



Relating Soil Organic Carbon Increases to Available Water Storage and Drought Vulnerability in South-Central Idaho

Permanent link

<http://nrs.harvard.edu/urn-3:HUL.InstRepos:37799741>

Terms of Use

This article was downloaded from Harvard University's DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at <http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA>

Share Your Story

The Harvard community has made this article openly available. Please share how this access benefits you. [Submit a story](#).

[Accessibility](#)

Relating Soil Organic Carbon Increases
to Available Water Storage and Drought Vulnerability in South-central Idaho

Helen D. Silver

A Thesis in the Field of Sustainability
for the Degree of Master of Liberal Arts in Extension Studies

Harvard University

March 2017

Abstract

Preventing topsoil loss and increasing soil water holding capacity is critical to the sustainability of dryland, drought-prone agricultural areas. The growing pressure on freshwater resources combined with an increased likelihood of drought requires that scientists, policymakers, and land managers alike consider all mechanisms to ensure food and water security and ecosystem integrity. The benefits of conservation agricultural practices on soil structure, fertility, and water holding capacity are well-known. Land managers, however, are often slow to adopt them for fear of financial losses and other diseconomies.

This thesis examines the impacts of building soil organic carbon (SOC) stocks from conservation agricultural practices on available water storage, drought vulnerability, and aquifer recharge in two agricultural areas of south-central Idaho: The Eastern Snake Plain and the Wood River Valley. Baseline SOC and available water storage (AWS) values were taken from gSSURGO, the U.S. Department of Agriculture's national soils database. To estimate SOC increases, I applied carbon (C) sequestration values derived from the scientific literature to four agricultural land types (alfalfa, barley, pasture, and shrub land). I then calculated the impact of increasing SOC using four parameters: 1) the time needed to reverse historic SOC losses from tillage; 2) the quantity of AWS increases over ten years; 3) the time needed to reverse "drought vulnerability" (< 0.5 af of AWS in the rootzone); and 4) the reductions in aquifer recharge from increased AWS. I analyzed the on-farm financial implications of adopting no till practices and compared the cost-

efficacy of these practices for soil-building to expenditures under the federal Conservation Reserve Enhancement Program (CREP).

The major conclusions from this work are:

1. Conservation agricultural practices can reduce historic SOC losses from tillage in relatively short periods of time (often one year or less).
2. These practices can also significantly increase soil AWS and thus may contribute to both water conservation and resiliency during drought and/or water shortages.
3. For shrub and pasture land, rotational grazing and other conservation agricultural practices can reverse drought vulnerability in relatively short periods of time (five to seven years), and these results imply even faster rates for other types of cropland.
4. While significant gains are likely in terms of resiliency, conservation agricultural practices can significantly impact recharge rates and therefore should be considered both in hydrological modeling and policy development.
5. While small farms in Idaho may incur a cost in moving to no till, large farms may gain financially, an important consideration given that farm sizes are increasing.
6. As compared to the CREP, no till is likely more cost effective for soil building.

This thesis concludes with a set of interrelated research and policy recommendations. Chief among these are the need to more directly establish the relationship between increasing AWS and net irrigation requirements and to employ a strategic, integrated impact assessment process to ensure that policies support a sustainable future by protecting water and land resources.

Acknowledgements

First, last, and always, a debt of gratitude to my husband, Jonathan Fertig. Of course, I am grateful for Dr. Joseph Hunt, who not only has been a dedicated and brilliant thesis director but is also a role model and mentor well beyond the confines of the academic world, and most importantly a friend. Thank you to my mother who travelled all over Idaho (without complaint no matter the weather) to gather background information for this thesis. Dad, thank you for your active encouragement and support. Lorraine Fanton, Tim Wilson, and Linda Powers Tomasso – thank you for your friendship and support.

Specific thanks go to Teri Murrison and Chuck Pentzer of the Idaho Soil and Water Conservation Commission not only for their technical support but also to their unwavering dedication to keeping Idaho a great and beautiful state. Thank you to the following for their technical support, patience, and enthusiasm for this topic: Dr. Allan Wylie and Jennifer Sukow (Idaho Department of Water Resources); Dr. Bob Dobos (USDA Natural Resources Conservation Service); and Tammi Taylor and Chad Watts (Conservation Technology Information Center); and Dr. Keith Weber (Idaho State University). I also extend my thanks to Stacy Bogan, who provided invaluable support with ArcGIS. Finally, special thanks to Dr. Mark Leighton who is a true teacher and without whom I would never have undertaken this work.

Table of Contents

Acknowledgements.....	v
List of Tables	xi
List of Figures	xiv
Definition of Terms.....	xxi
Abbreviations	xxiv
I. Introduction.....	1
Research Significance and Objectives	3
Background.....	4
Agriculture, Water Use, and Soil Degradation in the Western U.S.....	5
Land Degradation, Food Security, and Water Scarcity Worldwide	11
Soil Health, Soil Moisture, and Water Conservation.....	14
Importance of Available Water Storage	14
Relationship Between SOC, SOM, Available Water Storage, and Soil Water Content	15
Conservation Agricultural Practices, AWS, and Soil Moisture Retention	16
Evidence for Conservation Agricultural Practices.....	17
Adoption and Financial Implications of Conservation Agricultural Practices in the U.S.	19

Agriculture, Soil Degradation, and Water Scarcity in Idaho	20
Eastern Snake Plain.....	25
Wood River Valley	30
Impacts of Drought and Soil Degradation on Energy Production	31
Research Question, Hypotheses, and Specific Aims	31
II. Methods.....	33
Baseline Data and Conditions.....	35
Carbon Sequestration Potential.....	38
Soil Organic Carbon Loss Analysis.....	38
Crop-specific Soil Organic Carbon Benchmarks.....	40
Reconciling Depth Measurements and Estimating Accrual Time for Soil Organic Carbon.....	49
Determining Increases in Available Water Storage and Effects on Drought Vulnerability and Recharge	51
Costs of Soil Health Measures.....	55
Costs of Increases in Available Water Storage to Compared to Water Purchases and the Conservation Reserve Enhancement Program	59
III. Results.....	61
SOC and AWS Losses in the Eastern Snake Plain	61
SOC and AWS Losses in the Wood River Valley	66

Remediation Times of Historic Soil Organic Carbon Losses	67
Available Water Storage Increases: Eastern Snake Plain	70
Available Water Storage Increases: Wood River Valley.....	74
Reversing Drought Vulnerability Through Conservation Practices	75
Impacts on Total and Non-irrigated Recharge.....	76
Undiscounted Costs for No Till Barley	77
Impact of Discount Rates on Costs of Moving to No Till Barley	79
Scenarios of Available Water Storage Increases Over Ten Years.....	80
Monetary Impacts: Small Farms Sensitivity to Carbon Content of Soil Organic Matter	82
Soil Savings: Cost Efficacy of the Conservation Reserve Enhancement Program versus Conservation Agricultural Practices	83
IV. Discussion	85
Soil Organic Carbon Loss and Mitigation Opportunities	86
Available Water Storage Increases	88
Time Needed to Reverse Drought Vulnerability	90
Impacts on Recharge.....	90
Cost Implications of Moving to Conservation Practices	92
Effect of Varying Soil Organic Carbon: Soil Organic Matter Ratios on Available Water Storage Increases.....	94

Policy Recommendations and Research Needs	95
Soil Organic Carbon and Available Water Storage Accrual Rates.....	95
Impacts on Irrigation Requirements.....	97
Impacts on Recharge and Downstream Users	98
Financial Implications of Adopting Conservation Practices	99
Crop Switches as a Water Conservation Effort	100
Strategic Planning Considerations	101
Strategic Planning for Rotational Grazing in the ESP	102
Region-wide rotational grazing plan for shrub lands.....	103
Encourage Integrated Crop-Livestock Systems.....	106
Strategic Planning to Meet Food, Energy, and Water Needs	107
Shifting the paradigm of water policy.	108
Strategic energy assessment.....	110
Conclusion	111
Appendix 1 Greenhouse Gas Equivalencies for Historic SOC Losses.....	114
Appendix 2 Greenhouse Gas Equivalencies for SOC Increases from Conservation Practices	115
References.....	118
Ancillary Appendix 1 County-specific AWS Losses by Cropland Type in the ESP with Varying C Contents for SOC	134
Ancillary Appendix 2 Time to Remediate SOC by County and Agricultural Land in the ESP.....	141

Ancillary Appendix 3 Year 1 and Year 10 Percent Increases in AWS	145
Ancillary Appendix 4 Impacts of Varying C Contents.....	180
Ancillary Appendix 5 Concentrated Animal Feed Operations, Fertilized Acreage, and Nitrate Pollution.....	183

List of Tables

Table 1 Water conservation targets set by the ESP Comprehensive Aquifer Management Plan.....	29
Table 2 Road map of research design and process.	34
Table 3 Land uses examined in the ESP and corresponding percentages of land use totals.	40
Table 4 Land uses examined in the WRV and corresponding percentages of land use totals.	42
Table 5 Summary of published sources for crop-specific analysis and rationale for choice.	43
Table 6 Improved SOC Benchmark (kg/acre/year) by land use type.	43
Table 7 Farm sizes examined.....	58
Table 8 Volumetric AWS losses (af/acre) by cropland type over the entire ESP (2008 and ten-year average).	66
Table 9 Volumetric AWS losses (af/acre) per acre and for the entire WRV area (2008 and ten-year average).	67
Table 10 Remediation time of ten-year SOC losses for alfalfa and barley by county (kg/acre).	68
Table 11 Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for reduced till alfalfa in the ESP.	70

Table 12 Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for organic alfalfa in the ESP.	71
Table 13 Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for no till barley in the ESP.	71
Table 14 Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for Ogle pasture benchmarks in the ESP.	72
Table 15 Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for no till pasture benchmark in the ESP.	73
Table 16 Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for Ogle shrub land benchmarks in the ESP.	73
Table 17 Cumulative volumetric increases in AWS rotational grazing for Weber benchmark in the ESP.	74
Table 18 Percentage and volumetric increases in AWS in the WRV.	75
Table 19 Time for reversing drought vulnerability by land type in the WRV.	76
Table 20 Impacts of conservation agricultural practices on total irrigated recharge in the ESP.	76
Table 21 Impacts of conservation agricultural practices on nonirrigated recharge on shrub land in the ESP.	77
Table 22 CO ₂ equivalent of 1 year of SOC loss from tillage.	114
Table 23 CO ₂ sequestration from conservation agricultural practices in the ESP.	115
Table 24 CO ₂ sequestration from conservation practices in the WRV.	117
Table 25 Impacts of C content on time needed to reverse drought vulnerability (mean values).	181

Table 26 Impacts of C content on non-irrigated recharge for shrub land in the ESP (mean values).	182
Table 27 Impact of C content on total recharge for no till barley in the ESP (mean values).	182

List of Figures

Figure 1 Map of the U.S. (excluding Alaska) showing cumulative groundwater depletion in major U.S. aquifers from 1998-2008.	7
Figure 2 Map of United States desertification vulnerability.....	8
Figure 3 Drought risk in the continental United States.....	9
Figure 4 Map of global land degradation.....	12
Figure 5 Map of global drylands.....	13
Figure 6 Soil degradation/regeneration spiral and the role of SOC.....	16
Figure 7 Location of study areas: The Eastern Snake Plain and the Wood River Valley.	21
Figure 8. Map showing drought vulnerable cropland and shrub land areas in the ESP. .	22
Figure 9 Map showing drought vulnerable cropland and shrub land areas in the WRV..	23
Figure 10 Changes in precipitation by season under a rapid emissions reduction and a continued emissions benchmark.....	24
Figure 11 Trends in surface- and groundwater irrigation over time in the ESP.....	26
Figure 12 Map showing declines in aquifer levels in the ESP from 1998 to 2008.....	27
Figure 13 Conceptual diagram of research design.....	33
Figure 14 Land uses examined in the ESP.....	41
Figure 15 Land uses examined in the WRV (2015 acreage).	42

Figure 16 USDA Forest Service Ecoregions (Domains) (Hawaii and Territories excluded)	44
Figure 17. USDA Forest Service Ecoregions (Divisions) (Hawaii and Territories excluded).	45
Figure 18 SOC levels for shrub land, pasture, barley, and alfalfa in the ESP.	47
Figure 19 SOC levels for shrub land, pasture, barley, and alfalfa in the WRV.	48
Figure 20 AWS levels for shrub land, pasture, barley, and alfalfa in the ESP.	52
Figure 21 AWS levels for shrub land, pasture, barley, and alfalfa in the ESP.	53
Figure 22 Trends in average farm size and holdings by economic sales class in Idaho from 2005-2014.	57
Figure 23 SOC losses all for agricultural lands from the ESP by county (kg/acre).	63
Figure 24 Ten-year average AWS losses from pasture in the ESP by county with varying C contents.	64
Figure 25 Pasture 2008 AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).	65
Figure 26 Financial implications over the course of one year for different farm sizes (WRV and ESP).	78
Figure 27 Impact of discount rates on perceived costs of switching to no till barley after ten years for small farms (<640 acres).	79
Figure 28 Impact of discount rates on perceived costs of switching to no till barley after ten years for large farms (>640 acres).	80

Figure 29 AWS increases after ten years of no till barley with SOC accrual times compared (ESP; mean values).....	81
Figure 30 AWS increases after ten years of no till barley with SOC accrual times compared (WRV; mean values).	81
Figure 31 Impact of different SOC: SOM ratios on AWS increases for no till barley (WRV).....	82
Figure 32 Impact of different SOC: SOM ratio on AWS increases for no till barley (ESP).	83
Figure 33 Impact of different SOC: SOM ratios on the cost of building one ton of soil with no till barley.	84
Figure 34 Physical and climatological attributes of shrub land in the ESP.	104
Figure 35 Volumetric increases in AWS after ten years of rotational grazing (nominal to medium input) in the ESP (af/acre).....	105
Figure 36 Alfalfa 2008 AWS losses (af/acre) in ESP with varying assumptions of SOC: SOM content (mean values).....	135
Figure 37 Alfalfa ten-year average AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).....	136
Figure 38 Barley 2008 AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).....	137
Figure 39 Barley ten-year average AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).....	138

Figure 40 Pasture 2008 AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).....	139
Figure 41 Pasture ten-year average AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).....	140
Figure 42 Remediation time of ten-year total SOC losses for conservation practices for organic alfalfa by county.....	142
Figure 43 Remediation time of ten-year total SOC losses for conservation practices for reduced till alfalfa by county.....	143
Figure 44 Remediation time of ten-year total SOC losses for conservation practices for no till barley by county.....	144
Figure 45 Year 1 percent increases in AWS for reduced till alfalfa in the ESP.....	146
Figure 46 Year 10 percent increases in AWS for reduced till alfalfa in the ESP.....	147
Figure 47 Year 1 percent increases in AWS for reduced till alfalfa (groundwater irrigated) in the ESP.....	148
Figure 48 Year 10 percent increases in AWS for reduced till alfalfa (groundwater irrigated) in the ESP.....	149
Figure 49 Year 1 percent increases in AWS for organic alfalfa in the ESP.....	150
Figure 50 Year 10 percent increases in AWS for organic alfalfa in the ESP.....	151
Figure 51 Year 1 percent increases in AWS for organic alfalfa (groundwater irrigated) in the ESP.....	152

Figure 52 Year 10 percent increases in AWS for organic alfalfa (groundwater irrigated) in the ESP.....	153
Figure 53 Year 1 percent increases in AWS for no till barley in the ESP.....	154
Figure 54 Year 10 percent increases in AWS for no till barley in the ESP.....	155
Figure 55 Year 1 percent increases in AWS for no till barley (groundwater irrigated) in the ESP.....	156
Figure 56 Year 10 percent increases in AWS for no till barley (groundwater irrigated) in the ESP.....	157
Figure 57 Year 1 percent increases in AWS for nominal to medium input pasture in the ESP.....	158
Figure 58 Year 10 percent increases in AWS for nominal to medium input pasture in the ESP.....	159
Figure 59 Year 1 percent increases in AWS for nominal to medium input pasture (groundwater irrigated) in the ESP.....	160
Figure 60 Year 10 percent increases in AWS for nominal to medium input pasture (groundwater irrigated) in the ESP.....	161
Figure 61 Year 1 percent increases in AWS for no till pasture in the ESP.....	162
Figure 62 Year 10 percent increases in AWS for no till pasture in the ESP.....	163
Figure 63 Year 1 percent increases in AWS for no till pasture (groundwater irrigated) in the ESP.....	164

Figure 64 Year 10 percent increases in AWS for no till pasture (groundwater irrigated) in the ESP.	165
Figure 65 Year 1 percent increases in AWS for nominal to medium input shrub land in the ESP.	166
Figure 66 Year 10 percent increases in AWS for nominal to medium input shrub land in the ESP.	167
Figure 67 Year 1 percent increases in AWS for organic alfalfa in the WRV.....	168
Figure 68 Year 10 percent increases in AWS for organic alfalfa in the WRV.....	169
Figure 69 Year 1 percent increases in AWS for reduced till alfalfa in the WRV.....	170
Figure 70 Year 10 percent increases in AWS for reduced till alfalfa in the WRV.....	171
Figure 71 Year 1 percent increases in AWS for reduced till alfalfa in the WRV.....	172
Figure 72 Year 10 percent increases in AWS for reduced till alfalfa in the WRV.....	173
Figure 73 Year 1 percent increases in AWS for nominal to medium input pasture in the WRV.....	174
Figure 74 Year 10 percent increases in AWS for nominal to medium input pasture in the WRV.....	175
Figure 75 Year 1 percent increases in AWS for no till pasture in the WRV.....	176
Figure 76 Year 10 percent increases in AWS for no till pasture in the WRV.....	177
Figure 77 Year 1 percent increases in AWS for nominal to medium input shrub land in the WRV.....	178

Figure 78 Year 10 percent increases in AWS for nominal to medium input shrub land in the WRV.....	179
Figure 79 Map showing locations of enforcement actions at concentrated animal feed operations and Idaho Groundwater Priority Areas for Nitrate.....	185
Figure 80 Map showing density of concentrated animal feed operations and enforcement sections.....	186
Figure 81. Concentration of fertilized acres in the U.S..	187
Figure 82. Example of a nutrient- impaired water way from agricultural sources (Twin Falls, Idaho).....	188
Figure 83. Example of a nutrient-impaired water way from agricultural sources (Eastern Snake Plain).....	188

Definition of Terms

Available Water Storage: The maximum amount of water in a soil available to plants. Available water storage is a function of the soil's texture and aggregate composition. Alternative terms include "available water capacity" and "water holding capacity."

Comprehensive Aquifer Management Plan: A water management plan that integrates both groundwater from aquifer and surface water resources for budgeting and planning purposes. These are relatively new developments and have occurred because of concerns over groundwater mining (i.e., pumping above the natural rate of recharge).

Conservation Agricultural Practices or Conservation Practices: Agricultural management techniques generally recognized to increase soil health by reducing erosion and increasing water retention. Specific practices include no till, reduced till, and organic management practices. Rotational grazing is also defined as a conservation agricultural practice.

Continuous Grazing: A system of grazing where cattle remain on a pasture or other plot of land without rest for an extended period of time (e.g., an entire season or year).

Crop-pasture rotations: An umbrella term for an integrated livestock-crop land management system in which crops (whether for fodder or human consumption) are alternatively grown in the same plot as grazed pasture.

Conservation Reserve Enhancement Program: A federal program that pays an annual rental rate to landowners to take environmentally sensitive land out of production. Eligible land is determined pursuant to agreements between the state and the federal government.

Desertification: The term is often used interchangeably with degradation, but reflects a more severe loss of ecosystem function in which arid areas exhibit true desert-like conditions (UN Environmental Management Group, 2011).

Drylands: The United Nations defines drylands as having one overriding characteristic: relatively low amounts of precipitation and have an aridity index of below 0.65 (United Nations Environmental Management Group, 2011). Drylands are further divided into the following categories: hyper-arid deserts (<0.5 aridity index); arid (0.05-0.20 aridity index), semi-arid (0.20 to 0.50 aridity index), and dry sub-humid (0.50-0.65 aridity index) (United Nations Environmental Management Group, 2011).

Dry-leasing: The lease of water from one parcel of land for diversion of to another parcel of land or use.

Improved SOC benchmarks: SOC stocks achievable under conservation management techniques, such as rotational grazing and no till agriculture. Used interchangeably with “C sequestration rates.”

Integrated Livestock Management Systems: An umbrella term in which agricultural land use is intensified both for human food and livestock fodder production. A wide variety of techniques and systems exist.

Junior water right: Those rights to an amount of water acquired at a relatively later date than other rights, commonly referred to as senior water rights. For example, a water right acquired in 1885 is junior to one acquired in 1820 but senior to one acquired in 1900. See Senior Water Right.

Non-irrigated Recharge: Recharge to aquifers and groundwater from precipitation and other non-irrigation sources.

No Till: An agricultural management practice in which crops are grown and pasture managed without disturbing the soil through tillage.

Prior Appropriation Doctrine: The governing legal doctrine in Western states, including Idaho, whereby senior water rights have priority over later-in-time rights (junior water rights). Also known as “first in time, first in right.” See “junior water rights” and “senior water rights.”

Rangeland: Shrub steppe habitat used for grazing.

Reduced Till: An agricultural management technique in which 15% to 30% of crop residue is left on the field.

Ridge Top Till: An agricultural management technique in which tillage is not used except for in strips of up to 1/3 of the row width.

Rotational Grazing: Umbrella term for several grazing systems whereby cattle are moved from area to area so that vegetative cover remains on a given plot of land and forage is maximized. Other umbrella terms include prescribed grazing, mob grazing, adaptive management grazing.

Senior Water Rights: Those rights to an amount of water acquired at a relatively earlier date by putting water to beneficial use.

Shrub Land: Shrub steppe habitat.

Shrub Steppe: A type of perennial grassland dominant in South-central Idaho.

Total Recharge: Recharge from all water sources including excess irrigation water.

Western United States or Western States: Those states lying west of the 100th Meridian (excluding Alaska).

100th Meridian: 100th line of longitude (west) that demarcates a discrete change rainfall pattern in the United States, with areas lying West generally receiving less than 20 inches a year.

Abbreviations

af: Acre-feet (of water)

AWS: Available water storage

C: Carbon

CO₂e: Carbon dioxide equivalent

CAMP: Comprehensive aquifer management plan

CTIC: Conservation Technology Information Center, a leading nonprofit for education and research on conservation agricultural practices (Conservation Technology Information Center, 2017)

CREP: Conservation Reserve Enhancement Program

DR: Discount Rate

ESP: Eastern Snake Plain

ESPA: Eastern Snake Plain Aquifer

ESPAM: Eastern Snake Plain Aquifer Modelling Area

gSSURGO: Gridded Soil Survey Geographic

GW: Groundwater

IDWR: Idaho Department of Water Resources

ISWCC: Idaho Soil and Water Conservation Commission

IWRB: Idaho Water Resources Board

kaf: Thousand acre-feet (of water)

NIR: Non-irrigated recharge

NOAA: National Oceanic Atmospheric Administration

NRCS: Natural Resources Conservation Service

RACA: Rapid Assessment of Soil Carbon

SIA: Strategic impact assessment

SOC: Soil organic carbon

SOM: Soil organic matter

TR: Total recharge

UN: United Nations

UNEP: United Nations Environment Programme

UN FAO: United Nations Food and Agriculture Organization

USDA: United States Department of Agriculture

USDA NASS: United States Department of Agriculture National Agricultural Statistics Service

U.S. EPA: United States Environmental Protection Agency

USGS: United States Geological Survey

UNCCD: United Nations Convention to Combat Desertification

WRV: Wood River Valley

Chapter I

Introduction

Reducing agricultural irrigation requirements and halting topsoil loss are necessary to promote sustainable food systems, particularly in drought-prone areas. Widespread agricultural practices, such as tillage and continuous grazing, have caused significant soil organic carbon (SOC) losses, in turn undermining the structural integrity of soils and their ability to receive and make water available for crops. Further, many of the water supplies on which agricultural systems rely are over-appropriated. Simultaneous acceleration of climate change impacts (drought most notably) and socio-economic trends, such as an increasing population and rising standards of living, will exacerbate this already precarious situation.

The consequences of inertia to this escalating problem could be dire if commensurate policies are not enacted. Already the largest consumptive user of water, agricultural water requirements are expected to grow to meet a 60% increase food production (United Nations Food and Agriculture Organization, 2015).

Anthropogenically caused erosion is already an order of magnitude greater than that caused by natural processes (Goldhaber & Banwart, 2015), and bringing more land into production or intensifying production may accelerate this. Indeed, the United Nations Environment Programme (2014) estimates that agricultural requirements could overshoot the earth's capacity by 10% to 45% by 2050. Officials from the United Nations Food and

Agricultural Organization have stated that if continued, by 2050, current practices would reduce by 75% the amount of arable land per person from 1960 levels (da Silva, 2014).

Dryland agricultural systems are particularly vulnerable and unstable, due to naturally erodible soils and drought susceptibility. Both in the United States and globally, however, arid areas are important agricultural and economic sectors. Globally, dryland areas support a rapidly growing population of 2.1 billion, 44% of the world's cultivated lands, and 50% of the world's livestock (United Nations, n.d.). In the United States, the Western states are responsible for 47% of agricultural cash receipts, with California leading the way (U.S. Department of Agriculture, Economic Research Service, 2016).

Rebuilding SOC stocks through conservation agricultural practices would likely go a long way towards reducing topsoil loss, reducing drought vulnerability, and generally increasing soil fertility (Bot & Benites, 2005; Banwart, Noellemeyer, & Milne, 2015). In recent years, climate mitigation and the potential for a carbon market was a primary driver of interest in agricultural carbon sequestration, but policies have largely been ineffective. This is likely due to the absence of timely feedback loops from many climate change impacts and political inexpediency. In contrast, drought, water scarcity, and topsoil loss are accelerating, and the threats they pose to food and economic security are becoming more salient. Therefore, water conservation and food security might catalyze the needed policy and behavior changes.

Nonetheless, significant knowledge gaps exist regarding the role that soil health can play. These include the lack of a general understanding of how increasing soil health can reduce irrigation needs and/or increase the efficiency with which crops use

precipitation, though the few existing studies show extraordinary potential. Further, few studies address the hydrological impacts of soil health on a basin- or regional scale, instead focusing on site- and/or crop specific impacts. Uncertainty also surrounds the financial implications of adopting conservation agricultural practices. Several factors explain this knowledge gap. The first is simply scientific: soils, climate, and hydrology are extraordinarily heterogeneous – even in areas of close proximity. The second is socio-economic: technological and infrastructure developments – particularly those that have increased water supply – have masked the impacts of soil degradation while boosting production capacity, leading to general neglect in the research community of this topic.

Research Significance and Objectives

These research gaps present obstacles on two fronts. First, and foremost, the lack of regional or basin-wide estimates on the impacts of soil health measures and hydrology hampers the development of water budgets at this scale. Second, failure to systematically document the on-farm benefits of conservation practices has likely forestalled their adoption. This thesis seeks to fill some of these gaps by examining the impacts of conservation practices on topsoil loss and available water storage (AWS) in two arid areas of south-central Idaho, the Eastern Snake Plain and the Wood River Valley.

This study's primary objective is to estimate the impacts of conservation agricultural practices on agricultural, drought-prone areas by evaluating: 1) the effects on historic SOC losses from tillage; 2) the hydrological impacts of increasing AWS; and 3) the on-farm costs of adopting conservation agricultural practices and comparing them to

governmental programs. The two study areas – the Eastern Snake Plain (ESP) and the Wood River Valley (WRV) – are both located in south-central Idaho.

Evaluating the impact of conservation practices on topsoil loss and water holding capacity can provide useful information on matters ranging from the development of basin-scale water budgets to identifying the most effective areas to target for conservation practices. Specifically, in Idaho, these may 1) inform whether the Idaho Department of Water Resources should incorporate SOC stocks into its hydrological models; 2) identify cost-effective ways to conserve water and prevent topsoil loss; and 3) provide a roadmap for future research needs.

Background

Dryland agricultural systems may be on the brink of collapse due to widespread soil degradation and dwindling freshwater supplies. Future trends will likely further exacerbate the situation, including climate change and socio-economic trends, such as an increased population and rising standards of living. Not only must lands likely sustain doubling of food production by 2050 (Banwart, et al., 2015), but the concomitant rise in energy needs will place further pressure on fresh water resources, as nearly every all forms of energy production affect either or both water quantity and quality.

Whether water and land resources can meet these requirements is unclear. On the one hand, the United Nations Food and Agriculture Organization (UN FAO) (2015) estimates that if major policy modifications are implemented, total water and food production capacity can meet projected global needs through 2050. On the other, the United Nations Environment Program (UNEP) (2014) estimates that the demand for

productive land could overshoot the earth's land resource capacity by 10% to 45% by 2050. In any event, maintaining the status quo is precarious, at best.

Healthy soils are critical to sustainable food production, and soil organic carbon (SOC) is the primary driver of soil health (e.g., U.S. Department of Agriculture, Natural Resource Conservation Service (USDA NRCS), 2013; UN FAO, 2015). Since the 19th Century, however, some 60% of soil carbon has been lost from agricultural lands (Banwart, et al., 2015). Despite the gravity of the situation and the fact that the benefits of increasing SOC stocks are well-known, effective policies are all but absent. Probably the largest impediment has been technological developments that increase available water supply (e.g., dams and groundwater drilling) and that mask lost fertility (e.g., nitrogen-based fertilizers, fungicides, and pesticides) (Wallander, Aillery, Hellerstein, & Hand, 2013).

This chapter reviews two major topics. The first part describes how soil degradation and water scarcity jeopardize food security in the Western United States and globally, how the situation arose, and our knowledge of how increasing soil health might present a solution. The second part focuses specifically on the Eastern Snake Plain and the Wood River Valley.

Agriculture, Water Use, and Soil Degradation in the Western U.S.

Food security, water scarcity, and soil degradation are closely interrelated in the western United States. Western states are top agricultural producers – accounting for 47% of cash receipts (USDA Economic Research Service, 2016), with California and the Great Plains leading the way, and much of this agriculture relies on irrigation. Indeed,

only six percent of agricultural acreage in the United States is irrigated, and much of it is located in the West (USDA National Agriculture Statistics Service (USDA NASS) (2014)).

While constituting only a small portion of total acreage (6%), irrigated agricultural acreage accounts for an astoundingly disproportionate amount of water usage: ~33% of total U.S. withdrawals (surface and groundwater) (United States Geological Service (USGS), 2014) and 80% of national consumptive use (USDA Economic Research Service, 2016). Much of this water comes from nonrenewable groundwater supplies, with groundwater accounting for 43% of agricultural usage (USGS, 2013). Further, while groundwater withdrawal rates have remained steady in recent years (USGS, 2016), increased drought and/or higher temperatures could reverse this trend (U.S. Global Change Research Program, 2014). With aquifer levels declining all over the United States (Figure 1), the status quo clearly is not sustainable.

Only decades after the Dust Bowl and resulting mass migration, farmers in the Great Plains once again were encouraged to plough up deep-rooted grasslands. This time, however, the inducement was not cheap and abundant land, as was the case with the Homestead Act, but of cheap and abundant water. Because of the proliferation of more advanced groundwater drilling technology in the 1950s, the Great Plains region now supplies 1/5 of the nation's harvest, and irrigation uses a full 90% of withdrawals from the Ogallala Aquifer (Braxton, 2009). Unless significant changes are made, however, the area may once again experience a devastating agricultural bust. Given the size of the Ogallala Aquifer, projected depletion times vary, but all are distressingly close on the

horizon: for example, areas underlying Kansas could peak by 2040 (Steward, et al., 2013).

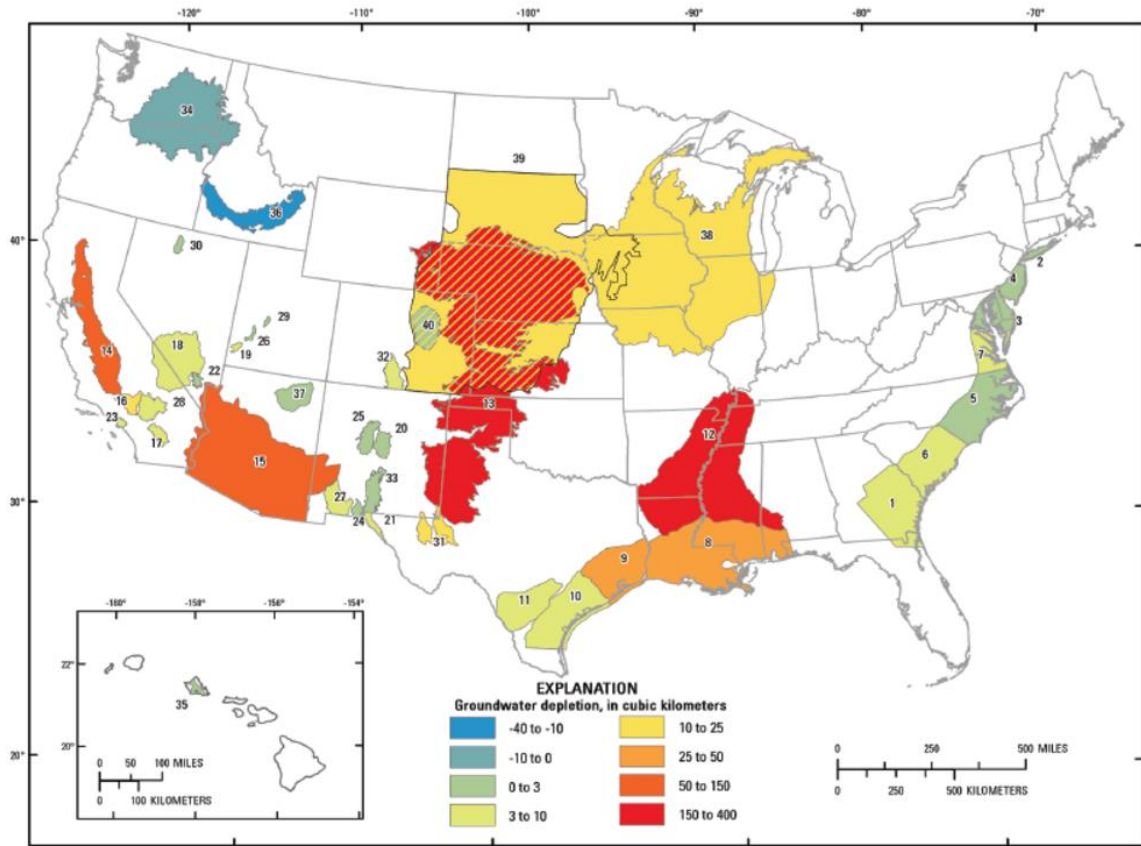


Figure 1. Map of the U.S. (excluding Alaska) showing cumulative groundwater depletion in major U.S. aquifers from 1998-2008 (USGS, 2013).

California's mega-drought presents a potentially more disturbing situation. Rife with political intrigue, the story of how California obtained the rights to vast amounts of water to harness the state's ideal, year-round growing conditions is well known (Reisner M., 1986). Coupled with its appropriation of water has been the California's historical reticence to require farmers to reduce their consumption, which currently stands at 80% of the state's total (Natural Resources Defense Council; Pacific Institute, 2014). The

severity of the current drought, however, may be changing matters. The past two years have witnessed ~\$2 billion annually in losses from the industry (Rice, 2015). Though only a small fraction of the industry's total value, it is widely recognized that relying on nonrenewable groundwater has been the only way to avert more serious consequences (Howitt, MacEwan, Medellin-Azuara-Josue, Lund, & Sumner, 2015).

Drought vulnerability and soil degradation are closely linked in the western United States. As Figure 2 and Figure 3 show, areas at significant desertification risk overlap with those at risk for significant drought (U.S. Government, n.d.).

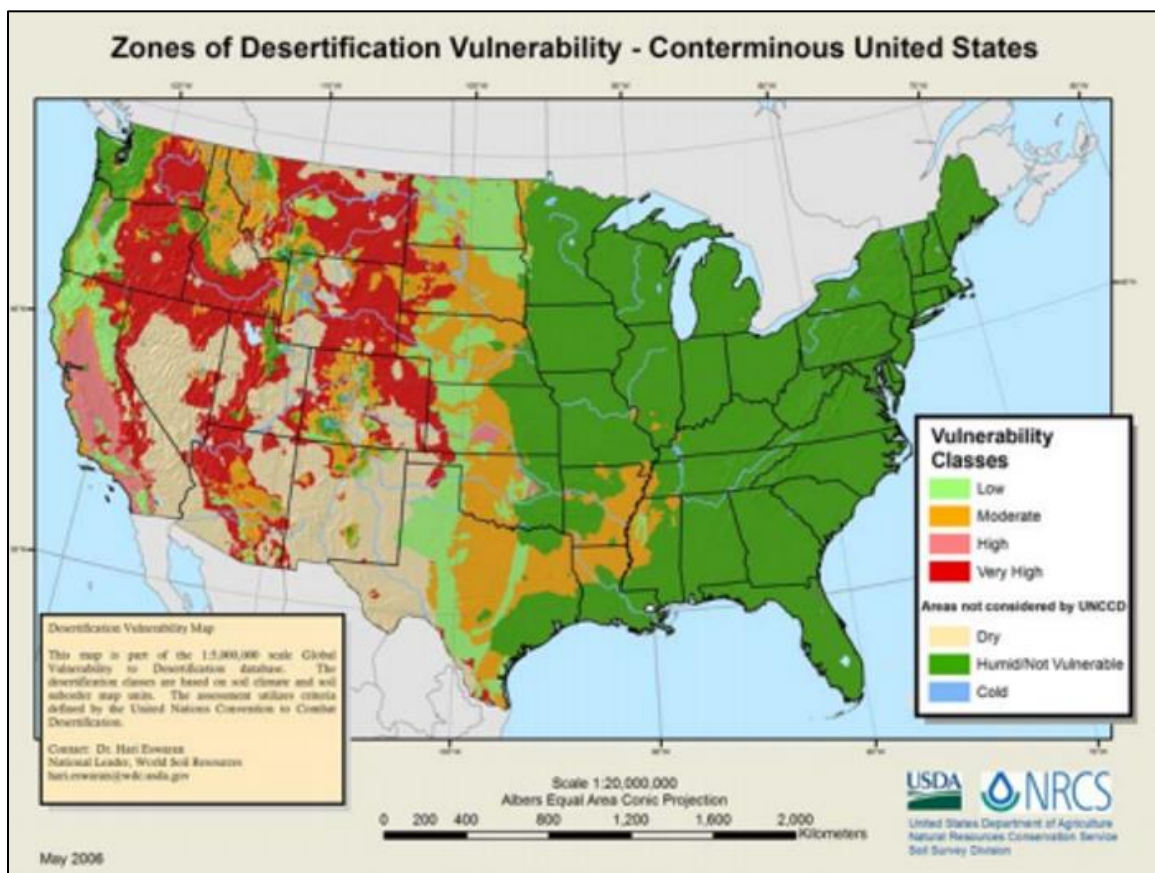


Figure 2. Map of United States desertification vulnerability (U.S. Government, n.d.).

Combined, soil degradation and drought have devastating impacts. The Dust Bowl of the 1930s is an extreme example, forcing 2.5 million people out of the Great Plains (including many farmers to California) (Public Broadcasting Service, n.d.) and contributing significantly to both the severity and the longevity of the Great Depression (Burns, 2012). Beyond drought, the main effect of topsoil loss is reduced fertility, and the problem is significant in the United States with losses amounting to 11% of global land area (Goldhaber & Banwart, 2015). While fertilizers may temporarily mask this fertility loss, over-application accelerates the downward degradation spiral by reducing subsurface biodiversity.

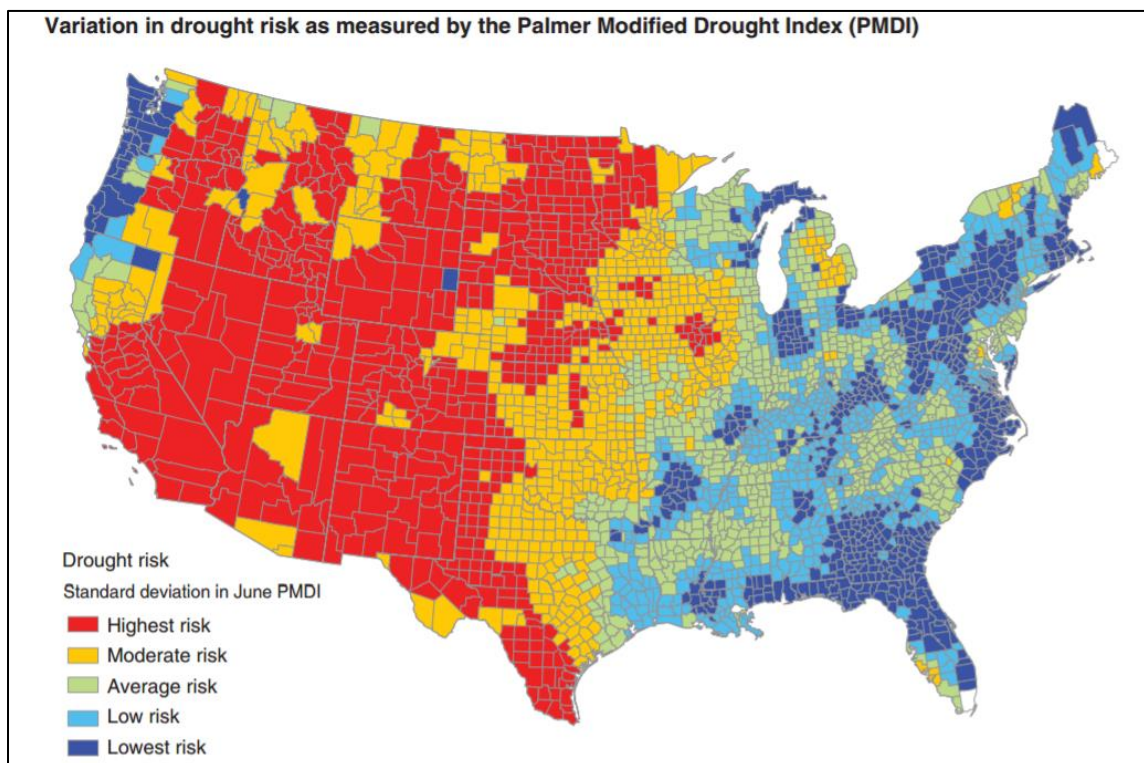


Figure 3. Drought risk in the continental United States (Wallander, Aillery, Hellerstein, & Hand, 2013).

Croplands are not the only vulnerable agricultural lands. Occupying 33% of the U.S. land mass, rangelands are also a critical agricultural and economic resource. The impacts of drought and soil degradation include reduced forage quality and quantity, increased invasive species, and potentially greater wildlife risk (Polley, et al., 2013; Wallander, Aillery, Hellerstein, & Hand, 2013). Indeed, recent drought has necessitated a reduction in cattle stocking allotments (U.S. Bureau of Land Management, 2013), with devastating social and economic consequences (Cart, 2014). A confounding factor is that grazing pressures on these lands may increase. Demand for grass-finished beef has been growing at an annual rate of 20% or more (Banker, 2016), and this trend may continue as concern over nutritional quality and environmental sustainability grows.

Beyond food production, grazing on public lands raises socio-political issues. Hopefully an anomalous outburst of extremism, the Oregon Malheur Wildlife Refuge standoff highlights the virulent emotionalism that accompanies threats to natural resource use and perceived government overreaching (Rogers, 2016). A less violent manifestation of these tensions is the widespread movement in Western States to reclaim federal lands (Barker, 2016).

Against this backdrop, the lack of integrated policies addressing soil health and water issues is alarming. The most prominent federal actor in soil health is the USDA Natural Resources Conservation Service (USDA NRCS), a nonregulatory body that provides essential educational, technical, and financial resources directly to land managers, while also performing important research. USDA NRCS implements several programs, including the Environmental Quality Incentives Program and the Conservation Reserve Enhancement Program (CREP). The latter pays farmers to fallow and improve

their land and are critical programmatic mainstays (Wallander, Aillery, Hellerstein, & Hand, 2013). Recently, USDA (2016) announced the Climate Smart Agriculture & Forestry program.

While CREP is a laudable program, there is at least one problem: The opportunity costs may be too high, and some areas have low enrollment rates because of the discrepancy between agricultural prices and annual CREP rental payments. The efficacy of these programs is also limited because they are subject to changing congressional and executive branch priorities.

Like federal policies, state soil health policies are generally confined to technical and financial assistance. Though anticipation of a federal climate bill did raise interest in agricultural and forest CO₂ sequestration policies, these efforts have largely stagnated with the corresponding federal inertia. Finally, some federal and state policies may discourage the adoption of soil health measures and thus perpetuate the industry's unsustainability. The most notable is the Federal Crop Insurance Program (FCIP), which many argue rewards farmers for not adopting cost-effective conservation practices to avert crop failure (O'Connor, 2013). On par with the drought that occasioned the Dust Bowl, the 2012 drought (Wallander, Aillery, Hellerstein, & Hand, 2013) caused a spike in FCIP payouts of \$13.2 billion (O'Connor, 2013). Given that drought is likely to increase, the FCIP is exemplary of policies that must be changed.

Land Degradation, Food Security, and Water Scarcity Worldwide

The situation at the global level is even more severe. Most of the world's soils are significantly degraded (Figure 4). Further, one-third of aquifers are stressed (U.S.

National Aeronautics and Space Administration, 2015), and by 2030, at least half of the world's population may live in water-stressed areas (United Nations (UN), n.d.).

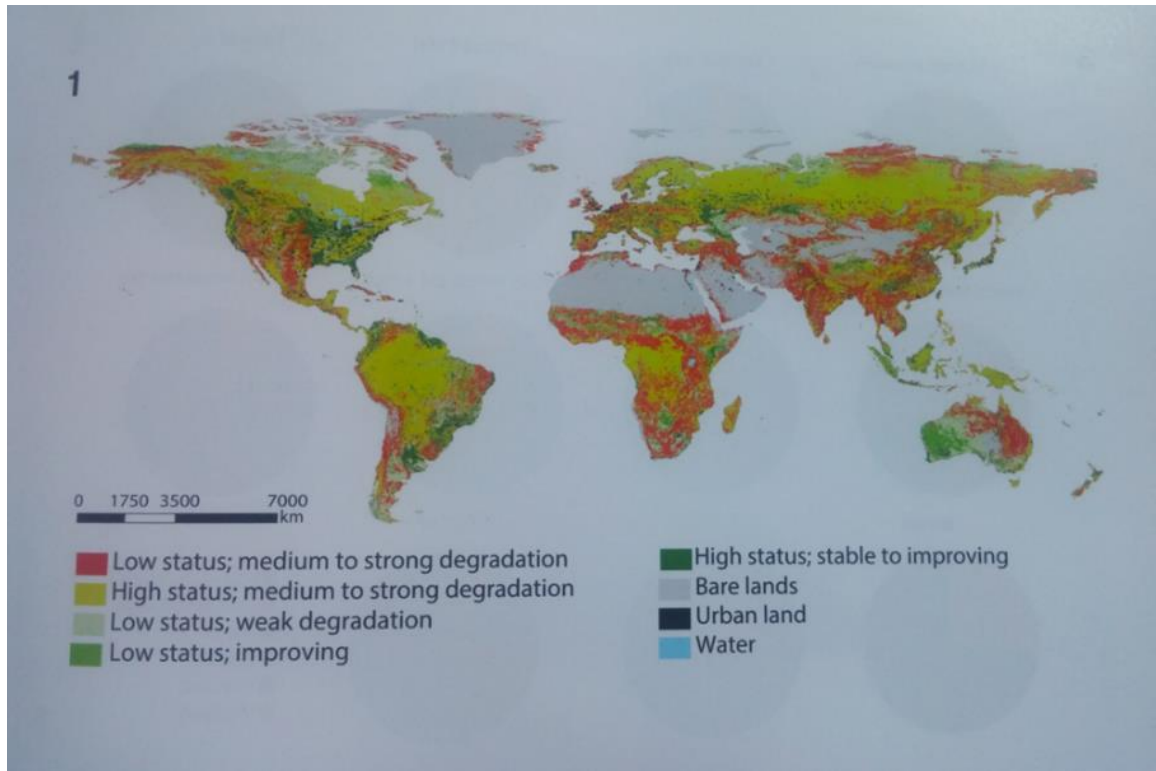


Figure 4. Map of global land degradation (Banwart, Noellemeier, & Milne, 2015, Plate 1).

Constituting 41% of global land mass (UN, n.d.) (Figure 5), degradation of drylands poses significant social, health, and economic risks. Drylands are already home to 2.1 billion people and have the fastest rate of population growth (UN, n.d.). They are also critical to global food security, containing 44% of agricultural systems and 50% of livestock (UN, n.d.). Nearly 24% of land is degrading, however, with 20% of that consisting of cropland (United Nations Convention to Combat Drought and Desertification (UNCDD), 2015).

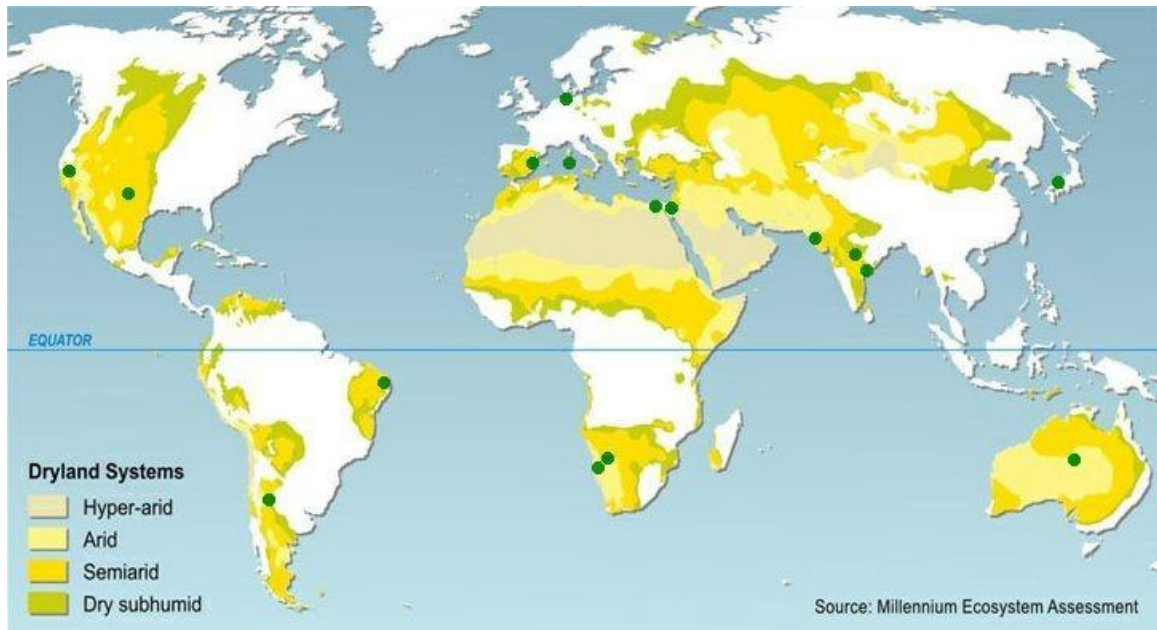


Figure 5. Map of global drylands (Global Network of Dryland Research Institutes, n.d.).

