evolve. New tool iterations (e.g., Grass-Cast,[5] The Rangeland Analysis Platform[6]) have increasingly addressed intersections with local knowledge while improving the accuracy of vegetation estimates to enhance positive conservation outcomes and ranch sustainability in the face of climate variability (Jansen et al., 2021). One recent study (Liu et al., 2021) found that higher use of drought monitoring information was associated with higher dollar values in avoided cost. That said, more work is needed to improve the usability of these tools, as evidenced by a recent survey of ranch operators (Coppock, 2020) in which respondents listed barriers to using weather decision-support information, including lack of awareness or resources to interpret the highly complex information.

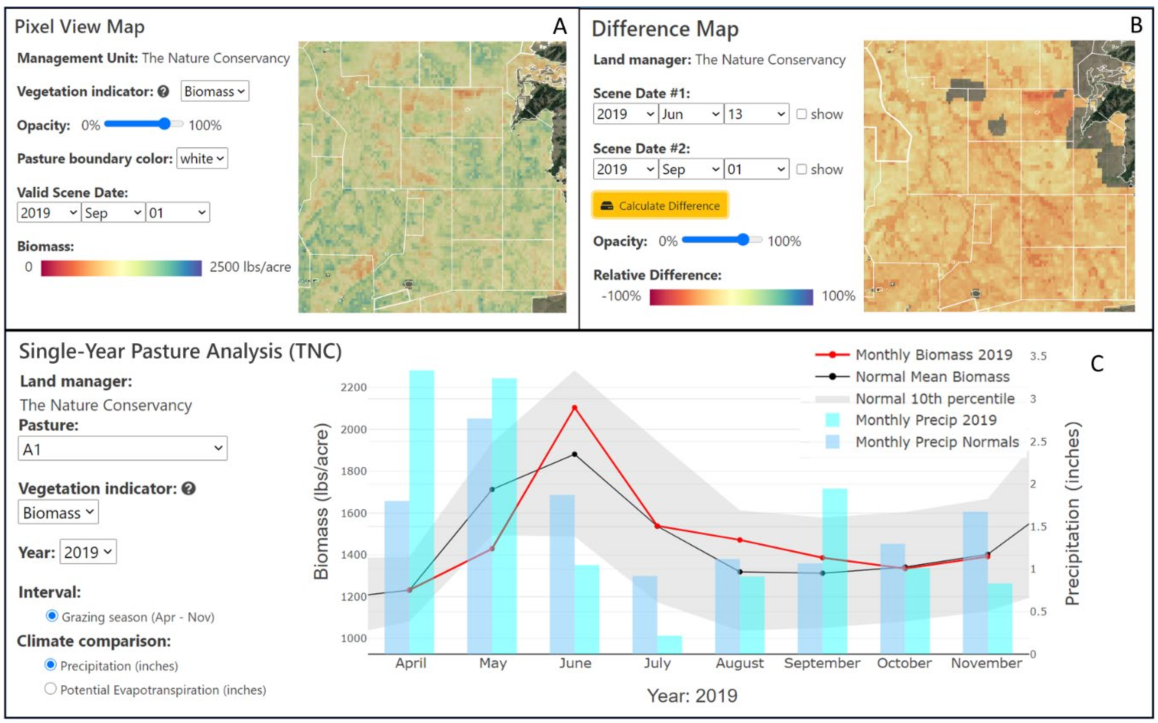
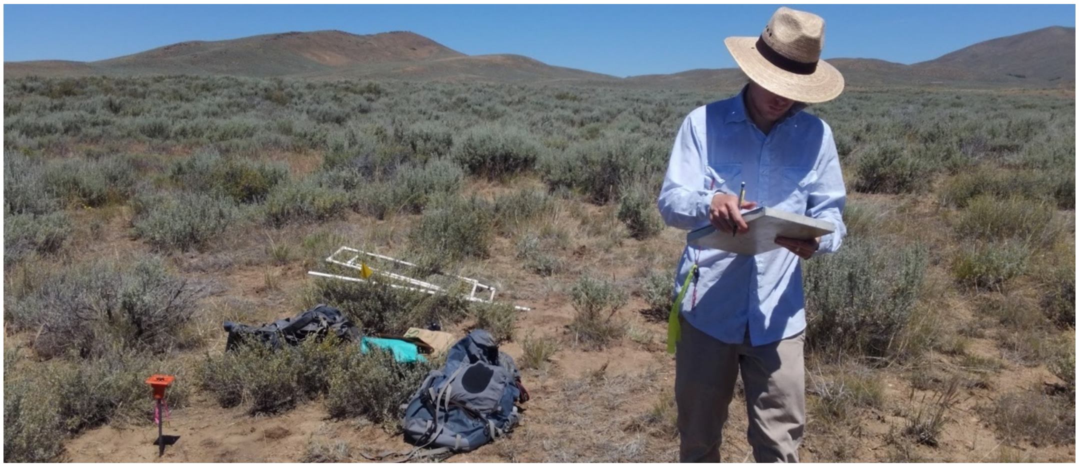