The cost of lost ecosystems services is enormous, with annual estimates ranging from \$6.3 and \$10.6 trillion (UNCDD, 2015). With respect to climate change, dryland SOC loss could be significant as these soils store 46% of the global carbon share (UN, n.d.). Particularly important for food security is maintaining rangeland health, as grazing is the only way to make these lands calorically productive. Indeed, the severity of the situation has prompted action by the UN, which declared 2010-2020 “The Decade for Deserts and the Fight against Desertification” (UN, n.d.). The Sustainable Development Goals also pledge to halt desertification by 2030 (UN, n.d.).

Through 2050, agriculture will continue to be the largest user water consumer (more than 50%) (UN FAO, 2015), but rapid urbanization, increased energy consumption, and a quadrupling of demand for meat (UN FAO (Regional Office for Asia and the Pacific), n.d.) will strain resources and jeopardize food security, potentially causing conflicts and social unrest. If the pattern of high-income countries is any

predictor, developing countries could the current allocation of water to industrial resources from 18% to 70% (World Business Council for Sustainable Development, 2005). Particularly concerning is the rise in hydropower development, which is expected to be the dominant form of renewable energy by 2030 (The World Economic Water Forum Initiative, 2011). Though hydropower can augment agricultural water supply, it also has significant evaporative losses (The World Economic Water Forum Initiative, 2011) and disrupts natural hydrological cycles necessary for ecosystem functioning.

Soil Health, Soil Moisture, and Water Conservation

Given these threats, stakeholders ranging from the UN to the U.S. federal government to nonprofits are touting soil health as a way to increase agricultural water productivity – that is to get “more crop per drop” (Banwart, Noellemeier, & Milne, 2015; USDA NRCS, 2013). There are, however, significant research gaps about how soil health translates into water savings.

Importance of Available Water Storage

While the critical resources are water and soil moisture, a soil’s AWS is the prime determinant of these factors because it indicates how much water soils can make available to plants and for how long (USDA NRCS, 2008). For irrigators, knowing the AWS is critical because it allows them to determine both the amount and the frequency of water applications (USDA NRCS, 2008). Other factors being equal, when AWS and infiltration are optimal, soil moisture responds positively and proportionally to precipitation/irrigation rates (USDA NRCS, 2008). In contrast, compaction and erosion

decrease infiltration and accelerate sedimentation, particularly when combined with furrow or flood irrigation.

The majority of states in the Western U.S. follow the Prior Appropriation Doctrine, whereby water is delivered according to when the right was acquired. Therefore, in these jurisdictions, junior water rights (see definition of terms) are cut off in the case of water shortages, and thus increasing AWS may have significant benefits. As one farmer put it, “We pay for every drop. So the longer we can keep water on the land [through increased AWS] the better.” (McIntyre, 2016)

Relationship Between SOC, SOM, Available Water Storage, and Soil Water Content

Good soil functioning starts with good soil structure, and SOC is a primary determinant. It is a major constituent of soil organic matter (SOM), which in turn is related to water infiltration and holding capacity. Figure 6 shows the reinforcing feedback loop that SOC loss causes and the resulting impacts on soil structure and moisture and, ultimately, vegetative health.

Increasing SOM directly increases AWS, and the most widely accepted relationship is that a 1% increase in SOM increases AWS by 3.7% (Hudson, 1994). This metric is used by both United States and international authorities (USDA NRCS, 2008; Bot & Benites, 2005).

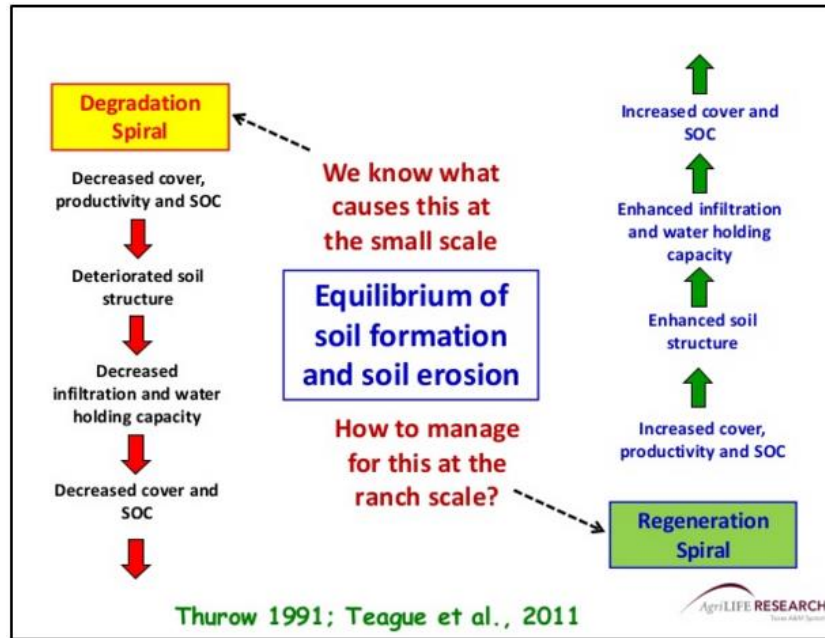


Figure 6. Soil degradation/regeneration spiral and the role of SOC (Teague, R. A., 2014).

SOC generally constitutes between 42% to 58% of SOM (Bot & Benites, 2005) and the ratio is a significant factor in determining increases in AWS from SOM augmentation. Most studies assume a 58% carbon (C) content (Franzluebbers, 2010; Hudson, 1994), but at least one study has questioned this convention, finding that 50% C content may be a more accurate assumption (Pribyl, 2010). Using a 58% C ratio, this results in a 2.15% increase in AWS for every 1% increase in SOC. An assumption of 42% results in a 1.55% increase, and 50%, a 1.85% increase.

Conservation Agricultural Practices, AWS, and Soil Moisture Retention

It is generally undisputed that building SOC stocks through conservation agricultural practices (see below) increases AWS and soil moisture retention (USDA NRCS, 2008). There are, however, both substantive and methodological research gaps;

as a result, there is no generally accepted relationship between water conservation and AWS gains. Substantively, few studies directly measure the effect on AWS or plant water efficiency and those that do tend to be crop- and region specific with little generalizability (e.g., Lafond, Loepky, & Derksen, 1992; Unger & Wiese, 1979; Rockstrom, et al., 2009; Kronen, 1994). Despite the paucity of data, the results are promising. For instance, Lafond, Loepky, and Derksen (1992) demonstrated in Canada that zero and minimum till increased soil water content by over 9% in the first 60 cm. More recently, USDA Agriculture Research Service trials in Washington showed that conservation till caused more uniform and increased recharge rates in wheat fields, with gains in AWS leading to significant yield and profit increases (Perry, 2012).

Methodologically, few studies examine the hydrological impacts of increasing SOC at the basin- or regional level (Scheierling, Treguer, Booker, & Decker, 2014; Nziguehab, et al., 2015). Again, a likely factor has been the seeming abundance of water occasioned by dams and advanced drilling technology. Indeed, while some research on these issues was ongoing in the Great Plains through the mid to late 20th century, it appears to have largely dropped off (Unger & Wiese, 1979; Klocke, 1984). Causes notwithstanding, these gaps impede policy development when basin-level and regional water planning needs are at an all-time high.

Evidence for Conservation Agricultural Practices

Several types of agricultural management fall under the rubric of conservation agricultural practices. On cropland, these include the adoption of no till (NT), reduced till (RT), mulch till, cover-cropping, and compost application. The overwhelming

majority of formal research and the experience of land managers demonstrate that these practices build SOC and benefit soil health (Karlen, Kovar, Cambardella, & Colvin, 2013; Bot & Benites, 2005), with many showing increased or “no-worse” yields (e.g., Warren, et al., n.d.).

In contrast, the science regarding range and pasture lands is more uncertain, given the greater variation in climate and soil characteristics (e.g., Schuman & Janzen, 2001; Joyce, et al., 2013; Polley, et al., 2013). This is particularly true for the Western United States, as most research focuses on the Midwest and Great Plains (Ogle, Conant, & Paustian, 2004). The most common form of grazing in the United States is continuous grazing, where cattle are stationed on a given parcel and allowed to eat freely and continuously. This type of grazing has been convincingly linked to a suite of environmental problems particularly in the arid West (e.g., Clancy, 2006; White, 2014).

Recently, however, increased attention is being paid to what is known as “rotational grazing” or “adaptive planned grazing” to: 1) restore degraded range and pasture lands; 2) provide grazers with a better product; 3) meet the growing demand for environmentally sustainable, ethically produced, and healthier meat and dairy; and 4) sequester CO₂. In contrast to continuous grazing, land health is the governing principle in rotational grazing, and cattle are moved accordingly. Whether rotational grazing is superior to continuous grazing has been vehemently debated (compare Teague, et al., 2016 with Briske, et al., 2011), and an effort by top researchers plans to assess the landscape impacts over the long-term of these practices (Apfelbaum, et al., 2015).

Nonetheless, a scientific consensus is emerging that incorporation of animal husbandry using the principles of rotational grazing is essential to maintaining soil health

(Teague, et al., 2016; Teague, et al., 2011). This is particularly true where ecosystems such as grasslands and shrub lands co-evolved with large herds of grazing ruminants (Retallack, 2013), as in much of North America. Accordingly, USDA NRCS is encouraging land managers to incorporate animal husbandry (Winger, 2016). Further, despite the dearth of data in arid areas, Weber and Gokhale (2011) showed significant increases in soil moisture shrub steppe in response to precipitation as compared to continuous grazing.

Adoption and Financial Implications of Conservation Agricultural Practices in the U.S.

Research on adoption rates of conservation practices in the United States is just beginning. For several years, the Conservation Technology Information Center (CTIC) pioneered this effort, but data collection ended in 2004. The federal government began research in 2009 but has only studied major crops, such as soy, wheat, corn, and cotton (Wade, Claassen, & Wallander, 2015). Nonetheless, adoption rates are increasing, though with regional variation. Prominent decisional factors include perceived benefits from reduced drought vulnerability, yield increases, and pest-resistance (Antle, Capalbo, Mooney, Elliot, & Paustian, 2001).

Closely related is the lack of studies on the financial implications of conservation practices. Studies tend to be site-, crop-, and/or region specific (Dumler, 2000; Boyle, 2006). Nonetheless, they generally show decreased short-term labor and operating costs (Boyle, 2006). For major crops, adopters tend to be “low-cost” producers (McBride, 2003). Finally, more research is needed on the short- and long-term yield impacts, but

most evidence suggests little to no impact (e.g., Karlen, Kovar, Cambardella, & Colvin, 2013).

Agriculture, Soil Degradation, and Water Scarcity in Idaho

The situation in south-central Idaho follows the previously described macro-trends of soil degradation, desertification risk, and water scarcity. Agriculture is the area's main industry, but water shortages, drought, and soil degradation threaten its viability. South-central Idaho is classified as "highest" in terms of both desertification risk (U.S. Government, n.d.) (Figure 2) and drought risk (Wallander, Aillery, Hellerstein, & Hand, 2013) (Figure 3). Water is further critical to Idaho's economic and social security because hydropower provides the majority of state's power (U.S. Energy Information and Administration, n.d.). Finally, farmers have been slow to adopt conservation agricultural practices. Chief among the causes of low adoption rates of conservation practices in Idaho may be the perceived risks of lower yields, particularly for large farms (J. Miller, personal communication, October 12, 2016).

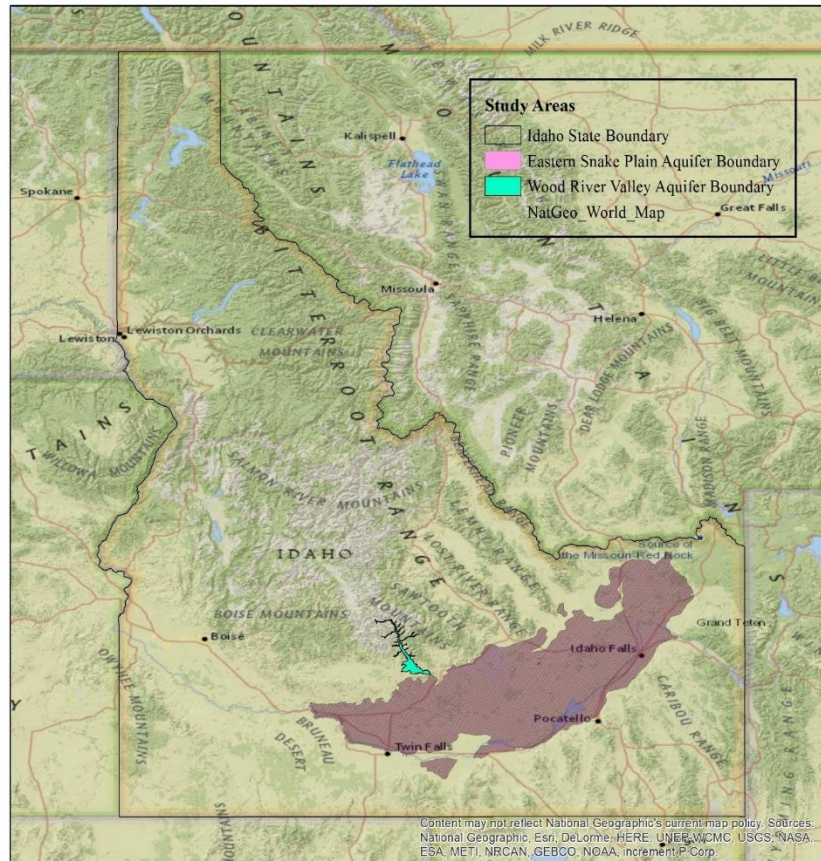


Figure 7. Location of study areas: The Eastern Snake Plain (pink) and the Wood River Valley (turquoise).

This thesis examines two specific areas in south-central Idaho, The Wood River Valley (WRV) and the Eastern Snake Plain (ESP), which exemplify the conundrum facing agricultural systems in other arid areas. Specifically:

- Both receive little precipitation and much of it during the non-growing/winter season.
- Agricultural irrigation is the dominant use of ground- and surface water.
- Much of crop- and rangelands are drought vulnerable (Figure 8 and Figure 9).

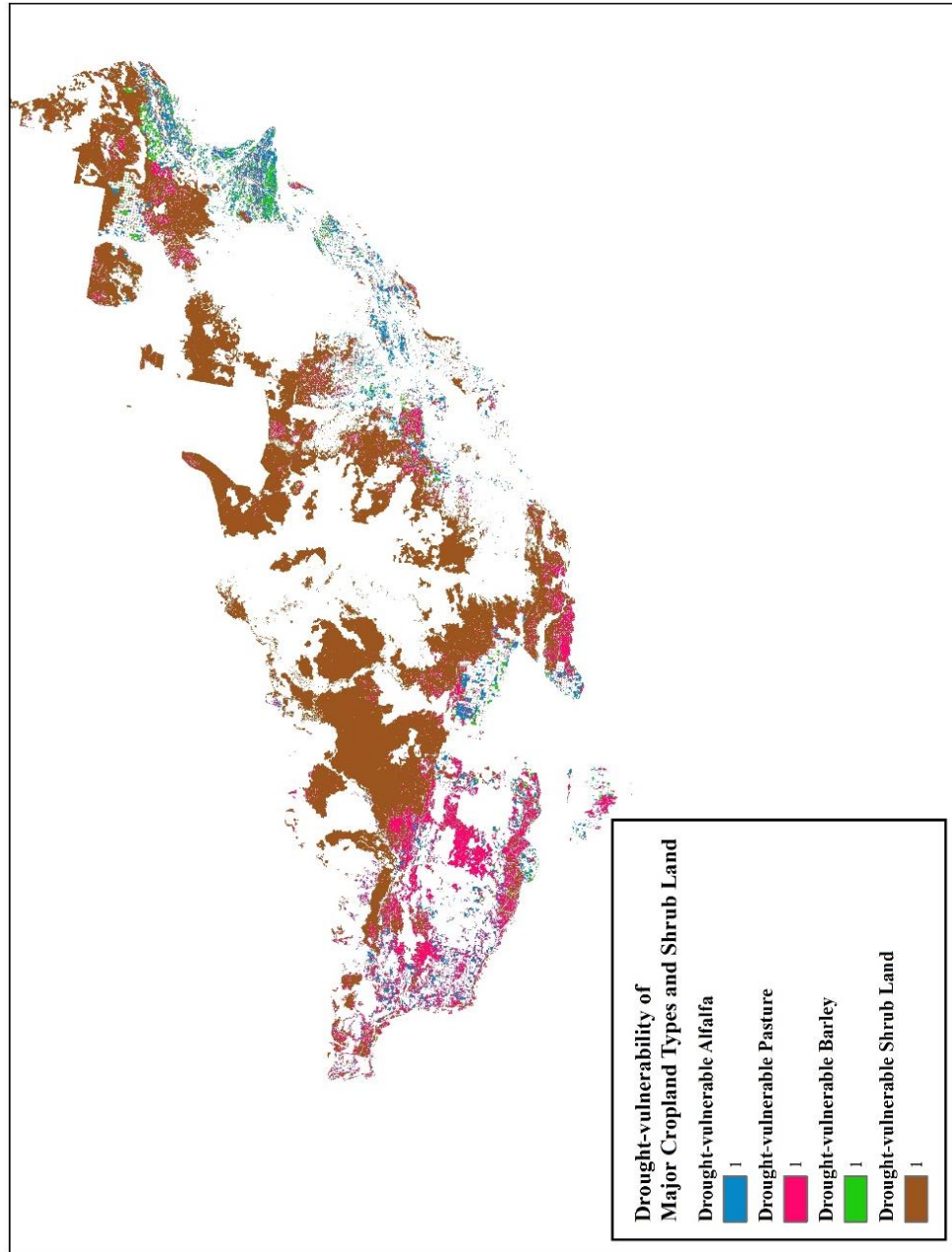


Figure 8. Map showing drought vulnerable cropland and shrub land areas in the ESP.

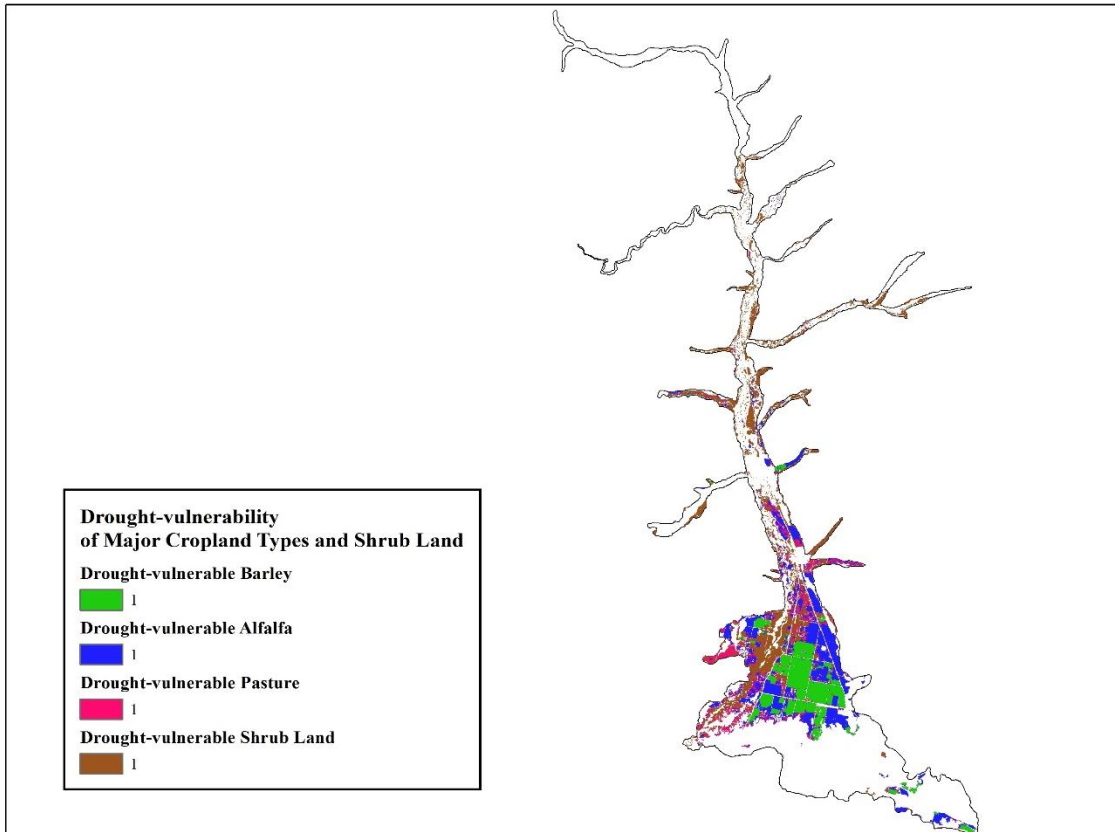


Figure 9. Map showing drought vulnerable cropland and shrub land areas in the WRV.

- Both areas overlie significantly stressed, “sole-source” aquifers, which are the areas’ only viable drinking water supply (United States Environmental Protection Agency, Region 10, 2016).
- Both aquifers have significant unconfined components, and thus levels are responsive to drought, precipitation, and water conservation measures.
- Conservation practices such as till, no till, and rotational grazing are not yet common.
- Climate change is expected to increase drought and change the timing and form of precipitation (Figure 10).

- Temperatures may increase anywhere from three to more than eight degrees Fahrenheit (U.S. Global Change Research Program, 2014).
- Population increases have been significant, with the ESP and WRV experiencing a 250% and 300% increase respectively since the 1970s (U.S. Geological Survey, 2015; Blaine County, n.d.).

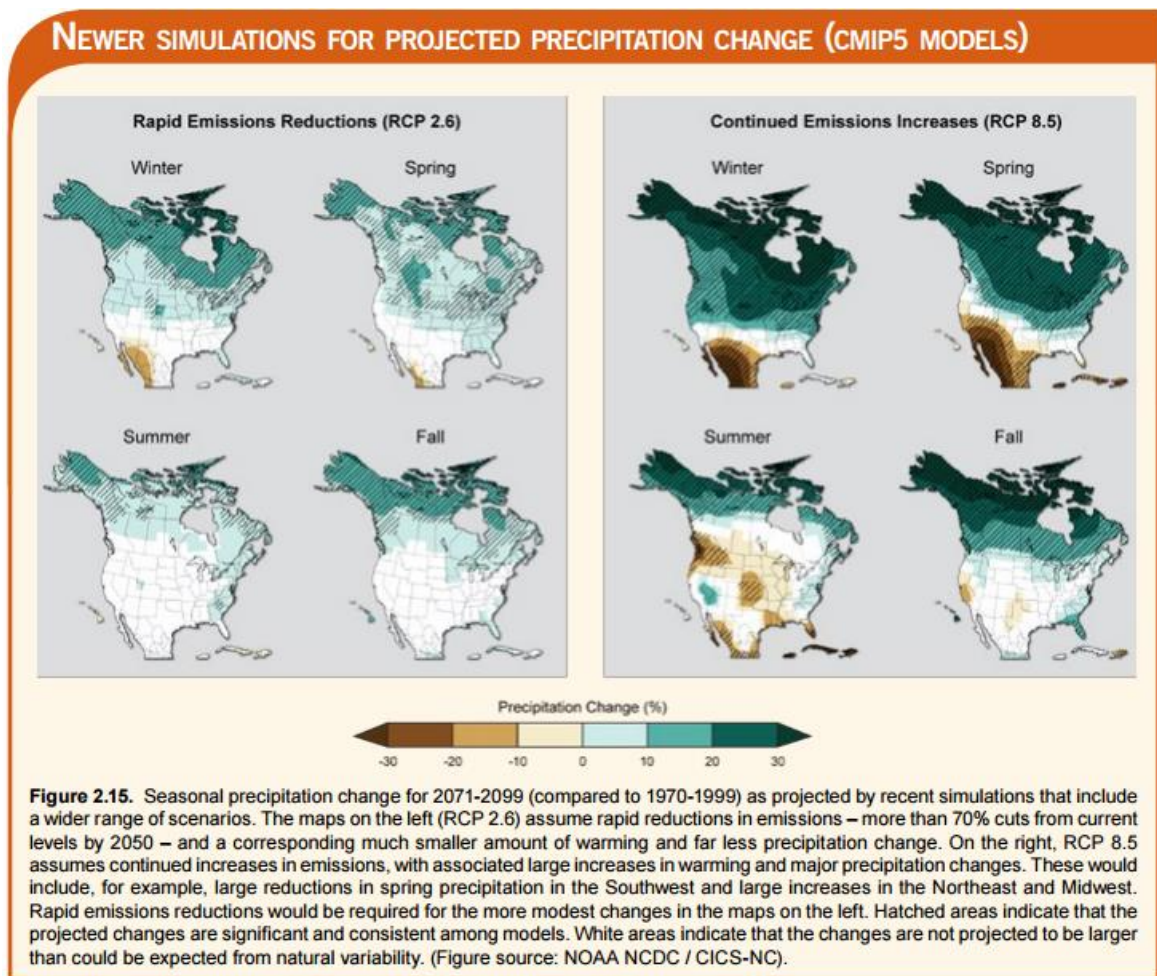


Figure 10. Changes in precipitation by season under a rapid emissions reduction and a continued emissions scenario (U.S. Global Change Research Program, 2014).

The most immediate concern is water availability. In 2015, 90% of Idaho counties had either been declared or were on the verge of being declared natural disaster areas due to drought (Associated Press, 2015; KTVB, 2015). Moreover, even absent drought, water shortages are a risk. This was the case in 2016 when, despite storage levels being within 99% of normal, authorities significantly curtailed junior water rights (Idaho Department of Water Resources (IDWR), 2016). Soil degradation is also a concern, but like other areas of the U.S., irrigation and ample fertilizers have masked the effects.

Idaho is also an appropriate case study from a policy perspective. Like other Western States, Idaho follows the Prior Appropriation Doctrine. Idaho's soil health policies are also voluntary and focused on providing educational, technical, and financial assistance to willing adopters (Idaho Soil and Water Conservation Commission, n.d.), and the state has also suspended its C sequestration efforts. Finally, soil health is largely absent from water budget and conservation policies (e.g. Idaho Water Resources Board (IWRB), 2009; IWRB, 2012).

Eastern Snake Plain

The ESP extends approximately 11,000 square miles (~7 million acres), and consists of 12 counties (either in whole or in part). It receives eight to fourteen inches of precipitation per year (IDWR, 2013), with the majority falling as snow (PRISM Climate Group, 2016). Runoff is stored in reservoirs for use during the growing season. The major water resources are the Snake River and the Eastern Snake Plain Aquifer (ESPA), both of which are heavily appropriated for irrigation. Aquifer recharge from precipitation

is low, and ~50% derives from incidental recharge from the Snake River, for instance from leaky irrigation canals or excessive irrigation (Idaho Department of Water Resources (IDWR), 2013). The Eastern Snake Plain provides the main drinking water supply for the area, though agricultural pollution, particularly from concentrated animal feed operations, presents a risk (Ancillary Appendix 5).

Agriculture activity is both the dominant land use (33%) and a main economic driver, producing approximately 21% of the state’s goods and services (IWRB, 2009). It is also the area’s largest consumptive user of water, accounting for 95% of groundwater withdrawals (Idaho National Laboratory, 2005). As in other areas, advanced drilling technology proliferated in the 1950s causing a shift in irrigation source from surface water to groundwater (Figure 11). As of 2006, groundwater accounts for 55% of irrigation (IDWR, 2013).

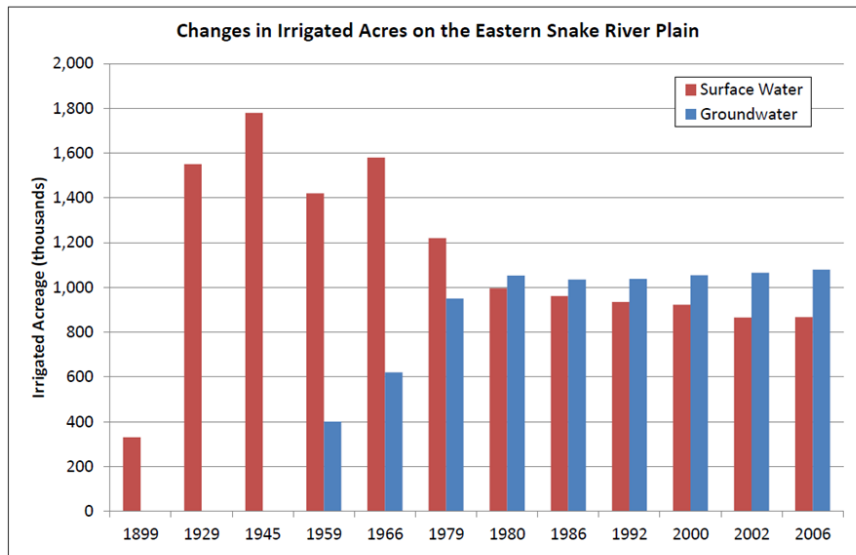


Figure 2. Surface-water and groundwater irrigated acres on the eastern Snake Plain (after Garabedian, 1992 and IDWR GIS shapefiles). The years 1899 through 1979 are represented in Garabedian (1992). The years 1980 – 2006 were acquired from IDWR GIS shapefiles.

Figure 11. Trends in surface- and groundwater irrigation over time in the ESP (IDWR, 2013).

Further, increased use of groundwater has caused aquifer levels to significantly decline (Figure 12). Coping with water shortages in the ESP is not new; for instance, the state placed a moratorium on permits for new consumptive uses for both surface and groundwater in 1992 (IWRB, 2009). Most recently, Idaho adopted the ESPA Comprehensive Aquifer Management Plan (ESPA CAMP) (IWRB, 2009) (discussed more fully below).

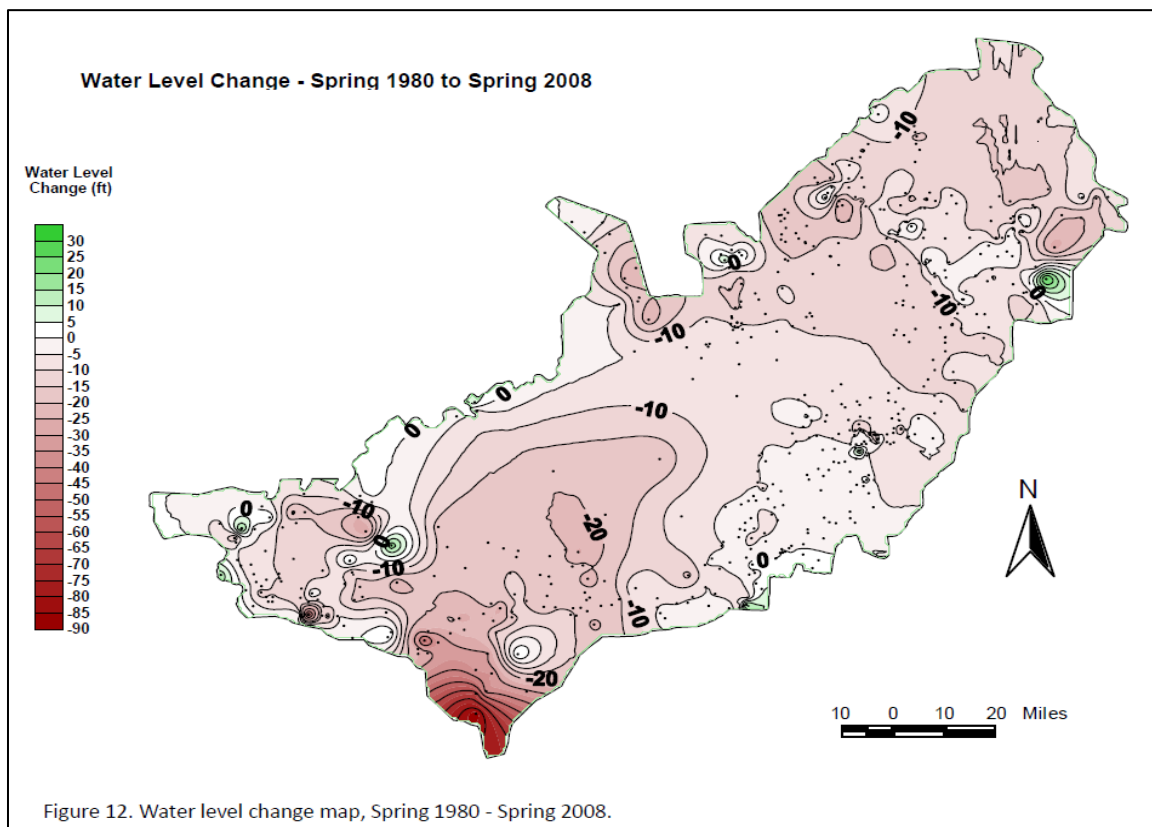


Figure 12. Map showing declines in aquifer levels in the ESP from 1998 to 2008 (IDWR, 2013).

Though avoiding water shortages is a top concern, there are four major hurdles to adopting conservation measures such as increased irrigation efficiency and/or

conservation agricultural practices: 1) risk aversion; 2) (perceived) costs; 3) ecosystem impacts; and 4) impacts on downstream users. First, farmers are often hesitant to try new technologies, and this is particularly true with switching tillage practices or moving to drip irrigation, which may require a significant financial investment and could decrease income from, for instance, yield declines. The financial risk could, of course, be overcome with increased funding and/or insurance from government sources.

The thorniest issue is, however, is that maintaining incidental recharge from irrigation is necessary to maintaining aquifer levels. Over 50% of positive aquifer inputs come from surface water irrigated agricultural lands and irrigation canal seepage (IDWR, 2013). Beyond aquifer levels, policymakers are careful to note that while advisable, “conservation measures may reduce water supplies utilized by others in other parts of the resource” (IDWR, 2016). Finally, reducing incidental recharge could affect the amount and timing of baseflows to the Snake River (Neibling, H. personal communication, August 11, 2016; IDWR, 2013).

To address these issues, Idaho adopted the ESPA CAMP in 2009, which has an annual goal of creating a net-positive water budget change of 600 thousand acre-feet (kaf) by 2030 (IWRB, 2009). Table 1 provides a list of the contemplated measures and amount of water to be saved and timeframe.

Phase I lasts between one to ten years and aims to create a positive change of 200 to 300 kaf annually. Over the long-term, implementing the ESPA CAMP is expected to cost over \$600 million. The plan contemplates building new reservoirs and purchasing water from other jurisdictions (IWRB, 2009). Most pertinent to soil health measures is that the plan envisions saving 5,000 af over ten years from crop mix modification and

40,000 af over ten years from measures such as enrollment in the Conservation Reserve Enhancement Program (CREP), dry leases, and rotational fallowing. While comprehensive, the supporting hydrological modeling for the ESPA CAMP (ESP Aquifer Model Version 2.1 (ESPAM 2.1) (IDWR, 2013)) did not include SOM, SOC, or other factors that affect soil moisture retention.

Regarding CREP, IDWR (2013) estimates that each enrolled acre conserves two af of groundwater, two tons of soil from water erosion, and six tons of soil from wind erosion (Idaho Soil and Water Conservation Commission, 2015).

Table 1. Water conservation targets set by the ESP Comprehensive Aquifer Management Plan (Idaho Water Resource Board, 2009).

Action	Phase 1 ^a Annual Average Target (KAF) (2020)	Long-Term Target KAF) (2030)
Groundwater to surface water conversion	100	100
Managed Aquifer Recharge	100	150-250
Demand Reduction		250-300
Surface Water Conversion ^b	50	
Crop mix modification ^b	5	
Rotating Fallowing, Dry-year Lease Agreements, and CREP Enhancements ^b	40	
Buy outs, buy downs, and/or subordination agreements ^b	No target (Opportunity based)	
Weather Modification (i.e. Cloud-seeding)	50	No Target
Total	200-300	600

a – Years 1 through 10 of ESP implementation (~2010-2020).

b – Included within “Demand Reduction” category.

CREP payments range from \$110 to \$130 an acre depending upon the county and irrigation type. Unfortunately, water savings from CREP is falling short of expectations, with enrollment at only 17% of the goal (ISWCC, 2015). Further, enrollment has been declining since 2007. The main reason for this is likely economic: land managers fear locking themselves into the 15-year commitment, particularly because rental payments are not competitive with commodity prices (ISWCC, 2015).

Wood River Valley

Entirely within Blaine County, the WRV spans 102 square miles and contains 17% of the county's agricultural land. Precipitation is between 12.2 and 29.5 inches annually (Sanford & Selnick, 2013), again mostly falling as snow. While much smaller in scale than the ESP, the area is a leader in organic production (Blaine County, n.d.). Agriculture is the leading consumptive use of water at 63.9% in Blaine County and draws from both surface- and groundwater sources (Blaine County, n.d.).

Drought is also problematic. Between 1995 and 2011, drought conditions were present in 61% of the months (USGS, 2012). 2011 through 2016 all witnessed drought conditions as well (U.S. Drought Monitor, 2016). Groundwater levels have also been declining at an alarming rate (USGS, 2012). Added to this are significant population pressures within Blaine County, whose population quadrupled between 1970 and 2010 (Blaine County, n.d.). As a result, Blaine County, USGS, and others are undertaking a comprehensive survey of the area's water resources (e.g. USGS, 2012). As in the ESP, increasing demand for water has spawned a series of water calls by senior water rights

holders, litigation, and ultimately modeling and policy efforts for sustainable management of these resources (e.g., IDWR, n.d.; IDWR, 2015)).

Impacts of Drought and Soil Degradation on Energy Production

As in other parts of the United States and world, soil and hydrological health are closely connected with energy supply. Drought has not only reduced hydropower capacity by 20% in recent years, soil erosion from increased wildfires and storm events may also accelerate dam sedimentation (U.S. Energy Information and Administration, n.d.; U.S. Army Corps of Engineers, November 2014; USGS, 2015). Reduced hydropower will likely cause even more reliance on natural gas, already a major source of energy. Unstable energy output and financial considerations may be one reason for the abrupt, surreptitious passage of Idaho SB 1339 in March 2016, which expanded authorization for hydraulic fracturing. For water resources, this development is particularly disconcerting, given potential impacts on water quantity and quality.

Research Question, Hypotheses, and Specific Aims

The research question addressed by this thesis is What are the impacts of increasing soil organic carbon (SOC) levels on agricultural lands on soil degradation remediation and hydrological functioning in south-central Idaho? The primary hypotheses I examine are:

1. Conservation practices can increase SOC levels quickly in agricultural lands, though the timeframe will vary by land use.

2. SOC increases from conservation practices can quickly remediate historic SOC loss and reverse drought vulnerability, though timeframes will vary by land use.
3. SOC increases can significantly increase available water storage (AWS), therefore significantly reduce both total and non-irrigated aquifer recharge.

To complete the analysis, the specific aims are to:

1. Estimate the time in which adopting conservation practices can reverse historic SOC losses from tillage;
2. Estimate the gains in AWS from SOC increases in both the short- and long-term;
3. Estimate the reductions in aquifer recharge from increased AWS;
4. Analyze the time in which conservation agricultural practices can increase AWS above 0.5 af in the rootzone, thereby reversing drought vulnerability;
5. Analyze the on-farm costs of adopting no till and associated benefits; and
6. Compare these with other on-farm expenditures and incentive-based governmental programs.

Chapter II

Methods

This thesis calculates the impacts of increasing SOC on remediating topsoil loss and increasing AWS on the following crops/land types in the ESP and WRV: alfalfa, barley, pasture, and shrub land. Baseline data was taken from USDA NRCS (n.d.a) gSSURGO raster datasets and online mapping tools. Figure 13 provides a diagram of the conceptual design of my research. Table 2 outlines each step of this research and the corresponding data source and methodology.

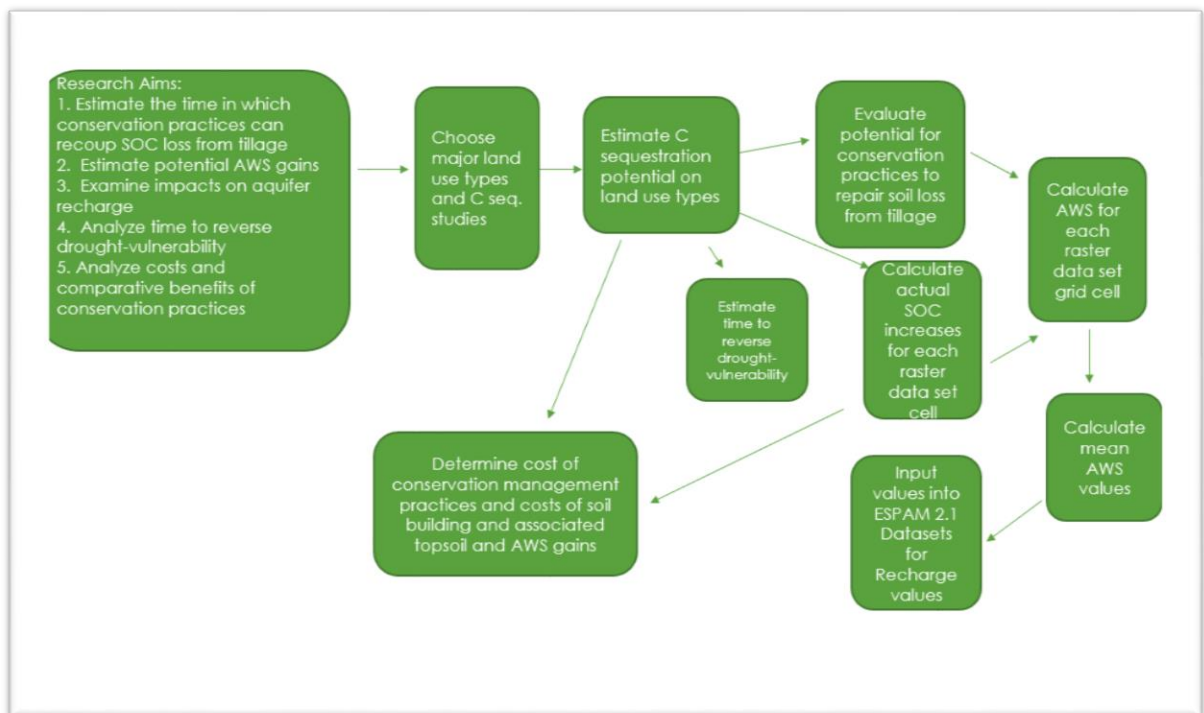


Figure 13. Conceptual diagram of research design.

Table 2. Road map of research design and process.

Step	Task	Data Sources; Methodological Tools
Step 1	Choose land use/crop types in the ESP and WRV	Data Sources: USDA CropScape (USDA NASS, 2015b) Methodology/Criteria for Decision: Percent of acreage of agricultural land and availability of carbon sequestration studies within appropriate ecoregions
Step 2	Determine baseline SOC and AWS levels on specific land use types	Data Sources: gSSURGO raster data sets and Value Table (USDA NRCS, n.d.a) Methodology: ArcGIS zonal and field statistics by land use type to determine values and standard deviation
Step 3	Calculate SOC losses due to tillage and other conservation practices in the ESP and the WRV	Data Sources: Carbon Dioxide Information Analysis Center (Oak Ridge National Laboratory), (n.d.a), USDA NASS (2015b); publicly available shapefiles of Idaho counties Methodology: Calculate the amount of SOC loss per acre in each county and overlaying them with the ESP and the WRV. Based on the percentage of land within each county derived from mapping, assign SOC losses.
Step 4	Determine the potential for increasing SOC levels through conservation practices (Improved SOC Benchmarks)	Data Sources: Various studies on carbon sequestration rates Methodology: Select studies based on peer review and publication and climatological similarity to study areas.
Step 5	Compare Improved SOC Benchmarks to 2008, 10-year average, and 1998-2008 SOC losses per county	
Step 6	Determine the conservation practices to increase baseline SOC and AWS levels	Data Sources: gSSURGO raster data sets and Value Table (USDA NRCS, n.d.a) Methodology: Calculate cell-by-cell increases in SOC and AWS using relationship between SOC and AWS from (Hudson, 1994). Evaluate these results using two metrics: 1) Percentage increases in Years 1 and 10; and 2) Volumetric of increases in Years 1 and 10.
Step 7	Estimate time needed to reverse drought vulnerability of agricultural lands	Data Sources: gSSURGO raster data sets and Value Table (USDA NRCS, n.d.a) Methodology: Evaluate baseline SOC and AWS levels in rootzone of all analyzed lands Adjust the carbon sequestration and AWS increase rates by the percentage of variation between C sequestration studies and rootzone depths
Step 8	Evaluate impacts of soil health measures on total and non-irrigated recharge for ESPAM area	Data Sources: Shapefiles provided by IDWR from the ESPAM 2.1 modeling effort; (USDA NASS, 2015b); author's calculation on AWS Increases Methodology: Intersect cropland areas with the ESPAM 2.1 shapefiles for total recharge and NIR recharge rates; assume a 1:1 reduction in recharge and AWS increases
Step 9	Evaluate the financial implications of adopting to no till	Data sources: Epplin, Stock, Kletke, & and Peeper (2005); (USDA NASS, 2015b) Methodology: Perform a literature review and conduct interviews regarding costs of adopting NT in Idaho for select

		agricultural lands; apply the findings to reported farm sizes in varying economy size classes for Idaho farms
Step 10	Evaluate the costs/benefits of increasing AWS for no till Barley using three different scenarios for SOC accrual time and three discount rates (5%, 7%, and 10%)	Data Sources: Author's findings from previous sections
Step 11	Compare the costs of soil health benefits through conservation practices to CREP	Data Sources: Information on CREP rental rates provided by Idaho NRCS; author's findings from previous sections Methodology: Calculate and compare on an af and 1-ton basis the differing costs

Baseline Data and Conditions

The first step in my research was to determine the baseline SOC and AWS levels for the study areas and to selected land uses for study. I used two sources of information. The first is USDA NRCS's Gridded SSURGO (gSSURGO) (U.S. Department of Agriculture, Natural Resource Conservation Service, n.d.), the most authoritative, federal soils database. Released in 2016, gSSURGO contains data in raster and tabular formats from the USDA NRCS Soil Survey Geographic Database system (SSURGO) (USDA NRCS, n.d). SSURGO data was compiled both through observation and laboratory analysis of field samples (USDA NRCS, n.d.). The information in this thesis relies primarily on the "Value Added Look Up Table Database," which contains the data on soil organic carbon, drought vulnerability, and available water storage, among other parameters (USDA NRCS, n.d.a). Of course, other site-specific information may be available, such as the Rapid Assessment of U.S. Soil Carbon (USDA NRCS, n.d.c), though these sources are not as comprehensive as gSSURGO.

The second source for baseline information is USDA's National Agricultural Statistics Service's (USDA NASS, 2015b) CropScape, an annually updated online

platform containing archived land use data. Spatial boundaries can be input and metadata downloaded in tabular (excel-based) and graphic formats.

The geographic boundaries of my analysis were the ESP Aquifer boundary as modelled in the Eastern Snake Plain Aquifer Modelling Version 2.1 (ESPAM 2.1) (Idaho Department of Water Resources, 2013) and the Wood River Valley (WRV) Aquifer boundary. Importing shapefiles for these areas into CropScape, I downloaded the land use data and then combined this in ArcGIS with data from gSSURGO. I then performed a cell-by-cell calculation of the impact of the increasing carbon levels on the baseline SOC levels and then on the baseline AWS levels. To obtain statistical information such as the variance, standard deviation, and range of values I used the Zonal Statistics and Field Statistics tool in ArcGIS.

I analyzed land use in each study area using a different year. For the ESP, I chose 2008 because that is the corresponding year for the ESPAM 2.1 modeling (IDWR, 2013). For the WRV, I used 2015, the most recent year for which data is available. Though updated periodically, gSSURGO is relatively static, and therefore baseline SOC and AWS values for land uses only change if acreage shifts.

To examine the long-term impacts of soil health practices, I calculated SOC and AWS increases over ten years. I chose a ten-year period for two reasons. First, carbon (C) saturation is only generally achieved after 20 years (Lewandrowski, et al., 2004). Second, ten years is the established Phase I of the ESPAM CAMP, which ends in 2019/2020. I assumed that soil health benefits from conservation practices begin in Year 1 of adoption, though I account for this uncertainty in other places.

Existing Acreage under Conservation Agriculture Practices

Idaho has one of the lowest adoption rates of conservation agricultural practices in the country (Wade, Claassen, & Wallander, 2015). I attempted to account for land already managed pursuant to conservation agricultural practices, but ultimately the information was too uncertain to include. Information on adoption rates is largely in its infancy, with the federal government's efforts only beginning for major commodity crop types in 2009 (Wade, Claassen, & Wallander, 2015). For this reason, the Conservation Technology Information Center (CTIC) has been the most reliable source for tillage adoption practices. Data collection, however, stopped in 2004.

Aside from being out-of-date, another obstacle was applying the CTIC information to the agricultural lands I analyzed. The only directly applicable data from CTIC would have been for no till barley. CTIC also reported barley acreage under other types of conservation practices (e.g., mulch till), but a literature search did not produce reliable information on either the C sequestration or the hydrological impacts of these practices.

For other land types analyzed in this thesis, CTIC (2004) either did not provide sufficiently specific information for the data to be useful or the type of management techniques do not have corresponding C sequestration values in the literature. For example, CTIC (2004) does not report alfalfa as a separate category but rather subsumes this crop under forage. Finally, incorporating the CTIC (2004) would have presented additional spatial uncertainty because practices are only reported at the county-level.

Carbon Sequestration Potential

I used two methods to estimate increases in SOC stocks. First, I estimated the potential gains if SOC losses were avoided, as calculated by the U.S. Department of Energy's Carbon Dioxide Information Center (CDIAC) (n.d.) (hereinafter "SOC Loss Analysis"). Second, I determined the potential for C sequestration on specific land types using conservation practices such as reduced till (RT), no till (NT), and rotational grazing.

I did not account for SOC – and consequent AWS loss and atmospheric CO₂ emissions – from degraded agricultural lands and rangelands and continued tillage, because they are highly uncertain (Ogle, Conant, & Paustian, 2004). Rather my analysis assumes that baseline SOC values remain constant. Accounting for continued SOC losses from management practices, however, is a valid area for research as ample studies show that they are significant (Goldhaber & Banwart, 2015).

Soil Organic Carbon Loss Analysis

Based on the methodology developed by West et al. (2008), CDIAC (n.d.) calculated the annual SOC losses from tillage for each United States county from 1998-2008. Because it is unclear how either source accounted for fallowed land, I analyzed the SOC losses per acre including and excluding fallowed acreage, with the latter always leading to higher per acre losses. I then calculated the SOC losses for 2008, the ten-year annual average (from 1998-2008), and the total SOC loss from 1998-2008. I chose 2008 as a reference year because it is the most recent year for which calculations are available, whereas the ten-year annual average accounts for annual variation and thus provides a

more representative picture of SOC losses over time. The ten-year total SOC losses shows the magnitude of SOC loss.