Figure 4. Select examples of RangeSAT (rangesat.org) tools, which can inform use-based monitoring and adaptive management.

Note: The Pixel View map (A) displays 30m [98.4 ft] resolution biomass data, with biomass for September 1st, 2019, across a section of the Zumwalt Prairie Preserve, Oregon. The difference map (B) displays 30-m resolution relative difference maps for selected dates. These maps show the relative difference in biomass between June 13th and September 1st, 2019 for this area. The Single-Year Pasture Analysis tool (C) is a graph of average biomass within a select pasture over the growing season and includes climate data, such as precipitation and temperature, for the same location as the vegetation data for interpretation. Reprinted from Jansen et al., in review).

[5] Available online: https://grasscast.unl.edu/.
[6] Available online: https://rangelands.app/rap.



Sampling on Rinker Rock Creek Ranch, Idaho. Photo credit: Jason Dingeldein.

Case study 3: Herbicide resistance and community-based management

Contributors: Chloe Wardropper and Katherine Dentzman

Rising CO_2 concentrations and associated changes in temperature and precipitation are likely to affect future agricultural weed management options. Weeds are liable to be resilient to CO_2 and temperature changes in competition with crops due to their diverse gene pool and greater physiological plasticity. Furthermore, climate change could influence the efficacy of herbicides, with further repercussions for weed management (Varanasi et al., 2016). Please see the weed subsection of this report for more details.

This case study describes how Idaho and other inland Pacific Northwest (iPNW) farmers have begun to address a problem likely to become more complex under future climate change: herbicide resistance. Due to the increasing resistance of weeds to glyphosate and other common herbicides, weed control may increasingly need to be carried out through cooperative, community-based management on a regional level.

In 2018, a survey of iPNW wheat growers (n=104) conducted by our team found that 80% of respondents were aware of the mobile nature of herbicide resistance, 60% communicated with their neighbors about herbicide resistance, and 67% agreed that herbicide resistance must be managed cooperatively. Combined with other research on herbicide resistance, these results point to the potential suitability of community-based management for pest resistance issues (Dentzman et al., 2020; Dentzman and Burke, 2021; Ostrom, 1994). This is especially relevant as herbicide resistance, like many natural resource issues, does not stop at farm borders. Rather, herbicide resistance operates at a landscape level, making it difficult for any individual farmer to manage weeds on their own land without cooperation from their neighbors.

Based on our research and political scientist Dr. Elinor Ostrom's principles for community management, we created a guided toolkit for developing community-based herbicide resistance management capacity. The purpose of this toolkit is to guide interested parties in asking questions and gathering the necessary information to develop successful community-based management for herbicide resistance. This helps tailor community-based management across geographically, agriculturally, and socio-economically diverse regions. Additionally, the structure of the toolkit ensures that best practices for community-based management development will be followed, including building social capital, reducing individual barriers to participation, establishing rules, gaining cooperation, resolving conflict, building trust, and incorporating consideration of external factors (i.e., changes in climate or markets).