A necessary uncertainty derives from the fact that the CDIAC analyses are not spatially explicit, but provide only county level information. While the WRV lies entirely within Blaine County, the ESP consists of 12 counties, some of which lie only partially within the study area. For counties not wholly within the ESP, I calculated the area of cropland within the study area by importing publicly available shapefiles into USDA NASS CropScape and intersected these in ArcGIS with the ESP boundaries. I then subtracted the remaining land acreage as a percentage of SOC losses. These steps produced a total amount of SOC lost over the entirety of the two study areas.

I calculated the SOC loss for 2008 as:

$$2008 \text{ Improved SOC Benchmark} = 2008 \text{ SOC Baseline Levels} + \text{SOC lost}$$

(2008 refers to baseline SOC levels for a given land type in 2008).

I calculated the ten-year SOC loss average as:

$$10\text{-year average Improved SOC Benchmark} = \text{Year}_n \text{ SOC Baseline Levels} + (\text{Average SOC losses } 1998\text{-}2008)$$

I derived the ten-year total SOC losses – from 1998 to 2008 – by summing the values calculated for each year by CDIAC. I then converted these values into SOC losses per acre. To calculate the AWS increases, I used the mean SOC values for each land use type. My rationale for using mean SOC values here is that SOC losses – whether annual or over ten years are extremely low (see Chapter III (Results)) – and therefore small differences in baseline values are unlikely to be material.

This analysis has two significant limitations. First, because CDIAC does not disaggregate SOC losses by cropland type, my analysis assumes that each land use lost

the same amount of SOC. Undoubtedly, this is not the case because 1) soil disturbance for cultivation varies with crop type, and 2) soil quality (i.e., gravel to SOM ratio) would likely affect SOC losses. Second, my calculations of the ten-year total losses do not account for any soil building that might occur during periods of cropland fallow or cover cropping, though the former may accelerate soil degradation.

Crop-specific Soil Organic Carbon Benchmarks

I examined the SOC increases from switching to conservation agricultural practices that actively build SOC stocks. The first step was to select cropland/ecosystems for evaluation. My two foremost decision criteria were 1) the extent of acreage within the study area and 2) the availability of peer-reviewed studies on C sequestration rates. Based on these considerations, I chose alfalfa, barley, grass/pasture, and shrub steppe/rangeland (hereinafter “shrub land”). Except for Barley in the ESP, these land use types constitute a significant portion of both total acreage and total agricultural acreage in the study areas (Table 3 and 4; Figure 14 and Figure 15).

Table 3. Land uses examined in the ESP and corresponding percentages of land use totals.

ESP	Percent of Total Acreage	Percent of Agricultural Acreage
Barley	~3%	~9%
Alfalfa	~6.5%	~19%
Grass/Pasture	~11%	~32%
Shrub Steppe/ Rangeland	51%	NA

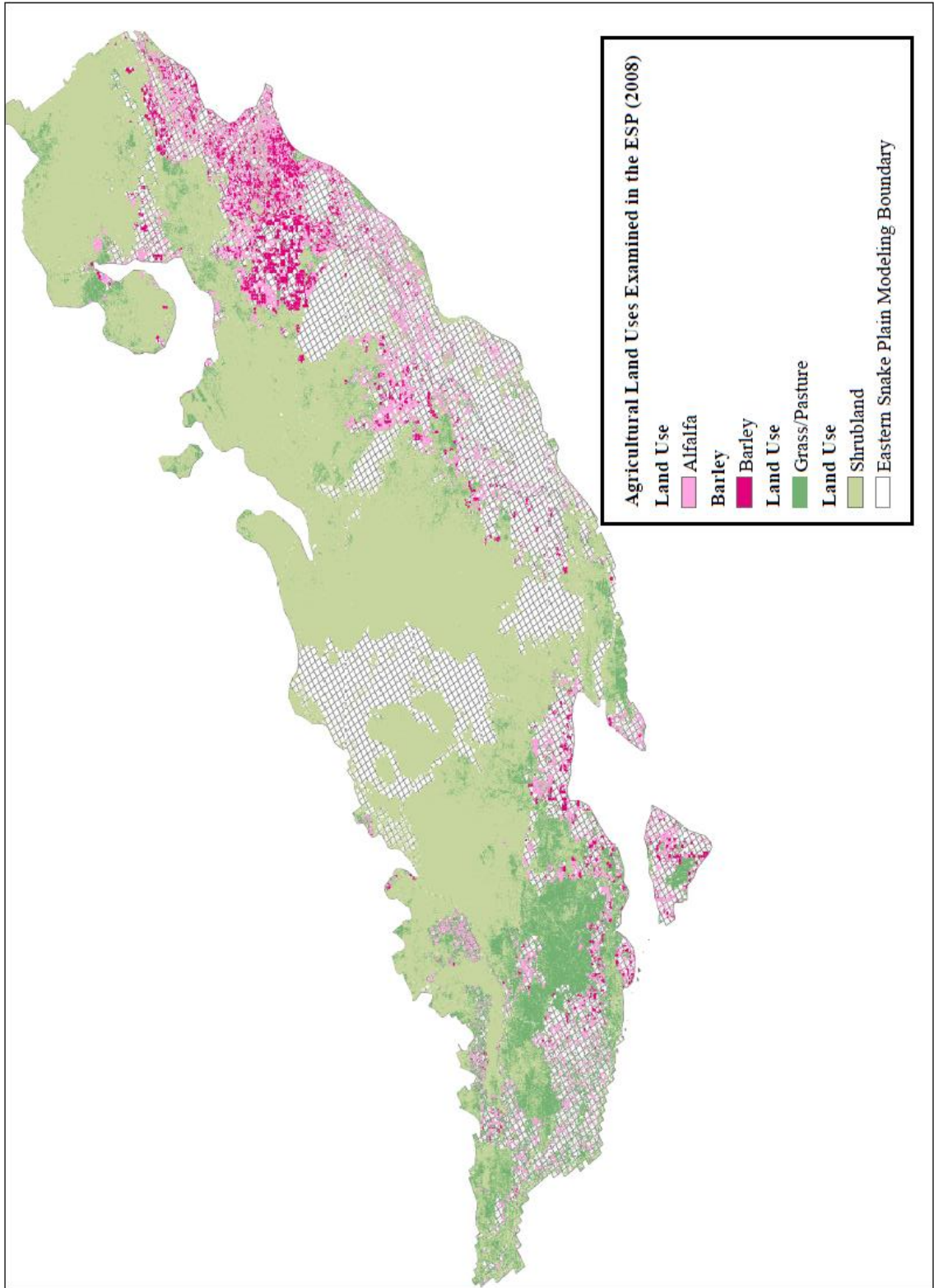


Figure 14. Land uses examined in the ESP (USDA NASS, 2015b).

Table 4. Land uses examined in the WRV and corresponding percentages of land use totals.

WRV 2015	Percent of Total Acreage	Percent of Agricultural Acreage
Alfalfa	21.5%	~45%
Grass/Pasture	~11%	~24%
Barley	~12%	~25%
Shrub/Rangeland	~25%	NA

* Includes fallowed cropland.

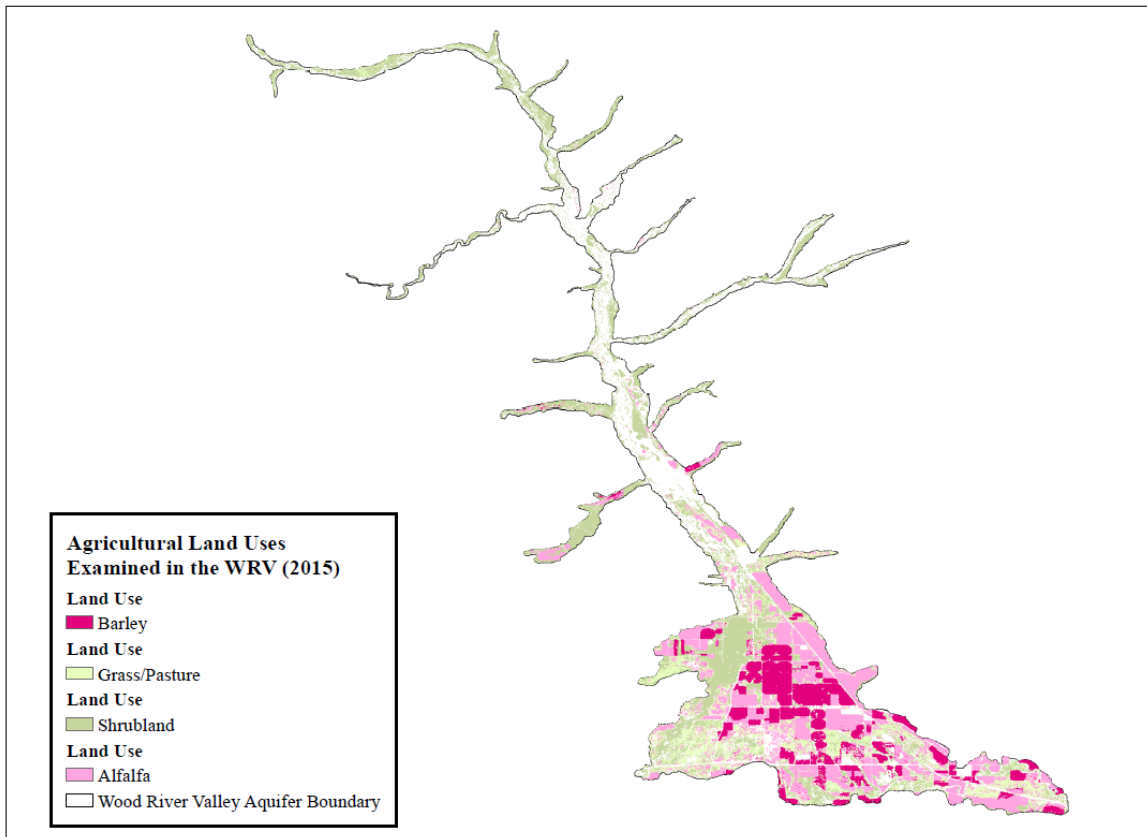


Figure 15. Land uses examined in the WRV (2015 acreage) (USDA NASS, 2015b).

The second step was to quantify the potential SOC increases on these land types. After reviewing published and unpublished sources, I chose the sources outlined in Table 5 (hereinafter collectively the “C sequestration studies”). Table 6 provides the C sequestration rates corresponding to each study and management scenario.

Table 5. Summary of published sources for crop-specific analysis and rationale for choice.

Land Type	Source	Study Location	Management Type
Shrub/rangeland	Weber & Gokhale (2011)	Pocatello, Idaho*	Rotational Grazing
Shrub/rangeland	Ogle, Conant, & Paustian (2004)	Meta-analysis from different studies	Various
Pasture	Ogle, Conant, & Paustian (2004)	Meta-analysis from different studies	Various
Barley	Lal & Follet (2009) (Ch. 3)	Idaho Falls, Idaho	No till
Alfalfa	Ghimire, Norton, & Pendall (2014)	Lingle, Wyoming	No till, Reduced till, and Organic
Grass/Pasture by Tillage Type	Industry & Investment New South Wales Government (Australia) (2010)	Wagga Wagga, New South Wales, Australia	No till

*Measures soil water content not SOC.

Table 6. Improved SOC Benchmark (kg/acre/year) by land use type.

Land Use	Conservation Practice	Improved SOC Benchmark
Alfalfa (Ghimire, Norton, & Pendall, 2014)	Reduced Till	1,100.745
Alfalfa (Ghimire, Norton, & Pendall, 2014)	Organic	220.554
Barley (Lal & Follet, 2009)	No Till	841.804
Pasture (Ogle, Conant, & Paustian, 2004)		
	Nominal to medium input	1,235.53
	Nominal to high input	1,729.74
	Degraded to medium input	1,482.63
	Degraded to high input	1,976.84
Pasture (Industry & Investment New South Wales Government (Australia), 2010)	No Till	257
Shrub land (Ogle, Conant, & Paustian, 2004)		
	Nominal to medium input	988.42
	Nominal to high input	1,976.84
	Degraded to medium input	1,235.525
	Degraded to high input	2,223.945

Two criteria guided my choice of data sources. First was that the crop/land use match my land use selections. Second because temperature and precipitation are controlling factors in C sequestration, I attempted to match the C sequestration studies with the climate of the WRV and the ESP. To determine climatological similarity, I used the ecoregions designated by the USDA Forest Service (n.d.) choosing only dry domains and temperate divisions (Figure 16 and Figure 17).

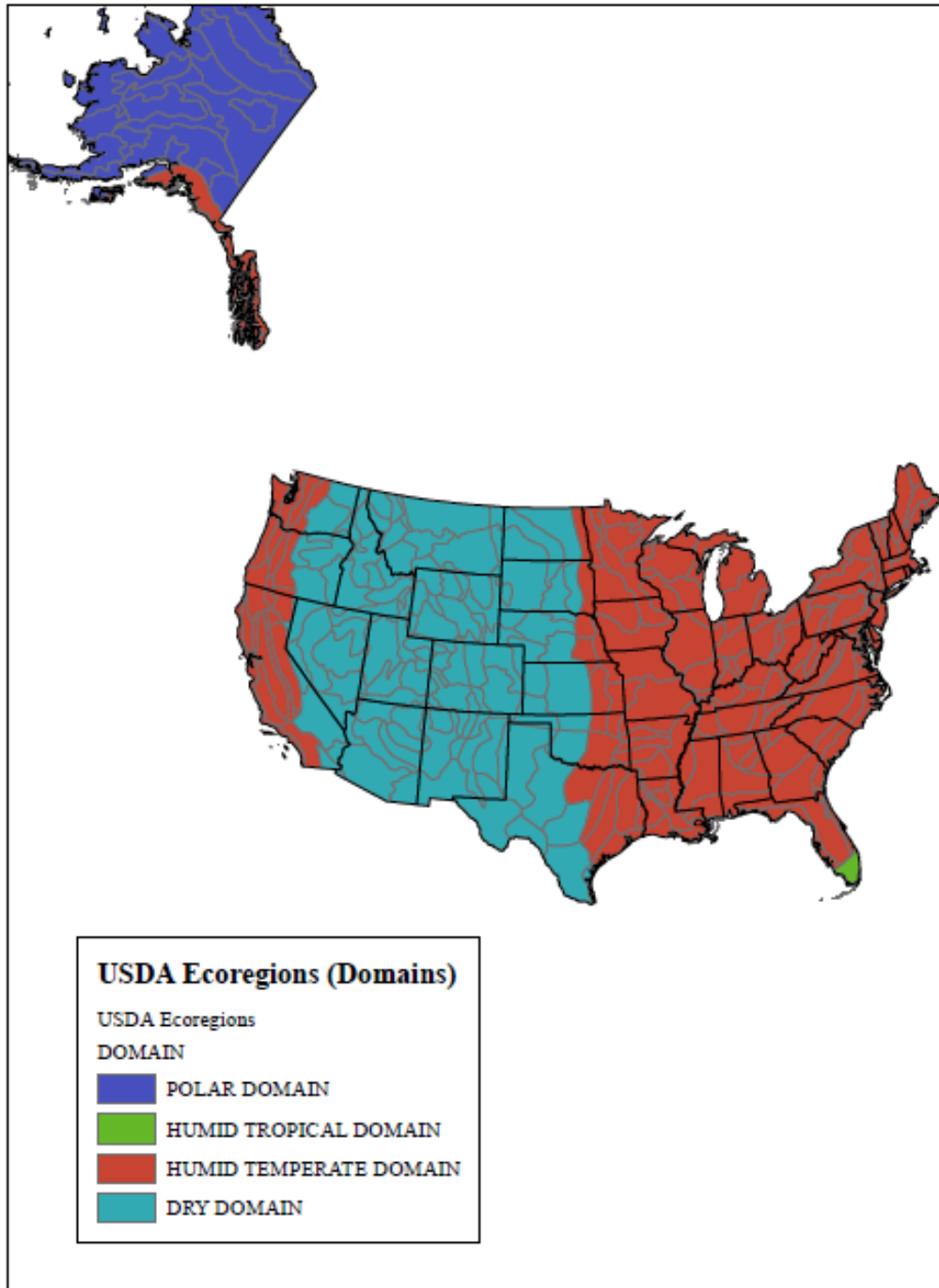


Figure 16. USDA Forest Service Ecoregions (Domains) (Hawaii and Territories excluded) (USDA Forest Service, n.d.).

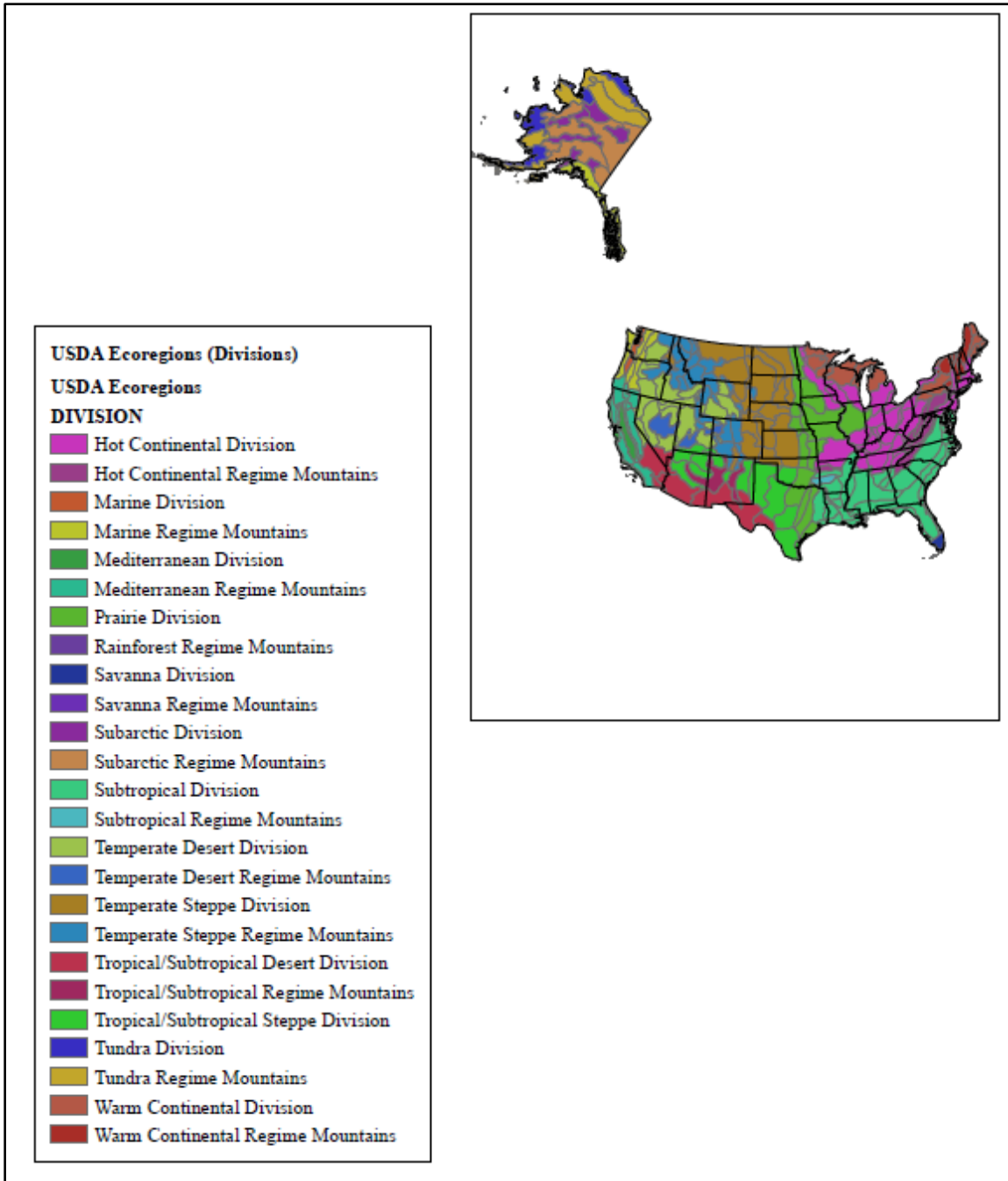


Figure 17. USDA Forest Service Ecoregions (Divisions) (Hawaii and Territories excluded) (USDA Forest Service, n.d.).

Two studies, however, do not conform to this second criterion but were chosen because no others met with the required rigor. The first is a meta-analysis of C sequestration rates for rangeland and pasture (Ogle, Conant, & Paustian, 2004). While the underlying studies do not include the Western United States, many of them report C sequestration in temperate dry areas. The second exception is Industry & Investment New South Wales Government (Australia) (2010), which provides C sequestration rates for no till pasture types (hereinafter no till pasture benchmark). New South Wales is a different ecoregion type (USDA Forest Service, n.d.) and the area receives ~21 inches of precipitation a year (Industry & Investment New South Wales Government (Australia), 2010). While this is certainly more precipitation than the ESP receives (approximately eight to fourteen inches per year), it is within the range of at least some areas of the WRV (~12.2 - ~29.5 inches). Importantly, baseline SOC values vary both by area and by land use type in the ESP and the WRV (Figure 18 and Figure 19).

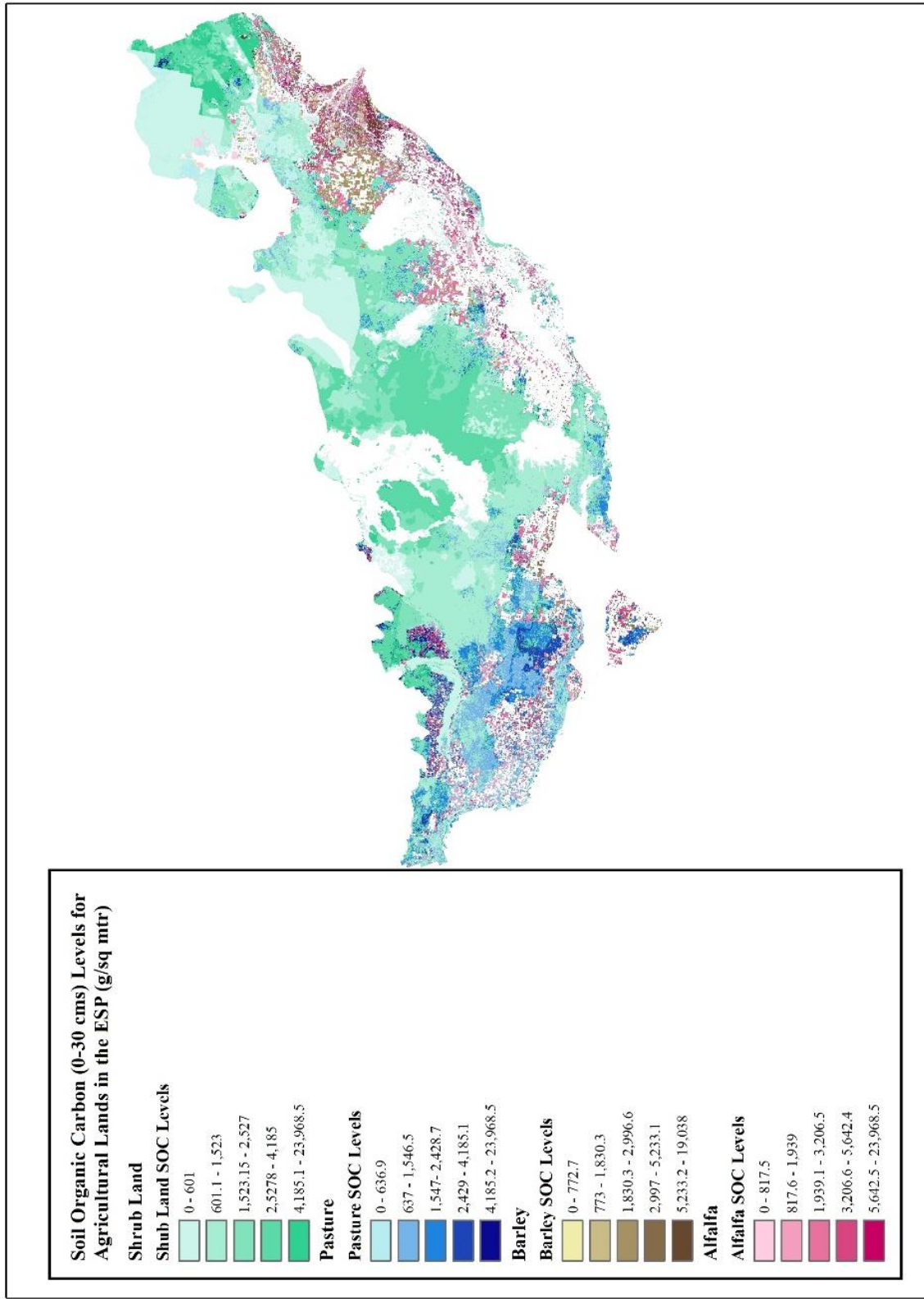


Figure 18. SOC levels for shrub land, pasture, barley, and alfalfa in the ESP.

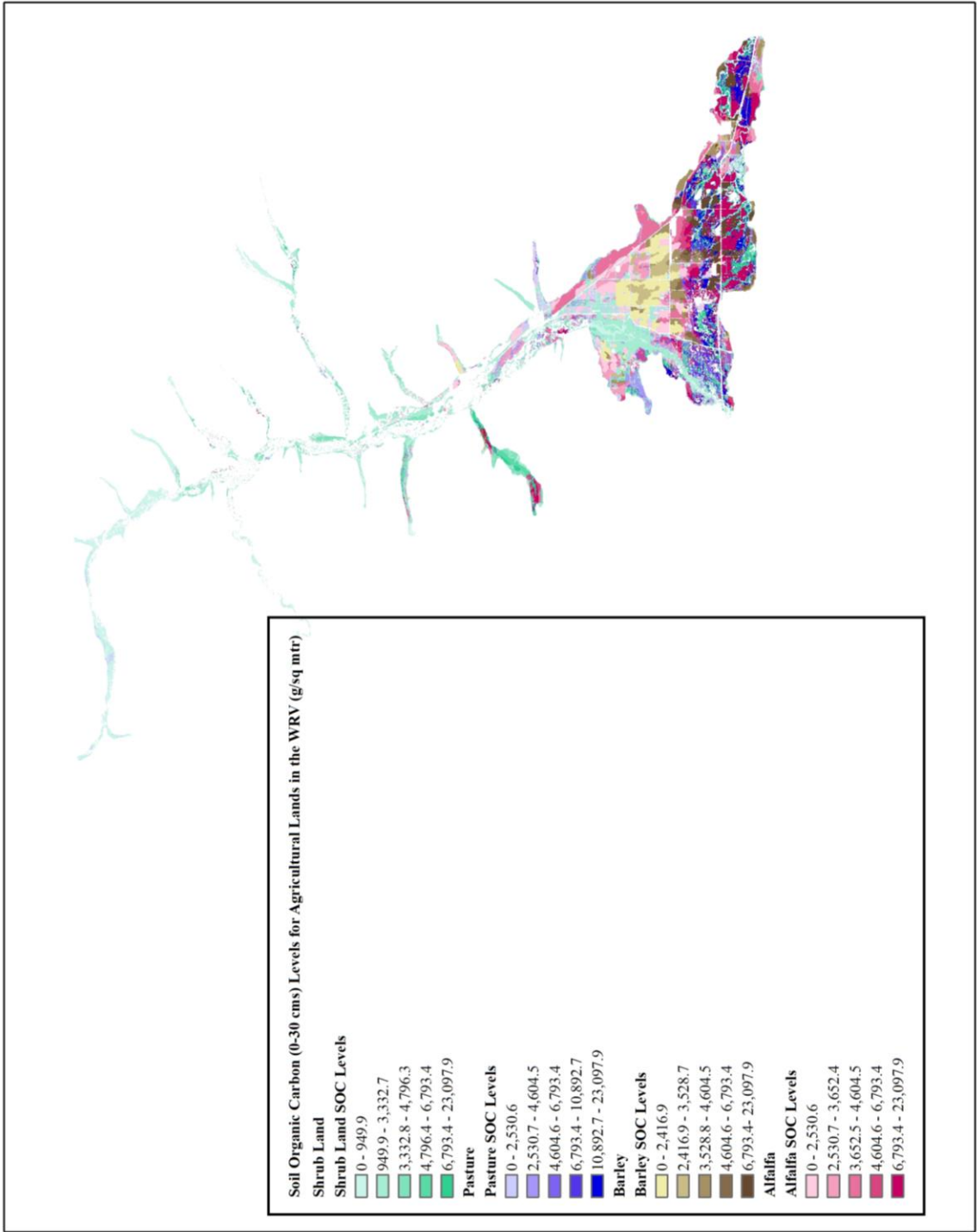


Figure 19. SOC levels for shrub land, pasture, barley, and alfalfa in the WRV.

Based on these baseline SOC values, I calculated the expected SOC increases from conservation practices over ten years. Here, I assumed that annual SOC increases remain the same annually. The equation for Year 1 is:

$$\text{Year 1 SOC Improved Level} = \text{Baseline SOC Level} + \text{Improved SOC Benchmark}$$

For Year 2 forward, the equation is:

$$\text{Year}_n \text{ SOC Improved Level} = \text{Year}_{n-1} \text{ SOC Improved Level} + \text{Improved SOC Benchmark}$$

I calculated the percent increase in SOC as follows:

$$\text{Year}_n \text{ Percent Increase} = \text{Improved SOC Benchmark} / \text{Year}_{n-1} \text{ SOC Level}$$

I then compared these results to the status quo scenario, which assumes that baseline values remain constant. This assumption is likely conservative because tillage and erosion would further reduce SOC stocks.

To estimate the time needed to reverse historic SOC losses, I applied the results from the ten-year build outs to the calculated SOC losses by land use type.

Reconciling Depth Measurements and Estimating Accrual Time for Soil Organic Carbon

To accurately account for SOC and AWS increases, it was necessary to match the depth of soil measurements in the C sequestration studies and in gSSURGO. Two issues arise however. The first issue is that gSSURGO SOC measurements do not correspond with the soil depths measured in Weber and Gokhale (2011) (10 cm) and Ghimire, Norton, and Pendall (2014) (15 cm). Because gSSURGO data is based on actual field samples, no algorithm or equation governs the amounts throughout the soil columns (B. Dobos, personal communication, June & July, 2016). Therefore, to account for this

discrepancy, I subtracted the baseline values reported by gSSURGO at 0-5cm from the reported baseline values for 0-30 cm. I then divided the remaining value by five to determine what would constitute an equal increment of SOC and AWS for every five cm and then adjusted the amount for 10 and 15 cm.

The second issue is the discrepancy between the depth of a plant's rootzone and the soil profile depth measured in C sequestration studies. The valid depth at which to measure AWS is through the rootzone, and SOC accrual can occur in depths of up to two meters (Guan, et al., 2016). Most SOC studies (including the ones used here) take measurements to more shallow depths (e.g., 30 cm), as this is generally the depth affected by tillage equipment (Intergovernmental Panel on Climate Change, 2003). However, since a goal of this study was to link SOC and water benefits, AWS was calculated only to the depth of the study reporting SOC increases. Therefore, the results likely underestimate both the SOC increases and the hydrological impacts of conservation agricultural practices.

In addition to the depth measurements, the year in which SOC accrual begins is also central component of this analysis. I assume that accrual begins in Year 1 of adopting conservation agricultural practices. Most of the studies I use directly support this assumption. This is true of Ogle, Conant, and Paustian (2004) and Industry & Investment New South Wales Government (Australia) (2010). Ghimire, Norton, and Pendall (2014) for alfalfa, however, was a two-year study. The greatest uncertainty derives from Lal and Follet (2009) for barley, which reports SOC increases after 18 years of no tillage. To estimate C sequestration for these studies, I calculated an average

annual rate of SOC accumulation by dividing the total SOC accumulation for the study period by the study period duration.

Determining Increases in Available Water Storage and Effects on Drought Vulnerability and Recharge

To calculate the potential for conservation agricultural practices to build AWS, I use the metric first published by Hudson (1994), which found that for every 1% increase in SOM, there is a 3.7% increase in AWS. Consistent with scientific convention and gSSURGO, all calculations assume that SOM is comprised of 58% C or a 2.146% increase in AWS for every 1% increase in SOC, unless otherwise stated. Unlike all other studies used in this thesis, Weber and Gokhale (2011) recorded soil moisture, as opposed SOC increases. To incorporate these findings, I assumed that the soil moisture increases correspond to an equal increase in AWS (1:1 ratio of soil moisture to AWS).

$$\text{Year}_1 \text{ AWS Levels} = \text{Year}_1 \text{ Baseline} + (\text{Year}_n \text{ Baseline} * (\% \text{ Increase in SOC} * 2.146^{\wedge}))$$

[^]Or appropriate C content corollary.

Based on the ten-year SOC build outs, I calculated increases in AWS over ten years, as follows:

$$\text{Year}_n \text{ AWS Levels} = \text{Year}_{n-1} + (\text{Year}_{n-1} * (\% \text{ Increase in SOC} * 2.146^{\wedge}))$$

[^]Or appropriate C content corollary.

These calculations were applied to the baseline AWS values in the ESP and the WRV, which – like the baseline SOC levels – vary both by and within land use type (Figure 20 and Figure 21).

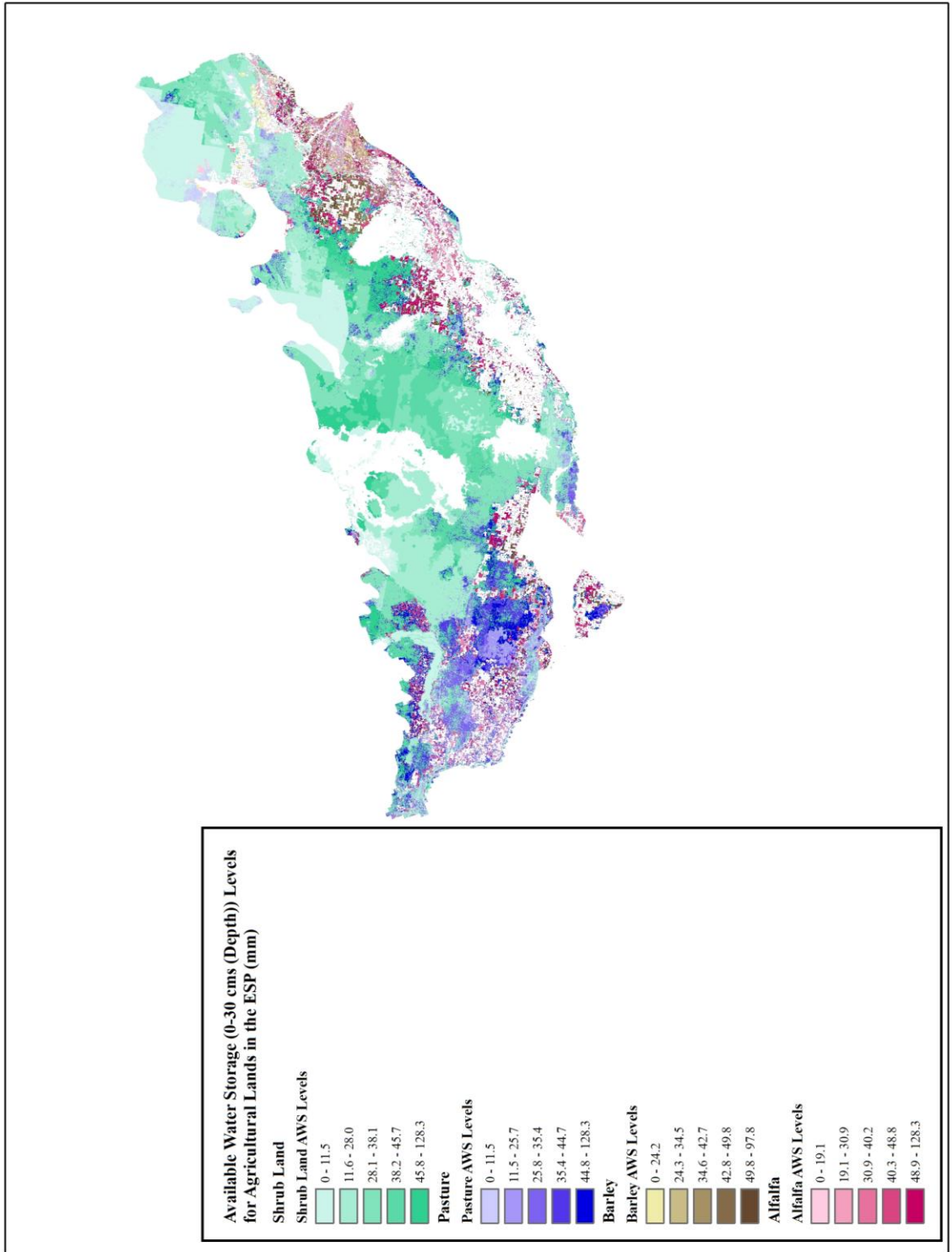


Figure 20. AWS levels for shrub land, pasture, barley, and alfalfa in the ESP.

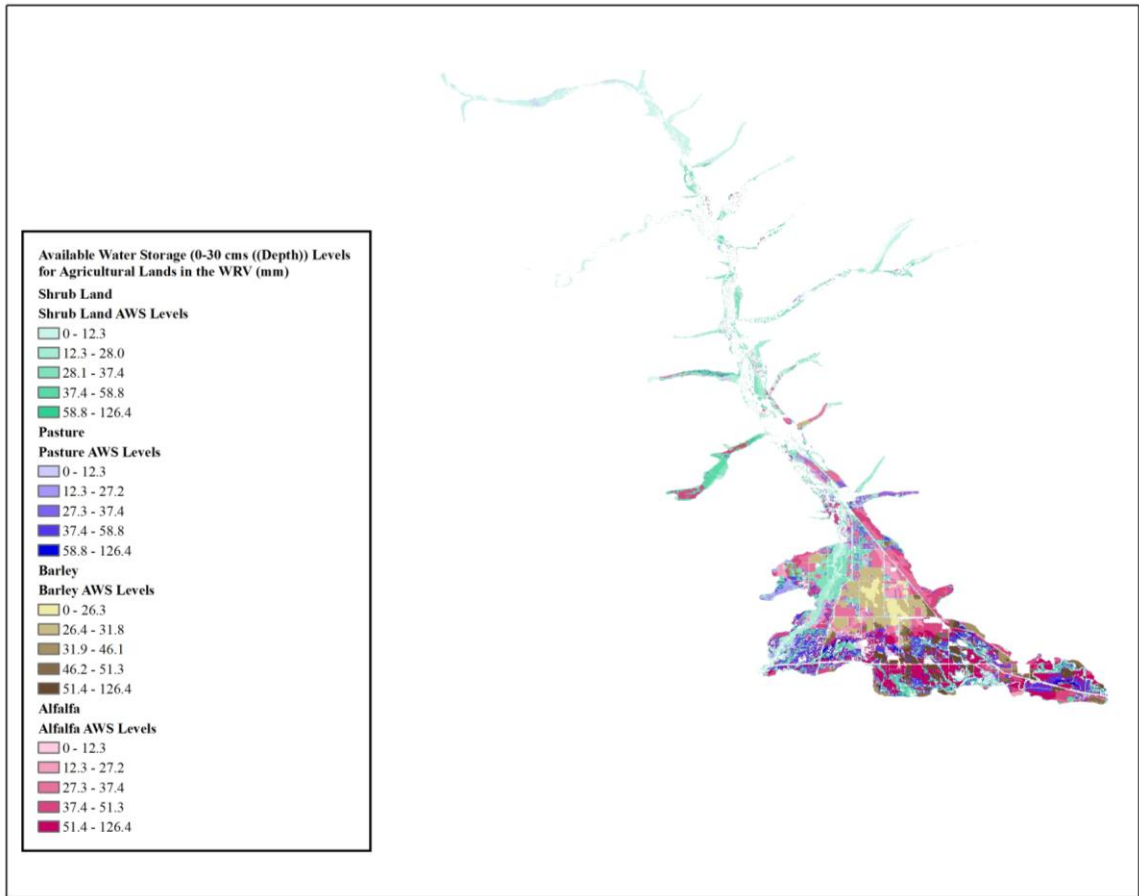


Figure 21. AWS levels for shrub land, pasture, barley, and alfalfa in the ESP.

Apart from the drought vulnerability analysis (see below), I analyzed the impacts that increasing SOC would have on AWS using 2 different metrics: 1) the percent increase in Years 1 and 10 and 2) the volumetric increases (af/acre) in Years 1 and 10. Each metric is important for different reasons. The percentage increase in Year 1 is important because while the volumetric increases may appear small, the percentage increase in many cases is quite large. Of course, this percentage increase declines each year with the concurrent decline percentage increase of SOC. Therefore, I also present the percentage increase from Year 10 to demonstrate the extent of diminishing returns. In addition to presenting this information in tabular format in the text, Ancillary

Appendix 3 contains maps showing the spatial distribution of Year 1 and Year 10 percent increases.

I also analyzed the potential for conservation practices to remove agricultural lands from the drought vulnerable category, which gSSURGO defines as soils with less than 0.5 af of AWS in the rootzone. Two factors limited the amount and type of land for which this analysis could be performed. The first is the depths of the C sequestration studies, which do not measure carbon all the way through the rootzone.

To limit uncertainty presented by this discrepancy, I analyzed only those lands that had less than a five-cm difference between the rootzone depth and the corresponding C sequestration studies. This confined the analysis to two raster cells each for pasture and shrub land in the WRV. From these cells, I then analyzed the impacts on the cell with the least amount of AWS in the rootzone, which would produce the most conservative results. Each raster cell for these lands measured AWS in the rootzone at 33 cm, which is 10% deeper than the depth of the C sequestration studies (0-30 cm). To adjust for the three-cm discrepancy, I added 10% to both the baseline SOC levels for the sample size and the C sequestration rate.

The second reason for the limited extent of this analysis is that gSSURGO does not contain field data for the AWS in the rootzone for several of the shrub and pasture land cells (e.g., 18 of 37 for shrub land and 19 of 31 for pasture), and thus used the default measurement of 150 cm (USDA NRCS, 2014).

Next I analyzed the impacts of increasing AWS on total and nonirrigated recharge on a per acre basis for alfalfa, barley, pasture, and shrub land. The major constituent of total recharge is excess irrigation water, and the major constituent of non-irrigated

recharge is precipitation (Idaho Department of Water Resources (IDWR), 2013).

Pursuant to conversations with IDWR (J. Sukow, personal communication, March 3), I assumed that increasing AWS reduces recharge on a 1:1 basis. I limited my analysis to the ESP because it has the most reliable recharge data from the ESPAM 2.1 modelling. To estimate recharge impacts, I overlaid raster data sets for these agricultural lands on polygon maps provided by IDWR estimating total and nonirrigated recharge and then subtracted the increased AWS in a given year ((IDWR, 2013).

Finally, though I generally assume a SOM content of 58% C, I examine the impacts of a varying C content in three places: 1) SOC losses in the ESP; 2) the average increase in AWS (af/acre) per \$100 or ten years of conservation practices; and 3) the cost-efficacy of CREP for soil-building.

Costs of Soil Health Measures

The second portion of my research examines the economic implications of adopting conservation practices. Both a literature review and discussion with state and federal officials failed to uncover any directly applicable studies or other information on the costs of switching to conservation practices.

Given the dearth of data, I extrapolated the costs of switching to no till (NT) barley from the findings of Epplin, Stock, Kletke and Peeper (2005), which calculated the costs of switching to NT for wheat in the Oklahoma Plains. This study found that for two farm sizes (320 and 640 acres) switching to NT increases operating and fixed machinery costs by \$10/acre, but that the switch created a cost-savings a \$3/acre for larger farms sizes (1,260 and 2,560 acres).

While this study is unpublished and pertains to a different crop and region, applying these findings to barley in Idaho is reasonable for several reasons. First, the authors themselves are prolific and, having published several articles, are credible. Second, their study is recent as compared to other studies pertaining to barley specifically (e.g., Klonsky, Pettygrove, Smith, & Livingston, 1994) and others regarding NT and RT more generally (e.g., Dumler (2000) and sources cited therein). The study's timing is important given that machinery improvements and decreases in the price of glyphosate due to patent expiration have significantly improved the costs of adopting NT or RT (Epplin, Stock, Kletke, & Peeper, 2005). Third, the costs of converting tillage practices for wheat are similar to barley, as they generally use the same inputs (e.g., glyphosate and nitrogen-based fertilizers). To be clear, I only generalize the findings of Epplin, Stock, Kletke, and Peeper (2005) to barley and not to alfalfa, as the crops are significantly different. For instance, alfalfa is a nitrogen-fixing legume and therefore does not require nitrogen-based fertilizers as barley does.

Fourth, the findings are conservative because the authors exclude other on-farm benefits such as the potential for yield increases, better nutrient cycling, and labor opportunity costs. Finally, a significant advantage is that the study analyzes costs for four farm sizes (340, 640, 1,280, and 2,560 acres). Though farm sizes are rapidly increasing both in Idaho and nationally, the vast majority are small (e.g., USDA NASS, 2015a) and this study allows for analysis across the spectrum.

Figure 22 summarizes the trends in farm size and value for Idaho farms from 2005 to 2014 and demonstrates that land holdings are being consolidated into larger, higher-revenue enterprises. Unfortunately, USDA's Agricultural Bulletins (USDA NASS,

2015; USDA NASS, 2012) do not disaggregate the economy size of farms or average farm size by crop. Therefore, I assume that barley farms reflect these trends.

Number of Farms by Economic Sales Class — Idaho: 2005-2014								
Year	Economic sales class							Total
	\$1,000 - \$9,999	\$10,000 - \$99,999	\$100,000 - \$249,000	\$250,000 - \$499,999	\$500,000 - \$999,999	\$500,000 - \$1,000,000 or more ¹	\$1,000,000 or more ¹	
	(number)	(number)	(number)	(number)	(number)	(number)	(number)	(number)
2005	15,000	6,000	1,600	1,100	(NA)	1,300	(NA)	25,000
2006	14,500	6,200	1,600	1,300	(NA)	1,400	(NA)	25,000
2007	14,100	6,800	1,700	1,100	(NA)	1,700	(NA)	25,400
2008	13,700	6,900	1,800	1,200	(NA)	1,800	(NA)	25,400
2009	14,000	7,000	1,600	1,200	(NA)	2,000	(NA)	25,800
2010	14,200	6,900	1,500	1,050	(NA)	1,750	(NA)	25,400
2011	12,900	7,600	1,700	1,100	(NA)	1,800	(NA)	25,100
2012	12,500	7,100	1,850	1,300	(NA)	2,050	(NA)	24,800
2013	12,300	7,000	1,900	1,300	800	(NA)	1,200	24,500
2014	12,200	7,000	1,900	1,300	800	(NA)	1,200	24,400

(NA) Not available.
¹ Starting in 2013 two new sales classes were published. The previous sales class of \$500,000 or more was divided into \$500,000 - \$999,999 and \$1,000,000 or more in sales.

Land in Farms by Economic Sales Class — Idaho: 2005-2014								
Year	Economic sales class							Total
	\$1,000 - \$9,999	\$10,000 - \$99,999	\$100,000 - \$249,000	\$250,000 - \$499,999	\$500,000 - \$999,999	\$500,000 - \$1,000,000 or more ¹	\$1,000,000 or more ¹	
	(1,000 acres)	(1,000 acres)	(1,000 acres)	(1,000 acres)	(1,000 acres)	(1,000 acres)	(1,000 acres)	(1,000 acres)
2005	1,100	3,100	2,300	1,600	(NA)	3,600	(NA)	11,700
2006	1,000	3,000	2,200	1,900	(NA)	3,500	(NA)	11,600
2007	950	2,500	1,950	1,400	(NA)	4,700	(NA)	11,500
2008	1,000	2,400	1,900	1,300	(NA)	4,900	(NA)	11,500
2009	1,000	2,100	1,700	1,300	(NA)	5,400	(NA)	11,500
2010	1,000	2,300	1,700	1,200	(NA)	5,300	(NA)	11,500
2011	800	2,300	1,600	1,200	(NA)	5,700	(NA)	11,600
2012	800	2,100	1,600	1,400	(NA)	5,900	(NA)	11,800
2013	800	2,100	1,600	1,400	1,800	(NA)	4,100	11,800
2014	800	2,050	1,650	1,400	1,900	(NA)	4,000	11,800

(NA) Not available.
¹ Starting in 2013 two new sales classes were published. The previous sales class of \$500,000 or more was divided into \$500,000 - \$999,999 and \$1,000,000 or more in sales.

Average Farm Size by Economic Sales Class — Idaho: 2005-2014								
Year	Economic sales class							Total
	\$1,000 - \$9,999	\$10,000 - \$99,999	\$100,000 - \$249,000	\$250,000 - \$499,999	\$500,000 - \$999,999	\$500,000 - \$1,000,000 or more ¹	\$1,000,000 or more ¹	
	(acres)	(acres)	(acres)	(acres)	(acres)	(acres)	(acres)	(acres)
2005	73	517	1,438	1,455	(NA)	2,591	(NA)	468
2006	69	484	1,375	1,462	(NA)	2,591	(NA)	464
2007	67	368	1,147	1,273	(NA)	2,320	(NA)	453
2008	73	348	1,056	1,083	(NA)	2,498	(NA)	453
2009	71	300	1,063	1,083	(NA)	2,641	(NA)	446
2010	70	333	1,133	1,143	(NA)	2,768	(NA)	453
2011	62	303	941	1,091	(NA)	2,808	(NA)	462
2012	64	296	865	1,077	(NA)	2,836	(NA)	478
2013	65	300	842	1,077	2,250	(NA)	3,417	482
2014	66	293	868	1,077	2,375	(NA)	3,333	484

(NA) Not available.
¹ Starting in 2013 two new sales classes were published. The previous sales class of \$500,000 or more was divided into \$500,000 - \$999,999 and \$1,000,000 or more in sales.

Figure 22. Trends in average farm size and holdings by economic sales class in Idaho from 2005-2014 (USDA NASS, 2015a).

Notably, the lowest economic class has the largest number of farms (58%), but the lowest value (\$1,000 to \$9,999) and the smallest average acreage (66 acres). Additionally, the average size of the two lowest economic class sizes (66 and 293 acres, respectively) are those predicted to incur a cost in moving to NT. Therefore, I examined the cost implications for the average farm size for the three economy classes in Table 7. All told, farms in these categories account for ~84% of all farms and ~58% of all farm acreage.

Table 7. Farm sizes examined (USDA NASS, 2015a) (2014 data).

Economy Class	Value	Average Farm Size (Acres)	Number of Farms	Land in Farms (Acres)
Class 1	\$1,000-\$9,999	66	12,200	800,000
Class 2	\$10,000 to \$99,999	293	7,000	2,050,000
Class 7	≥\$1 million	3,300	1,200	4,000,000

I did not adjust costs for inflation given the complexity of this for agricultural commodities and equipment (USDA Economic Research Service, 2016). I also assumed that costs of adoption do not vary between ESP and the WRV, which is reasonable given the relatively few number of heavy-equipment dealerships in Idaho. Nonetheless, other factors might affect labor costs, such differences in ethnicity or the percentage of migrant workers.

Relevance of Carbon Sequestration Economic and Financial Studies to Financial Analysis

In researching the costs of switching to conservation practices, I reviewed literature from the broad array of studies estimating the costs or optimal payments for carbon sequestration in the context of a CO₂ cap-and-trade framework. This research was of limited value because it generally examines the costs of incentivizing behavior change instead of the actual switch costs. For instance, in 2004, USDA issued a comprehensive report analyzing the effects of C sequestration payments (Lewandrowski, et al., 2004), but even the highest carbon price (\$44.25/metric ton) produced only a 4.6% shift in acreage from conventional till to conservation till (calculations available from author). Further, other studies do not analyze tillage switches but instead focus on afforestation, conversion of cropland to grassland, or cover-cropping (e.g., Antle, Capalbo, Mooney, Elliot, & Paustian, 2001; Lewandrowski, et al., 2004 and sources cited therein).

Costs of Increases in Available Water Storage to Compared to Water Purchases and the Conservation Reserve Enhancement Program

Using the increases in AWS derived from the ten-year buildouts, I analyzed the costs of increasing AWS (af/acre). I used three scenarios to account for the uncertainty in the start time of SOC accrual. Scenario 1 is the least conservative and assumes benefits begin in Year 1. Scenario 2 is the mid-point, with a Year 5 start time. Scenario 3 is the most conservative with benefits beginning in Year 7.

Most of the analysis uses either undiscounted dollars or a discount rate of 5%. I chose 5% because 1) various USDA NRCS financial planning documents cite this rate

(USDA NRCS, n.d.c) and 2) it is relatively conservative. Higher discount rates may be warranted if – because of experience, research, and/or education – farmers perceive less risk in switching to NT practices. Therefore, I also applied discount rates of 7% and 10%.

I also compared the cost of increasing AWS on an af/acre basis with the cost of purchasing additional irrigation water from rental pools. Because Idaho follows the Prior Appropriation Doctrine, my comparison necessarily assumes that the water is purchased from the rental pool, as water attainment is otherwise a matter of property right. I limit my analysis to the ESP area, where the rental pool is well-developed, in contrast to the WRV where the interim policy expired in December 2016 (Idaho Department of Water Resources, 2015). Further, since useful averages for irrigation rates and precipitation deficits are unavailable for specific crops, I use the average amount of irrigation applied to an acre, which is 1.86 af (range: 1.56 to 2.02 af) (USDA, Economic Research Service, 2013).

Finally, I compare the costs of one ton of soil savings under the federal Conservation Reserve Enhancement Program (CREP) program to soil saved by switching to NT barley. CREP currently applies only in the ESP, with each enrolled acre saving two tons of soil from water erosion and six from wind erosion (Idaho Soil and Water Conservation Commission, 2015). Annual rental payments range between \$55.00 and \$65.00 per acre. Therefore, I divided these annual rental payments by two and six. To estimate soil savings, I assumed a 42%, 50%, and 58% C content.

Chapter III

Results

The results for this thesis' six specific aims are presented: 1) the time required for conservation practices to reverse historic soil organic carbon (SOC) losses from tillage; 2) the gains in available water storage (AWS) from SOC increases in both the short- and long-term; 3) the reductions in aquifer recharge from increased AWS; 4) the time required for conservation agricultural practices to increase AWS above 0.5 af in the rootzone, thereby reversing drought vulnerability; 5) the on-farm costs of adopting no till and associated benefits; and 6) a comparison of on-farm costs for adopting no till with other on-farm expenditures and incentive-based governmental programs.

SOC and AWS Losses in the Eastern Snake Plain

The SOC losses from all agricultural lands by county for the years 2008, 2010, and the ten-year average are generally low and hence maybe largely unnoticeable (Figure 23). Except for four counties (Fremont, Gooding, Bonneville, and Power), all SOC losses for 2008 and the ten-year average are low, remaining under ~35 kg/acre, and some between two and five kg/acre.

The ten-year average SOC losses are generally higher than for 2008. In 2008, SOC loss from all agricultural lands including fallowed areas was 132,986 metric tons; excluding fallowed land, the loss was 141,615 metric tons. Using the ten-year average,

annual losses were 253,050 metric tons (including fallowed land) and 1,490,363 metrics tons (excluding fallowed land).

Bonneville and Power counties had the highest SOC losses and also have a high amount of agricultural acreage. Respectively, losses were 86.4 kg/acre and 145.7 kg/acre for 2008, 187.0 and 250.7 kg/acre for the ten-year annual average, and 1585.0 and 2743.3 kg/acres for the ten-year total (Figure 23). These losses account for approximately 38% and 29% of the total SOC lost from the ESP respectively in 2008. While not as severe, Fremont likewise also had high losses (1083.2 kg/acres from 1998-2008). These results thus suggest that Bonneville, Power, and Fremont should be priority areas for policymakers to encourage conservation practices. Although climate change mitigation is not a focus of this thesis, Appendix 1 contains the results of my calculations of the GHG equivalencies for the SOC lost from these lands.

Ancillary Appendix 1 contains maps showing the AWS losses per acre for alfalfa, barley, and pastures and, as with SOC losses, demonstrates that volumetric AWS losses are small and likely unnoticeable in a given year. By way of example I provide Figure 24Figure 25 below (reproduced from Ancillary Appendix 1). Only one result even attains 1/10 of an af/acre – the Clark county ten-year average losses for pasture (Figure 24). Using the less conservative 2008 loss rate, this falls to less than 0.0003 af/AWS (Figure 25). These numbers suggest that erosion from tillage would be difficult to detect in any given year, and thus maintaining water holding capacity would be unlikely to incentivize a shift in management practices. Figures 24 and 25 also show that different C contents (42% and 58%) have little effect, generally less than an 0.0006 af increase, with other land uses showing even smaller amounts (Ancillary Appendix 1).

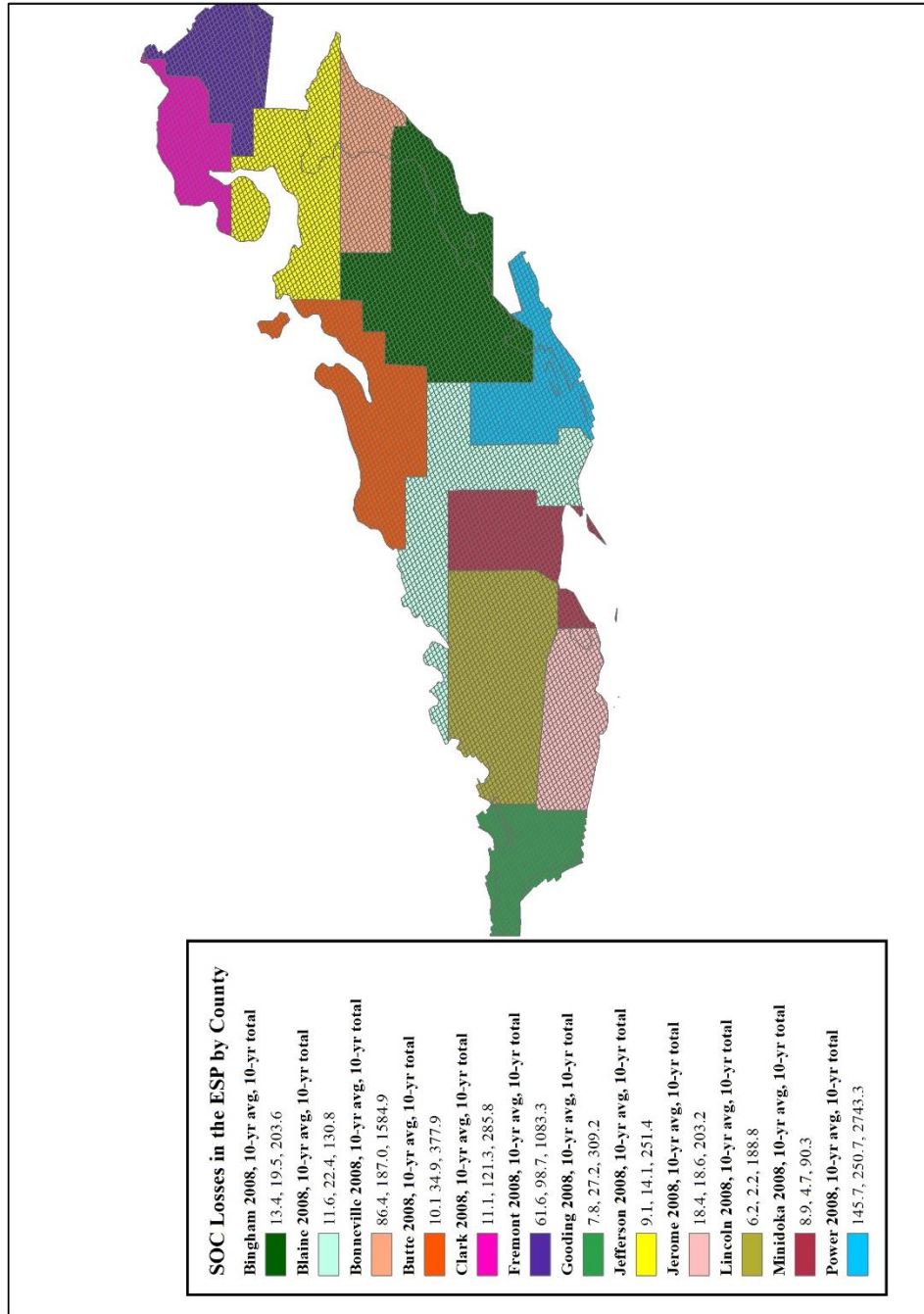


Figure 23. SOC losses all for agricultural lands from the ESP by county (kg/acre).

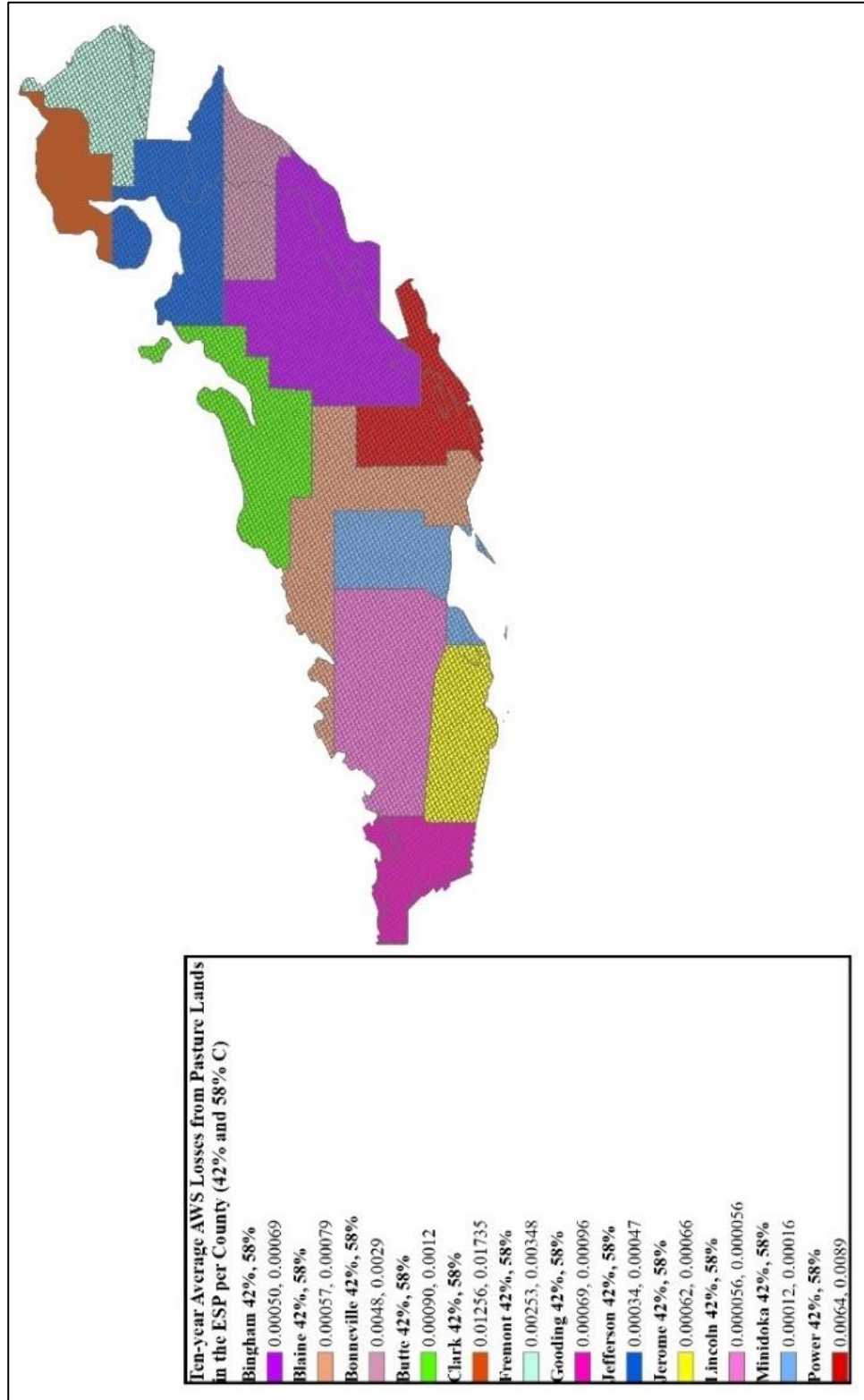


Figure 24. Ten-year average AWS losses from pasture in the ESP by county with varying C contents.

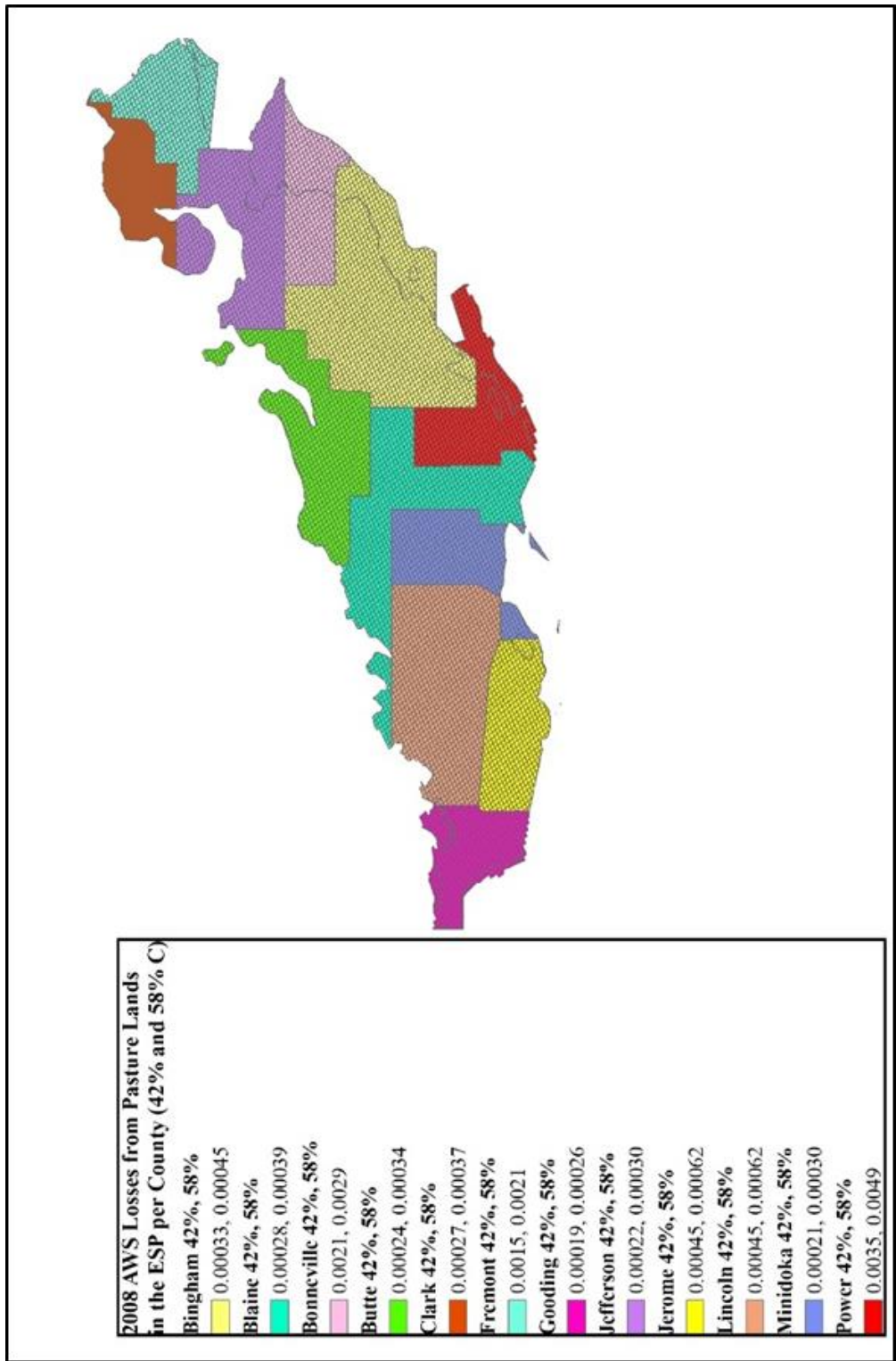


Figure 25. Pasture 2008 AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).

Summed over the entire ESP study area, AWS losses are small suggesting that impacts on recharge or baseflows are not felt at a landscape scale (Table 8). Of course, however, such losses may be impacting nearby waterways through excess sedimentation. The highest is ~900 af for pasture land, which occupies 648,051 acres, likely due to its high AWS baseline levels. Accounting for AWS losses over a ten-year period would produce highly uncertain results because one could not account for soil gains from crop annual crop growth, and therefore is excluded from the analysis.

Table 8. Volumetric AWS losses (af/acre) by cropland type over the entire ESP (2008 and ten-year average).

Crop	Year	Including Fallow	No Fallow	Total Area (Acres)*
Alfalfa	2008	213	220	378,643
	10-year average	398	413	378,643
Barley	2008	201	204	177,424
	10-year average	395	419	177,424
Grass/Pasture	2008	364	471	648,051
	10-year average	578	892	648,051

*Ten-year average uses acreage from 2015.

SOC and AWS Losses in the Wood River Valley

SOC losses are even more minimal in the WRV, amounting only to 2.26 kg/acre for 2008, 7.6 kg/acre for the ten-year average, and a ten-year total of 131 kg/acre from 1998 to 2008. Consequently, AWS losses per acre are also low (Table 9). Area-wide losses are usually below 0.6 af and in all cases below 1.25 af. Appendix 1 contains the results for my calculations of the GHG equivalences from these SOC losses.

Table 9. Volumetric AWS losses (af/acre) per acre and for the entire WRV area (2008 and ten-year average).

Crop	Year	Per Acre - Including Fallow	Entire Area – Including Fallow	Per Acre Excluding Fallow	Entire Area - Excluding Fallow	Total Area (Acres)
Alfalfa	2008	0.0000266	0.32	0.0000268	0.32	11,856
	10-year average	0.0000867	1.22	0.0000888	1.25	14,068
Barley	2008	0.0000263	0.31	0.0000265	0.31	6,598
	10-year average	0.0000925	0.73	0.0000947	0.75	7,863
Grass/Pasture	2008	0.0000252	0.38	0.0000253	0.38	14,992
	10-year average	0.0000777	0.57	0.0000795	0.59	7,392

*Ten-year average uses 2015 acreage.

Remediation Times of Historic Soil Organic Carbon Losses

Replacement or remediation time for SOC losses were calculated by applying the carbon sequestration rates from conservation agricultural practices (Table 6) to the historic SOC losses (Figure 23). In many cases, conservation practices can rapidly remediate SOC loss for barley and alfalfa in the ESP (e.g., less than one year) (Table 10). As would be expected from the C sequestration rates (see Table 6), moving to RT alfalfa has the most rapid remediation times followed by NT barley and organic alfalfa.

Table 10. Remediation time of ten-year SOC losses for alfalfa and barley by county (kg/acre).

County	Land Use and Conservation Practice	Time to Remediate 10-year Total SOC Loss
Bingham	Organic Alfalfa	<1 year
	RT Alfalfa	<1 year
	NT Barley	<1 year
Blaine	Organic Alfalfa	<1 year
	RT Alfalfa	<1 year
	NT Barley	<1 year
Bonneville	Organic Alfalfa	7.186 years
	RT Alfalfa	1.440 years
	NT Barley	1.883years
Butte	Organic Alfalfa	1.714 years
	RT Alfalfa	<1 year
	NT Barley	<1 year
Clark	Organic Alfalfa	1.296 years
	RT Alfalfa	<1 year
	NT Barley	<1 year
Fremont	Organic Alfalfa	<1 year
	RT Alfalfa	<1 year
	NT Barley	1.287 years
Gooding	Organic Alfalfa	1.402 years
	RT Alfalfa	<1 year
	NT Barley	<1 year
Jefferson	Organic Alfalfa	1.140 years
	RT Alfalfa	<1 year
	NT Barley	<1 year
Jerome	Organic Alfalfa	<1 year
	RT Alfalfa	<1 year
	NT Barley	< 1 year
Lincoln	Organic Alfalfa	<1 year
	RT Alfalfa	<1 year
	NT Barley	<1 year
Minidoka	Organic Alfalfa	<1 year
	RT Alfalfa	<1 year
	NT Barley	<1 year
Power	Organic Alfalfa	12.438 years
	RT Alfalfa	2.492 years
	NT Barley	3.259 years

For six of the 12 counties, moving to organic alfalfa would recoup SOC losses in less than one year, and for ten counties, RT alfalfa also would recoup losses in less than one year. NT Barley would recoup losses in less than one year for nine of the 12 counties. For other counties, most remediation times remain under two years, except for Bonneville and Power. Even for Bonneville, however, moving to RT alfalfa and NT barley conservation practices would remediate the loss in under two years, though organic management of alfalfa would take a little over seven years. For Power, moving to RT alfalfa and NT barley would remediate the losses in less than 3.25 years, though organic alfalfa again would take longer (~12.5 years). Ancillary Appendix 2 contains maps giving a spatial representation of the results contained in Table 10.

For pasture land in the ESP, remediation times are likewise rapid. Under all the Ogle pasture benchmark, remediation times are less than one year except for Bonneville and Power, which require 1.28 and 2.22 years respectively. Even using the more conservative no till pasture benchmark, times are less than one year, except for Bonneville (6.17 years), Butte (1.47 years), Clark (1.11 years), Fremont (4.13 years), Gooding (1.20 years), and Power (10.67 years).

In contrast to the ESP, remediation times for all land uses in the Wood River Valley are within 1 year, as this study area had one of the lowest ten-year total SOC losses (131.0 kg/acre).

Available Water Storage Increases: Eastern Snake Plain

It is useful to highlight AWS increases – including when the standard deviation is accounted for –that exceed 0.5 af/acre of water as this becomes relevant to my analysis of the time required for soil health measures to reverse drought vulnerability.

Moving to RT alfalfa results in significant AWS gains. Values increase by ~93% (~0.035 af/acre) in Year 1 for all irrigated lands (Table 11). Year 10 increases exceed 0.5 af, suggesting that drought vulnerability would be reversed within this timeframe. For groundwater-irrigated (GW) areas, the percentage increases are largely the same, but volumetric increases are significantly less (approximately nine times less after ten years).

Significant variation also exists within these parameters (Table 11). For instance – Year 1 % increases vary between 6% and more than 150% for surface water (SW) irrigation, and 39% to 1,409%+ for GW-irrigated areas (Ancillary Appendix 3, Figure 45).

Table 11. Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for reduced till alfalfa in the ESP.

Irrigation Type	Year 1 Percent	Standard Deviation	Year 10 Percent	Standard Deviation	Year 1 (Af/Acre)	Standard Deviation	Year 10 (Af/Acre)	Standard Deviation
All	92.9	149.8	17.5	3.2	0.035	0.023	0.990	1.212
GW Only	91.3	150.3	17.6	2.9	0.007083	0.004634	0.111	0.147

* All irrigation refers to SW only and mixed SW and GW sources.

In contrast to RT alfalfa, increases in AWS from moving to organic practices are much lower, with Year 1 percent increases only 18.6% and 9.6% in Year 10 on all irrigated lands (Table 12). Volumetric increases are concomitantly low: Year 1 increases for GW only areas are 91% but the standard deviation is high, and thus volumetric

increases are similar to those achievable on SW-irrigated lands. As with RT alfalfa, however, there is significant variation in AWS increases, with Year 1 increases ranging from 1% to more than 125% on all irrigated lands (Ancillary Appendix 3, Figure 49) and between less than 1% to more than 282% for GW only areas (Ancillary Appendix 3, Figure 51).

Table 12. Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for organic alfalfa in the ESP.

Irrigation Type	Year 1 Percent	Standard Deviation	Year 10 Percent	Standard Deviation	Year 1 (Af/Acre)	Standard Deviation	Year 10 (Af/Acre)	Standard Deviation
All	18.6	30.0	9.7	4.8	0.007	0.005	0.112	0.152
GW Only	91.3	150.3	17.6	2.9	0.007	0.005	0.111	0.147

* All irrigation refers to SW only and mixed SW and GW sources.

Moving to no till barley causes an intermediate increase in AWS for croplands. For all lands, mean Year 1 increases are 28.7% and 0.029 af/acre (Table 13), with a range of 2% to over 600% (Ancillary Appendix 3, Figure 53). While the percentage gains are modest, Year 10 volumetric increases are significant and exceed 0.5 af. Finally, the opportunities for increasing AWS on GW irrigated areas do not differ significantly, with a difference of 0.8% in mean values and a similar range in variation for Year 1 percent increases (Ancillary Appendix 3, Figure 55).

Table 13. Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for no till barley in the ESP.

Irrigation Types	Year 1 Percent	Standard Deviation	Year 10 Percent	Standard Deviation	Year 1 (Af/Acre)	Standard Deviation	Year 10 (Af/Acre)	Standard Deviation
All	28.7	42.1	11.8	4.3	0.029	0.017	0.521	0.619
GW Only	29.5	44.8	11.8	3.9	0.030	0.018	0.545	0.684

* All irrigation refers to SW only and mixed SW and GW sources.

For the Ogle pasture benchmarks, the opportunities for AWS increases under all scenarios are high, exceeding 0.5 af in Year 10 for all lands (Table 14). The percentage increases are likewise high, with the most conservative scenario having a 44.6% mean increase. Finally, there is no significant difference in AWS increases for GW-irrigated areas. There is, however, significant variation in the Year 1 percent increases for both SW and GW-irrigated lands, with the nominal to medium input scenario ranging from 2% to more than 300% and 2% to over 100% respectively (Appendix 3, Figure 57 and Figure 59). Due to the significant uncertainty about pasture quality, I do not assume which Ogle pasture benchmark would be most applicable.

Table 14. Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for Ogle pasture benchmarks in the ESP.

Ogle Scenario	Type	Year 1 Percent	Standard Deviation	Year 10 Percent	Standard Deviation	Year 1 (Af/Acre)	Standard Deviation	Year 10 (Af/Acre)	Standard Deviation
Nominal to Medium	All	45.5	67.4	14.1	4.1	0.044	0.027	0.753	0.802
	GW Only	44.6	61.2	14.1	3.4	0.046	0.025	0.774	0.746
Nominal to High	All	64.8	94.4	15.4	3.7	0.061	0.038	1.167	1.217
	GW Only	60.9	85.1	15.8	3.2	0.062	0.036	1.170	1.133
Degraded to Medium	All	54.6	80.9	15.0	3.9	0.052	0.033	0.954	1.006
	GW Only	53.5	73.4	15.0	3.3	0.055	0.030	0.981	0.936
Degraded to High I	All	72.9	107.9	16.4	3.5	0.070	0.044	1.389	1.432
	GW Only	69.5	97.3	16.4	3.0	0.071	0.041	1.394	1.333

* All irrigation refers to SW only and mixed SW and GW sources.

As the C sequestration rates for NT pasture are much lower than the Ogle pasture benchmarks, it logically follows that the AWS increases are as well (Table 15). Further,

no significant differences exist between SW- and GW-irrigated areas either in mean values or in the variation of Year 1 percent increases, which range from 1% to ~24% (Ancillary Appendix 3, Figure 61 and Figure 63).

Table 15. Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for no till pasture benchmark in the ESP.

Irrigation Type	Year 1 Percent	Standard Deviation	Year 10 Percent	Standard Deviation	Year 1 (Af/Acre)	Standard Deviation	Year 10 (Af/Acre)	Standard Deviation
All	9.5	14.0	6.7	4.9	0.009	0.006	0.108	0.103
GW Only	9.0	12.7	6.3	3.9	0.009	0.005	0.108	0.096

* All irrigation refers to SW only and mixed SW and GW sources.

Significant opportunities exist to increase AWS on shrub land pursuant to the Ogle shrub land benchmarks, with all Year 10 scenarios exceeding 0.5 af/acre (Table 16), though significant variation in Year 1 increases exists (~2% to > 500%) (Ancillary Appendix 3, Figure 65). As with pasture lands, I make no assumption as to which Ogle shrub land benchmark is most applicable given the uncertainty of range land quality.

Table 16. Year 1 and Year 10 percent and volumetric increases in AWS by irrigation type for Ogle shrub land benchmarks in the ESP.

Ogle Benchmark	Year 1 Percent	Standard Deviation	Year 10 Percent	Standard Deviation	Year 1 (Af/Acre)	Standard Deviation	Year 10 (Af/Acre)	Standard Deviation
Nominal to Medium	37.2	60.7	12.9	4.4	0.034	0.021	0.673	0.843
Nominal to High	74.5	121.5	16.4	3.6	0.069	0.044	1.749	2.073
Degraded to Medium	46.5	75.9	14.1	14.1	0.043	0.027	0.913	1.133
Degraded to High	83.7	136.6	16.9	3.4	0.078	0.049	2.060	2.402

*Assumes no irrigation of shrub land.

The results for shrub land using the Weber benchmark vary significantly from the Ogle benchmarks (Table 17). Weber (2011) shows a much higher percentage improvement in Year 2 from just rotational grazing than from that plus other management improvement pursuant to the Ogle benchmarks. Volumetric increases, however, are significantly lower.

Table 17. Cumulative volumetric increases in AWS rotational grazing for Weber benchmark in the ESP.

Unit	Year 1	Standard Deviation	Year 2	Standard Deviation	Year 3	Standard Deviation	Cumulative Total
% Increase	21.4	NA	89.3	NA	3.9	NA	
AWS per acre (Mean)	0.009	0.004	0.058	0.025	0.0098	0.042	0.039

*Assumes no irrigation of shrub land.

Available Water Storage Increases: Wood River Valley

Opportunities for increasing AWS in the WRV are significantly lower—generally by ~50% (Table 18). The cause is the generally higher SOC and AWS baseline values. As with the ESP, however, significant variation in AWS percent increases exists within land type (Ancillary Appendix 3, Figure 67-Figure 78). Additionally, the scenarios in which drought vulnerability can be reversed are fewer than in the ESP. Again, I have highlighted those results where AWS increase ≥ 0.5 af/acre. Appendix 2 contains my results showing the CO₂ equivalencies for carbon sequestration from conservation agricultural practices.

Table 18. Percentage and volumetric increases in AWS in the WRV.

Land Type	Year 1% Increase	Standard Deviation	Year 10% Increase	Standard Deviation	Year 1 AWS Increases	Standard Deviation	Year 10 AWS Increases	Standard Deviation
RT Alfalfa	48.7	63.4	23.8	4.5	0.017	0.006	0.331	0.184
Organic Alfalfa	9.8	12.7	6.50	4.4	0.003	0.001	0.042	0.018
NT Barley	14.2	20.4	4.5	8.3	0.013	0.004	0.178	0.068
Shrub Land								
Conant Degraded to High	40.8	51.2	13.3	4.3	0.035	0.013	0.662	0.421
Conant Nominal to High	36.3	45.5	12.7	4.4	0.031	0.011	0.548	0.333
Conant Degraded to Medium	22.7	28.5	10.3	4.4	0.019	0.007	0.301	0.179
Conant Nominal to Medium	18.7	22.9	9.9	4.8	0.016	0.005	0.233	0.125
Pasture								
Conant Degraded to High	36.6	47.1	12.7	4.5	0.031	0.011	0.568	0.361
Conant Nominal to High	32.0	41.3	11.9	4.5	0.027	0.010	0.474	0.298
Conant Degraded to Medium	27.5	35.4	11.2	4.5	0.024	0.009	0.386	0.238
Conant Nominal to Medium	22.9	29.5	10.3	4.5	0.020	0.007	0.304	0.182
NT Pasture	4.8	6.1	4.1	4.3	0.004	0.001	0.046	0.020

Reversing Drought Vulnerability Through Conservation Practices

Conservation practices can reverse drought vulnerability in relatively short timeframes (three to nine years, except for the no till pasture benchmark (>25 years) (Table 19). Further, the previous sections demonstrated that conservation practices would increase AWS above 0.5 acres by Year 10 for several scenarios. Those results would likely represent the outside boundary of time in which drought vulnerability would be reversed because of the shallow depths measured.

Table 19. Time for reversing drought vulnerability by land type in the WRV.

Crop/Land Use Type	Year
Ogle Pasture Benchmarks	Time to Increase AWS Baseline AWS Above 0.5 Af
Degraded to High Input	6 years
Nominal to High Input	7 years
Degraded to Medium Input	7 years
Nominal to Medium Input	9 years
NSW NT Pasture Benchmark	>25 years
Shrub land	
Conant Degraded to High Input	3 years
Conant Nominal to High Input	3 years
Conant Degraded to Medium Input	5 years
Conant Nominal to Medium Input	5 years

Impacts on Total and Non-irrigated Recharge

Over time, conservation practices can significantly affect recharge rates and thus water budgets (Table 20). Year 1 values are all below 5.5%, but by Year 10 many exceed 28%, with at least two values for pasture completely negating recharge.

Table 20. Impacts of conservation agricultural practices on total irrigated recharge in the ESP.

Impact	Year 1	Year 5	Year 10 (Cumulative)
Crop land			
RT Alfalfa	1.3%	9.8%	28.1%
Organic Alfalfa	0.3%	1.5%	3.3%
NT Barley	1.1%	6.4%	15.2%
Pasture			
Ogle Nominal to High Input	4.9%	37.2%	114.4%
Ogle Degraded to High Input	5.6%	39.5%	108.7%
Ogle Nominal to Medium Input	3.5%	22.3%	56.8%
Ogle Degraded to Medium Input	4.2%	27.8%	72.8%
No Till Pasture	0.7%	3.9%	8.3%

Increasing soil health on shrub land can significantly reduce NIR (Table 21). All the Ogle shrub land benchmarks indicate conservation practices would negate recharge in Year 1. Though far lower, applying Weber and Gokhale (2011) predicts more than 30% reduction by Year 2.

Table 21. Impacts of conservation agricultural practices on nonirrigated recharge on shrub land in the ESP.

Scenario	Year 1	Year 5	Year 10
Ogle Degraded to High Input	226.9%	2443.4%	8450.7%
Ogle Nominal to High Input	201.7%	2099.5%	7162.7%
Ogle Degraded to Medium Input	126.1%	1140.2%	3651.0%
Ogle Nominal to Medium Input	100.9%	853.3%	2639.6%
Weber	Year 1	Year 2	Year 3
	5.9%	36.0%	38.5%

Undiscounted Costs for No Till Barley

These results show that while the vast majority of farms will incur costs moving to no till because of their smaller size, large farms will have significant financial benefits. However, farms in all economy classes except the lowest (classes one and two) stand to gain more than \$2,500 per farm annually, while the lower classes would incur costs of \$660 or \$2,930 annually, respectively (Figure 26).

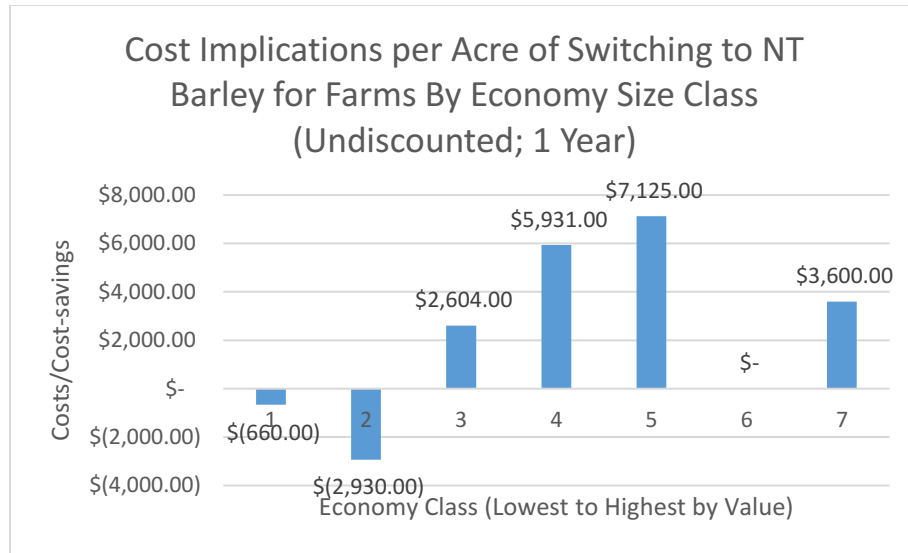


Figure 26. Financial implications over the course of one year for different farm sizes (WRV and ESP).

* As of 2014, there were no farms in economy class size six (USDA NASS, 2015a).

Classes one and two, however, constitute 79% of farms, demonstrating that the vast majority would incur costs of \$10/acre. This additional cost, however, may not prove unduly burdensome. Since 2005 the prices received and the value per harvested acre of barley have been increasing, the latter from \$262 in 2005 to \$480 in 2014 (USDA NASS, 2015a). Therefore, the cost of switching to NT is only a small portion of this income (3.8% for 2005 and 2% for 2014). Given the other likely benefits of moving to NT, \$10 an acre may well overestimate actual costs versus benefits.

Regarding the potential water savings benefits of soil health measures, I compared the costs of moving to NT with water rental costs, which range from \$11.16 and \$40.92 per af in the ESP (IDWR, 2015). Consequently, switching to NT Barley (\$10/acre) is cheaper than purchasing irrigation water from the rental pool, constituting between 89.6% to 24.4% of the cost of irrigation (excluding delivery costs).

Impact of Discount Rates on Costs of Moving to No Till Barley

As discussed earlier, a chief reason for the low adoption rates of conservation practices in Idaho may be the perceived risks, which affects the conscious or unconscious discount rate (DR) that land managers apply. Changes in discount rates significantly alter the financial analysis (Figure 27 and 28). For small farms, a 5% DR rather than a 0%, alters the analysis by as much ~22% (\$22.78) per acre over ten years, and a 10% DR by ~39% per acre over ten years (Figure 27). The impact of different DRs stands out when the effects are compared to farm income. For the 58% of farms within in the lowest economy size class (average size 66 acres), the difference between a 0% and a 5% DR (\$22.78 applied over 66 acres) is equal to 5% of income over ten years (using the income midpoint of \$5000). The difference between applying a 5% and 10% DR (\$15.77 applied over 66 acres), however, is equal to ~2% of income.

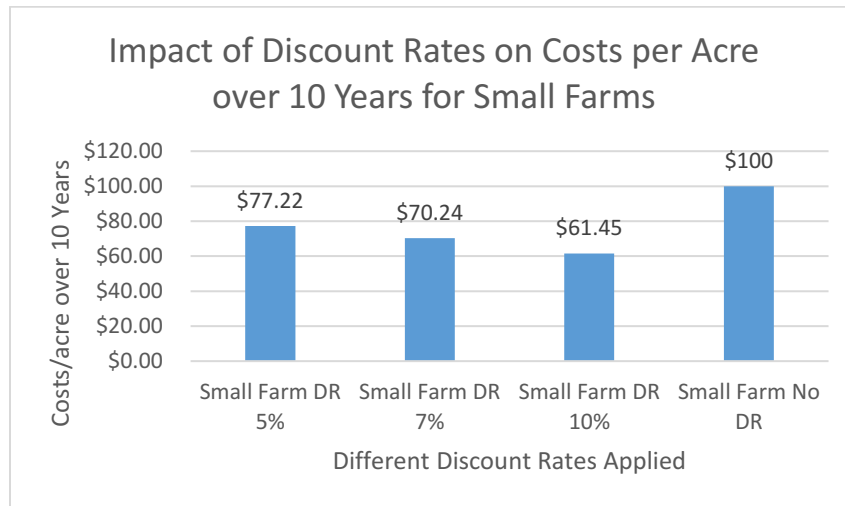


Figure 27. Impact of discount rates on perceived costs of switching to no till barley after ten years for small farms (<640 acres).

For large farms, differences in discount rates change the outcome by as much as 61% (\$18.43 vs. \$30.00) (Figure 28).

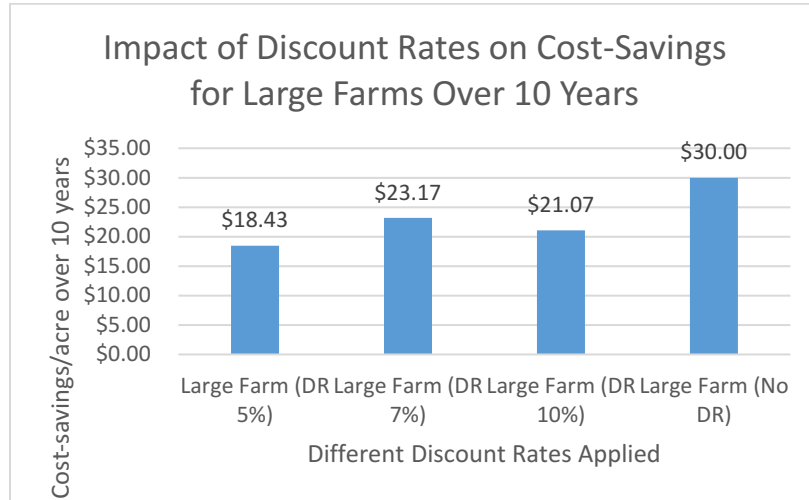


Figure 28. Impact of discount rates on perceived costs of switching to no till barley after ten years for large farms (>640 acres).

Scenarios of Available Water Storage Increases Over Ten Years

The year in which soil health benefits begin is critical to estimating long-term benefits of conservation benefits (Figure 29 and 30). Assuming that soil health benefits begin in Year 1 (Scenario 1) as opposed to Year 7 (Scenario 3) affects the analysis by as much as 311% (0.211 af) for the ESP (Figure 29) and 283% (0.09 af) in the WRV (Figure 30). When the standard deviation is incorporated for Scenario 1 (0.619 af/acre for the ESP and 0.069 for the WRV), the return is much higher. These results are specific to NT barley, but the importance of the starting year applies to every land use.

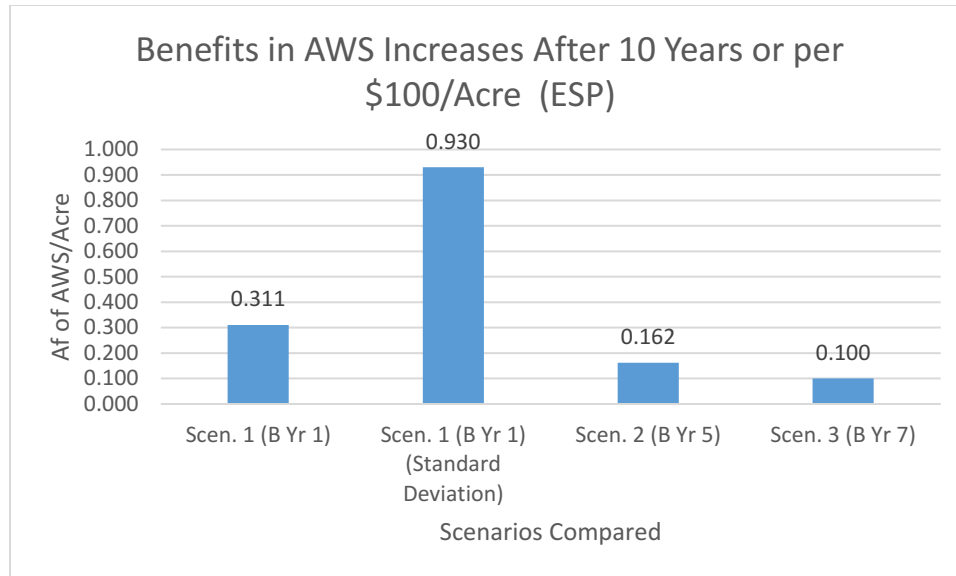


Figure 29. AWS increases after ten years of no till barley with SOC accrual times compared (ESP; mean values).

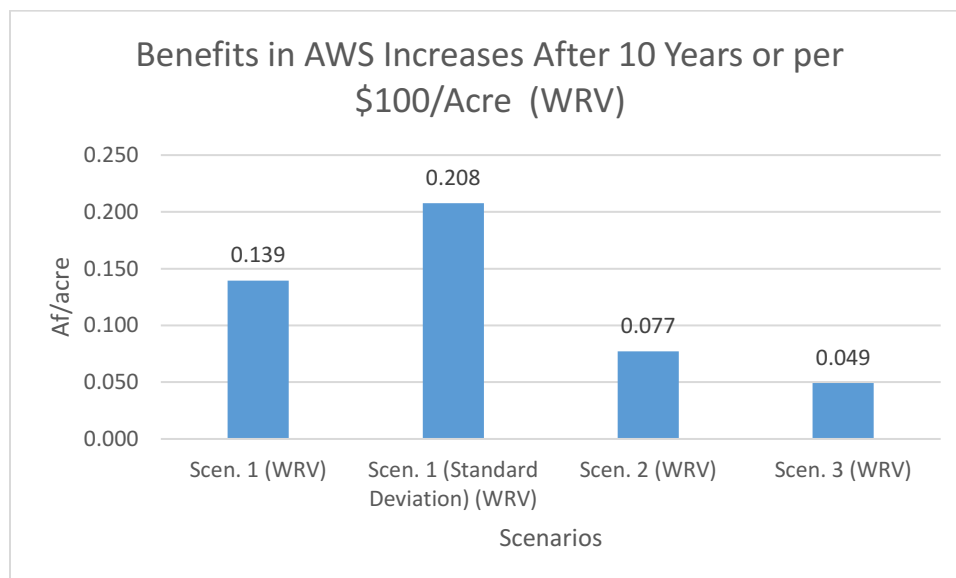


Figure 30. AWS increases after ten years of no till barley with SOC accrual times compared (WRV; mean values).

Comparing the AWS increases in the WRV to those in the ESP demonstrates that baseline values significantly affect the cost of AWS and increases in AWS (Figure 29 and

30), and therefore it is not possible to assign a single numerical value to all areas where a given crop is grown.

Monetary Impacts: Small Farms Sensitivity to Carbon Content of Soil Organic Matter

This thesis has not explored the impacts of varying SOC: SOM ratios in detail, but varying C contents significantly impact AWS increases. Assuming a 58% C (as compared to 42% C) increases AWS gains by 66% for the WRV and ~165% for the ESP (Figure 31 and 32).

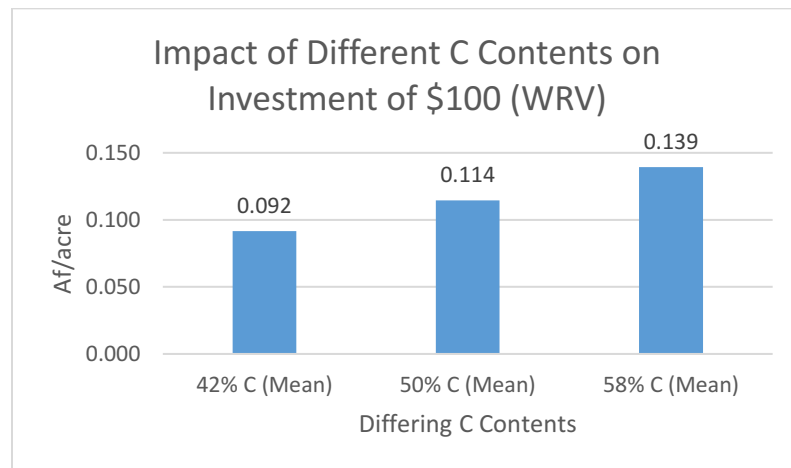


Figure 31. Impact of different SOC: SOM ratios on AWS increases for no till barley (WRV).

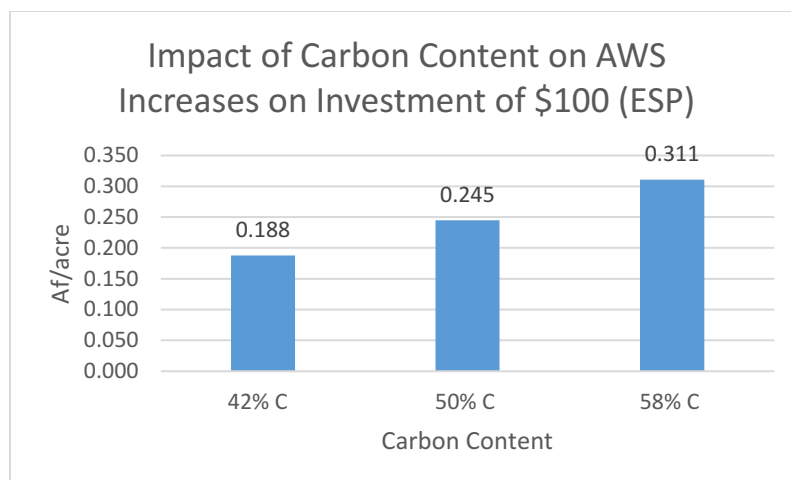


Figure 32. Impact of different SOC: SOM ratio on AWS increases for no till barley (ESP).

The impact of these varying C contents on AWS gains in terms of af/acre was very small (Ancillary Appendix 1, Figure 20 and Figure 21). These results, however, highlight that small changes in volume can translate into significant financial impacts. Appendix 2 contains results showing the CO₂ equivalencies for carbon sequestration from conservation agricultural practices, and Ancillary Appendix 4 contains a further analysis of the impacts of the C content.

Soil Savings: Cost Efficacy of the Conservation Reserve Enhancement Program versus Conservation Agricultural Practices

As noted above, CREP annual rental payments range from \$110 to \$130 an acre, and each enrolled acre conserves two tons of soil annually from water erosion and six tons from wind erosion (Idaho Soil and Water Conservation Commission, 2015). This results in a cost of between \$55.00 and \$65.00 and \$18.33 and \$21.67 per unit of soil respectively. At \$10/acre, building one ton of soil with NT practices costs \$7.59,

assuming 58% C content. However, the C content significantly changes the analysis with lower C contents increasing cost-efficacy (Figure 33). Even under the most conservative scenarios (58% C content; \$110 CREP rental rate), switching to NT is ~86% more cost effective than CREP in terms of water erosion and 41% more effective for wind erosion. As with AWS increases, however, baseline values will affect costs, and this may warrant a more fine-grained analysis.