Groups of dryland wheat producers and other stakeholders have been holding monthly community meetings in three regions of Idaho and Washington to work through the Community-Based Herbicide Resistance Management Toolkit and develop a plan specific to the needs and resources of each community. Group goals include increasing cooperation and involvement on the issue in their region, lowering input costs, and sharing local achievements with policymakers and industry stakeholders. Creativity and collaboration have been hallmarks, with groups suggesting management techniques, including incentives, emergency funds, NRCS programming, cost-sharing of innovative equipment, economic impact spreadsheets, social media education campaigns, and more.

As climate change continues to accelerate, more types of management will likely require increased cooperation as resources become scarcer (e.g., water) or when threats to resources become more prevalent (e.g., weeds, fire). Community-based management offers a model for communities managing resources that will likely be affected by climate change impacts, including increases in complexity and landscape-wide participation needs that go beyond the capabilities of individual land managers.

8. Conclusions

The goal of this report is to describe the current composition of the agricultural sector in Idaho and the implications for observed and projected climatic changes for agricultural productivity in key sectors. This report began with a description of the importance of agriculture in Idaho's overall economy, accounting for a substantial amount of output and cash receipts. It is particularly prominent for regions with high agricultural sector concentration, such as the Magic Valley in southern Idaho. Next, climate changes observed over the past several decades and projected over future decades in Idaho were described in the context of the key variables that would be relevant for agriculture, namely temperature and CO_2 emissions. Within the context of ongoing climate change, yield data were examined to evaluate evidence of productivity effects of climate change to date. The historical yield data show generally positive yield growth over the past several decades, although the yield changes have been much greater for non-irrigated crops. Future climate change projections based on the information in the assessment's Climate Report were then discussed under the BAU scenario that projects increases in temperatures and CO_2 levels through the mid-21st century. Under such climate change projections, the annual average number of heat stress days and frost-free season length are expected to increase and become longer, respectively. However, the extent of the changes will vary across regions of Idaho that have differing topographic and ecological characteristics.

Based on the projections of increased temperatures and CO_2 levels, the informative irrigated yields and irrigation demand projections that account for these climatic changes of Rajagolan et al. (2018) for the Columbia River Basin were described. Notably, based on their projections, it is expected that higher temperatures will lead to growing seasons that begin earlier and, for annual crops, are shorter. Additionally, higher temperatures are expected to drive greater irrigation demand overall, especially in the early growing season and mid-summer. Lastly, irrigated yields for hay, hops, and wheat are expected to be higher, while those for potatoes are projected to be lower.

University of Idaho Extension and Idaho agricultural stakeholder experts then used findings in peer-reviewed research to describe in detail the mechanisms through which climate variables influence plant growth and livestock well-being. These individual sector analyses in the aggregate demonstrated that there is increasing study of climatic variable effects on agricultural production-related variables, but the extent to which these variables will impact production relative to the current period varies across sectors. For example, onions were observed to likely be more sensitive to changing climatic variables than grains (Backlund et al., 2008).

In the context of these projections for increased and earlier water demand for irrigation, the assessment's Water Report was consulted to examine the prospects for overall water availability. The main messages from both the Water Report and Rajagolan et al. (2018) are that increased temperatures will increase demand for water by plants and change the timing of streamflow to be greater during spring and lower in summer. Whether the expected changes in streamflow timing and growing season timing adjust the aggregate demand for water for agricultural production will depend on decisions made by water management institutions and producers. The interactions among these key stakeholders will explain a large part of the changes in the agricultural economy of Idaho in the decades ahead.

The final component of the report was a description of how Idaho farmers are demonstrating leadership and ingenuity in experimenting with adjustments in practices that may prove helpful in maintaining productivity levels amidst a changing climate. Considering that there is a substantial amount of uncertainty regarding climatic and general economic conditions in the decades ahead, one thing is certain: Idaho and U.S. farmers have demonstrated an immense capacity to meet the challenges of the past through successful adaptation (Walthall et al., 2013). It is expected that such demonstration of leadership and ingenuity among Idaho farmers and their stakeholder partners will continue and that future challenges will be met and opportunities seized.

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