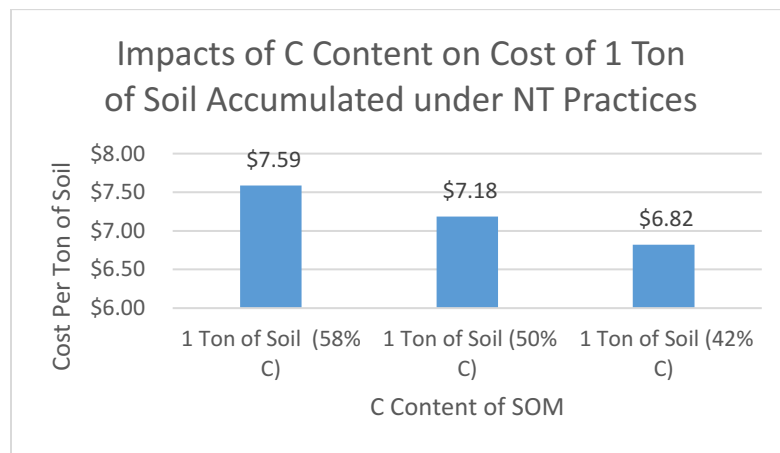


Figure 33. Impact of different SOC: SOM ratios on the cost of building one ton of soil with no till barley.

Chapter IV

Discussion

The three primary objectives of this thesis were to estimate: 1) the ability of conservation agricultural practices to recoup SOC losses from agricultural practices; 2) the hydrological impacts of increasing SOC on AWS; and 3) the on-farm costs of moving to no till (NT) compared with the costs of soil-health building under federal programs – namely the federal Conservation Reserve Enhancement Program (CREP).

The results of this thesis demonstrate several overarching concepts. The first is that adopting conservation agricultural practices could significantly increase the resiliency of agricultural lands in both the short and long term (e.g., over ten years). Second – and relatedly – both the spatial and temporal variation in the results demonstrate that scientists and policymakers must assess the impacts of conservation practices along both of these lines. Third, the financial analysis demonstrates that while small farms may incur costs, large farms stand to benefit significantly, an important point given the trend in farm consolidation. The results also show that adopting agricultural conservation practices can be a cost-effective alternative to the CREP program for conserving soil.

Finally, as research develops on the relationship between net irrigation requirements and AWS, these results can inform several decisions by scientists, policymakers, and land managers, including 1) which lands to prioritize for conservation practices; 2) whether and how to modify water budgets; and 3) which water and soil

conservation practices to incentivize. This chapter first addresses the findings with respect to each of these objectives and then outlines interrelated policy and research objectives that Idaho may wish to consider.

Soil Organic Carbon Loss and Mitigation Opportunities

Despite the best efforts of state and federal agencies, topsoil loss and erosion remain problems in Idaho. The SOC and corresponding AWS losses reported herein help explain why land managers have been slow to adopt conservation practices to halt erosion. Both on a per acre and area-wide basis, SOC and AWS losses are small and hence likely go largely unnoticed by land managers, particularly on annual basis. Moreover, the well-known phenomenon of “shifting baselines” may explain the inertia even after decades of soil loss.

Except Power and Bonneville counties, annual SOC losses in the other ten ESP counties are generally less than 35 kg/acre and very often between two and five kg/acre annually (Figure 23). Accordingly, AWS losses were low, often less than ~0.0003 af/acre annually (Figure 24). Even in Power county with the highest SOC losses, the most conservative scenario shows AWS losses at only 0.0066 AWS af/acre. Similarly, area-wide annual AWS losses range between 400 and 900 af. Thus, even if farmers notice erosion effects, impacts on water-holding capacity are likely to go unnoticed.

Whether Idaho is at a tipping point in terms of soil loss is unclear, but the off-farm impacts are substantial and include increased sedimentation, potential reduction in hydropower capacity, and other pollution of surface water bodies. Further, abundant water supplies and chemical inputs have masked the impacts of soil fertility losses.

Moreover, south-central Idaho is classified in the “highest” risk category for desertification (U.S. Government, n.d.). The situation thus exemplifies the common scenario where private costs are less than, or at least less salient than, societal costs.

Future trends, however, will likely bring the private and public costs more in line. Less abundant groundwater and the diminishing efficacy of fertilizers will render the consequences of topsoil loss more apparent. Drier soils will be more likely to be picked up by heavy winds or washed away in storms, and soils will both absorb less water and hold it for less time. Indeed, the actual process of soil loss itself may become more visible, in the form of larger dust clouds. Aside from increased drought, other climate change impacts will accelerate soil loss. Higher temperatures will speed degradation by increasing soil temperature and accelerating the decline of sub-surface microbial activity (Teague R. A., 2014).

Nonetheless, the results of this thesis show that conservation agricultural practices offer hope. For all agricultural lands in the WRV and many of the counties in the ESP, conservation practices would recoup ten-year SOC losses within one year (Table 10). Even in Bonneville and Power counties (those with the highest SOC loss), recoupment would occur in under five years. An ancillary implication of these findings is that Idaho policymakers may wish to spearhead soil health efforts in Bonneville and Power counties, as these areas would likely see the most dramatic benefits.

Of course, soils system are notoriously heterogenous and influenced by multiple factors, rendering their response to interventions highly uncertain. One critical uncertainty is the timing of SOC accrual from conservation practices. This analysis assumes that SOC accrual begins in Year 1, and the studies generally support that

assumption. Even if, however, SOC accrual begins in Year 3 – or more aggressively, Year 5 – of conservation practice implementation, the topsoil loss remediation times would remain relatively rapid.

Finally, while beyond this study’s scope, preventing erosion and rebuilding topsoil may likely also have significant water quality impacts. Healthy and visually appealing water bodies are important economically (particularly for tourism) and culturally in Idaho. Therefore, surface water quality would likely serve as an additional incentive. Recent years have witnessed a significant reduction in the number of impaired water bodies, with the number of sediment impaired river miles declining from 4,780 to 3,413 and nutrient-impaired river miles from 714 to 244 between 2010 and 2012 (Idaho Department of Environmental Quality, 2014). This success lies in part from either restoring degraded farm and pasture land and changing management practices on existing agricultural lands (Idaho Department of Environmental Quality, 2014).

Available Water Storage Increases

I analyzed the ability of conservation practices to increase AWS over a ten-year period in terms of the percentage and the volumetric increase. These results show not only the capacity for conservation practices to improve soil health in a relatively short timeframe, but also that significant benefits accrue over span of ten years and potentially longer. Understanding baseline conditions, however, is essential – as demonstrated by the ~50% lower AWS values in the WRV.

More than any other metric, the percentage increases in AWS demonstrate the power of conservation practices to improve soil health. For cropland, adopting reduced

till (RT) represents the highest Year 1 and Year 10 percent increases (~92% and 18% in the ESP and ~49% and 24% in the WRV). Using the Ogle pasture benchmarks, even the most conservative improvement benchmark (nominal to medium input) offers significant soil health opportunities (~45% and ~14% in Years 1 and 10). For shrub land in the ESP, the opportunities are lower (~37% and ~13% in Years 1 and 10 for nominal to medium input), but are nonetheless significant. Due to differences in SOC and AWS baseline values, the AWS percentage increases for the WRV are dramatically lower (~50% for each land use type), but for many land types would still offer significant increases (e.g., ~49% Year 1 increase in AWS for RT alfalfa and ~23% Year 1 increase for nominal to medium input improvement of pasture).

In contrast to the percentage increases, volumetric increases seem quite low. For both study areas, no scenario creates a Year 1 increase of more than 0.03 af/acre, except for the Ogle pasture and shrub land benchmarks in the ESP. The dramatic increases after 10 years, however, demonstrates why impacts must be assessed in both the short and long run (Table 10-15). For instance, in the ESP, the AWS increase exceeds 0.5 af for RT alfalfa and NT Barley, and 0.9 af for pasture and shrub land. Again, the results for the WRV are much lower (e.g., 0.331 af for RT alfalfa and less than 0.9 af for pasture and shrub land).

Finally, policymakers may wish to target groundwater irrigated areas for soil health practices to minimize both the use of groundwater and to maintain incidental recharge from surface water irrigation. Except organic alfalfa, opportunities to increase AWS are the largely the same on groundwater-irrigated as others, with mean values within 4% or less each other.

Time Needed to Reverse Drought Vulnerability

Data limitations confined this analysis to limited a small portion of shrub and pasture land in the WRV. Nonetheless, the results speak again to the rapidity with which conservation practices can increase soil resiliency. Under all scenarios for shrub land, conservation practices reversed drought vulnerability in five years or less (Table 19). Using the Ogle pasture benchmarks, the timeframe is six to seven years except for the most conservative improvement benchmark (nominal to medium input), for which the time increases to nine years. The no till pasture benchmark, however, would require more than 25 years.

Finally, even though this analysis could not be extended to any lands within the ESP and or to cropland in the WRV, results from other parts of this thesis support two inferences. First, reversing drought vulnerability could occur in ten years or less for lands in which conservation practices results in an increase of 0.5 af by that time. This occurs for several types of lands, but namely RT alfalfa, shrub land, and pasture in the ESP. Second, since AWS increases on pasture and shrub land in the ESP are 50% higher than in the WRV, one can infer that reverse drought vulnerability would likewise take $\frac{1}{2}$ the time. To better estimate these impacts, however, more research is needed to characterize 1) the AWS in the rootzone and 2) SOC increases below 15-30 cm.

Impacts on Recharge

Maintaining aquifer recharge from surface-water irrigation and conserving water are competing priorities in the ESP. As a member of the Idaho Water Resources Board

recently said (Idaho Department of Water Resources, 2016), “There’s a lot of new technology that could be adopted to be more efficient in our use of water. But you have to be careful about that. One man’s waste is another man’s gain.”

Given this potential conflict, I calculated how much increasing AWS would reduce incidental surface-water recharge and non-irrigated recharge. The results vary significantly by land use and recharge type. For cropland, in Year 10, NT Barley would reduce recharge by 15%, organic alfalfa by 3%, and RT alfalfa by 28%. For pasture, depending on the SOC benchmark, the impacts could be much greater, between 55% and 115% in Year 10. The no till pasture benchmark, however, presents much lower impacts, barely exceeding 8%. For shrub land, the results are much higher because of the comparatively low volumes of non-irrigated recharge. For each of the Ogle benchmarks, soil health improvements would completely negate recharge (>100%) in Year 1. For the Weber benchmark, increased AWS would reduce recharge by 36% in Year 2 and 38.5% in Year 3.

These results demonstrate that the effect of conservation practices should be considered in developing water budgets in the ESP and elsewhere. Relatedly, because interest in drip irrigation is growing (e.g., (Vegetable Growers News, 2012) (Toro Crop Solutions, 2013)), further research should examine scenarios in which both conservation practices and drip irrigation become more common as a combination of these measures would further amplify recharge reduction.

Cost Implications of Moving to Conservation Practices

Though the financial analysis is both limited and conservative, the results provide further direction on how to encourage conservation practices effectively. The first portion examined the general financial implications of moving to NT Barley. This analysis showed that most farms, because of their small size (<640 acres), would incur a cost of \$10/acre. The countervailing consideration, however, is that when compared to the value of barley per harvested acre, the investment in switching to NT is insignificant (between 2 and 3.8% depending upon the year). Further, if the per acre value of barley continue to rise, this percentage will go down.

On the other hand, large farms (>1,260 acres) – which constitute the vast majority of land holdings – would save \$3/acre. Ironically, it is the larger farms that exhibit the strongest reticence to adopting conservation practices (Miller J., personal communication, October 12, 2016), though they stand to gain the most. With farms consolidating, many farmers will likely be investing in new farm equipment. Thus, increasing education and research efforts and research now may allow Idaho to effectuate management changes before significant investments are made.

To account for uncertainty about the year in which SOC accrual begins, I evaluated the effect of three different start times on increases over ten years. The effect was significant, sometimes by as much as 250%. This finding suggests that while both large and small farmers could stand to gain significantly – both financially and otherwise – from moving to no till, more research should be conducted on SOC accrual start times.

Additionally, the perceived risks and benefits – as reflected in discount rates – significantly affect the financial analysis (Figure 27 and Figure 28). Over ten years, this

could affect perceived costs for small farms by as much as ~\$38 an acre or 5% of farm income compared to discount rates of 0% and 5%. The difference between a 5% and 10% discount rate accounts for 2% of farm income or ~\$16 an acre. Discount rates also affect perceived cost-savings for large farms, though not as significantly.

I also analyzed the costs of AWS increases and then compared them to the cost of renting additional irrigation water. One striking aspect of these results was when looked at in isolation, impacts on AWS volumes may have been small (far less than 0.001), but these translated into significant impacts on cost. These results also show again that the time in which SOC accrual begins significantly affects the return per \$100/acre for small farms (Figure 29 and Figure 30). Comparing the results for the WRV and the ESP also demonstrates that baseline SOC and AWS values significantly affect the cost/benefit analysis and, importantly, counsel against assigning a single monetary value.

Finally, I compared the costs of AWS increases with the cost of renting additional irrigation water. These results showed that is cheaper, constituting between 89.6% to 24.4% of the cost of irrigation (excluding delivery costs). While additional research on the link between increasing AWS and reductions in irrigation requirements is needed to put these numbers in practice, two factors are notable. Compared to irrigation – a fixed cost with only a one-time benefit – the benefits of building soil health are cumulative and thus a long-term investment. Given these cumulative benefits, irrigation requirements would also likely decline each year. The second factor is that if water shortages increase, water rental costs may rise, thus increasing the appeal of building AWS.

Finally, this study shows that moving to NT Barley (and potentially other higher C-sequestering practices) is a cost-effective alternative to CREP: 86% more effective for

water erosion and 41% more effective for wind erosion. Reallocating funds to incentivize conservation practices may be more efficient given that that CREP enrollment rate is currently 83% below its target.

Together, these findings suggest that policymakers may be able to significantly increase adoption of conservation agricultural practices by educating land managers on resulting benefits. In particular, these efforts should highlight the financial gains for large farms, and stress to small farms that conservation agricultural practices constitute a small cost compared to current profits and could have significant long-term benefits, such as yield increases, soil conservation, and water savings. Avenues for education might include demonstration farms and media highlighting the success of local farms, as evidence of similarly situated individuals is highly persuasive (Thaler & Sunstein, 2009).

Effect of Varying Soil Organic Carbon: Soil Organic Matter Ratios on Available Water Storage Increases

This thesis examined the effect of varying SOC: SOM ratios in three places: 1) the effect on SOC losses in the ESP; 2) the average return on in AWS (af/acre) of \$100 (ten years); and 3) the effect on the cost-efficacy of CREP for soil-building. When looked at in isolation (see, e.g., Figure 24), the impacts of different C contents appear small in terms of volume, with the 16% differential in C content creating less than 0.001 or 0.0001 af/acre depending on the baseline values. Over ten years, however, the 16% difference has significant impacts on costs, with a 66% difference in AWS for the WRV and 165% difference in the ESP (Figure 31 and Figure 32). Therefore, understanding the true ramifications of the difference in C content requires a longer-term temporal horizon

and an economic context. Similarly, the impacts of different C ratios are instructive when examining the impacts on soil building under different programs, with a 42% C content increasing the cost efficacy of NT by 11% compared to CREP. Together, these findings indicate that a coordinated and consistent effort to reconcile assumptions about the SOC:SOM ratio is needed between scientists and policymakers from the inception of research efforts to a policymaking.

Policy Recommendations and Research Needs

While powerful, the results of this thesis are limited by a lack of site-specific data and research. Therefore, I suggest several research and policy priorities. Fortunately, many of the research problems overlap and therefore could be consolidated to increase cost efficiency. Many also correspond to identified needs in the State Water Plan (Idaho Water Resources Board, 2012). Further, while these recommendations are primarily aimed at policymakers, several stakeholders would likely be willing to assist either financially or in terms of expertise. Land managers are the first to come to mind and often already enjoy a close working relationship with the federal and state officials, but others include local food alliances, land trusts, and watershed and river health organizations.

Soil Organic Carbon and Available Water Storage Accrual Rates

This study's results of course hinge on the accuracy of the C sequestration studies used and the assumption that every 1% increase in SOM creates a corresponding 3.7% increase in AWS. Changes in these parameters would thus have cascading impacts on

the results. Regarding SOC accrual rates, I used studies that matched the ESP's and WRV's climatological characteristics as much possible. This, however, is no substitute for site-specific research – as the varying impacts both within and between those areas demonstrates. Regarding the Hudson (1994) metric, this study is over 20 years old and limited in terms of soil type, and therefore updating this metric is critical.

In conducting site-specific research, several factors should be considered. First and foremost is establishing the time when SOC and AWS accrual and AWS begin, with sampling conducted annually or more frequently. The studies used in thesis and elsewhere strongly support a finding that accrual begins immediately, but the financial analysis demonstrates that errors in this assumption can have significant impacts.

Second, SOC and AWS measurements should be extended below 30 cm, and if possible through the vegetation's entire rootzone. Extending this analysis would advance knowledge of both the time needed to reverse drought vulnerability and the impacts of increasing AWS on net irrigation requirements.

Third, research on SOC: SOM ratio is also advisable and should include variables such as soil type, crop type, and different inputs (e.g., manure-based compost vs. stubble). While not examined in-depth, the results of this thesis demonstrate that differing SOC: SOM ratios can materially affect the financial analysis for land managers and policymakers, both in terms of AWS gains and soil-building capacity. Should climate change mitigation become a state, regional, or national priority, research on the C content of SOM and on the depth of SOC accrual would likely result in more accurate accounting frameworks. Finally, while these results do not suggest a material difference (e.g. >5%) between the impacts of conservation agricultural practices in surface- versus

ground-water irrigated areas, should policymakers face budgetary or other constraints, they may wish to begin studies in the latter areas.

Impacts on Irrigation Requirements

A major gap is the link between increasing AWS and reducing net irrigation requirements. This is a function of the general research environment and policymakers' failure to prioritize increasing soil health as a water conservation measure. Given the importance of agriculture to the state both economically and culturally, Idaho should be examining all possible avenues for water conservation. In particular, it would be useful for land managers and scientists alike to have access to average evapotranspiration and net irrigation requirements by crop type. While the University of Idaho at Kimberly maintains meticulous annual and monthly records (University of Idaho, 2012), their very specificity undermines their ability to make more generalized projections.

Relatedly, Idaho's reliance on fallowing land to conserve water is likely misguided, as several factors indicate that farmers will likely resist fallowing land due to opportunity costs. Farmer incomes and the value of crops are generally rising (USDA NASS, 2012; USDA NASS, 2015a). Thus, CREP rental rates at \$110 to \$130 may not be sufficiently high, as suggested by the fact that the CREP enrollment rate is currently 83% below its target (Idaho Soil and Water Conservation Commission, 2015). Further, at \$40 or less an acre, revenues from dry-leasing and sale of water to rental pools will likely fall short. The loss of agricultural jobs would also likely have a ripple effect through the economy, particularly in rural communities. Of course, a decrease in food prices or severe water shortages may reverse this trend. Additionally, there is the related issue that

simply following land accelerates degradation and erosion (USDA NRCS, 2013) and thus reduces future productivity.

If research bears out that increasing AWS conserves a significant amount of water, several policy implications are raised. First would be for Idaho to prioritize soil health measures in its policy documents, such as the Idaho State Drought Plan, whose content is strictly informational (IDWR, 2001) and the Idaho State Water Plan (Idaho Water Resources Board (IWRB), 2012). Second, policymakers should consider additional mechanisms to incentivize the voluntary adoption of soil health measures. These may include reducing prices from water rental pools and/or the cost of water delivery, as well as guaranteeing the delivery of water or other forms of insurance if soil health measures do not perform as expected. Third, Idaho should consider proactively promoting the products of land managers who voluntarily adopt conservation practices through the Idaho Preferred Program (Idaho Department of Agriculture, 2016). This is a state-sponsored program that already promotes consumption of local products and thus could likely incorporate environmentally sustainable practices easily. Finally, state officials might facilitate the development of an online information exchange, such as an email listserv or a blog, which would likely entail minimal administrative burdens and costs.

Impacts on Recharge and Downstream Users

Science and policy documents repeatedly suggest that that improving irrigation efficiency and/or conserving water competes with maintaining aquifer recharge rates and preserving the rights of downstream users (e.g., IWRB, 2009). Yet disruption may be

inevitable if water shortages continue to occur even in normal precipitation years, leading more land managers to adopt water conservation practices. Therefore, policymakers must prioritize both further research on how water conservation affects recharge and downstream users and how to mitigate these risks. Fortunately, this research overlaps with the proposed research on the impacts of AWS on net irrigation requirements. The WRV might be an opportune place to begin research, as IDWR is in the process of groundwater modeling and could incorporate soil health parameters at the modelling's early stages (IDWR, 2014).

Financial Implications of Adopting Conservation Practices

If Idaho wishes to encourage soil health practices, then it must provide a convincing reason for farmers to adopt them, and this likely requires evidence of financial gain or at least reduced risk. Such evidence would include reduced machinery and operating costs, yield increases, and/or reduced irrigation costs. It is particularly important to overcome the recalcitrance of large farms (J. Miller, personal communication, October 12, 2016). The trend toward large farm sizes, however, presents Idaho with an important opportunity: highlight the benefits of conservation practices before these farms make significant financial investments in machinery.

While ample evidence from across the county (and world) indicates that conservation practices result in significant financial benefits (McBride; 2003; Boyle, 2006), nothing is persuasive like evidence originating from the same or nearby communities (Thaler & Sunstein, 2009). Neither the state of Idaho nor the NRCS office, however, tracks rates of conservation practice adoption rates, the reasons for adoption, or

the financial implications for those farms employing them. Regarding rotational grazing and cover cropping, some research is underway, but more is needed (Miller J. T., n.d.).

Several relatively inexpensive mechanisms exist to gather the required data. For instance, officials could condition awards of cost-sharing grants on the reporting of easy-to-calculate metrics such as yield increases and changes to machinery and operating costs. Regarding livestock, monitoring should include changes in animal weight gain, available price premiums, and the additional costs associated with rotational grazing, and (for pasture) seeding improvements. Importantly, the additional reporting burden on land managers is likely minimal, as they are likely tracking these metrics already. Officials might require reporting of these metrics annually for five years or longer, given that a transition period is often required for soil health benefits, expertise, and operational efficiencies to accrue.

Crop Switches as a Water Conservation Effort

The state has set a modest goal of conserving 40,000 af of water over ten years through crop switches (IWRB, 2009). If crop switches to less thirsty plants were a readily-available and profitable option, voluntary switches would likely be more commonplace. Aside from shifting alfalfa acreage to barley – which requires $\frac{1}{2}$ or less water but also fails to fix nitrogen– two crops stand out as potential candidates, hemp and quinoa, and additional research funds from the state might hasten their cultivation.

Hemp is a deep-rooted, drought-resistant crop with high-profit potential given its wide-ranging uses, including as a livestock feed supplement (Fine, 2014). Idaho, however, would have to enact legislation permitting agricultural hemp, as 30 other states

have done (National Conference of State Legislatures, 2016). Quinoa, another hearty, profitable crop, also presents a good alternative. Successful cultivation has been slow in the United States, particularly because of the complex harvesting, weeding, and processing requirements. Nonetheless, a small number of Idahoan farmers are having some success (O'Connell, 2016).

Strategic Planning Considerations

Soil and water are the foundation of ecosystem integrity in Idaho and thus are also the foundation of public health and welfare. With a well-established history of rivers and wells running dry (Stuebner, 1995; Barnhill, 2013) and water shortages occurring even in normal precipitation years, some debate whether current management and legal regimes are sustainable. What is clear, however, is that climate change and a growing population's increased water and energy needs could cause feedback loops that threaten the system's collapse. Therefore, either maintaining the status quo or new policies could commit Idaho to a path of irreversible natural resource damage. Policymakers should seize this opportunity to engage in considered regional planning using a strategic impact assessment (SIA) framework. SIA is advisable on several fronts, but I highlight two here: 1) creating a framework in which sustaining a vibrant livestock industry and enhancing shrub land and agricultural resiliency are mutually supportive and 2) balancing competing demands to meet food, water, and energy needs by reassessing overarching legal paradigms.

While Idaho lacks an overarching impact assessment law, it can still draw upon the long-standing experience developed under National Environmental Policy Act (42

USC §§4321-4332) and the recently-enacted European Commission Directive 2001/42/EC on Strategic Environmental Assessment for guidance. Consistent with these frameworks, the SIA should include a transparent and inclusive stakeholder engagement process and consider public health, environmental, social, and economic impacts both in the short- and long-term.

Strategic Planning for Rotational Grazing in the ESP

Maintaining a healthy livestock industry in Idaho is important for several reasons. The first is economic: Idaho ranks thirteenth in the Nation for cattle (including dairy cows) and seventh for sheep (USDA NASS, 2015a). The second is socio-cultural: herders are often seen and pride themselves as being stewards of the land, and open range grazing is a critical part of both the Western ethos. Now threatened by drought, soil degradation, and public opposition, grazing also contains a political dimension: conflicting perceptions of the rights of the individual and state vis-a-vis the federal government. These tensions were not only brought to the fore by the Malheur Wildlife Refuge tragedy, but are also apparent in the movement in Idaho to assume state ownership of federal lands (Barker, 2016).

The status quo of grazing may, however, be unsustainable. The livestock industry utilizes significant amounts of land: excluding concentrated animal feed operations, grazing and other supporting land occupied at least 15% total area in the ESP (excluding developed and shrub land and open water) and at least 46% of agricultural lands (USDA NASS, 2015b (2015 statistics)) – though information is not available to determine how much feed remains in state. This current land allocation may involve high opportunity

costs in the form of foregone switches to higher income crops or other land uses. Further, decades of continuous grazing have severely compromised ecosystems and garnered significant public backlash.

Strategic encouragement of rotational grazing and integrated crop livestock systems may present a way to enhance ecosystem health and preserve socio-cultural institutions. Two obvious avenues exist: 1) increase rotational grazing strategically on shrub lands in the ESP and other areas and 2) encourage integrated crop-livestock systems.

Region-wide rotational grazing plan for shrub lands. The sheer expanse of shrub land in the ESP (~4,481 square miles) merits a multifactorial approach to targeting areas for rotational grazing. Of course, a key consideration would be targeting degraded lands, but unfortunately reliable information on this issue does not exist. Other key factors include: 1) evapotranspiration rates, 2) precipitation rates, 3) recharge rates and 4) drought vulnerability.

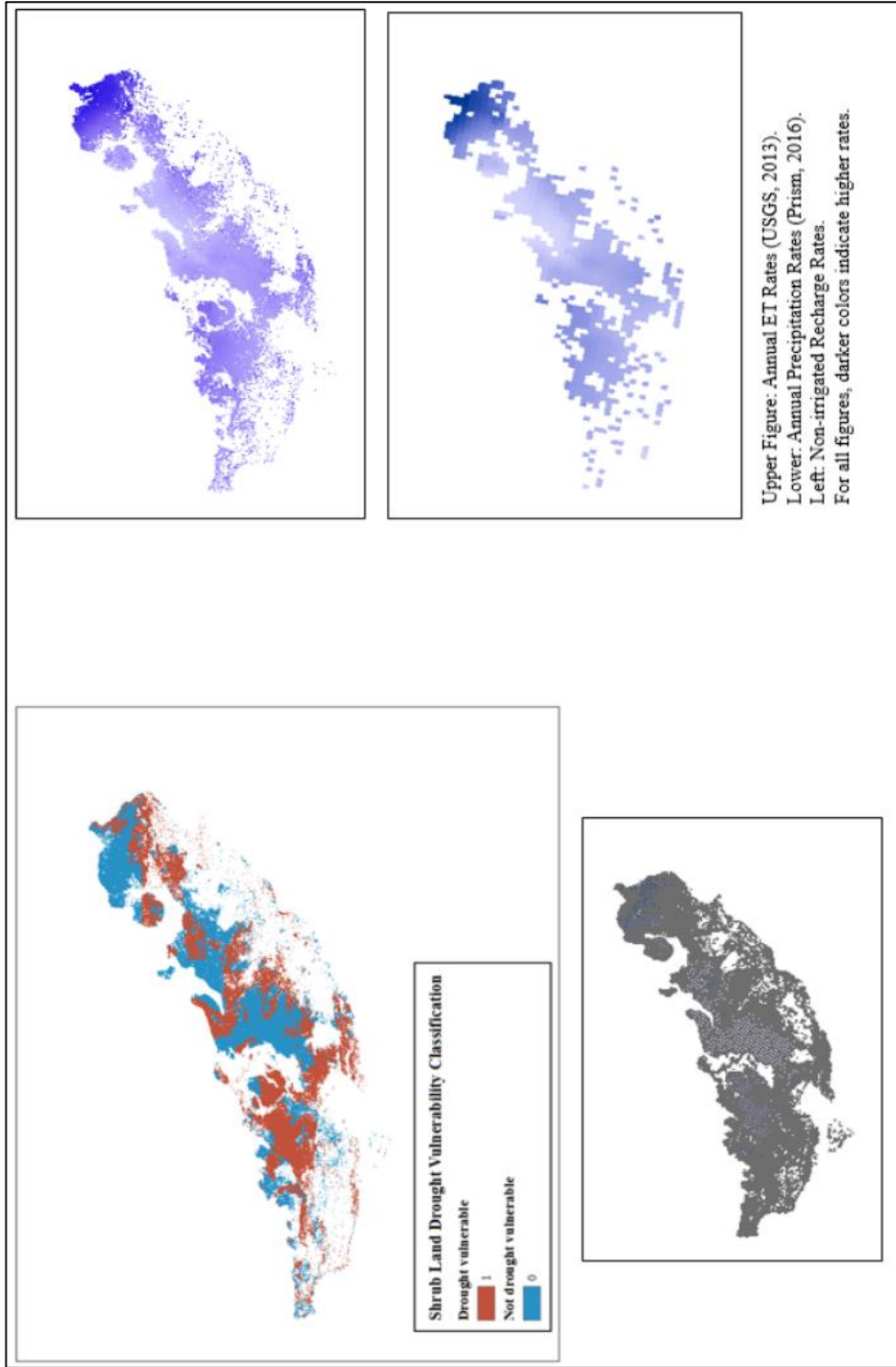


Figure 34. Physical and climatological attributes of shrub land in the ESP.

Clockwise: Drought vulnerability characterization, annual evapotranspiration rates, annual precipitation rates, non-irrigated recharge rates. Darker colors indicate higher values.

Unsurprisingly, these factors track each other, with higher precipitation, evapotranspiration, and recharge rates located in the northwest corner and generally declining southward. More drought vulnerable land is concentrated in the southwest corner. Therefore, as a starting point, policymakers may wish to target the southwest portion of the aquifer. Beginning there also has the advantage of limiting disruptions to groundwater movement, which flows from north to south. Figure 35 shows the projected impacts on recharge after ten years of rotational grazing from the most conservative Ogle shrub land benchmark.

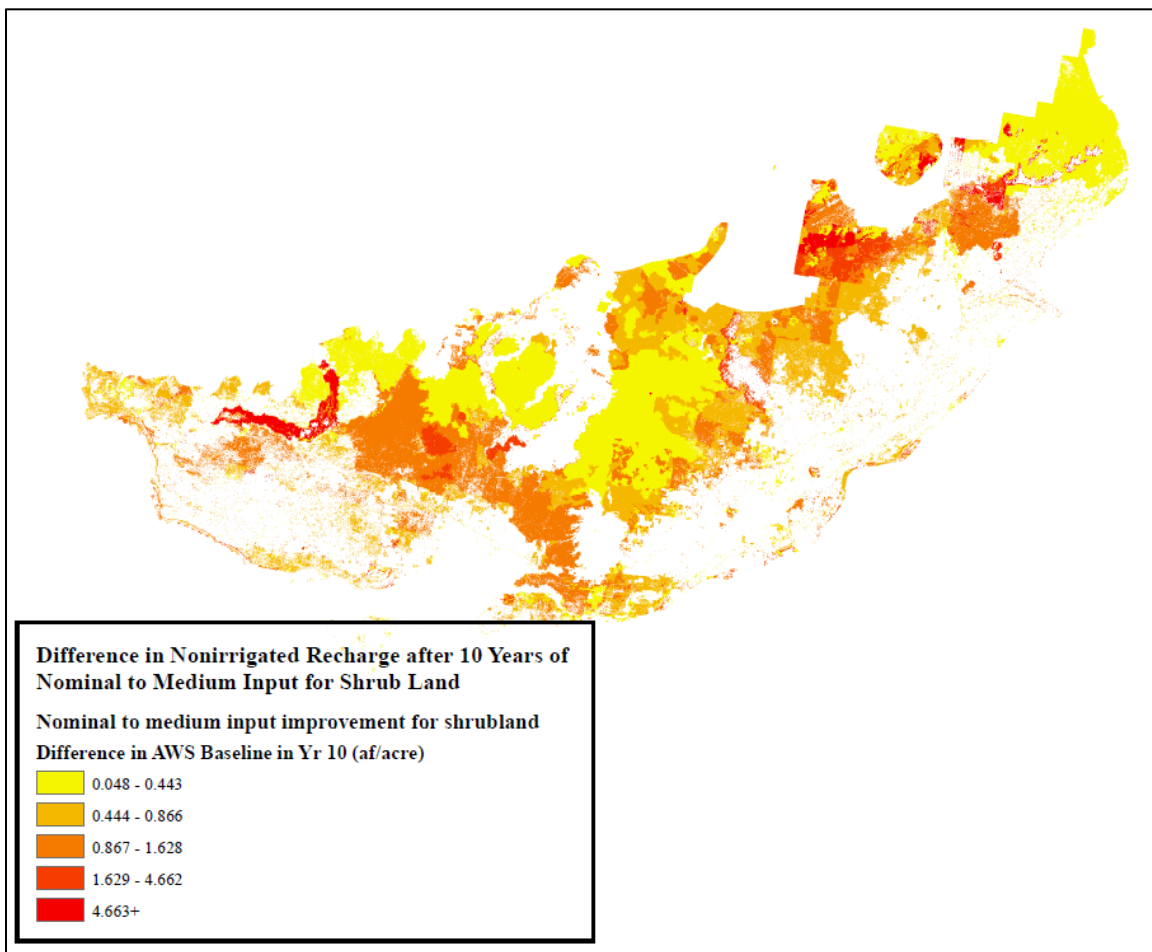


Figure 35. Volumetric increases in AWS after ten years of rotational grazing (nominal to medium input) in the ESP (af/acre).

Implementing rotational grazing in the southwest portion of the aquifer will also allow scientists to study the impacts of actual disruptions to recharge, again while minimizing impacts throughout the hydrological system.

Encouraging rotational grazing on shrub land may help with other environmental problems. First, at least some evidence suggests that rotational grazing not only has minimal impact on the habitat of sage grouse (a keystone species protected by federal law), but improves habitat quality (USDA NRCS, Montana, n.d.). Additionally, grazing is often touted as mechanism to control the ubiquitous cheat grass problem (University of Idaho, 2006), though this requires additional research (Reisner, Brace, Pyke, & Doescher, 2013). Finally, increasing soil health through rotational grazing may also reduce wildfire intensity and resulting sedimentation by promoting healthier vegetation and soils.

Encourage Integrated Crop-Livestock Systems. Encouraging farmers to adopt integrated crop-livestock systems, particularly crop-pasture rotations (CPR) and cover-crop grazing, should also be considered to more efficiently utilize land, soil, and water resources. This would have several benefits. First, the overwhelming weight of the evidence suggests that such systems significantly increase soil health (Franzluebbbers & Studemann, 2008; Kirkegaard, et al., 2014; Garcia-Prechac, Ernst, Siri-Prieto, & Terra, 2004). While CPR is only now gaining momentum in the U.S. (Franzluebbbers & Studemann, 2008), a rich literature documenting its benefits has emerged from Australia and Uruguay (e.g., Garcia-Prechac, Ernst, Siri-Prieto, & Terra, 2004; Kirkegaard, et al., 2014), where rampant soil degradation catalyzed voluntary, widespread adoption of such systems.

Second, integrated crop-livestock systems maximize the efficiency of crop and food production per unit of land. Therefore, farmers may have more flexibility to grow

higher profit and/or less water intensive crops. Relatedly, the economic output per unit of land would likely increase (Kirkegaard, et al., 2014). Indeed, a small-scale study by Jason Miller – both a cattle farmer and an employee of the Idaho State Soil and Water Conservation Commission – demonstrated that grazing cattle on cover crops during the winter was both economically viable in terms of feed costs and resulted in good weight gain (Miller J. T., n.d.). Finally, such systems could help Idaho become a leader in supplying grass-finished beef. This is an important economic consideration because while the general decline in beef consumption is projected to continue (National Chicken Council, 2016), demand for grass-finished beef has risen significantly – by some estimates 25-30% annually over the last decade (Thurlow, 2016).

Strategic Planning to Meet Food, Energy, and Water Needs

Water is both the critical and the weakest link in the food, water, and energy nexus in Idaho, with river management standing at the center. Hydropower provides the bulk of Idaho's energy– though water shortages have reduced this by 20% in recent years (U.S. Energy Information and Administration, n.d.). Irrigation itself is energy-intensive, and dams of course provide the necessary storage for irrigation water. Irrigation and energy stand at odds, however, with the former requiring diversion and the latter maintaining instream flow. Balancing these tensions is not new in Idaho– in fact, conflict necessitated two major legal revisions in the late 1970s and 1980s: The first changed legal title to and requirements for minimum flow for hydropower ((Idaho Code § 42-203)(B)), and the second confirmed the state's authority to issue minimum stream flow requirements for ecosystem integrity (Idaho Code §§ 42-1501-1507). These

developments illustrate a maxim of sustainability: policies can and must be shifted based on changing societal and environmental needs.

The process by which Idaho recently expanded hydraulic fracturing rights on private property (Idaho Senate Bill 1339 (2016)) is, however, alarming. The bill was introduced in and passed by the legislature in less than one month (Idaho Legislature, n.d.), and debate during the closed session lasted only two hours (Russel, 2016). Ranging from contaminated water supplies, to crop uptake, to land degradation, and boom-and-bust effects, the systemic effects of fracking are unknown, likely long-term, and potentially irreversible. Indeed, U.S. EPA recently reversed its long-standing neutrality and now acknowledges the potential for drinking water contamination (Davenport, 2016).

With demands on natural resources and societal needs changing, Idaho might consider two interrelated legal changes. The first is to shift from current water laws from a temporal, rights-centric paradigm to one that more carefully balances societal and environmental well-being with existing property rights. The second is to conduct an SIA on how to meet future energy demands. To ensure that trade-offs and synergies between the food, water, and energy sectors are identified, Idaho might consider establishing a new governmental or quasi-governmental entity dedicated to coordinating and/or leading these policy efforts.

Shifting the paradigm of water policy. Instead of a tragedy of the commons (Hardin, 1968), Idaho could face a tragedy of property rights. While the state retains the right to regulate water uses (Idaho Constitution Article XV § 1), the legal structure renders two factors nearly unassailable: 1) “beneficial” (i.e., productive) uses of water and 2) the temporal seniority of property rights.

The laws governing minimum stream flows illustrate the situation (Idaho Code §§ 42-1501-1507). First, the legislature had to enact a law recognizing that habitat, aesthetic, and recreational values constitute legitimate beneficial uses (Idaho Code § 42-1501). Second, even now when a minimum stream flow is “necessary” for environmental or other values, it cannot be granted if it interferes with the senior water rights, regardless of their purpose (Idaho Code §§ 42-1503 para. 2 (a) and (b)). Third, the allocation is only made for the “minimum amount” – not “the ideal or more desirable” amount (Idaho Code § 42-1503 para. 2 (d)). Importantly, Idaho has only enacted minimum stream flows for 2% of streams (IWRB, n.d.). Minimum streamflow for portions of the Snake River were enacted only in 2005 – and only after extensive litigation (Idaho Code § 42-1507). Additionally, a minimum stream flow for the Wood River Basin has been repealed (Idaho Code § 42-1508). Others have examined the problems with this “first-in-time, first-in-right” legal structure in depth (e.g., (Richter, 2014), but they are obvious: no provisions are made if water supplies are unable to meet municipal and environmental needs, with priority remaining with senior right holders even if municipalities face shortages.

Fortunately, two other legal regimes exist that are not wholly inconsistent with Idaho’s governance structure but that prioritize and protect environmental and human needs. The first entails creating on a priority reserve an annual basis to meet basic environmental and human needs, with the remainder then allocated through an entitlement system (Richter, 2014). As Richter (2014) explains, that while a legal break through, South Africa’s experience highlights the drawbacks of this structure: namely the annual reserve is a moving target that varies with ecological and human needs.

The second option is a cap-and-flex system (akin to that in the Australia Murray Darling Basin) and is likely more politically feasible. A cap-and-flex system would set a floor cap on water use during dry years, but permit additional diversions in wetter years (Richter, 2014). The cap on allocations is the mechanism that protects environmental parameters, as opposed to a moving ecological target. Entitlements are divided into high- and low- security categories with high-security rights being met first.

It is this last part that makes this structure particularly amendable to Idaho. In fact – except for the consumption cap (which Idaho lacks) – Idaho’s legal framework is arguably the functional equivalent, with senior and junior water rights being high- and low-security respectively. Further, even with all its caveats, the Coase theorem (Coase, 1960) would dictate that the exact allocation of the remaining entitlements would not be determinative. This is particularly true in Idaho, which has several provisions ensuring that water rights are transferable (e.g., Idaho Code §§ 42-1761-42-1766). Finally, legal authority to enact moratoriums could provide precedent to establish an overall consumptive cap (Idaho Code §42-1805; Idaho Code of Administrative Procedure (Water Appropriation Rules) §37.03.08). Given the fervor that understandably surrounds water rights in Idaho, it is imperative that policymakers consult stakeholders and maintain a transparent, impartial assessment process to avoid repeating farmer backlash as experienced at the release of the Australia Murray Darling Basin Water Plan (Walton, 2010).

Strategic energy assessment. Part and parcel of the SIA must be addressing a sustainable energy supply for the state. Amendments to water policy would affect the amount of water available for both hydropower and agriculture. While the degree to which fracking

will become prominent is uncertain, several energy alternatives exist that would balance energy needs with fewer impacts on water resources. Most prominent is wind power, which is already abundant in Idaho and has the capacity to grow (U.S. Energy Information and Administration, n.d.). In addition to all the advantages common to renewable energy resources, wind power is compatible with current agricultural uses and if – properly incentivized – could offset financial losses experienced by farmers from water reductions, thereby stabilizing income. For these reasons, land managers have strongly supported wind power (Messick, 2012). Other alternatives to consider would be geothermal and solar power.

Conclusion

This thesis examined the potential for conservation agricultural practices to increase the resiliency of agricultural systems in south-central Idaho by reversing historic soil organic carbon (SOC) losses, increasing available water storage (AWS), and reversing drought vulnerability. Given the tension between water conservation (including through increases irrigation efficiency) and preserving aquifer recharge rates and the rights of downstream users, I also analyzed the impact that increasing AWS would have on both incidental and non-irrigated recharge. Finally, I examined the on-farm financial impacts of adopting conservation agricultural practices and compared their cost-efficacy to the federal Conservation Reserve Enhancement Program (CREP) in regards to soil-building.

Using gSSURGO, the national soils data base developed by USDA NRCS, I mapped and calculated potential SOC increases and their impacts on four major land use

categories, alfalfa, barley, pasture, and shrub land. Carbon sequestration rates were for the most part taken from regions with similar climatic characteristics as the study area.

The major conclusions from this work are:

1. Conservation agricultural practices can reduce historic SOC losses from tillage in relatively short periods of time (often one year or less);
2. These practices can also significantly increase soil's AWS and thus may contribute to both water conservation and resiliency during drought and/or water shortages;
3. For shrub and pasture land, rotational grazing and other soil health practices can reverse drought vulnerability in relatively short periods of time (five to seven years), and the results of this thesis imply even faster rates for cropland;
4. While significant gains are likely in terms of resiliency, this thesis also demonstrated that conservation agricultural practices can have significant impacts on recharge rates and therefore should be considered both in hydrological modeling and policy development;
5. While small farms in Idaho may incur a cost in moving to no till, large farms stand to gain financially, an important consideration given that farm sizes are increasing; and
6. As compared to the CREP, no till is likely more cost effective for soil building.

Nonetheless, this study also highlights significant research and information gaps, both at the national level and in Idaho. Foremost among them is the water consumption impacts of increasing AWS, a particularly important consideration given the increasing

pressures on water resources in Idaho from energy production, agriculture, population growth, and the likelihood of future water shortages.

Appendix 1

Greenhouse Gas Equivalencies for Historic SOC Losses

Table 22. Maximum CO_{2e} from one year of SOC loss from tillage in the ESP and WRV, assuming full oxidation of SOC and no burial (Carbon Dioxide Information Analysis Center, n.d.).

Area/Year	Loss – Entire Area (metric tons)	Wind Turbines	Miles Driven	Coal-fired Power Plants	C Sequestered (Forest Acres) ^a	C Sequestered (Acres of Avoided Forest Conversion) ^{a,b}
ESPAM 2008 (including fallow land)	132,986	33.6	318,720,840	0.039	125,885	1,060
ESPAM 2008 (excluding fallow land)	141,615	35.8	339,401,426	0.041	134,053	1,129
ESPAM (10-year average) (including fallow land)	253,050	63.9	606,474,872	0.74	239,539	2,017
ESPAM (10-year average) (excluding fallow land)	1,490,363	376	3,571,886,235	0.434	1,410,784	11,879
WRV 2008 (including fallow land)	~285	0.072	684,175	0.0001	270	2.3
WRV 2008 (excluding fallow land)**	~285	0.072	684,175	0.0001	270	2.3
WRV (10-year average) (including fallow land)	854	0.216	2,046,551	0.0002	808	6.8
WRV (10-year average) (excluding fallow land)	852	0.215	2,0442,631	0.0002	807	6.8

^a Values are for one year of sequestration.

^b Amount of C that would have been sequestered by forest acres saved from conversion to agricultural land.

** Values are the same as only 0.85% of agricultural lands were fallow in the WRV in 2008.

Appendix 2

Greenhouse Gas Equivalencies for SOC Increases from Conservation Practices

Table 23. CO₂ sequestration from one year of conservation agricultural practices in the ESP.

Crop Type	Sequestration – Entire area (Metric Tons in CO ₂ e)	Wind Turbines	Miles Driven	Coal-fired Power Plants	C Sequestered (Forest Acres) ^a	C sequestered (Acres of Avoided Forest Conversion) ^{a,b}
Organic Alfalfa	306,207	77.3	733,873,260	0.089	289,857	2,441
RT Alfalfa	1,528,228	386	3,662,636,269	0.445	1,446,627	12,181
NT Barley	547,641	138	1,312,507,029	0.159	518,399	4,365
Conant Shrub Land Nominal to Medium Input	10,773,454	2,721	25,820,260,065	3.1	10,198,198	85,872
Conant Shrub Land Nominal to High Input	21,546,909	5,441	51,640,520,148	6.3	20,396,396	171,744
Conant Shrub Land Degraded to Medium Input	13,466,818	3,401	32,275,325,092	3.9	12,747,747	107,340
Conant Shrub Land Degraded to High Input	24,240,273	6,122	58,095,585,166	7.1	22,945,945	193,212
Conant Pasture Nominal to Medium Input	2,935,841	741	7,036,200,191	0.855	2,779,080	23,401
Conant Pasture Nominal to High Input	4,110,178	1,038	9,850,680,269	1.2	3,890,712	32,761
Conant Pasture Degraded to Medium Input	3,523,009	890	8,443,440,230	1	3,334,896	28,081
Conant Pasture	4,697,346	1,186	11,257,920,307	1.4	4,446,528	37,441

Degraded to High Input						
No Till Pasture	610,681	154	1,463,591,143	0.178	578,073	4,868

^a Values are for one year of sequestration.

^b This is the amount of C that would have been sequestered by forest acres saved from conversion to agricultural land.

Table 24. CO₂ sequestration from one year of conservation agricultural practices in the WRV.

Crop Type	Sequestration – Entire area (Metric Tons CO ₂ e)	Wind Turbines	Miles Driven	Coal-fired Power Plants	C sequestered (Forest Acres) ^a	C sequestered (Acres of Avoided Forest Conversion) ^{a,b}
Organic Alfalfa	11,377	2.9	27,267,091	0.003	10,770	90.7
RT Alfalfa	56,781	14.3	136,084,502	0.017	53,749	453
NT Barley	24,270	6.1	58,166,954	0.007	22,974	193
Conant Shrub Land Nominal to Medium Input	60,004	15.2	143,808,481	0.017	56,800	478
Conant Shrub Land Nominal to High Input	120,008	30.3	287,616,961	0.035	113,600	957
Conant Shrub Land Degraded to Medium Input	75,005	18.9	80,037,221	0.022	71,000	598
Conant Shrub Land Degraded to High Input	135,009	34.1	323,569,081	0.039	127,800	1,076
Conant Pasture Nominal to Medium Input	33,489	8.5	80,260,583	0.01	31,700	267
Conant Pasture Nominal to High Input	46,884	11.8	112,364,816	0.014	44,381	374
Conant Pasture Degraded to Medium Input	40,186	10.1	96,312,699	0.012	38,041	320
Conant Pasture Degraded to High Input	53,582	13.5	128,416,932	0.016	50,721	427
NT Pasture	6,966	1.8	16,694,903	0.002	6,594	55.5

^a Values are for one year of sequestration.

^b C that would have been sequestered by forest acres from conversion to agricultural land.

References

- Antle, J. M., Capalbo, S. M., Mooney, S., Elliot, E. T., & Paustian, K. H. (2001). Economic analysis of agricultural soil carbon sequestration: An integrated assessment approach. *Journal of Agricultural and Resource Economics*, 26(2), 344-367.
- Apfelbaum, S., Byck, P., Conser, R., DeLong, M. H., Johnson, D., Jones, C., . . . Williams, A. (2015, March). Proposed research summary: What livestock grazing practices are most effective at sequestering carbon in soils and improving delivery of ecosystem services and socio-ecological resilience in grazing systems?
- Associated Press. (2015, July 16). USDA: Nearly all of Idaho affected by natural disaster areas. Retrieved from <http://www.opb.org/news/article/usda-nearly-all-of-idaho-affected-by-natural-disaster-areas/>
- Banker, S. (2016, January 29). The Grass-fed beef supply chain. *Forbes*. Retrieved October 15, 2016, from <http://www.forbes.com/sites/stevebanker/2016/01/29/the-grass-fed-beef-supply-chain/#67a53f42258a>
- Banwart, S. A., Black, H., Zucong, C., Gicheru, P. T., Joosten, H., Victoria, R. L., . . . Pascual, U. (2015). The global challenge for soil carbon. In S. A. Barwart, E. Noellemeyer, & E. Milne (Eds.), *Soil carbon: Science, management and policy for multiple benefits* (pp. 1-9). Boston, MA: CAB International.
- Banwart, S. A., Noellemeyer, E., & Milne, E. (2015). *Soil carbon: Science, management and policy for multiple benefits*. Boston: CAB International.
- Barker, R. (2016, March 14). Public lands bills come to head in Idaho Legislature. *Idaho Statesman*. Retrieved November 25, 2016 , from <http://www.idahostatesman.com/news/local/news-columns-blogs/letters-from-the-west/article66101532.html>
- Barnhill, F. (2013, June 17). Why the Snake River in Idaho runs dry for miles. *Boise State Public Radio*. Retrieved December 12, 2016, from <http://boisestatepublicradio.org/post/why-snake-river-idaho-runs-dry-miles#stream/0>
- Blaine County. (n.d.). *Blaine County Idaho Master Plan (Chapter 4 Agriculture)*. Retrieved July 15, 2016, from <http://www.co.blaine.id.us/index.asp?SEC=12FFB628-E301-438F-998F->

657BEA35EA7B&DE=D427E741-586A-4D3D-9E35-3536EA580F68&Type=B_BASIC

- Blaine County. (n.d.). *Blaine County Master Plan*. Retrieved from [http://www.co.blaine.id.us/vertical/sites/%7BBB2A7BCF-1E38-4DB2-AE8E-3A22829A1987%7D/uploads/Recreation_as_approved_BCC_5-10-16\(1\).pdf](http://www.co.blaine.id.us/vertical/sites/%7BBB2A7BCF-1E38-4DB2-AE8E-3A22829A1987%7D/uploads/Recreation_as_approved_BCC_5-10-16(1).pdf)
- Bot, A., & Benites, J. (2005). The importance of soil organic matter: Key to drought resitant soil and sustained food production. Retrieved from <http://www.fao.org/3/a-a0100e.pdf>
- Boyle, K. (2006). The Economics of on-site conservation tillage (West National Technology Information Center technical note: Econ 101.01).
- Briske, D. D., Sayre, N. F., Huntsinger, L., Fernandez-Gimenez, M., Budd, B., & Derner, J. D. (2011). Origin, persistence, and resolution of the rotational grazing debate: Integrating human dimensions Into rangeland research. *Rangeland Ecology & Management*, 64(4), pp. 325-334.
- Burns, K. (Director). (2012). *The Dust Bowl* [Motion Picture].
- Carbon Dioxide Information Analysis Center (Oak Ridge National Laboratory). (n.d.). Estimated annual net change in soil carbon per US county. Retrieved July 16, 2016, from <http://cdiac.ornl.gov/carbonmanagement/soilcarbonchange/>
- Cart, J. (2014, June 15). Grazing on federal land under threat because of drought. *Los Angeles Times*. Retrieved October 15, 2016, from <http://www.latimes.com/local/la-me-drought-grazing-20140616-story.html>
- Clancy, K. (2006). *Greener pastures*. Union of Concerned Scientists. Retrieved from http://www.ucsusa.org/sites/default/files/legacy/assets/documents/food_and_agriculture/greener-pastures.pdf
- Coase, R. H. (1960, October). The problem of social cost. *The Journal of Law and Economics*, 3, 1-44.
- da Silva, J. G. (2014, December 5). A statement by FAO Director-General José Graziano da Silva (World Soil Day and launch of the International Year of Soils). Retrieved November 26, 2016, from <http://www.fao.org/about/who-we-are/director-gen/faodg-statements/detail/en/c/271237/>
- Davenport, C. (2016, December 13). Reversing course, EPA says fracking can contaminate drinking water. *The New York Times*. Retrieved December 13, 2016, from <http://www.nytimes.com/2016/12/13/us/reversing-course-epa-says-fracking-can-contaminate-drinking-water.html?rref=collection%2Ftimestopic%2FEnvironmental%20Protection%20>

Agency&action=click&contentCollection=timestopics®ion=stream&module=stream_unit&vers

- B. Dobos, personal communication, June & July, 2016. (USDA NRCS Soil Scientist (Lincoln Nebraska)).
- Dumler, T. J. (2000). *Costs of converting to no-till*. Conference Report (Risk and Profit 2000 Conference). Retrieved September 12, 2016, from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.630.9148&rep=rep1&type=pdf>
- Epplin, F. M., Stock, C. J., Kletke, D. D., & Peeper, T. J. (2005). *Costs of conventional tillage and no-till continuous wheat production for four farm sizes*. Retrieved September 12, 2016, from <http://ageconsearch.umn.edu/bitstream/190714/2/231.pdf>
- European Commission Directive 2001/42/EC.
- Fine, D. (2014). *Hemp bound: Dispatches from the front lines of the next agricultural revolution*. White River Junction, Vermont: Chelsea Green.
- Franzluebbers, A. (2010). Will we allow soil carbon to feed our needs? *Carbon Management, 1*(2), 237-251. Retrieved July 13, 2016.
- Franzluebbers, A. J., & Studemann, J. A. (2008). Early response of soil organic fractions to tillage and integrated crop-livestock production. *Soil, Biology, and Biochemistry, 72*(3), 613-625.
- Garcia-Prechac, F., Ernst, O., Siri-Prieto, G., & Terra, J. A. (2004). Integrating no-till into crop-pasture rotations in Uruguay. *Soil & Tillage Research, 77*, 1-13.
- Ghimire, R., Norton, J. B., & Pendall, E. (2014). Alfalfa-grass biomass, soil organic carbon, and total nitrogen under different management approaches in an irrigated agroecosystem. *Plant Soil, 374*, 173-184.
- Global Network of Dryland Research Institutes. (n.d.). *Global Network of Dryland Research Institutes*. Retrieved December 10, 2016, from Map of the member institutions: <http://www.gndri.net/>
- Goldhaber, M., & Banwart, S. (2015). Soil formation. In S. A. Banwart, & E. Milne, *Soil carbon: Science, management and policy for multiple benefits* (pp. 82-97). Boston: CAB International.
- Guan, X. K., Turner, N. C., Song, L., Gu, Y. J., Wang, T. C., & Li, F. M. (2016). Soil carbon sequestration by three perennial legume pastures is greater in deeper soil layers than in the surface soil. *Biogeosciences, 13*(2), 527-534.

- Hardin, G. (1968). The tragedy of the commons. *Science*, 162(3859), 1243-1248.
- Howitt, R., MacEwan, D., Medellin-Azuara-Josue, Lund, J., & Sumner, D. (2015). *Economic analysis of the 2015 drought for California agriculture*. UC Davis Center for Watershed Sciences. Retrieved December 5, 2016, from https://watershed.ucdavis.edu/files/biblio/Final_Drought%20Report_08182015_Full_Report_WithAppendices.pdf
- Hudson, B. D. (1994, Mar). Soil organic matter and available water capacity. *Journal of Soil and Water Conservation*, 49(2), 189-194.
- Idaho Code § 42-203.
- Idaho Code §§ 42-1501-1508.
- Idaho Code §§ 42-1761-42-1766.
- Idaho Code §42-1805.
- Idaho Code of Administrative Procedure (Water Appropriation Rules) §37.03.08.
- Idaho Constitution Article XV § 1.
- Idaho Department of Agriculture. (2016). *About Idaho Preferred*. Retrieved November 26, 2016, from Idaho Preferred: <https://idahopreferred.com/about-us/>
- Idaho Department of Environmental Quality. (2014, January). *Idaho's 2012 integrated report (final)*. Retrieved from <http://www.deq.idaho.gov/media/1117323/integrated-report-2012-final-entire.pdf>
- Idaho Department of Water Quality; Idaho Soil Conservation Commission; Lewis Soil Conservation District. (2008). *Camas Prairie nitrate priority area: Groundwater quality management plan*. Retrieved December 13, 2016, from http://www.deq.idaho.gov/media/470848-camas_prairie_nitrate_gw_plan.pdf
- Idaho Department of Water Resources. (2001). *Idaho drought plan*. Retrieved from <https://www.idwr.idaho.gov/files/water-data/Idaho-Drought-Plan.pdf>
- Idaho Department of Water Resources. (2013). *Enhanced Snake Plain Aquifer model: Version 2.1 (final report)*. Retrieved July 14, 2016, from http://www.idwr.idaho.gov/Browse/WaterInfo/ESPAM/ESPAM_2_Final_Report/ESPAM21FinalReport.pdf
- Idaho Department of Water Resources. (2014). Wood River Valley groundwater flow model. Retrieved from <https://www.idwr.idaho.gov/WaterInformation/Projects/woodriver/>

- Idaho Department of Water Resources. (2015). *Idaho water supply bank 2015 rental pools report*. Retrieved October 15, 2016, from <https://www.idwr.idaho.gov/files/water-supply-bank/2015-rental-pools-report.pdf>
- Idaho Department of Water Resources. (2015). *Water supply bank interim ground water rental policy for the Wood River Valley*. Retrieved from <https://www.idwr.idaho.gov/files/water-supply-bank/20151016-WRV-Interim-Ground-Water-Rental-Policy.pdf>
- Idaho Department of Water Resources. (2016, May 18). IDWR issues curtailment order to approximately 160 junior groundwater users. Retrieved September 9, 2016, from <https://www.idwr.idaho.gov/files/news-release/20160518-news-release-2016-10.pdf>
- Idaho Department of Water Resources. (2016, July 13). IDWR to hold 10 public meetings to gather public input on proposed. Retrieved September 9, 2016, from <https://www.idwr.idaho.gov/files/news-release/20160713-news-release-2016-14.pdf>
- Idaho Department of Water Resources. (2016). Proposed sustainability section to be added to the Idaho state water plan. Retrieved September 9, 2016, from <https://www.idwr.idaho.gov/files/board/20160531-Proposed-Sustainability-Section-to-the-SWP.pdf>
- Idaho Department of Water Resources. (n.d.). *Legal actions (water delivery call actions)*. Retrieved September 8, 2016, from <https://www.idwr.idaho.gov/legal-actions/>
- Idaho Enterprise Open Data Portal. (n.d.). *Nitrate priority areas (2014)*. Retrieved December 12, 2016, from Overview: http://data.gis.idaho.gov/datasets/81c54516f0a6492fbcf28ca942b3f7b5_7?geometry=-147.47%2C39.967%2C-92.055%2C50.728
- Idaho Laws. (2016, March 31). Senate Bill 1339 (Oil and Gas). Retrieved from <https://legislature.idaho.gov/legislation/2016/S1339.htm>
- Idaho National Laboratory. (2005). Idaho's treasure: The Eastern Snake Plain Aquifer. Retrieved July 14, 2016, from https://www.deq.idaho.gov/media/552772-newsletter_0505.pdf
- Idaho Soil and Water Conservation Commission. (2015). *Idaho's Conservation Reserve Enhancement Program Eastern Snake Plain Aquifer - GY 2015 CREP annual performance report*. Retrieved August 8, 2016, from http://swc.idaho.gov/media/24785/CREP_Annual_Report_FY15.pdf
- Idaho Water Resource Board. (2009). *Eastern Snake Plain Aquifer comprehensive aquifer management plan*. Retrieved from

https://www.idwr.idaho.gov/waterboard/WaterPlanning/CAMP/ESPA/PDFs/ESP_A_CAMP_lowres.pdf

- Idaho Water Resources Board. (2012). *Idaho state water plan*. Retrieved from <https://www.idwr.idaho.gov/waterboard/WaterPlanning/Statewaterplanning/PDFs/ADOPTED%20State%20Water%20Plan%202012.pdf>
- Idaho Water Resources Board. (n.d.). *Water planning*. Retrieved December 11, 2016 , from Stream Flows: https://www.idwr.idaho.gov/waterboard/WaterPlanning/Minimum%20Stream%20Flow/minimum_stream_flow.htm
- Industry & Investment New South Wales Government (Australia). (2010). *A farmer's guide to increase soil organic carbon under pastures*. Retrieved August 5, 2016, from http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0014/321422/A-farmers-guide-to-increasing-Soil-Organic-Carbon-under-pastures.pdf
- Intergovernmental Panel on Climate Change. (2003). *Good practice guidance for land use, land-use change and forestry*. Retrieved from http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf_files/GPG_LULUCF_FULL.pdf
- Joyce, L. A., Briske, D. D., Brown, J. R., Polley, H. W., McCarl, B. A., & Bailey, D. W. (2013). Climate change and North American rangelands: Assessment and mitigation and adaptation Strategies. *Rangeland Ecology & Management*, 66(5), 512-528.
- Karlen, D. L., Cambardella, C. A., Kova, J. L., & Colvin, T. S. (2013). Soil quality response to long-term tillage and crop rotation practices. *Soil & Tillage Research*, 133, 54-64.
- Karlen, D. L., Kovar, J. L., Cambardella, C. A., & Colvin, T. S. (2013). Thirty-year tillage effects on crop yields and soil fertility indicators. *Soil & Tillage Research*, 130, 24-41.
- Kimble, J. M., Rice, C. W., Reed, D., Mooney, S., Follett, R. F., & Lal, R. (Eds.). (2007). *Soil carbon management: Economic, environmental and societal benefits*. Boca Raton, Fla, USA : CRC Press.
- Kirkegaard, J. A., Conyers, M. K., Hunt, J. R., Kirby, C. A., Watt, M., & Rebetzke, G. J. (2014). Sense and nonsense in conservation agriculture: Principles, pragmatism and productivity in Australian mixed farming systems. *Agriculture, Ecosystems and Environment*, 187, 133-145.
- Klocke, N. (1984). Maximizing water use efficiency of limited irrigation plus natural precipitation systems using conservation cropping systems. University of Nebraska.

- Klonks, K., Pettygrove, S., Smith, M., & Livingston, P. (1994). *Sample costs and energy required to produce barley under dryland and nontillage conditions in the Central Coast*. University of California (Davis) Cooperative Extension. Retrieved October 15, 2016, from http://coststudyfiles.ucdavis.edu/uploads/cs_public/8d/a0/8da00116-0f91-42ac-93b3-65af006069a9/bl-cc-94-3-barley-1994-costsenergynotillslocountycc.pdf
- Kronen, M. (1994). Water harvesting and conservation techniques for smallholder crop production systems. *Soil & Tillage Research*, 32(1), 71-86.
- KTVB. (2015, July 20). Farmers across Idaho deal with drought conditions. Boise, ID.
- Lafond, G. P., Loeppky, H., & Derksen, D. A. (1992). The effects of tillage systems and crop rotation on soil water conservation, seedling establishment and crop yield. *Canadian Journal of Plant Science*, 72(1), 103-115.
- Lal, R., & Follet, R. F. (2009). *Soil carbon sequestration and the greenhouse effect* (2 ed.).
- Lewandowski, J., Peters, M., Jones, C., House, R., Sperow, M., Eve, M., & Paustian, K. (2004). Economics of sequestering carbon in the U.S. agricultural sector. USDA. Retrieved September 9, 2016, from http://www.ers.usda.gov/media/434512/tb1909_1_.pdf
- Little, J. B. (2009, March 1). *The Ogallala Aquifer: Saving a vital U.S. water source*. Retrieved February 27, 2017, from Scientific American: <https://www.scientificamerican.com/article/the-ogallala-aquifer/>
- Mann, D. (2016, August 24). Statement of Darin Mann (M/M Feedlot). *CTIC Tour 2016*. Idaho, Treasure Valley.
- McBride, W. D. (2003, September 1). *Production costs critical to farming decisions*. USDA Economic Research Service. Retrieved September 1, 2016, from <http://www.ers.usda.gov/amber-waves/2003-september/production-costs-critical-to-farming-decisions.aspx#.V9dMNpgrJhE>
- McIntyre, B. (2016, August 24). Statement of Brad McIntyre of McIntyre Farms. Caldwell, Idaho.
- Messick, M. (2012, September 21). *After the wind boom, a fight over Idaho's energy future*. Retrieved November 10, 2016, from State impact (A reporting project of NPR member stations): <https://stateimpact.npr.org/idaho/2012/09/21/after-the-wind-boom-a-fight-over-idahos-energy-future/>
- J. Miller, personal communication, October 12, 2016. (Water Quality Resource Conservationist (Idaho Soil and Water Conservation Commission)).

- Miller, J. T. (n.d.). Eleven livestock.
- National Chicken Council. (2016, September 21). *Per capita consumption of poultry and livestock, 1965 to estimated 2016 in pounds*. Retrieved November 22, 2016, from <http://www.nationalchickencouncil.org/about-the-industry/statistics/per-capita-consumption-of-poultry-and-livestock-1965-to-estimated-2012-in-pounds/>
- National Conference of State Legislatures. (2016, August 19). *State industrial hemp statutes*. Retrieved November 26, 2016, from <http://www.ncsl.org/research/agriculture-and-rural-development/state-industrial-hemp-statutes.aspx>
- Natural Resources Defense Council; Pacific Institute. (2014). *Agricultural water conservation and efficiency potential in California*. Retrieved November 29, 2016, from <https://www.nrdc.org/sites/default/files/ca-water-supply-solutions-ag-efficiency-IB.pdf>
- H. Neibling, personal communication, August 11, 2016. (Professor (University of Idaho, Moscow, Agricultural Engineering, Soil Science, Water Science Department)).
- Nzigugehab, G., Vargas, R., Bationo, A., Black, H. B., de Brogniez, D., Joosten, H., . . . Termansen, M. (2015). Soil carbon: A critical natural resource - wide-scale goals, urgent actions. In S. A. Banwart, E. Noellemeyer, & E. Milne (Eds.), *Soil carbon: Science, management and policy for multiple benefits* (p. 11). Boston, MA, CABI.
- O'Connell, J. (2016, August 19). *Idaho quinoa growers get encouraging news in second season*. Retrieved November 26, 2016, from Capital Press: The West's Ag Website: <http://www.capitalpress.com/Idaho/20160819/idaho-quinoa-growers-get-encouraging-news-in-second-season>
- O'Connor, C. (2013). Soil matters: How the Federal Crop Insurance Program should be reformed to encourage low-risk farming methods with high reward environmental outcomes. *NRDC Issue Paper*. Retrieved September 17 2016, from <https://www.nrdc.org/sites/default/files/soil-matters-IP.pdf>
- Ogle, S. M., Conant, R. T., & Paustian, K. (2004). Deriving grassland management factors for a carbon account method developed by the Intergovernmental Panel on Climate Change. *Environmental Management*, 33(4), 474-484.
- Perry, A. (2012, 30 August). *No-till farming helps capture snow and soil water*. Retrieved November 28, 2016, from <https://www.ars.usda.gov/news-events/news/research-news/2012/no-till-farming-helps-capture-snow-and-soil-water/>
- Polley, H. W., Briske, D. D., Morgan, J. A., Wolter, K., Bailey, D. W., & Brown, J. R. (2013, September). Climate change and North American rangelands: Trends, projections, and implications. *Rangeland Ecology Management*, 66, 493-511.

- Pribyl, D. W. (2010). A critical review of the conventional SOC to SOM conversion factor. *Geoderma*, 156(3), 75-83.
- PRISM Climate Group. (2016). *30-year normals*. Retrieved July 16, 2016, from PRISM Climate Data: <http://www.prism.oregonstate.edu/normals/>
- Public Broadcasting Service. (n.d.). *Mass exodus from the Plains*. Retrieved July 13, 2016, from Surviving the Dust Bowl (American Experience): <http://www.pbs.org/wgbh/americanexperience/features/general-article/dustbowl-mass-exodus-plains/>
- Reisner, M. (1986). *Cadillac desert*. New York, New York : Penguin Books.
- Reisner, M. D., Brace, J. B., Pyke, D. A., & Doescher, P. S. (2013). Conditions favouring *Bromus tectorum* dominance of endangered sagebrush steppe ecosystems. *Journal of Applied Ecology*, 50(4), 1039-1049.
- Retallack, G. J. (2013). Global cooling by grassland. *Annual Review of Earth and Planetary Sciences*, 41, 69-86.
- Rice, D. (2015, August 19). California drought cost is 2.7 billion in 2015. *USA Today*. Retrieved November 29, 2016 , from <http://www.usatoday.com/story/weather/2015/08/19/california-drought-cost-27-billion-2015/32007967/>
- Richter, B. (2014). *Chasing water: A guide for moving from scarcity to sustainability*. Washington, D.C.: Island Press.
- Rockstram, J., Steffen, W., Persson, A., Chapin III, F., Lambin, E., Lenton, T., . . . Folke, C. (2009). A safe operating space for humanity. *Nature*, 461, 472-475.
- Rockstrom, J., Kaumbutho, P., Mwalley, J., Nzabi, A., Temesgen, M., Mawenya, L., . . . Damgaard-Larsen. (2009). Conservation farming strategies in east and southern Africa: Yields and rain water productivity from on-farm action research. *Soil & Tillage Research*, 103(1), 23-32.
- Rogers, W. (2016, February 11). There's a very important reason you should care about the Oregon Standoff. *Fortune Magazine*. Retrieved October 15, 2016, from <http://fortune.com/2016/02/11/reason-oregon-standoff/>
- Russel, B. Z. (2016, February 25). Senate passes oil/gas bill after two-hour debate. *The Spokesman Review*. Retrieved December 11, 2016, from <http://www.spokesman.com/blogs/boise/2016/feb/25/senate-passes-oilgas-bill-after-two-hour-debate/>

- Sadler, M. (n.d.). *Large concentrated animal feeding operations (CAFOs) and EPA CAFO inspections and enforcement actions (2008-2012)*. Retrieved December 13, 2016, from ArcGIS:
<http://www.arcgis.com/home/item.html?id=bec4add383d64ed7806531e7393af1c3>
- Sanford, W. E., & Selnick, D. L. (2013). Estimation of evapotranspiration across the coterminous United States using a regression with climate and land-cover data. *Journal of the American Water Resources Association*, 49(1), 217-230.
- Scheierling, S. M., Treguer, D. O., Booker, J. F., & Decker, E. (2014). *How to assess agricultural water productivity? Looking for water in the agricultural productivity and efficiency literature*. World Bank Group. Retrieved from <http://documents.worldbank.org/curated/en/757951468146378459/How-to-assess-agricultural-water-productivity-looking-for-water-in-the-agricultural-productivity-and-efficiency-literature>
- Schuman, G. E., & Janzen, H. H. (2001). Soil carbon dynamics and potential carbon sequestration by rangelands. *Environmental Pollution*, 116(3), 391-396.
- Shiptalo, M. J., Owens, L. B., Bonta, J. V., & Edwards, W. M. (2013, June 11). Effect of no-till and extended rotation on nutrient losses in surface runoff. *Soil & Water Management & Conservation*, 77, 1329-1337.
- Steward, D. R. (2013). Tapping unsustainable groundwater stores for agricultural production in the High Plains Aquifer of Kansas, projections to 2110. *Proceedings of the National Academy of Sciences of the United States of America*, 110(37), 3477-3846.
- Stuebner, S. (1995, February 20). No more ignoring the obvious: Idaho sucks itself dry. *High Country News*. Retrieved December 11, 2016, from <http://www.hcn.org/issues/29/813>
- J. Sukow, personal communication, March 2-3, 2016. (Idaho Department of Water Resources).
- Teague, R. A. (2014, November). Grazing down the carbon: The scientific case for grassland restoration. *Poster presented at Biodiversity for a Livable Climate Conference (Tufts University)*. Somerville, MA.
- Teague, W. R., Apfelbaum, S., Lal, R., Kreuter, U. P., Browntree, J., Davies, C. A., . . . Byck, P. (2016). The role of ruminants in reducing agriculture's. *Journal of Soil and Water Conservation*, 71(2), 156-164.
- Teague, W. R., Dowhower, S. L., Baker, S. A., Haile, N., DeLaune, P. B., & Conover, D. M. (2011). Grazing management impacts on vegetation, soil biota and soil

chemical, physical and hydrological properties in tall grass prairie. *Agriculture, Ecosystems and Environment*, 141(3-4), 310-322.

- Thaler, R. H., & Sunstein, C. R. (2009). *Nudge: Improving decisions about health, wealth, and happiness*. New York, New York : Penguin Books.
- Thurlow, K. (2016). *Grass finished beef marketing update*. Retrieved November 22, 2016, from Ag Web: <http://www.agweb.com/article/grass-finished-beef-marketing-update-naa-university-news-release/>
- Toro Crop Solutions. (2013). Drip irrigation on peppermint. *Drip Irrigation News*. Retrieved October 15, 2016 , from <http://driptips.toro.com/2014/04/?cat=5>
- Unger, P. W., & Wiese, A. F. (1979). Managing irrigated winter wheat residues for water storage and subsequent dryland grain sorghum production. *Soil Science Society of America Journal*, 43, 582-588.
- United Nations Convention to Combat Drought and Desertification; The Global Mechanism; Mirova. (n.d.). *Land degradation neutrality fund: An innovative investment project*. Retrieved July 13, 2016, from http://www.unccd.int/Lists/SiteDocumentLibrary/Publications/2015_ldn_fund_brochure_eng.pdf
- United Nations Environment Programme. (2014). *Assessing global land use: Balancing consumption with sustainable supply*. Retrieved from [http://www.unep.org/resourcepanel/Portals/50244/publications/Full_Report-Assessing_Global_Land_UseEnglish_\(PDF\).pdf](http://www.unep.org/resourcepanel/Portals/50244/publications/Full_Report-Assessing_Global_Land_UseEnglish_(PDF).pdf)
- United Nations Food and Agriculture Organization (Regional Office for Asia and the Pacific). (n.d.). *Meat processing technology for small- to medium-scale producers*. Retrieved November 28, 2016, from <http://www.fao.org/docrep/010/ai407e/AI407E02.htm>
- United Nations Food and Agriculture Organization. (2015). *Towards a water and food secure future*. Retrieved July 17, 2016, from http://www.fao.org/nr/water/docs/FAO_WWC_white_paper_web.pdf
- United Nations. (n.d.). *Sustainable development knowledge platform*. Retrieved from Sustainable Development Goals: <https://sustainabledevelopment.un.org/?menu=1300>
- United Nations. (n.d.). *Why now?* Retrieved from United Nations decade for deserts and the fight against desertification: http://www.un.org/en/events/desertification_decade/whynow.shtml

- United States Environmental Protection Agency, Region 10. (2016, December 16). *Sole source aquifer program*. Retrieved December 18, 2016, from <https://yosemite.epa.gov/r10/water.nsf/sole+source+aquifers/SSA>
- United States Geological Survey. (2009). Ground water atlas of the United States: Idaho, Oregon, and Washington - Snake River Plain regional aquifer system (HA 730-H). Retrieved from http://pubs.usgs.gov/ha/ha730/ch_h/H-Snake_River.html
- United States Geological Survey. (2014). *Estimated use of water in the United States in 2010*. Retrieved from <http://pubs.usgs.gov/circ/1405/pdf/circ1405.pdf>
- University of Idaho. (2006). *Rangeland ecology and management*. Retrieved November 21, 2016, from Cheatgrass or Downy Brome: <http://www.webpages.uidaho.edu/rx-grazing/Grasses/Cheatgrass.htm>
- University of Idaho. (2012). *ETIdaho2012 - Evapotranspiration and consumptive irrigation requirements for Idaho*. Retrieved from <http://data.kimberly.uidaho.edu/ETIdaho/>
- U.S. Army Corps of Engineers. (November 2014). *Lower Snake River programmatic sediment management plan, final environmental impact statement (record of decision)*. Retrieved from http://www.nww.usace.army.mil/Portals/28/docs/programsandprojects/psmp/PSMP_RODs_Package_Corrected4.pdf
- U.S. Bureau of Land Management. (2013). *Worsening drought impacts western rangelands on public lands*. Retrieved October 15, 2016, from http://www.blm.gov/wo/st/en/info/newsroom/2013/july/worsening_drought.html
- U.S. Department of Agriculture, Forest Service. (n.d.). *Ecoregions of the continents*. Retrieved August 5, 2016, from <http://www.fs.fed.us/rm/ecoregions/products/map-ecoregions-continents/>
- U.S. Department of Agriculture. (2015). *Ogallala Aquifer initiative*. Retrieved July 12, 2016, from <https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/programs/initiatives/?cid=stelprdb1048809>
- U.S. Department of Agriculture. (2016, June 3). *Agriculture and forestry: Part of the climate solution*. Retrieved July 17, 2016, from <http://www.usda.gov/wps/portal/usda/usdahome?contentidonly=true&contentid=climate-smart.html>
- U.S. Department of Agriculture, Economic Research Service. (2013). *Western irrigated agriculture*. Retrieved from <http://www.ers.usda.gov/data-products/western-irrigated-agriculture.aspx>

- U.S. Department of Agriculture, Economic Research Service. (2016, November 30). *Cash receipts by commodity state ranking*. Retrieved November 29, 2016, from Famr Income and Wealth Statistics: <https://data.ers.usda.gov/reports.aspx?ID=53580>
- U.S. Department of Agriculture, Economic Research Service. (2016, October 12). *Irrigation & water use*. Retrieved November 3, 2016, from <http://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use.aspx#definitions>
- U.S. Department of Agriculture, Economic Research Service. (2016). *Producer price index*. Retrieved October 15, 2016, from [http://www.ers.usda.gov/topics/food-markets-prices/consumer-price-index-\(cpi\)/producer-price-index.aspx](http://www.ers.usda.gov/topics/food-markets-prices/consumer-price-index-(cpi)/producer-price-index.aspx)
- U.S. Department of Agriculture, National Agricultural Statistics Service. (2007). USDA agricultural census - acres of cropland fertilized (excluding cropland pasture) as percent of all cropland acreage (excluding cropland pastured): 2007. Retrieved December 13, 2016, from https://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Ag_Atlas_Maps/Farms/Agricultural_Chemicals_Used/07-M104-RGBChor-largetext.pdf
- U.S. Department of Agriculture, National Agricultural Statistics Service. (2012). *2012 census volume 1, chapter 1 (state level data: Idaho)*. Retrieved October 15, 2016, from https://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_State_Level/Idaho/
- U.S. Department of Agriculture, National Agricultural Statistics Service. (2015b, October). 2015 Idaho annual statistical bulletin. Retrieved from https://www.nass.usda.gov/Statistics_by_State/Idaho/Publications/Annual_Statistical_Bulletin/Annual%20Statistical%20Bulletin%202015.pdf
- U.S. Department of Agriculture, National Agricultural Statistics Service. (2015a). *Cropscape - cropland data layer*. Retrieved from Cropscape: <https://nassgeodata.gmu.edu/CropScape/>
- U.S. Department of Agriculture, National Agriculture Statistics Service. (2014). *USDA census of agriculture 2012*. Retrieved from https://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/
- U.S. Department of Agriculture, Natural Resource Conservation Service. (2008, June). Soil quality indicators: Available water capacity. Retrieved July 14, 2016, from <http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/health/assessment/?cid=stelprdb1237387>

- U.S. Department of Agriculture, Natural Resource Conservation Service. (2013, February). Soil health: Key points. Retrieved July 14, 2016, from http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1082147.pdf
- U.S. Department of Agriculture, Natural Resource Conservation Service. (2014). *Gridded Soil Survey Geographic (gSSURGO) database user guide*. Retrieved from https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/home/?cid=NRCS142P2_053628
- U.S. Department of Agriculture, Natural Resource Conservation Service. (n.d.a). *Description of SSURGO*. Retrieved from http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627
- U.S. Department of Agriculture, Natural Resource Conservation Service. (n.d.b). *Rapid Assessment of U.S. Soil Carbon (RaCA)*. Retrieved December 13, 2016, from Rapid Assessment of U.S. Soil Carbon (RaCA): https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054164
- U.S. Department of Agriculture, Natural Resource Conservation Service. (n.d.c). *Time and money training*. Retrieved from http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/econ/prices/?cid=nrcs143_009688
- U.S. Department of Agriculture, Natural Resource Conservation Service, Montana. (n.d.). *NRCS, livestock producers benefit sage grouse*. Retrieved November 21, 2016, from https://www.nrcs.usda.gov/wps/portal/nrcs/detail/mt/programs/landscape/?cid=nrcs144p2_056598
- U.S. Drought Monitor. (2016). *U.S. Drought Monitor archive*. Retrieved July 16, 2016, from <http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx>
- U.S. Energy Information and Administration. (n.d.). *Idaho state profile and energy estimates*. Retrieved from <http://www.eia.gov/state/?sid=ID>
- U.S. Environmental Protection Agency. (2016, May). *Greenhouse gas equivalencies calculator*. Retrieved July 25, 2016, from <https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator>
- U.S. Environmental Protection Agency. (2016). *My WATERS mapper*. Retrieved September 8, 2016, from <https://watersgeo.epa.gov/mwm/>

- U.S. Geological Survey. (2012). *Hydrogeologic framework of the Wood River Valley Aquifer system, south-central Idaho*. Retrieved July 15, 2016, from <http://pubs.usgs.gov/sir/2012/5053/pdf/sir20125053.pdf>
- U.S. Geological Survey. (2013). *Groundwater depletion in the United States*. Retrieved July 12, 2016, from <http://pubs.usgs.gov/sir/2013/5079/SIR2013-5079.pdf>
- U.S. Geological Survey. (2015). Groundwater Quality in the Columbia Plateau and Snake River Plain Basin-Fill and Basaltic-Rock Aquifers and the Hawaiian Volcanic-Rock Aquifers, Washington, Idaho, and Hawaii, 1993–2005. *Circular 1359*. Retrieved November 9, 2016, from <http://pubs.usgs.gov/circ/1359/>
- U.S. Geological Survey. (2016, May 2). *Irrigation water usage*. Retrieved July 12, 2016, from Water use in the United States: <http://water.usgs.gov/watuse/wuir.html>
- U.S. Geological Survey. (2015, November 15). *Wildfires may double erosion across a quarter of Western US watersheds by 2050*. Retrieved December 11, 2016, from National Climate Change and Wildlife Science Center: <https://nccwsc.usgs.gov/content/wildfires-may-double-erosion-across-quarter-western-us-watersheds-2050>
- U.S. Global Change Research Program. (2014). *Climate change impacts in the United States*. Retrieved July 12, 2016, from http://s3.amazonaws.com/nca2014/low/NCA3_Climate_Change_Impacts_in_the_United%20States_LowRes.pdf?download=1
- U.S. Government. (n.d.). National report on efforts to mitigate desertification in the Western United States.
- U.S. National Aeronautics and Space Administration. (2015, June 16). *Study: Third of big groundwater basins in distress*. Retrieved July 17, 2016, from <http://www.jpl.nasa.gov/news/news.php?feature=4626>
- Vegetable Growers News. (2012, January 17). Drip irrigation frees up more land for Idaho growers. *Vegetable Growers News*. Retrieved October 15, 2016, from <http://vegetablegrowersnews.com/article/drip-irrigation-frees-up-more-land-for-idaho-growers/>
- Wade, T., Claassen, R., & Wallander, S. (2015). *Conservation practice adoption rates vary widely by crop and region*. USDA. Retrieved September 11, 2016, from <http://www.ers.usda.gov/publications/eib-economic-information-bulletin/eib147.aspx>
- Wallander, S., Aillery, M., Hellerstein, D., & Hand, M. (2013). *The role of conservation programs in drought risk adaptation*. Retrieved October 17, 2016, from <http://www.ers.usda.gov/media/1094660/err148.pdf>

- Walton, B. (2010, October 14). *Murray-Darling Basin Plan angers Australian farmers*. Retrieved December 11, 2016, from Circle of Blue:
<http://www.circleofblue.org/2010/water-food/agriculture/murray-darling-basin-plan-angers-australian-farmers/>
- Warren, J., Alspach, S., Arnall, B., Viatle, J., Taylor, R., Schrock, M., . . . Osborne, S. (n.d.). *No-till cropping systems in Oklahoma*. Oklahoma Cooperative Extension Service, Division of Agricultural Sciences and Natural Resources, Oklahoma State University. Retrieved September 16, 2016, from
<http://notill.okstate.edu/publications/notillcroppingsystemsoklahoma/index.htm>
- Weber, K. T., & Gokhale, B. S. (2011). Effect of grazing on soil-water content in semiarid rangelands of southeast Idaho. *Journal of Arid Environments*, 75(5), 464-470.
- West, T. O., Brandt, C. C., Wilson, B. S., Tyler, D. D., Marland, G., De La Torre Ugarte, D. G., & Nelson, R. (2008, March-April). Estimating regional changes in soil carbon with high spatial resolution. *Soil Science Society of America*, 72(2), 285-294.
- White, C. (2014). *Grass, soil, hope*. White River Junction, Vermont: Chelsea Green Publishing.
- Winger, M. (2016, August 24). Statement of Marlon Winger (Idaho State Agronomist, NRCS).
- World Business Council for Sustainable Development. (2005). *Water: Facts and trends*. Retrieved July 17, 2016, from
http://www.unwater.org/downloads/Water_facts_and_trends.pdf

Ancillary Appendix 1

County-specific AWS Losses by Cropland Type in the ESP with Varying C Contents for

SOC

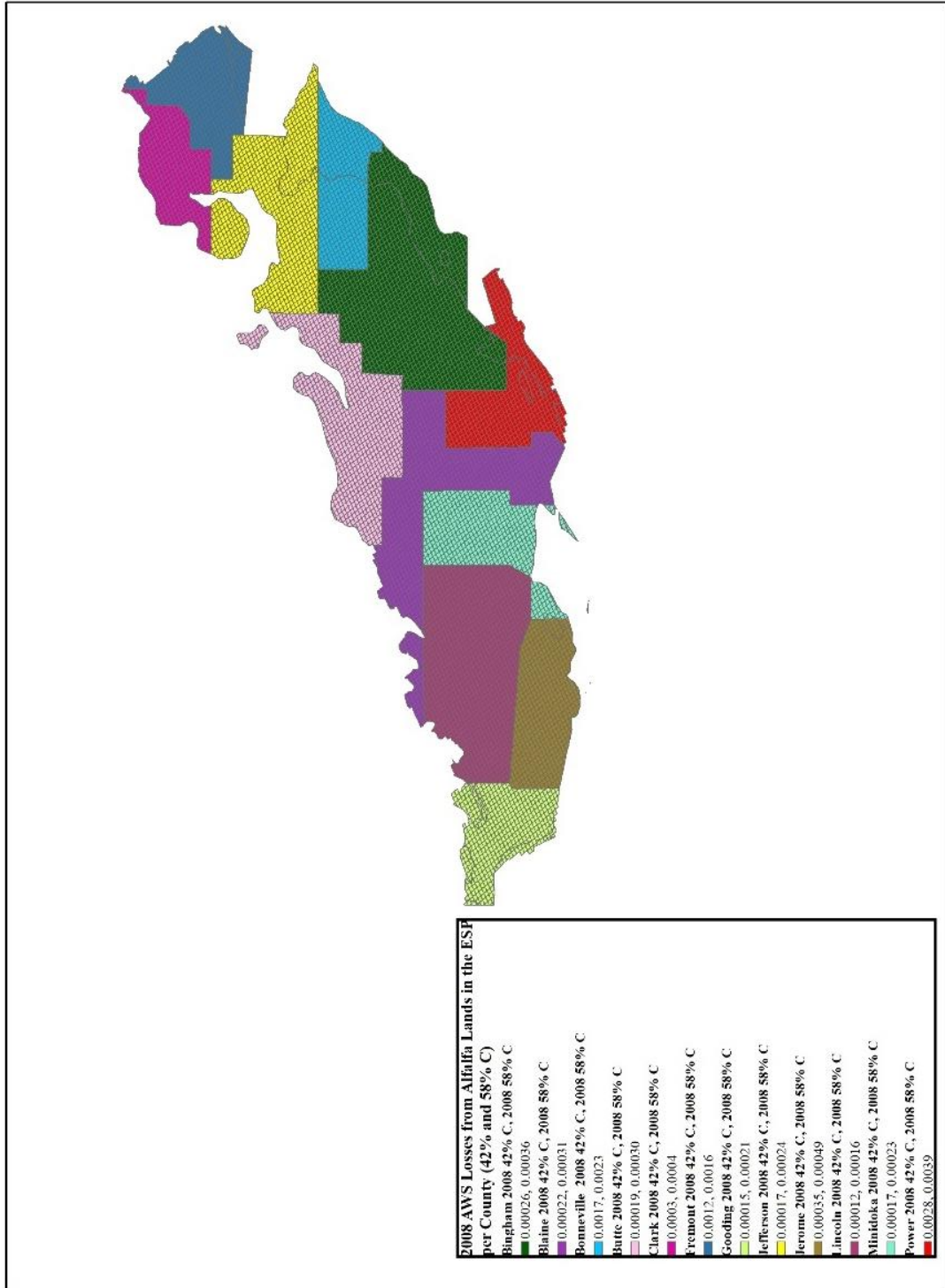


Figure 36. Alfalfa 2008 AWS losses (af/acre) in ESP with varying assumptions of SOC: SOM content (mean values).

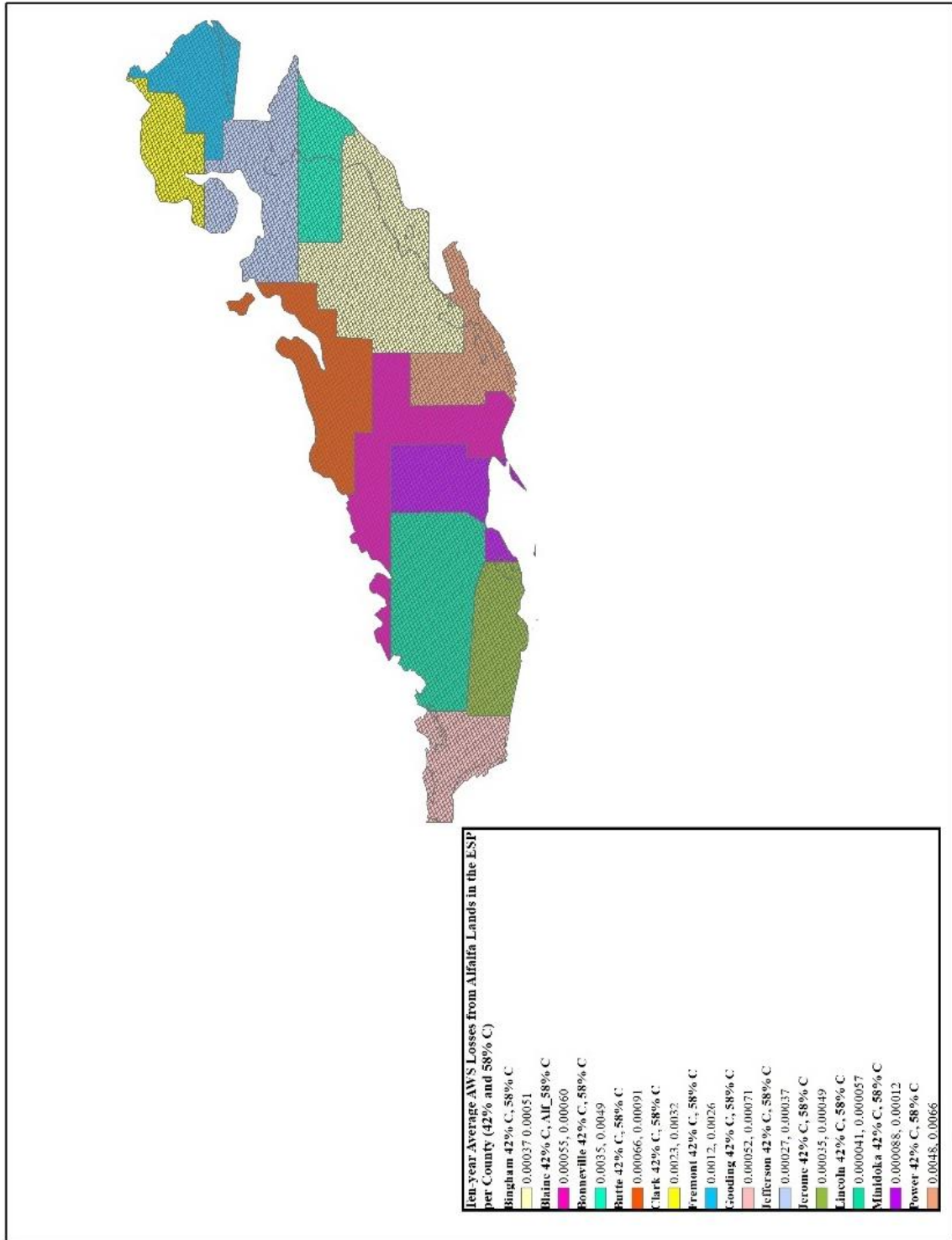


Figure 37. Alfalfa ten-year average AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).

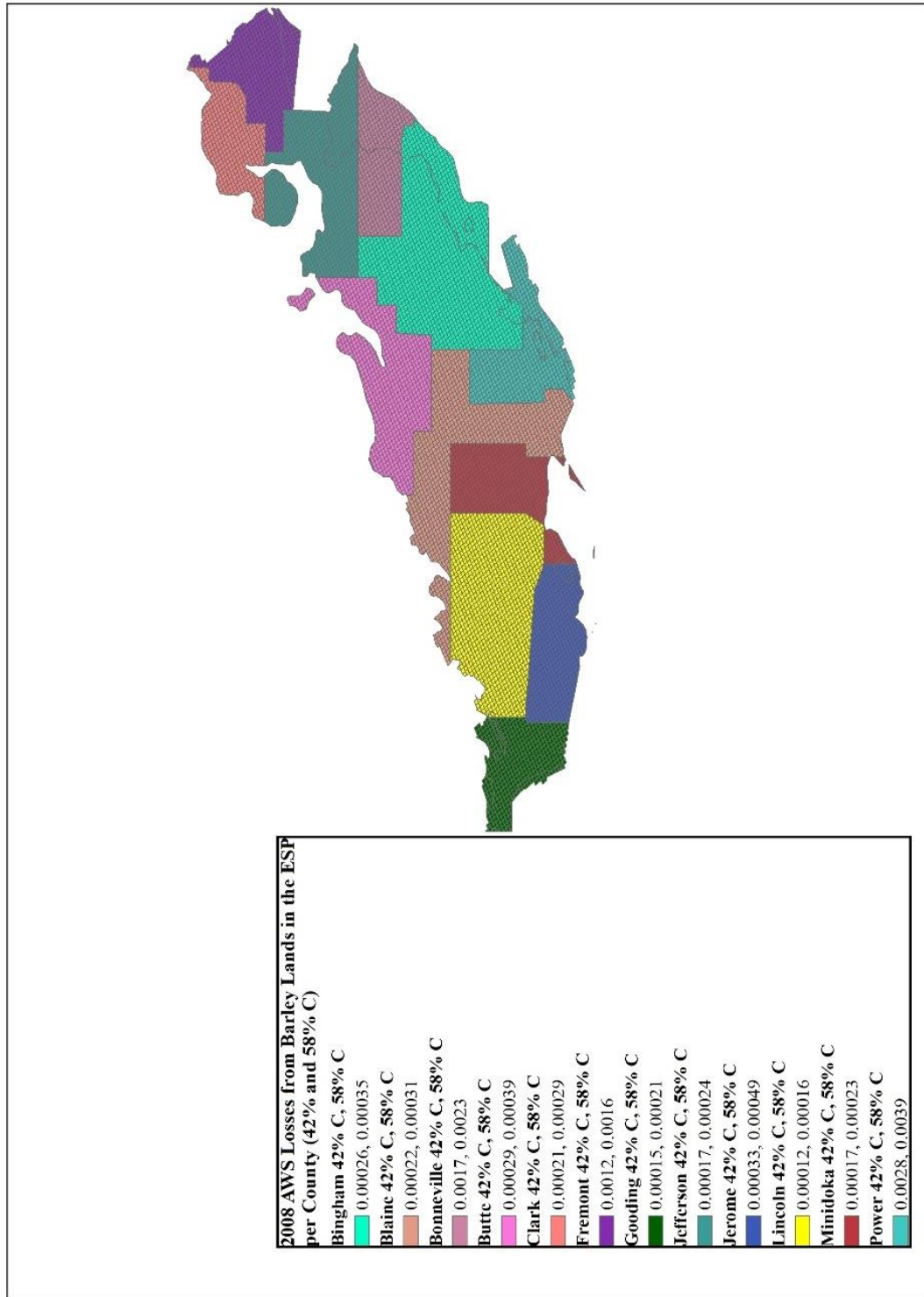


Figure 38. Barley 2008 AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).

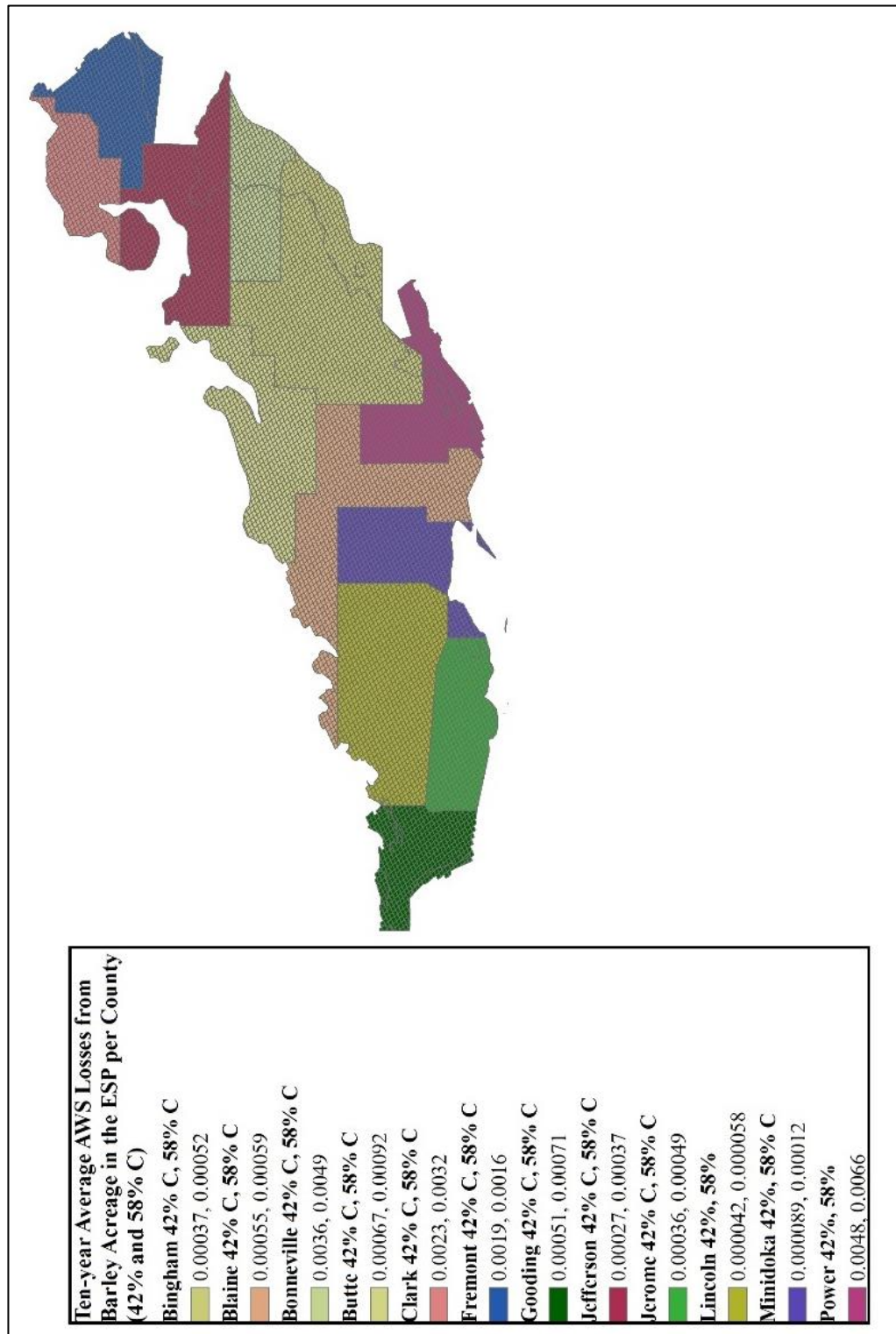


Figure 39. Barley ten-year average AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).

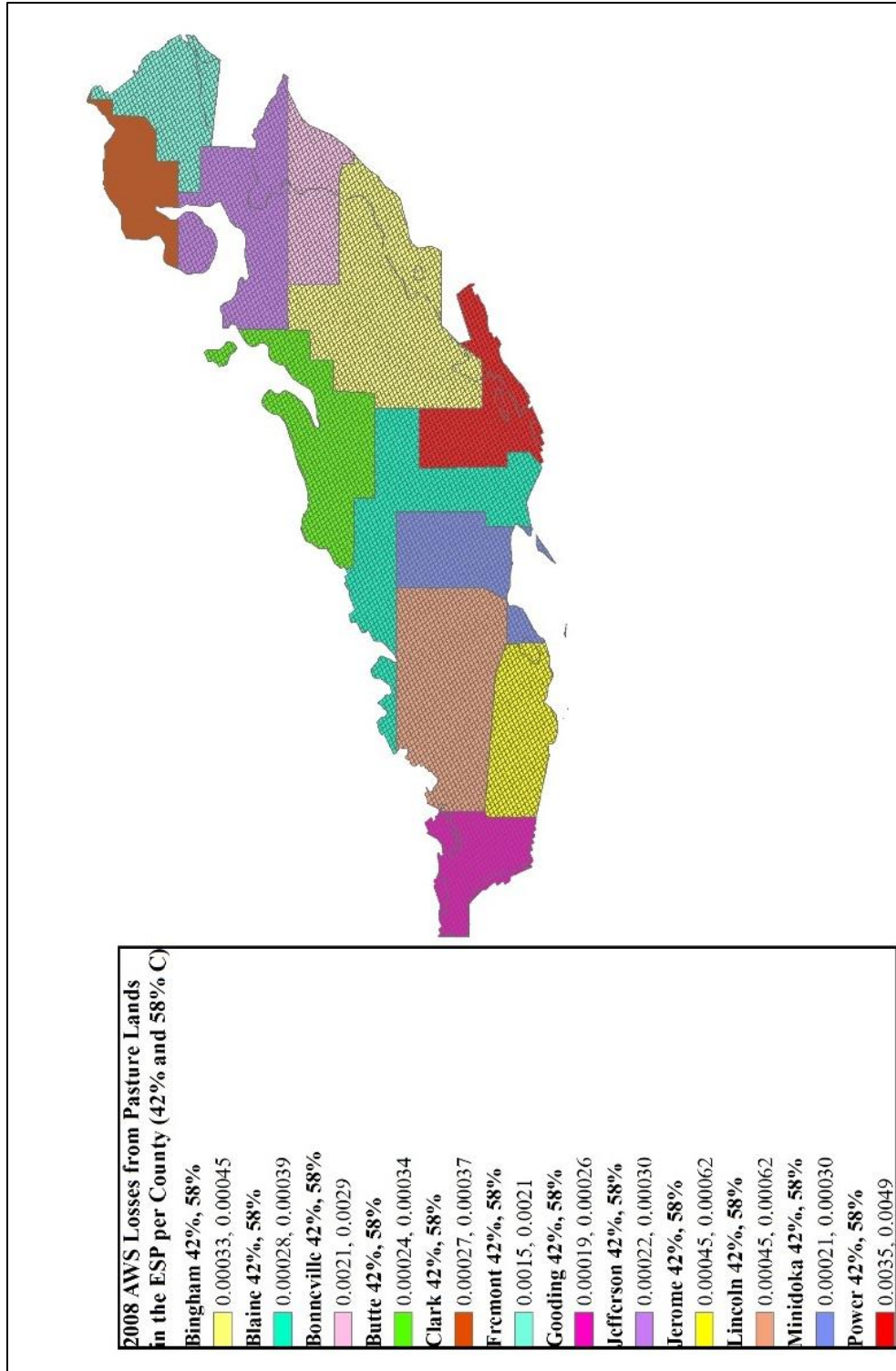


Figure 40. Pasture 2008 AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).

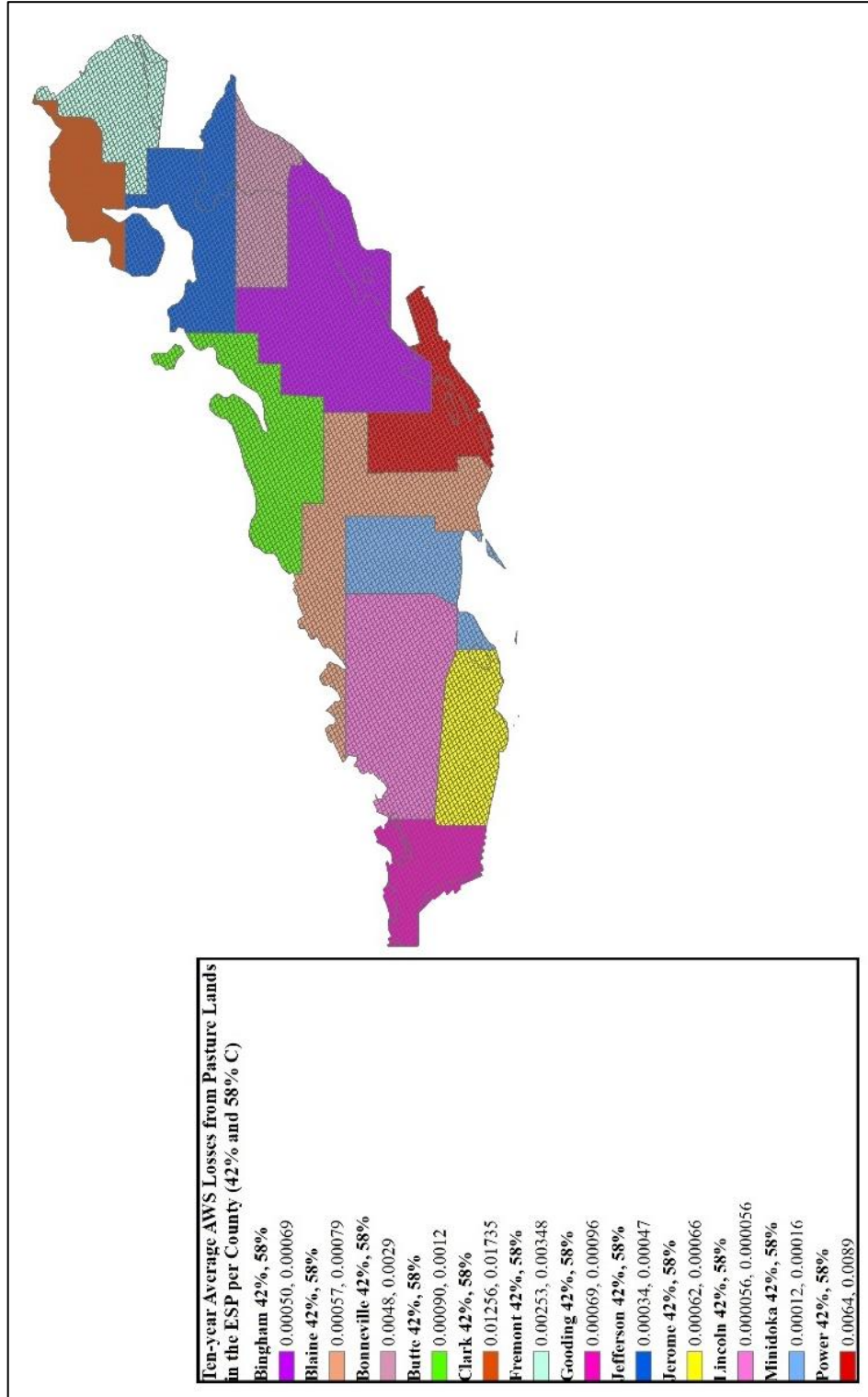


Figure 41. Pasture ten-year average AWS losses (af/acre) in the ESP with varying assumptions of SOC: SOM content (mean values).

Ancillary Appendix 2

Time to Remediate SOC by County and Agricultural Land in the ESP

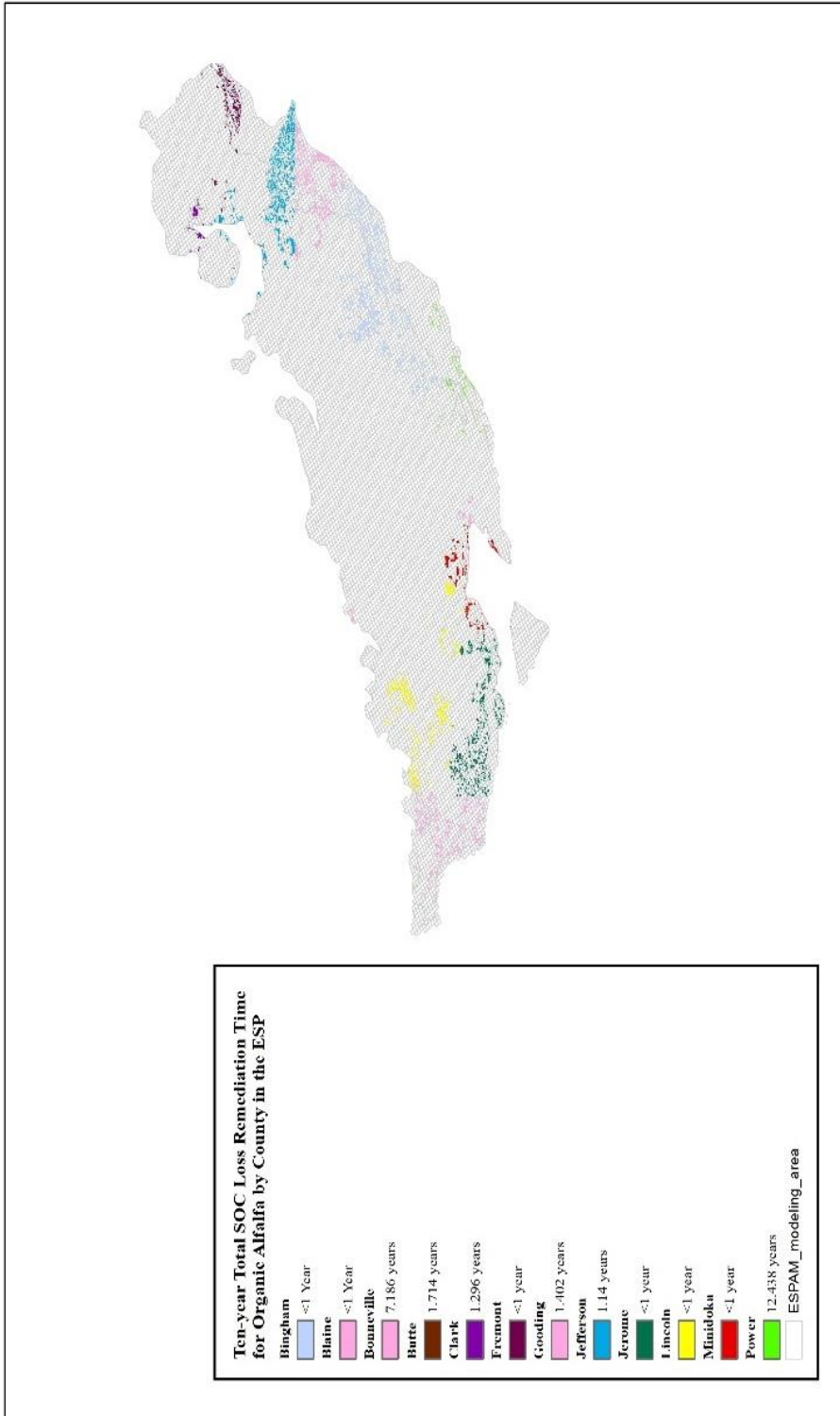


Figure 42. Remediation time of ten-year total SOC losses for conservation practices for organic alfalfa by county.

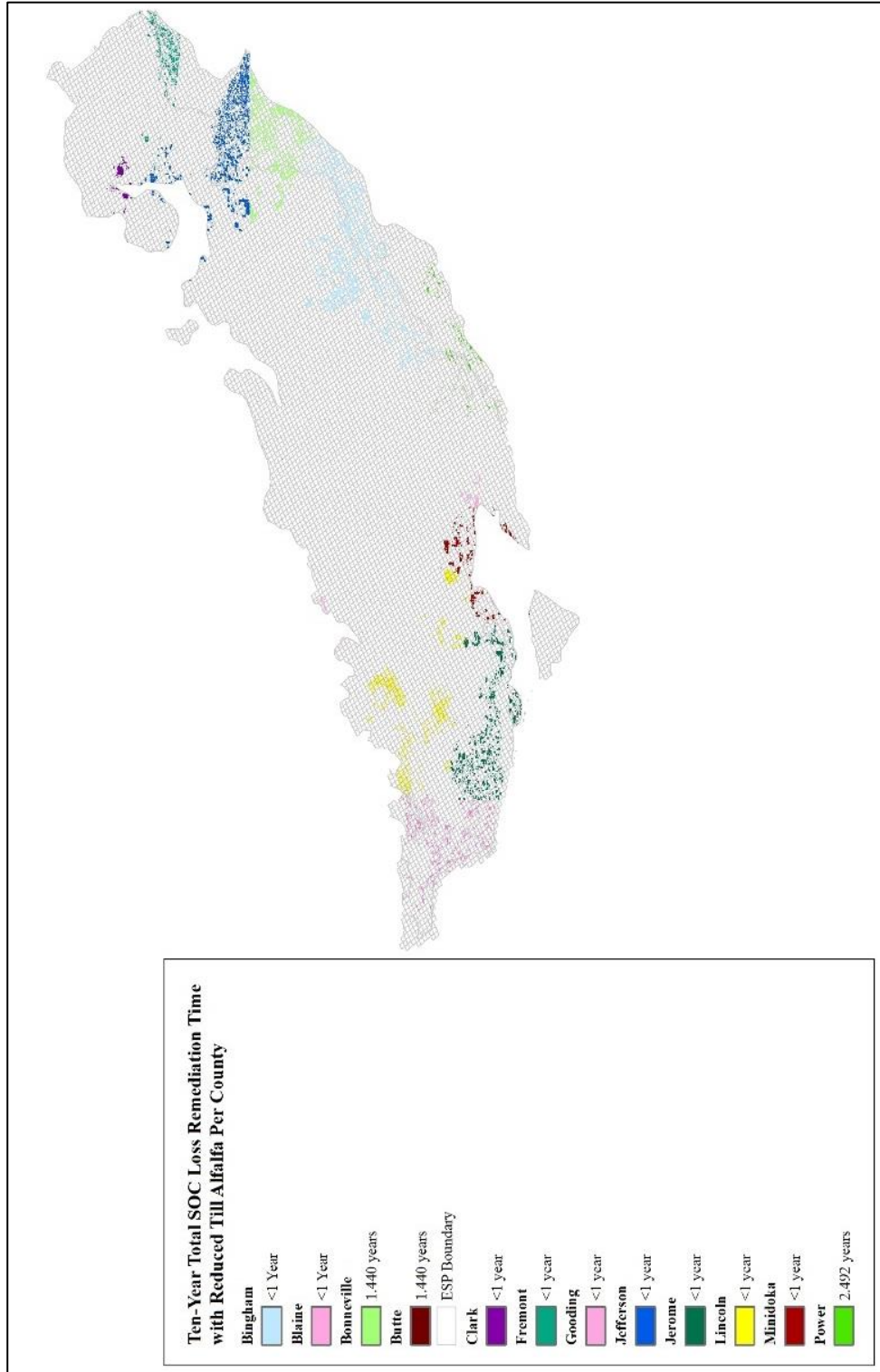


Figure 43. Remediation time of ten-year total SOC losses for conservation practices for reduced till alfalfa by county.

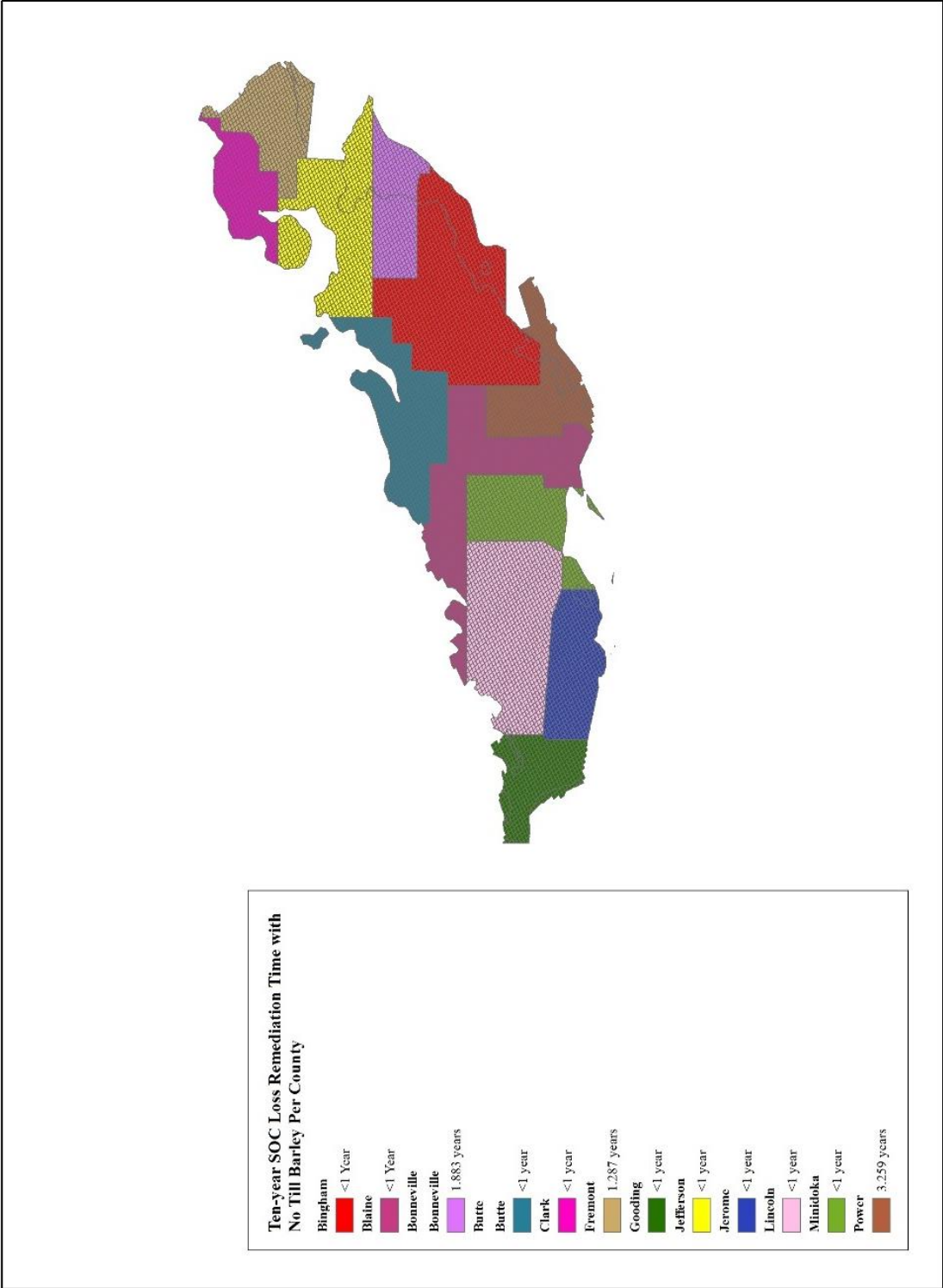


Figure 44. Remediation time of ten-year total SOC losses for conservation practices for no till barley by county.

Ancillary Appendix 3

Year 1 and Year 10 Percent Increases in AWS

Maps of volumetric increases are available from the author.

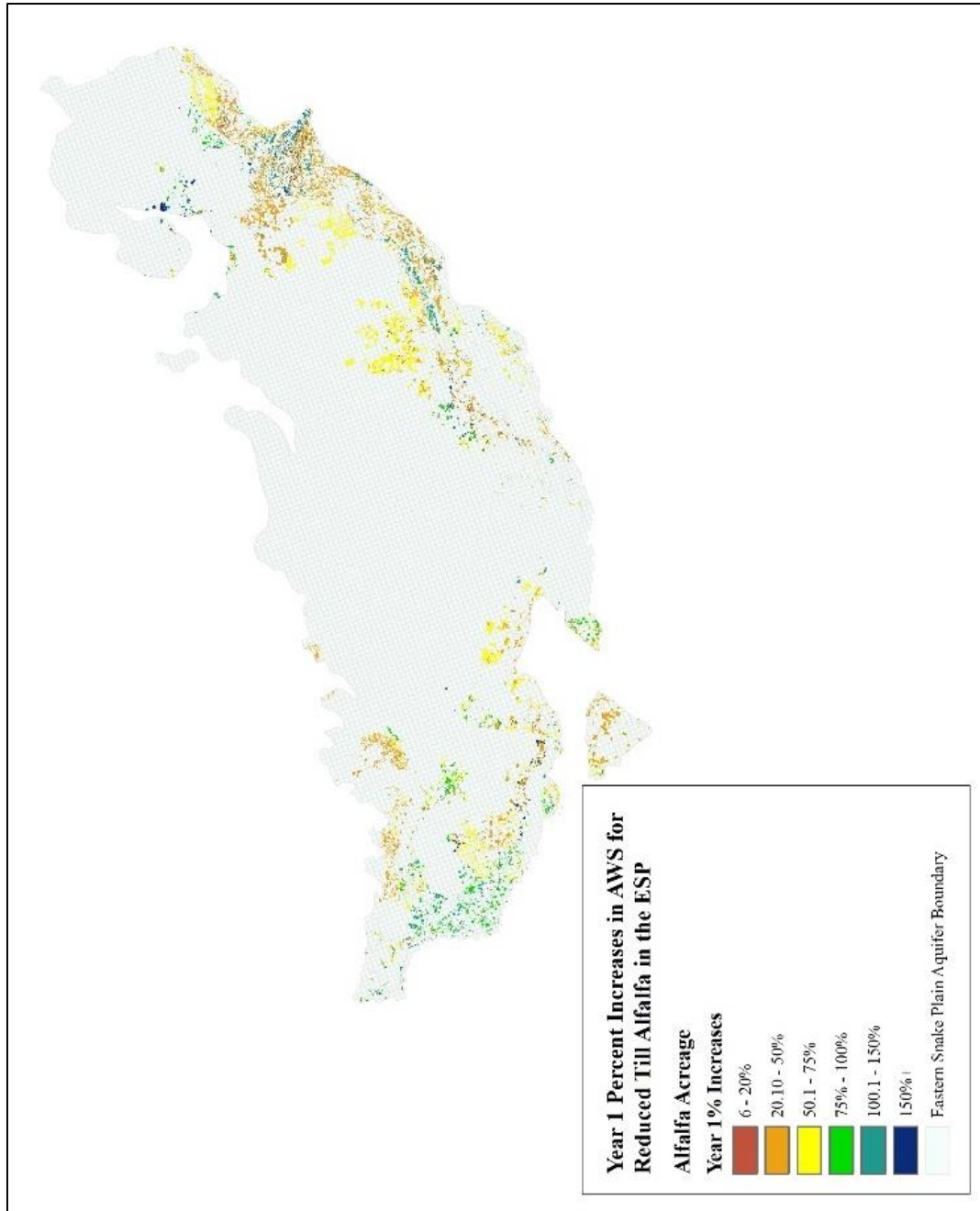


Figure 45. Year 1 percent increases in AWS for reduced till alfalfa in the ESP.

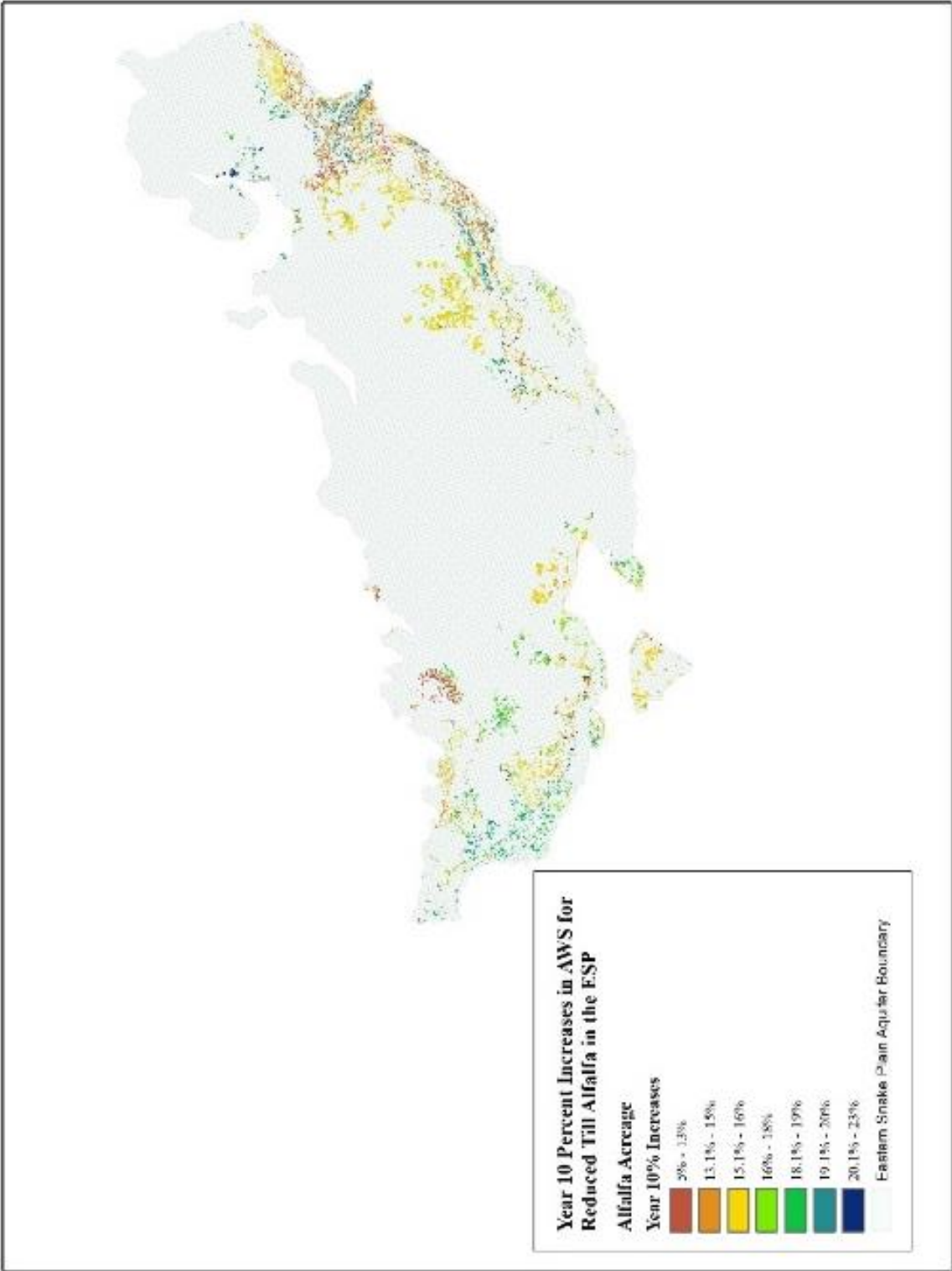


Figure 46. Year 10 percent increases in AWS for reduced till alfalfa in the ESP.

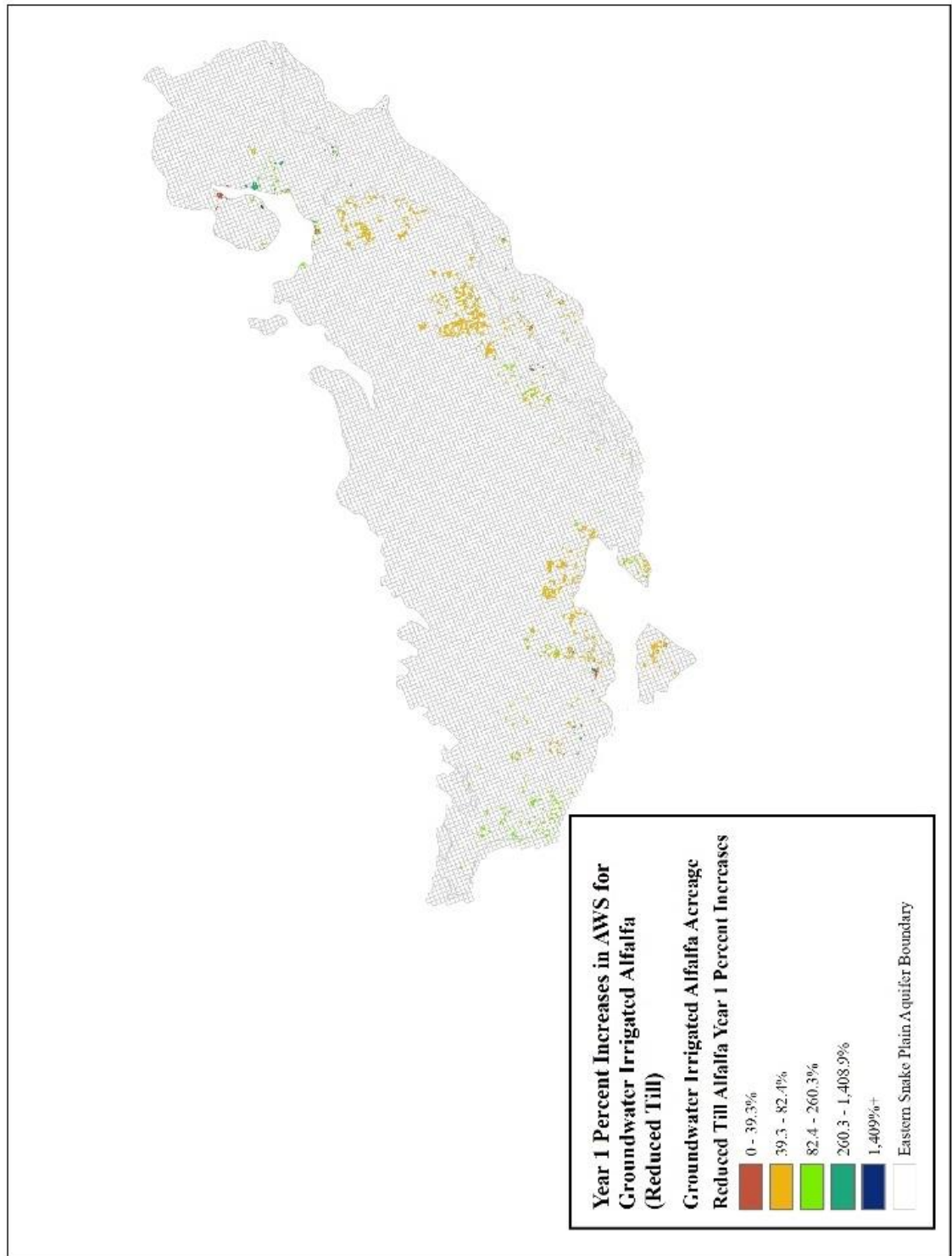


Figure 47. Year 1 percent increases in AWS for reduced till alfalfa (groundwater irrigated) in the ESP.

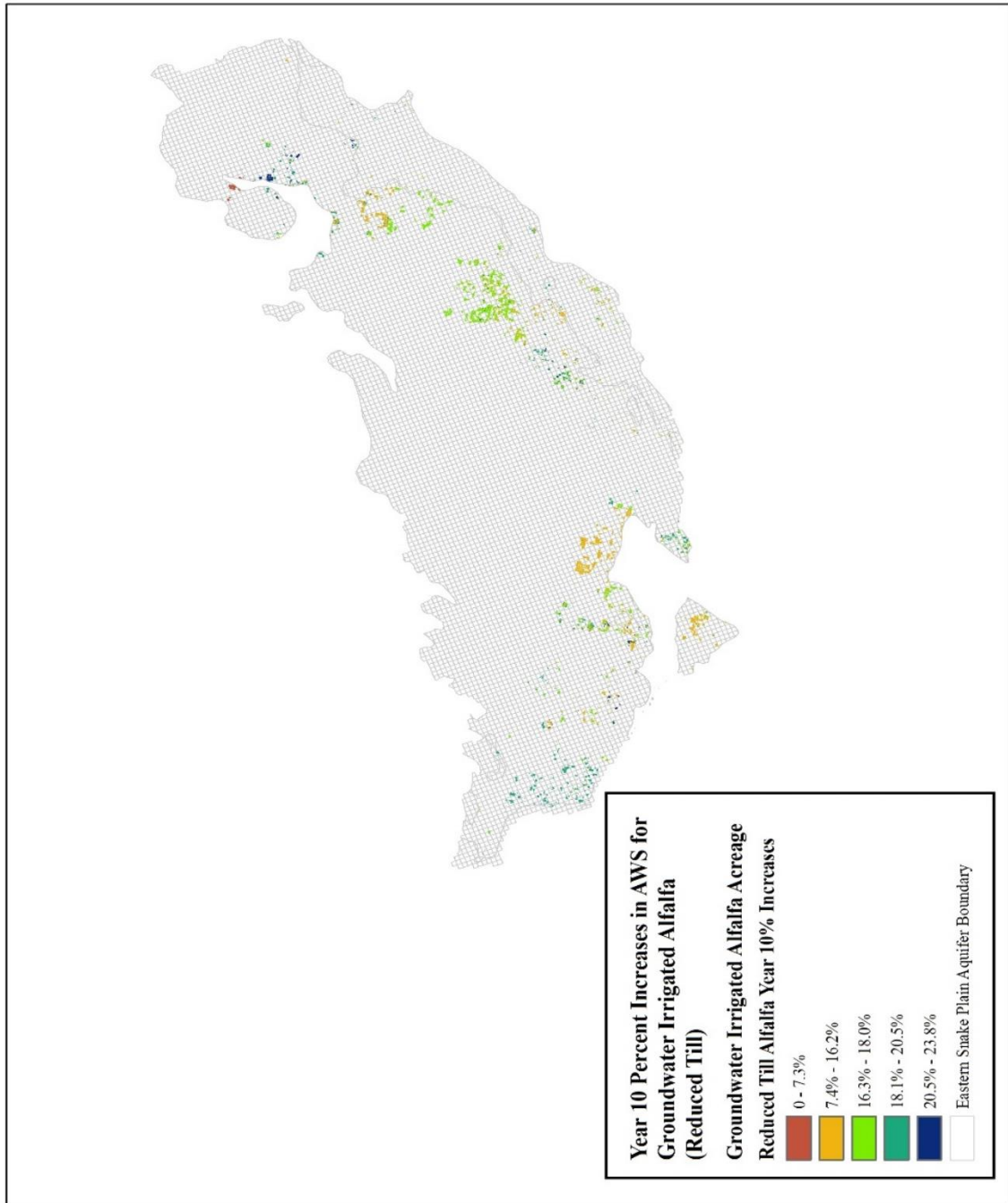


Figure 48. Year 10 percent increases in AWS for reduced till alfalfa (groundwater irrigated) in the ESP.

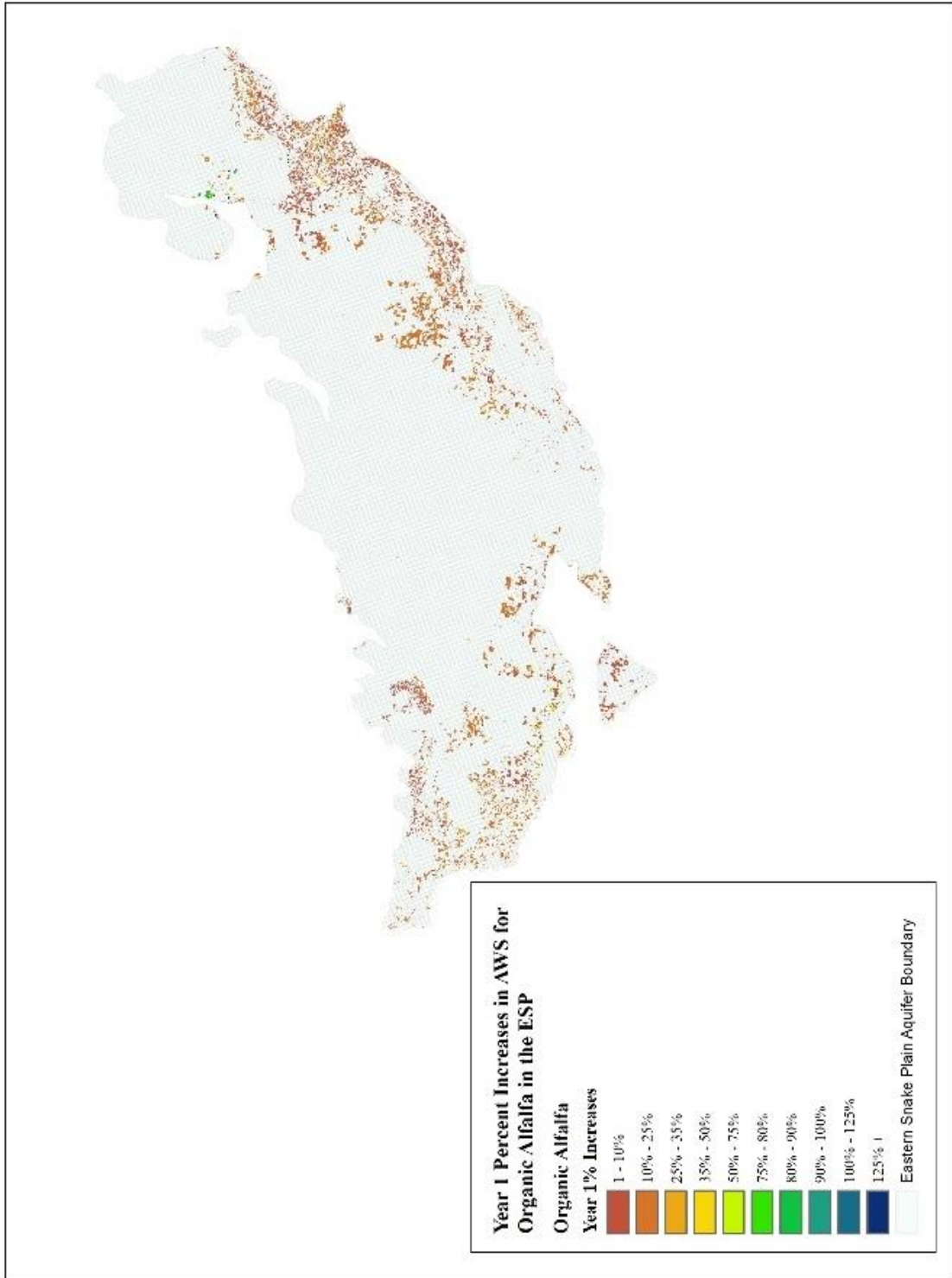


Figure 49. Year 1 percent increases in AWS for organic alfalfa in the ESP.

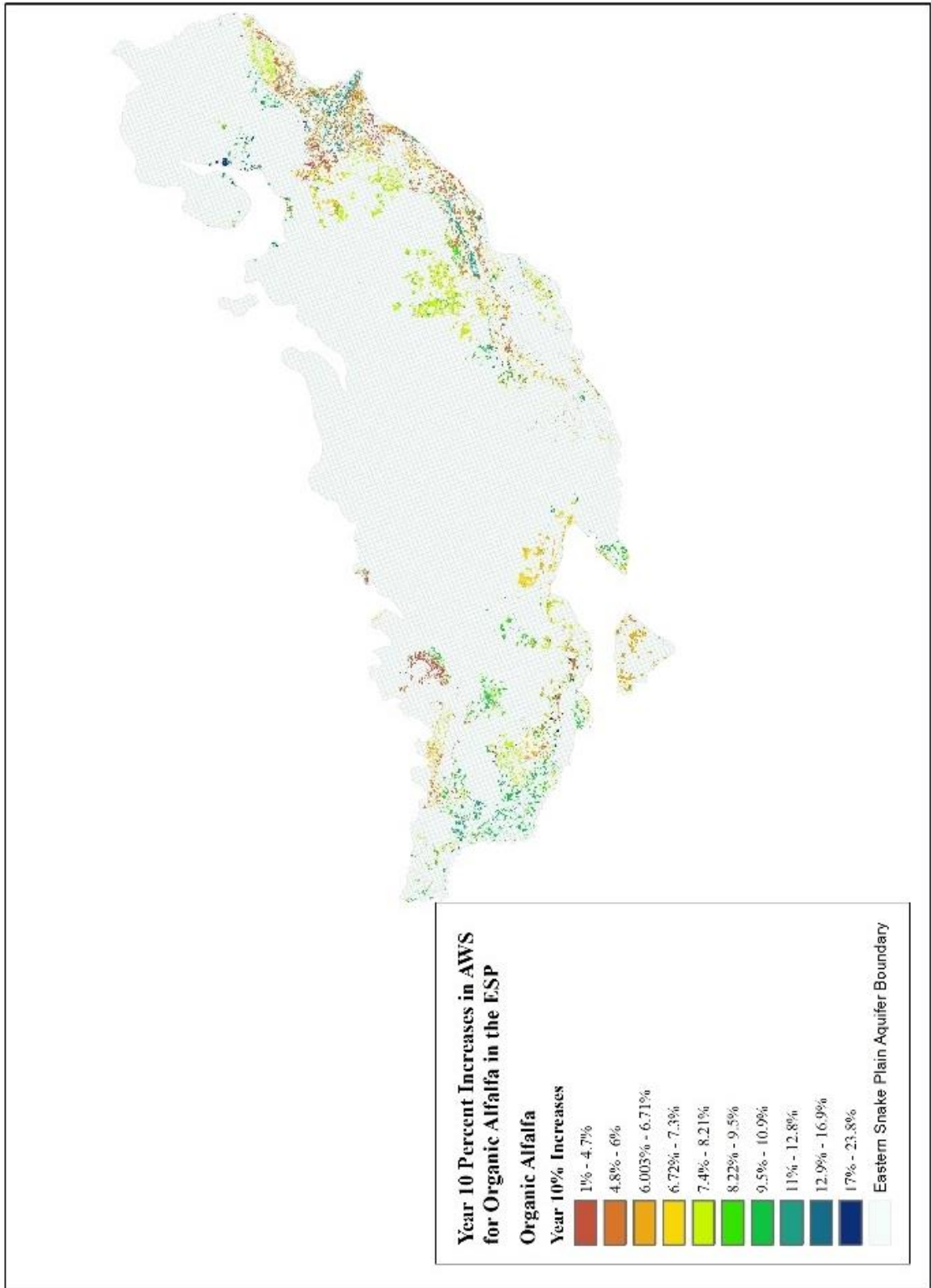


Figure 50. Year 10 percent increases in AWS for organic alfalfa in the ESP.

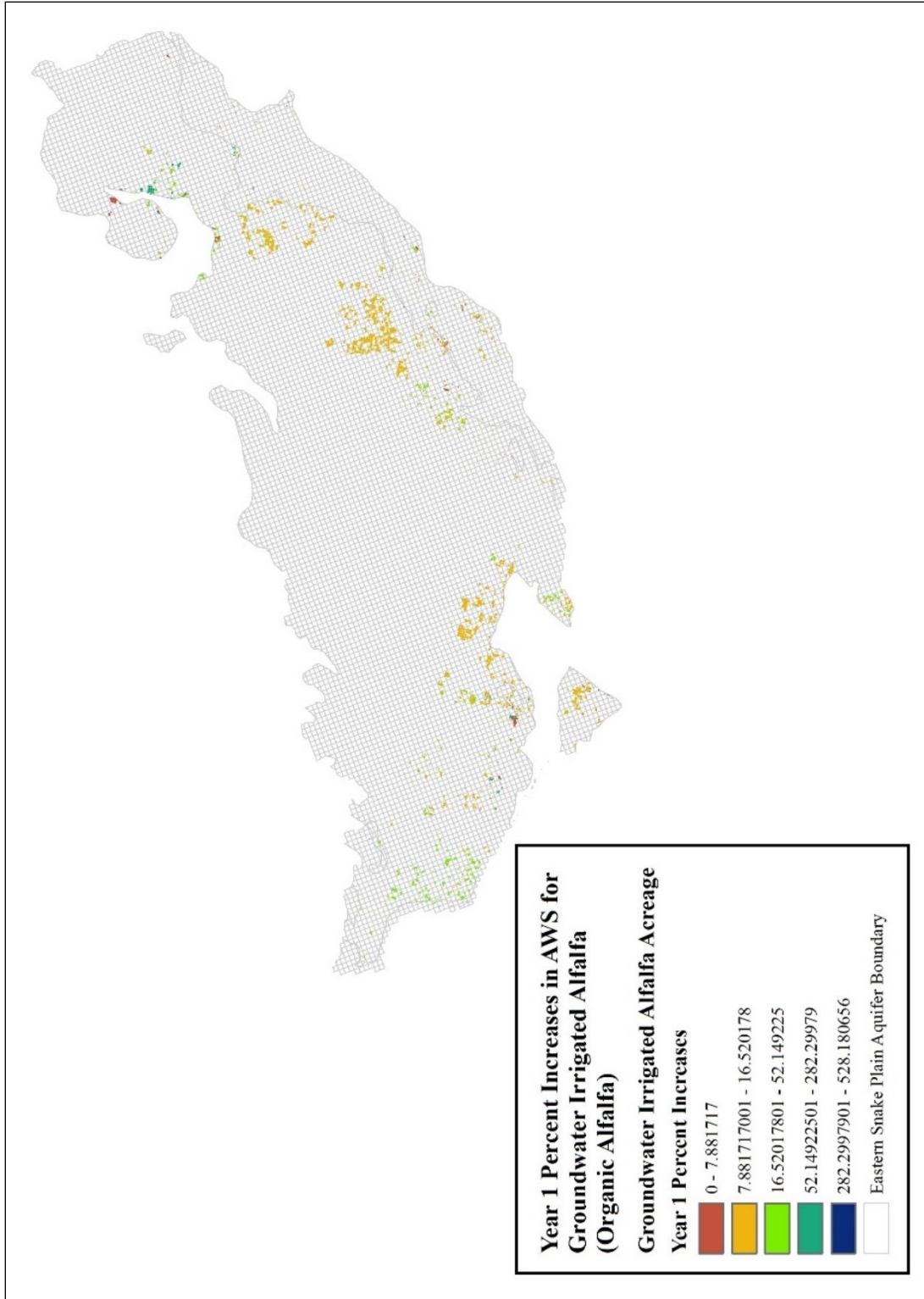


Figure 51. Year 1 percent increases in AWS for organic alfalfa (groundwater irrigated) in the ESP.

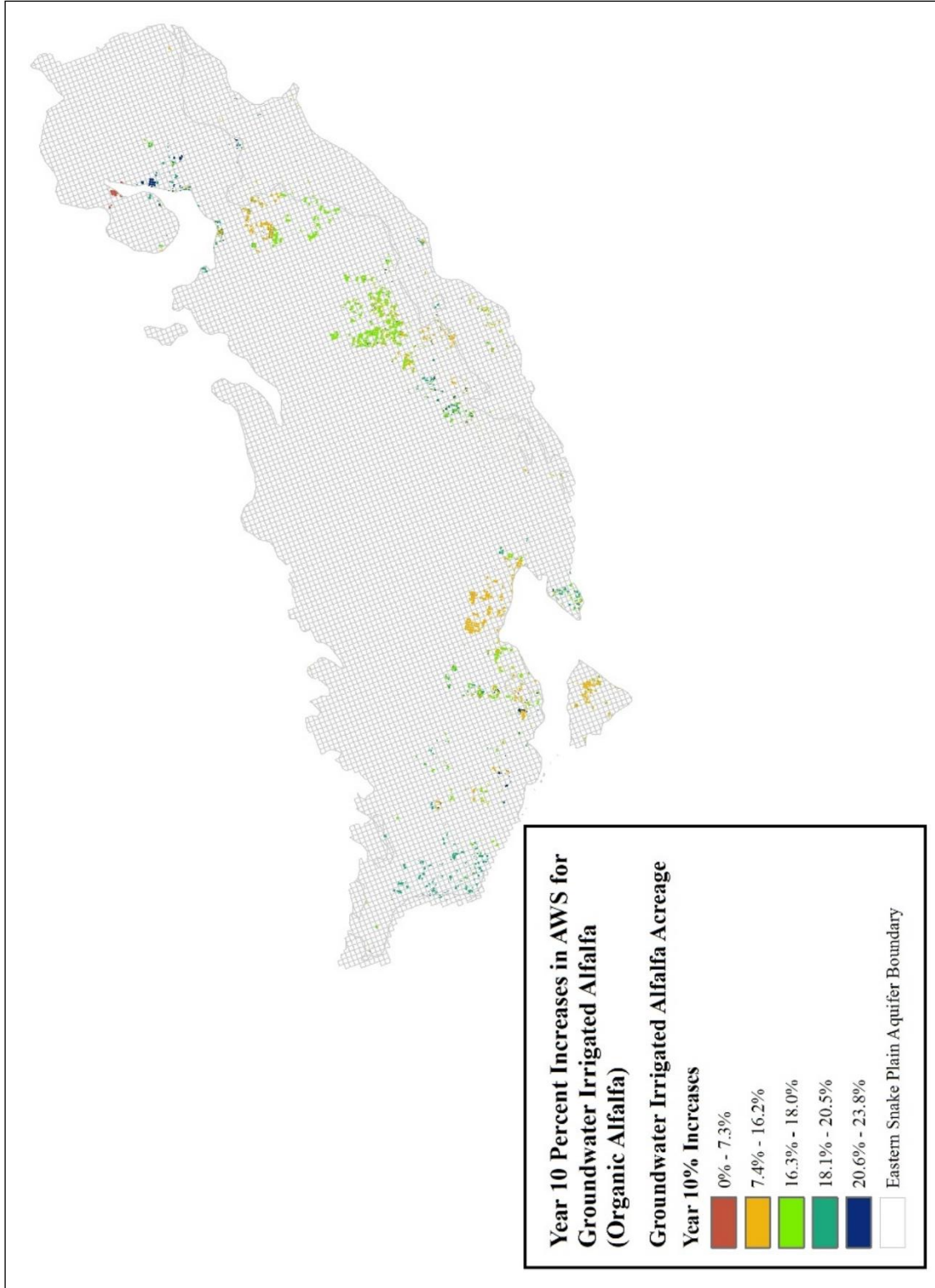


Figure 52. Year 10 percent increases in AWS for organic alfalfa (groundwater irrigated) in the ESP.

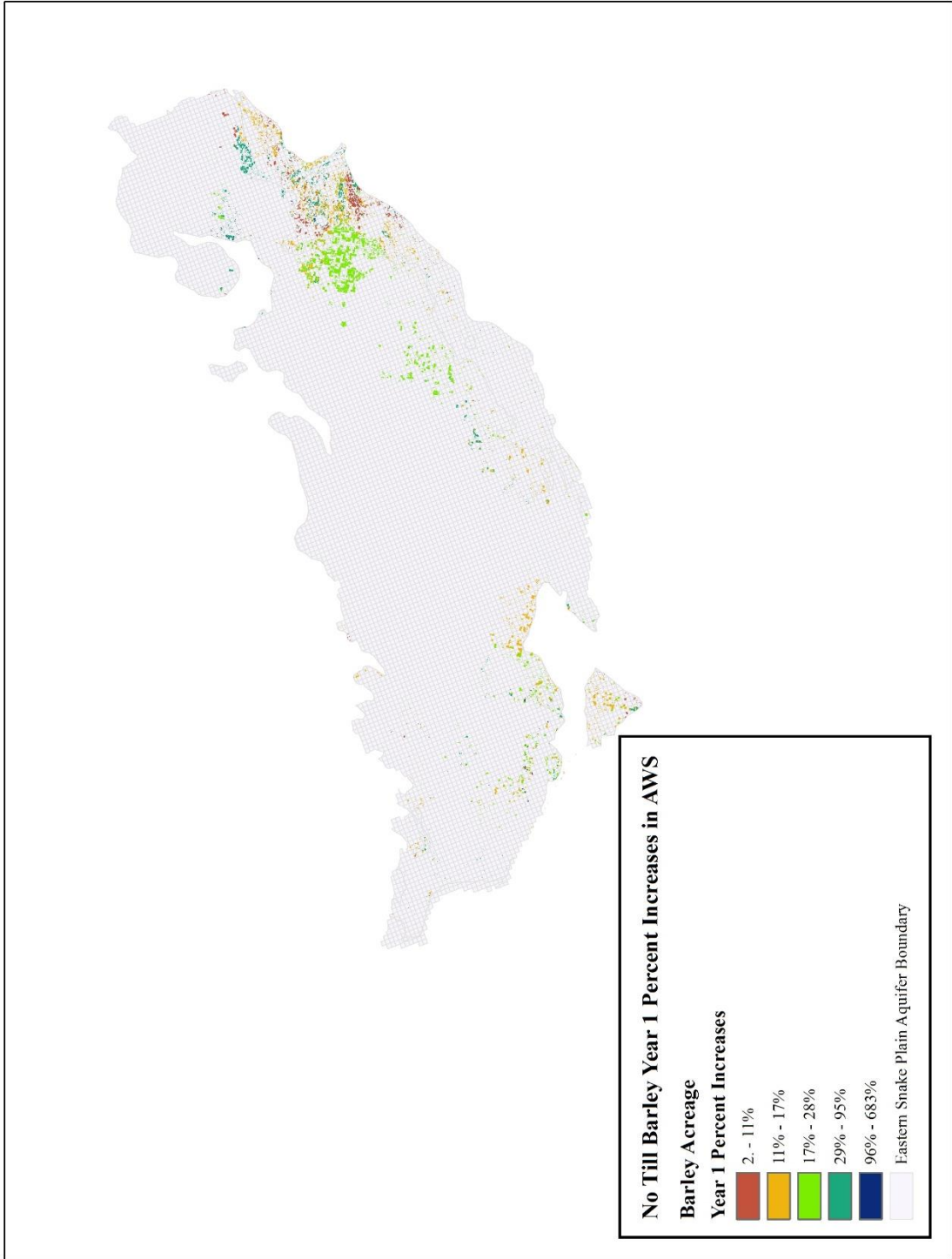


Figure 53. Year 1 percent increases in AWS for no till barley in the ESP.

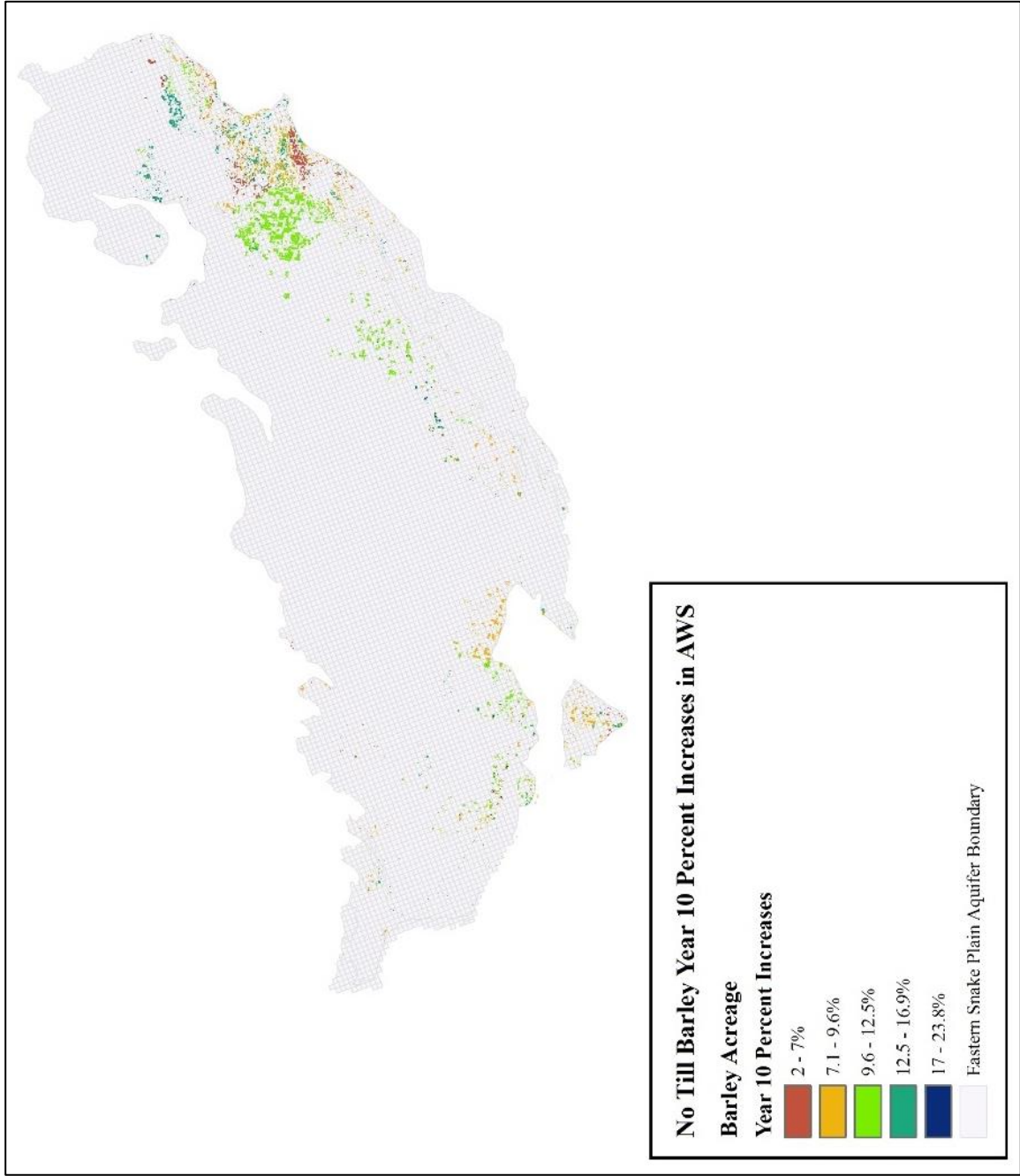


Figure 54. Year 10 percent increases in AWS for no till barley in the ESP.

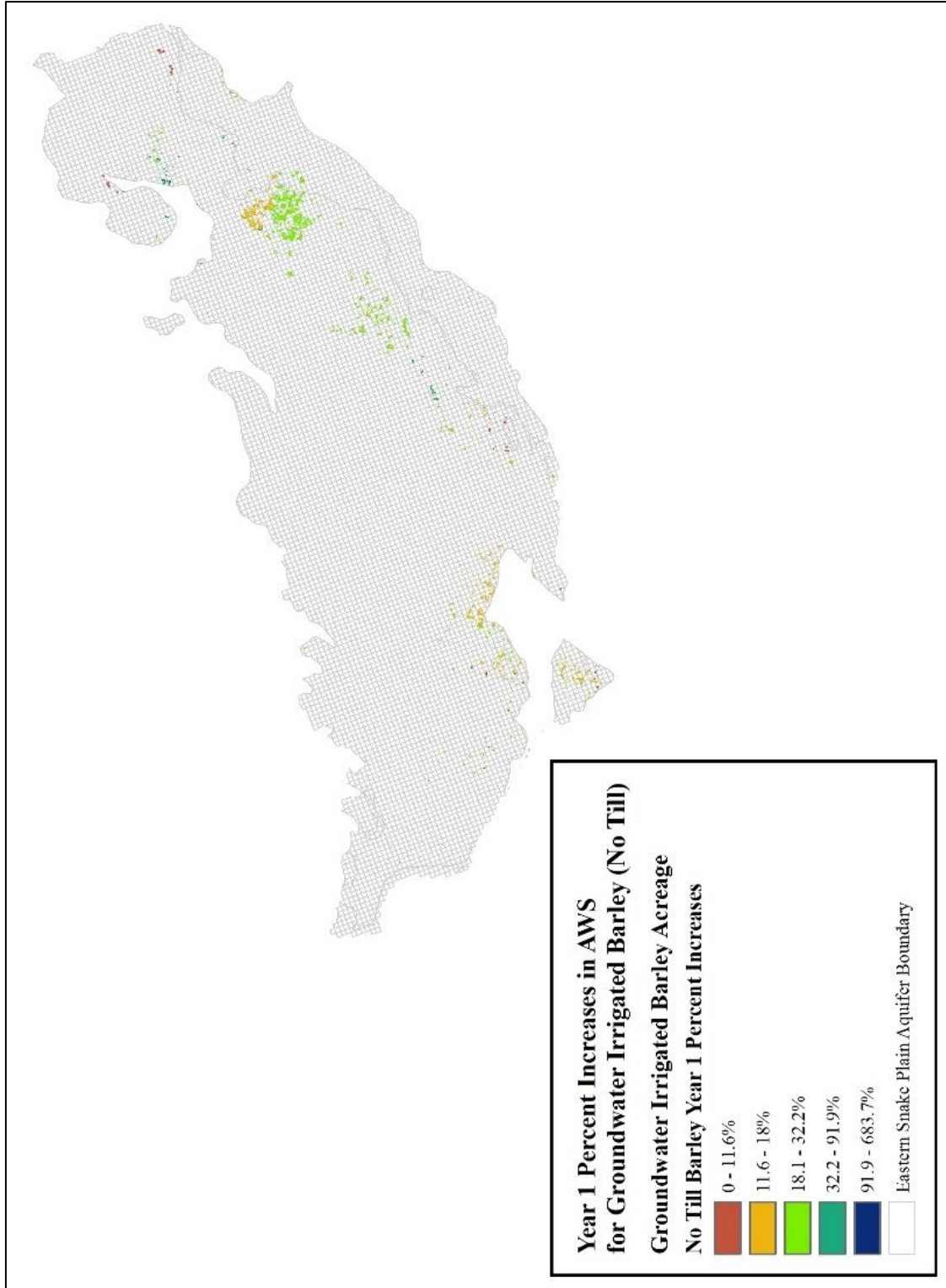


Figure 55. Year 1 percent increases in AWS for no till barley (groundwater irrigated) in the ESP.

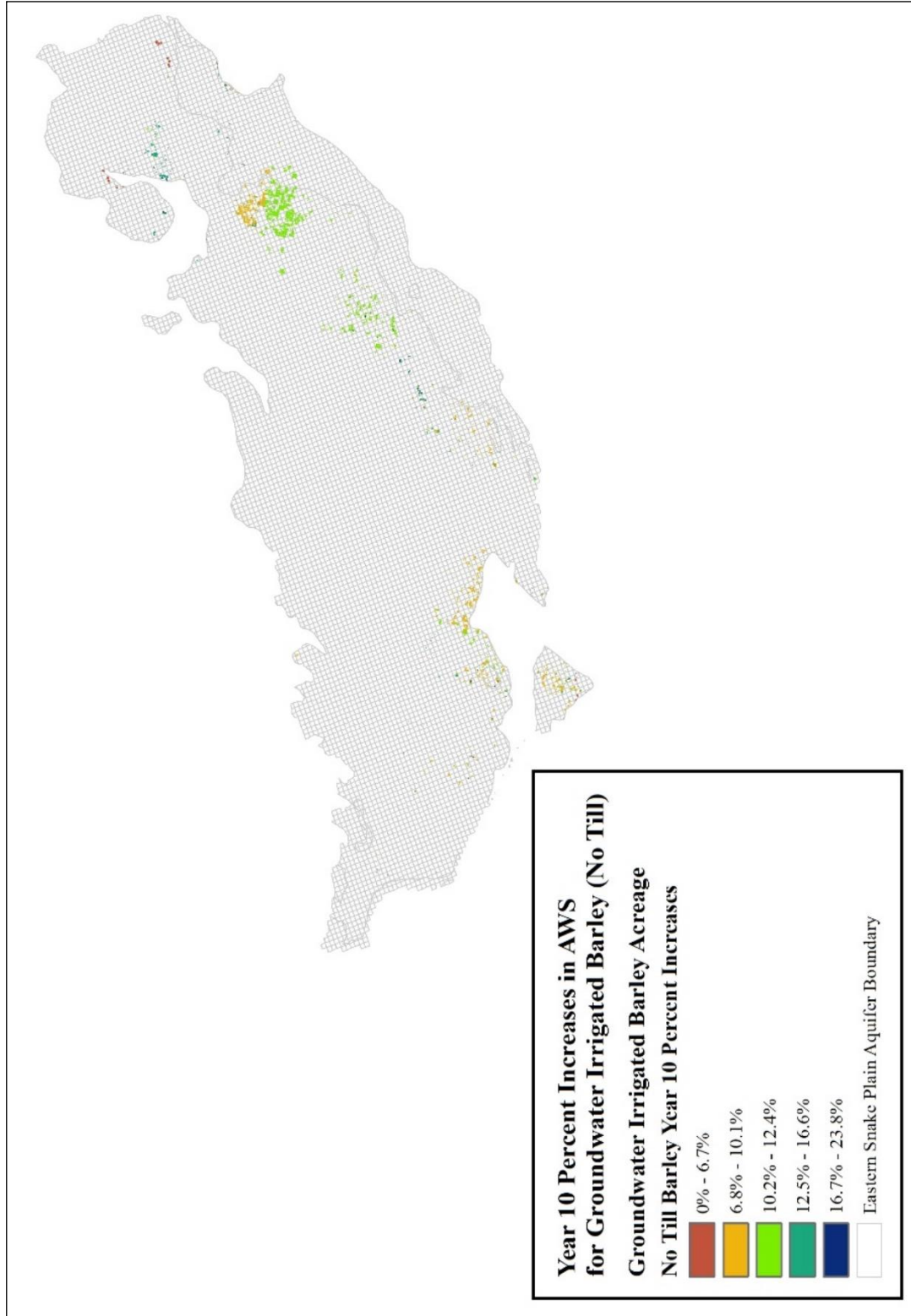


Figure 56. Year 10 percent increases in AWS for no till barley (groundwater irrigated) in the ESP.

Figures 57-60 represent the most conservative scenario (nominal to medium input) for the Ogle pasture benchmarks. Results for other scenarios are available from the author.

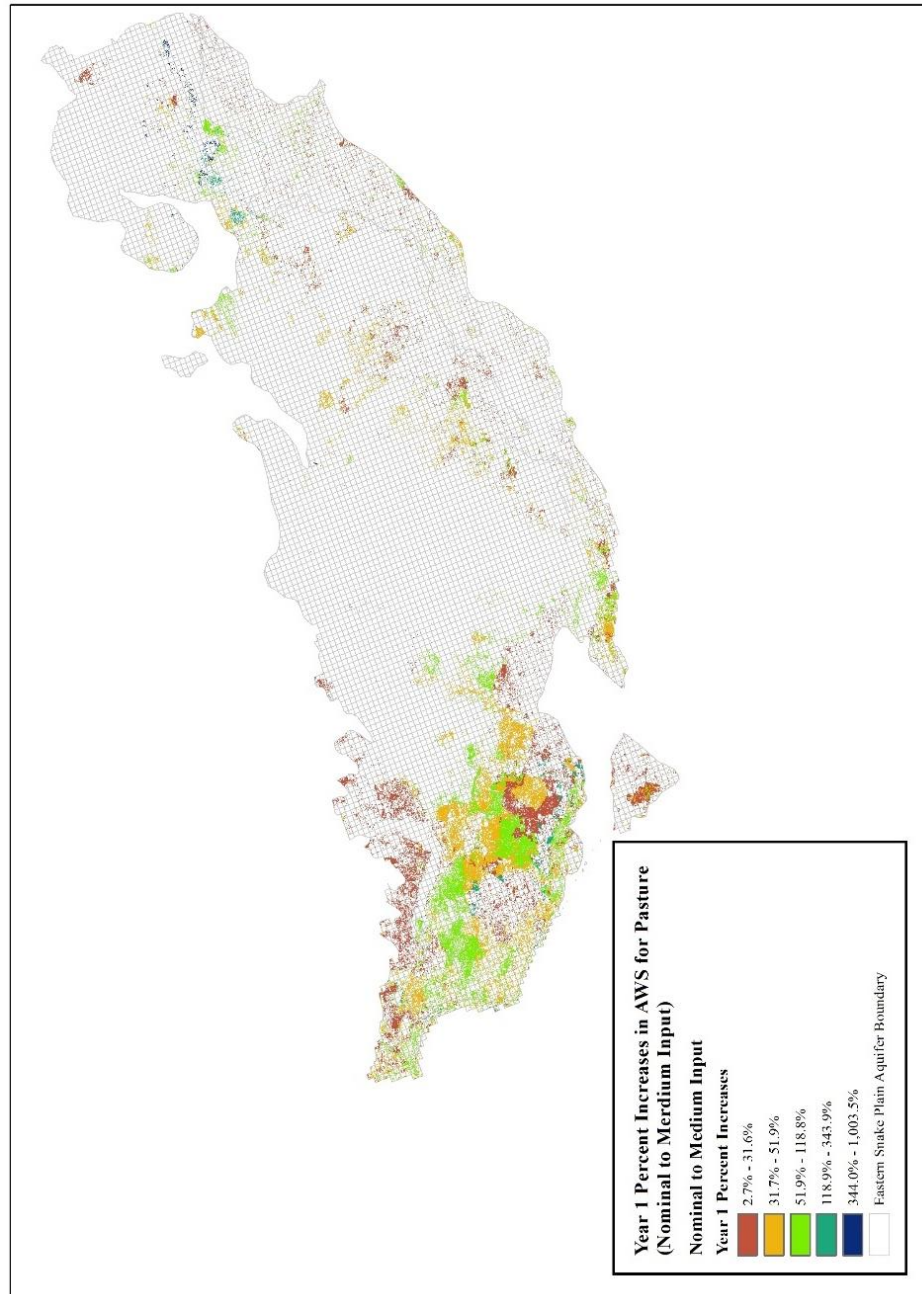


Figure 57. Year 1 percent increases in AWS for nominal to medium input pasture in the ESP.

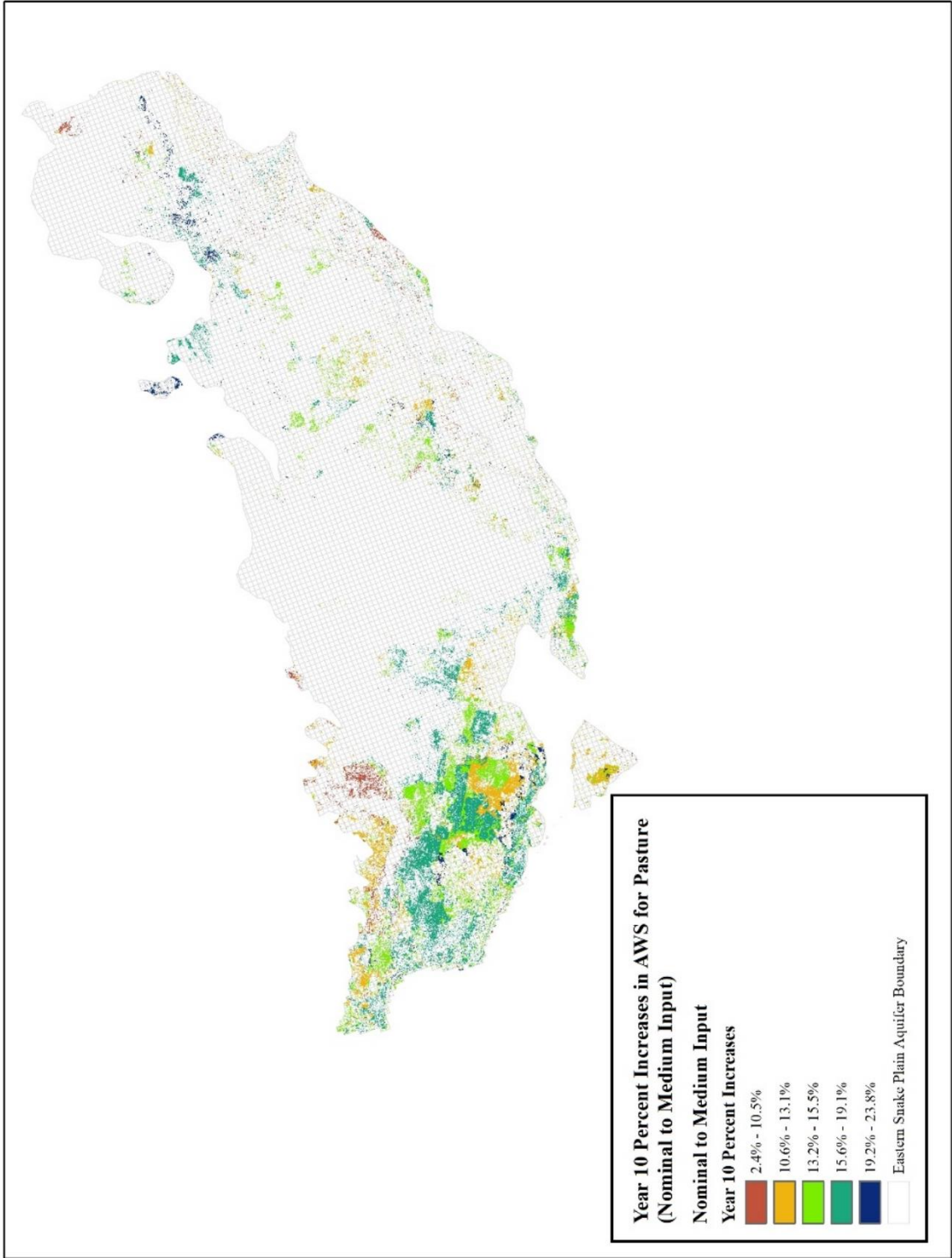


Figure 58. Year 10 percent increases in AWS for nominal to medium input pasture in the ESP.



Figure 59. Year 1 percent increases in AWS for nominal to medium input pasture (groundwater irrigated) in the ESP.



Figure 60. Year 10 percent increases in AWS for nominal to medium input pasture (groundwater irrigated) in the ESP.

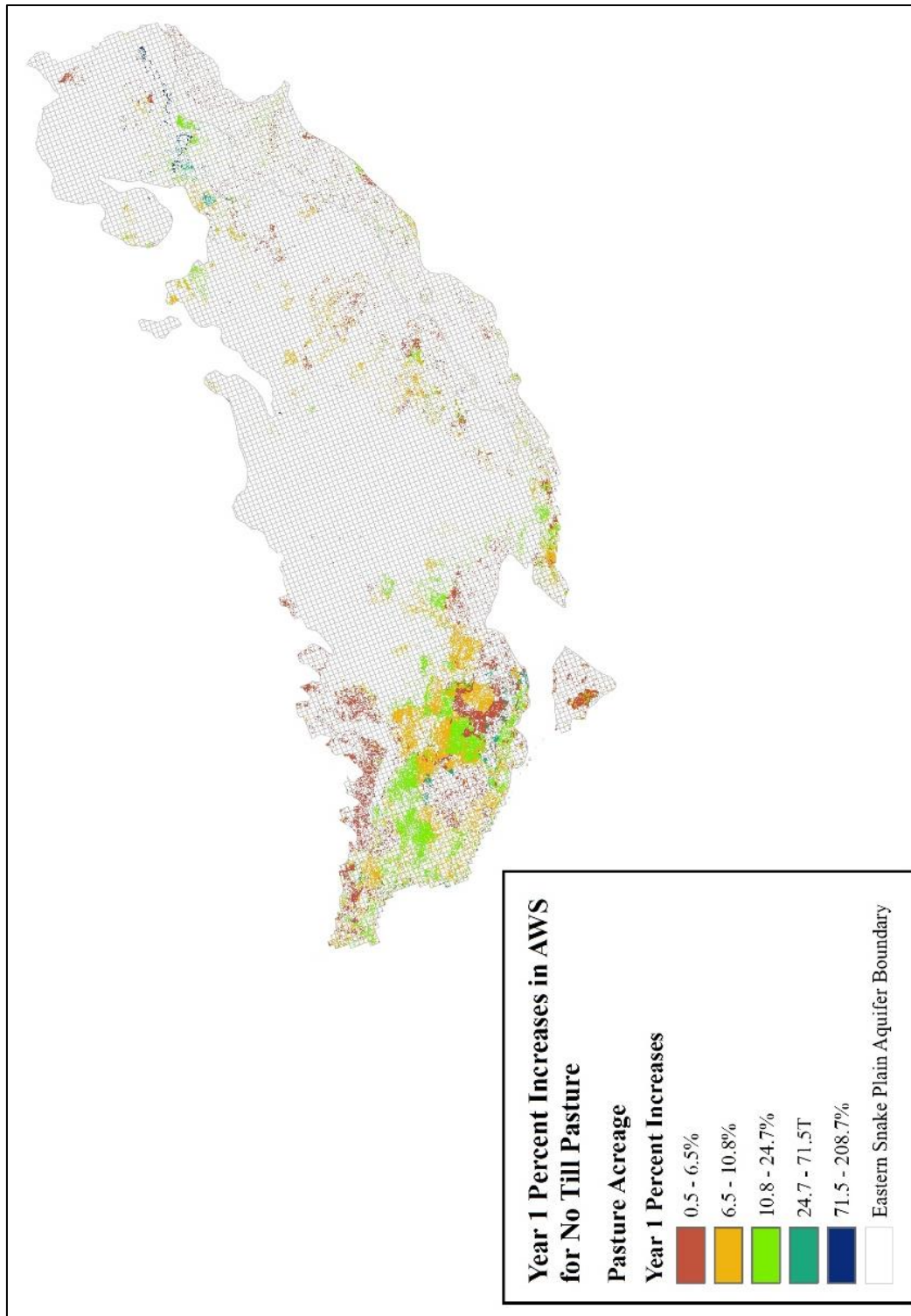


Figure 61. Year 1 percent increases in AWS for no till pasture in the ESP.

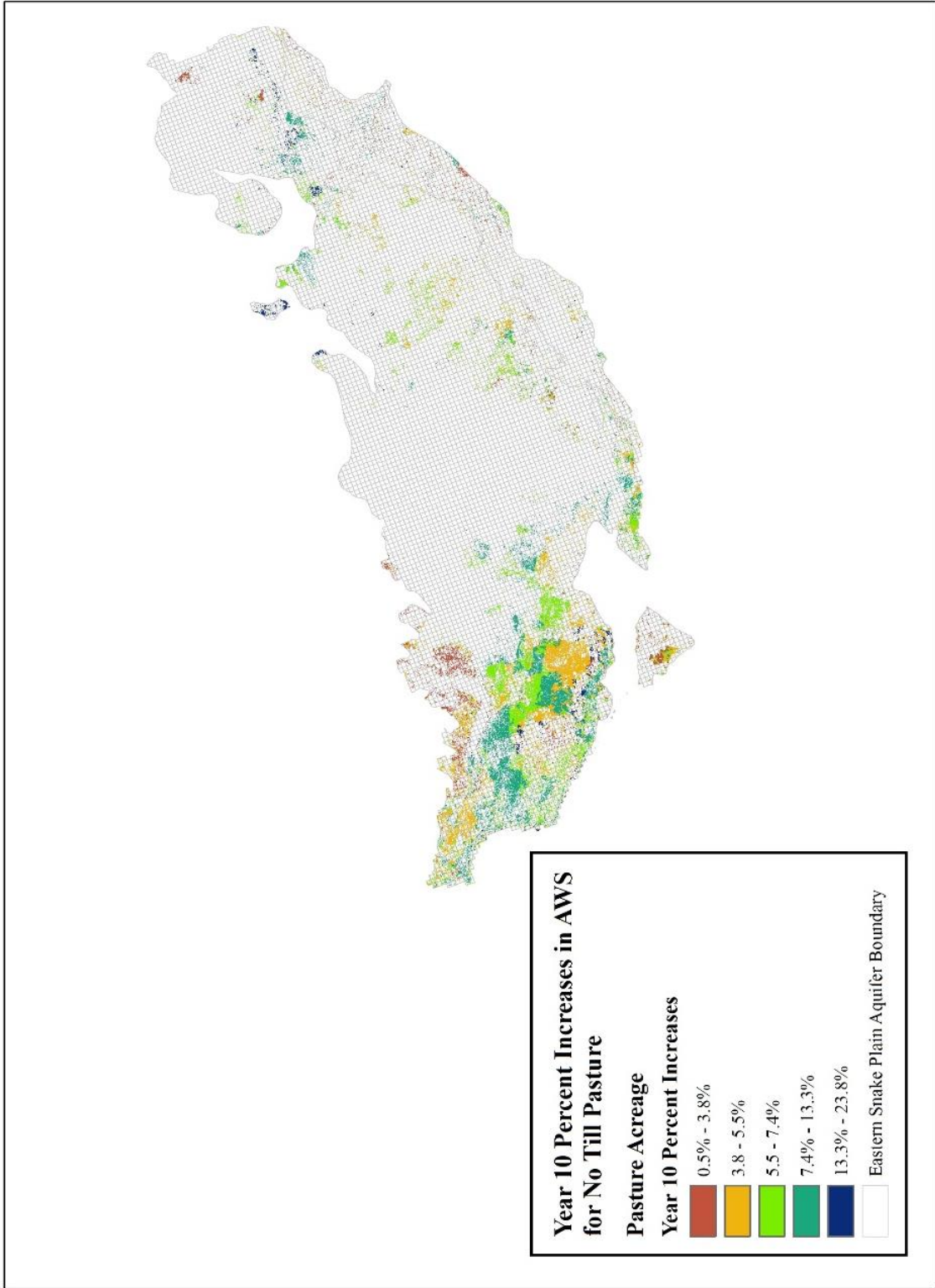


Figure 62. Year 10 percent increases in AWS for no till pasture in the ESP.



Figure 63. Year 1 percent increases in AWS for no till pasture (groundwater irrigated) in the ESP.



Figure 64. Year 10 percent increases in AWS for no till pasture (groundwater irrigated) in the ESP.

Figures 65-66 show the most conservative scenario (nominal to medium input).

Results for other scenarios are available from the author.

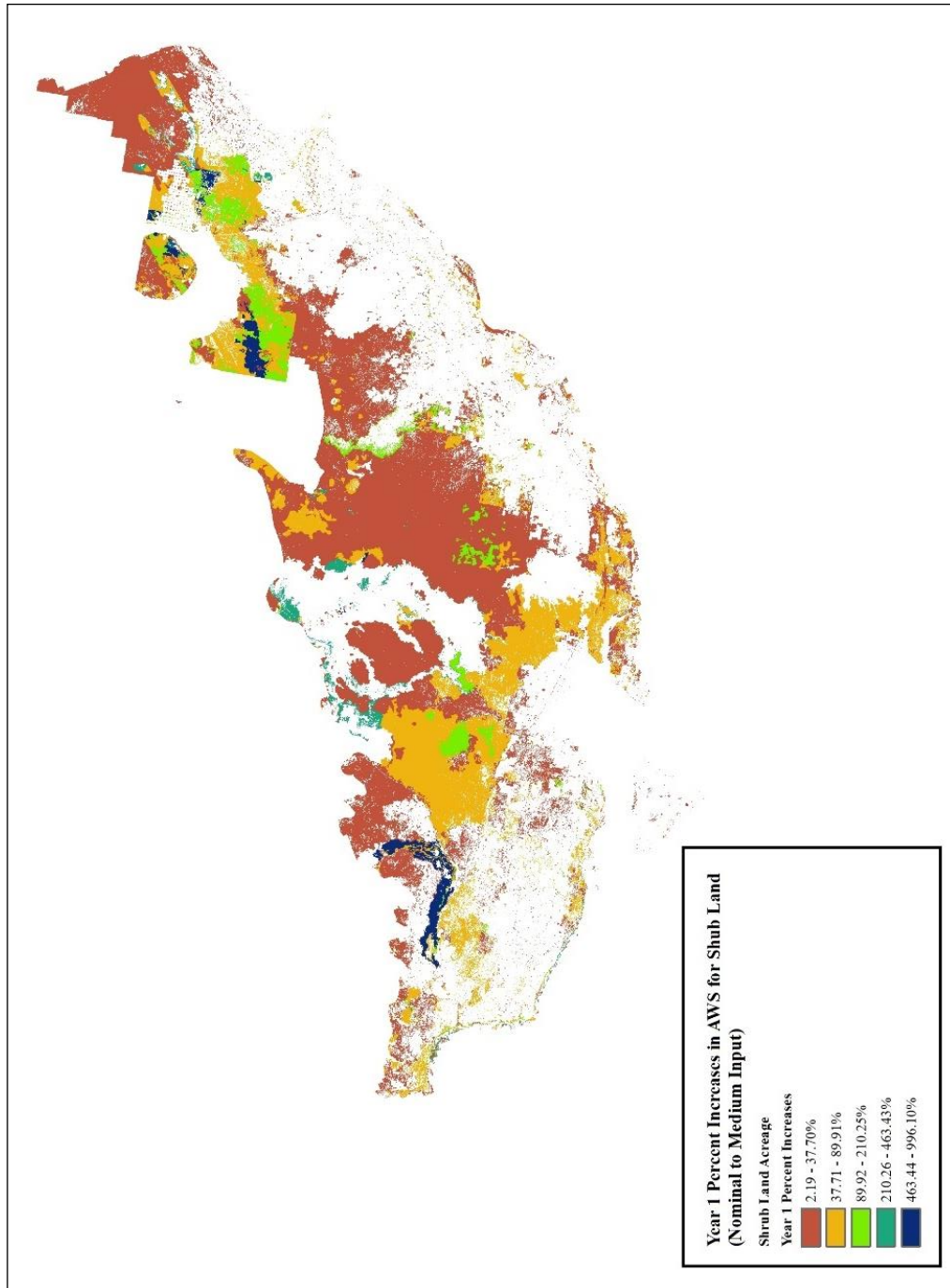


Figure 65. Year 1 percent increases in AWS for nominal to medium input shrub land in the ESP.

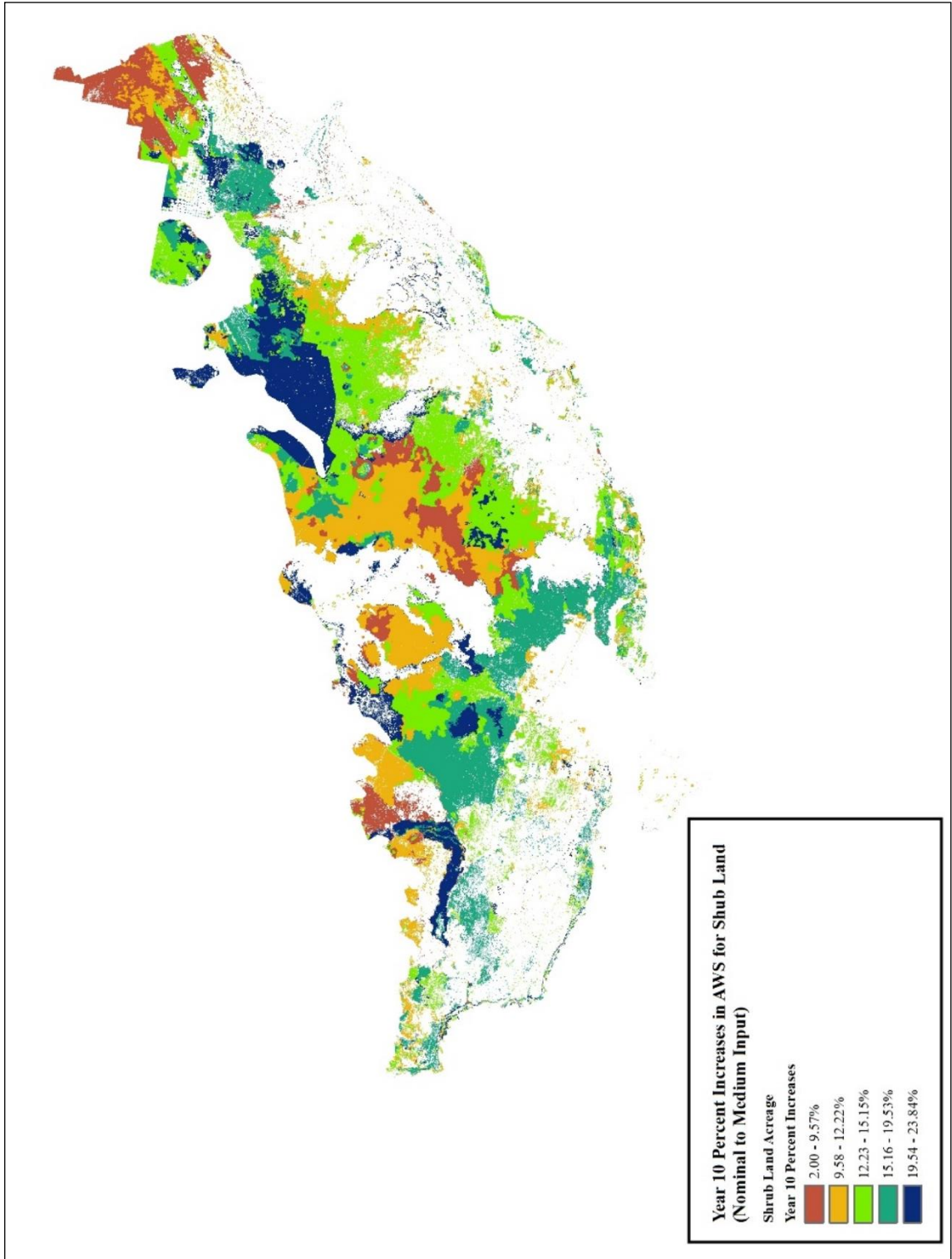


Figure 66. Year 10 percent increases in AWS for nominal to medium input shrub land in the ESP.

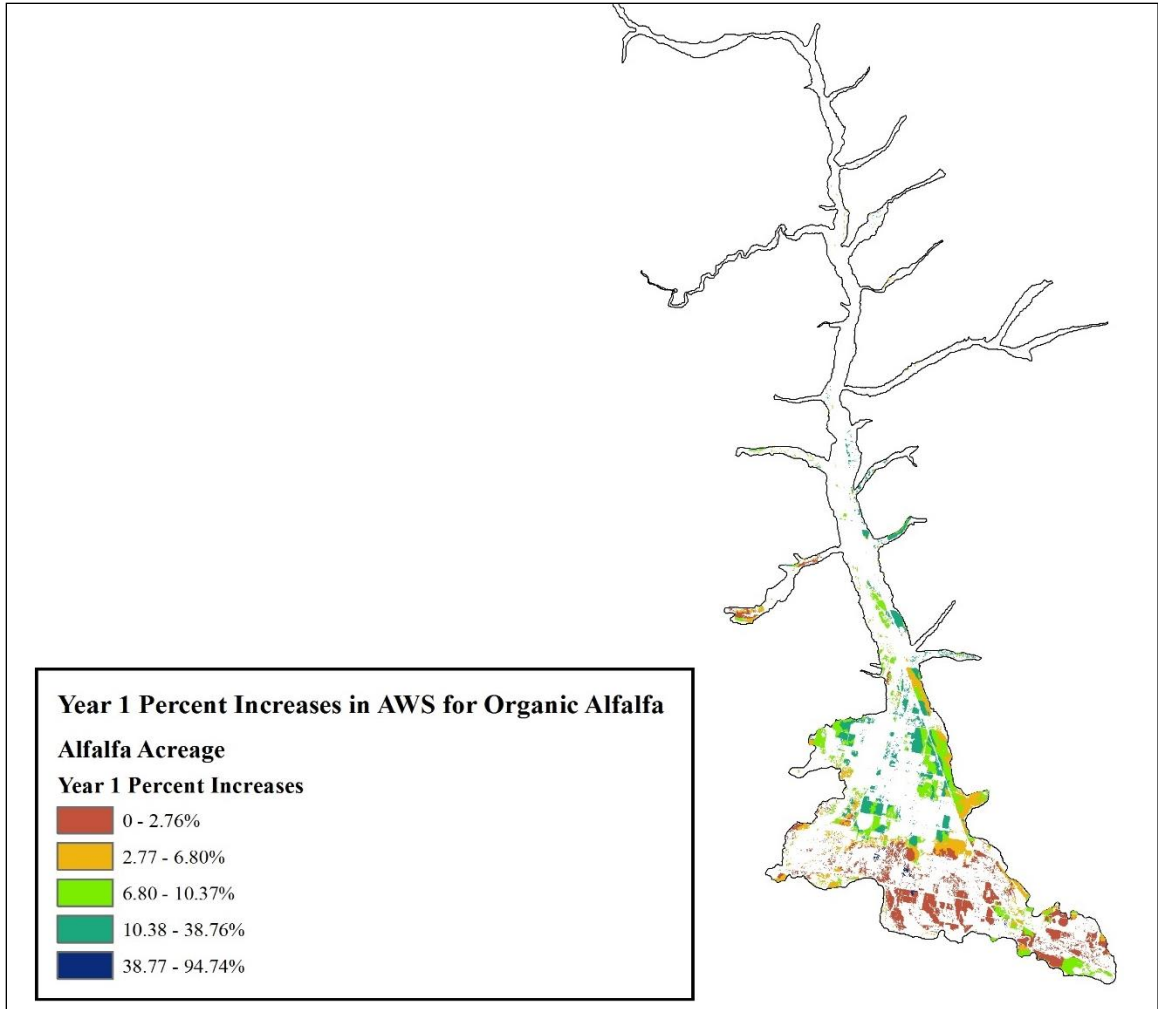


Figure 67. Year 1 percent increases in AWS for organic alfalfa in the WRV.

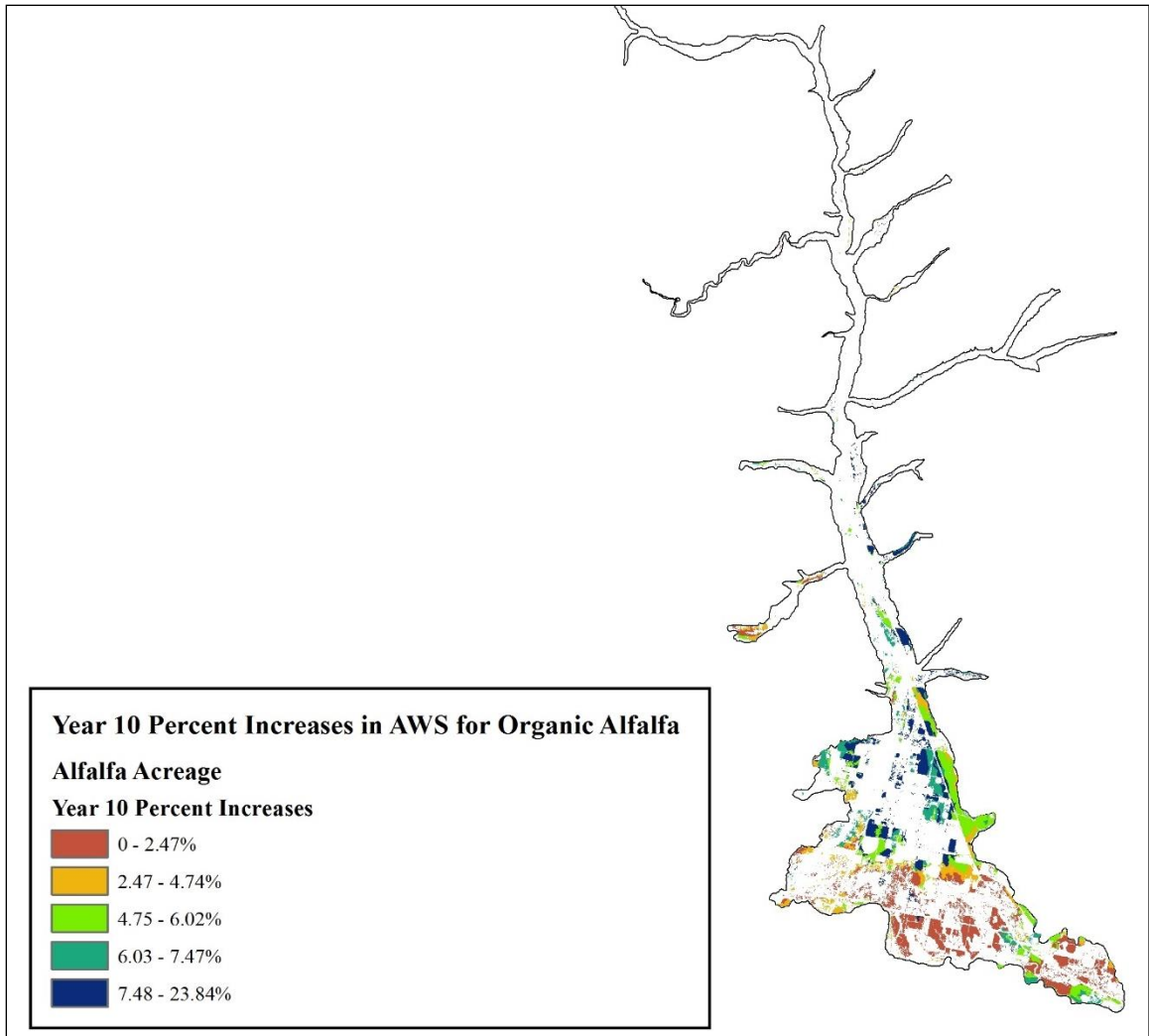


Figure 68. Year 10 percent increases in AWS for organic alfalfa in the WRV.

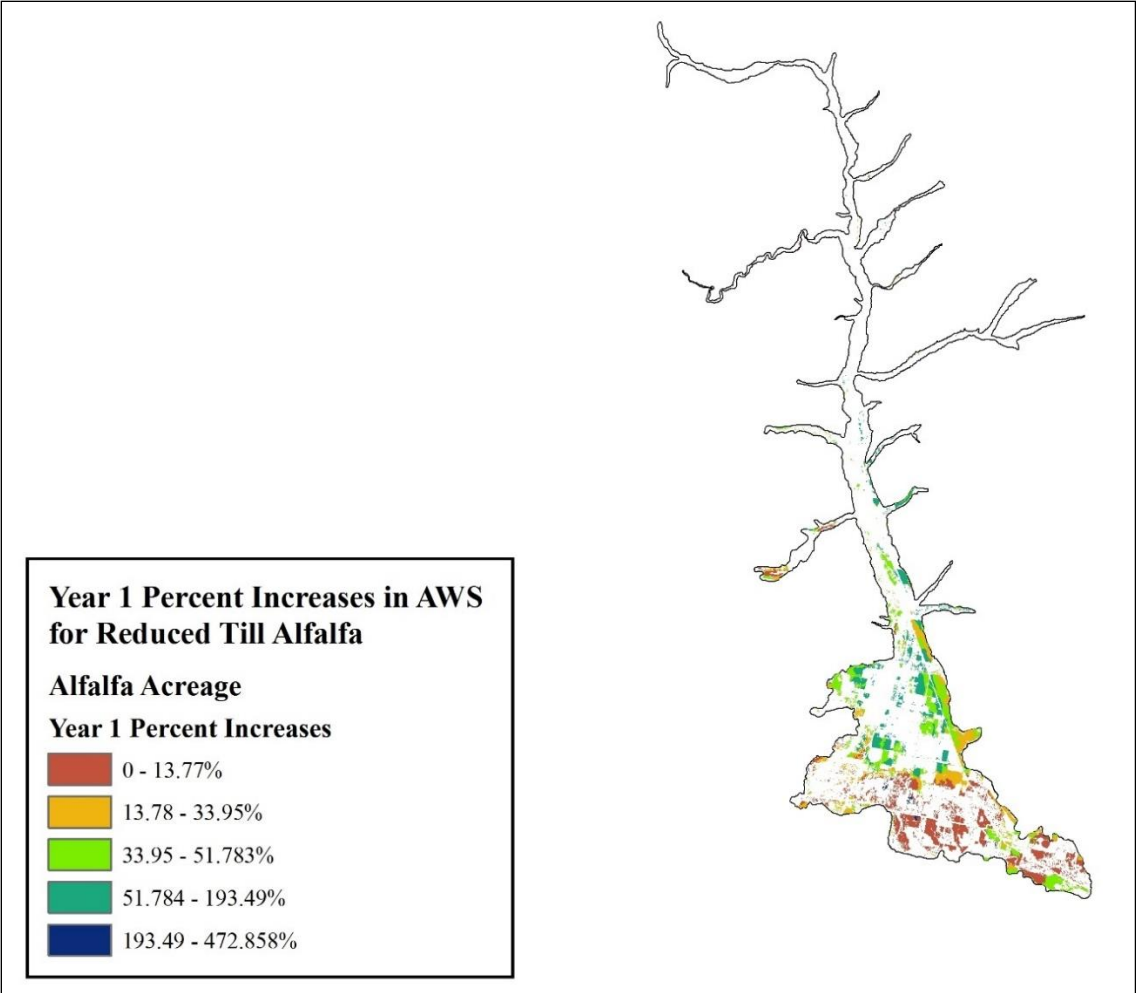


Figure 69. Year 1 percent increases in AWS for reduced till alfalfa in the WRV.

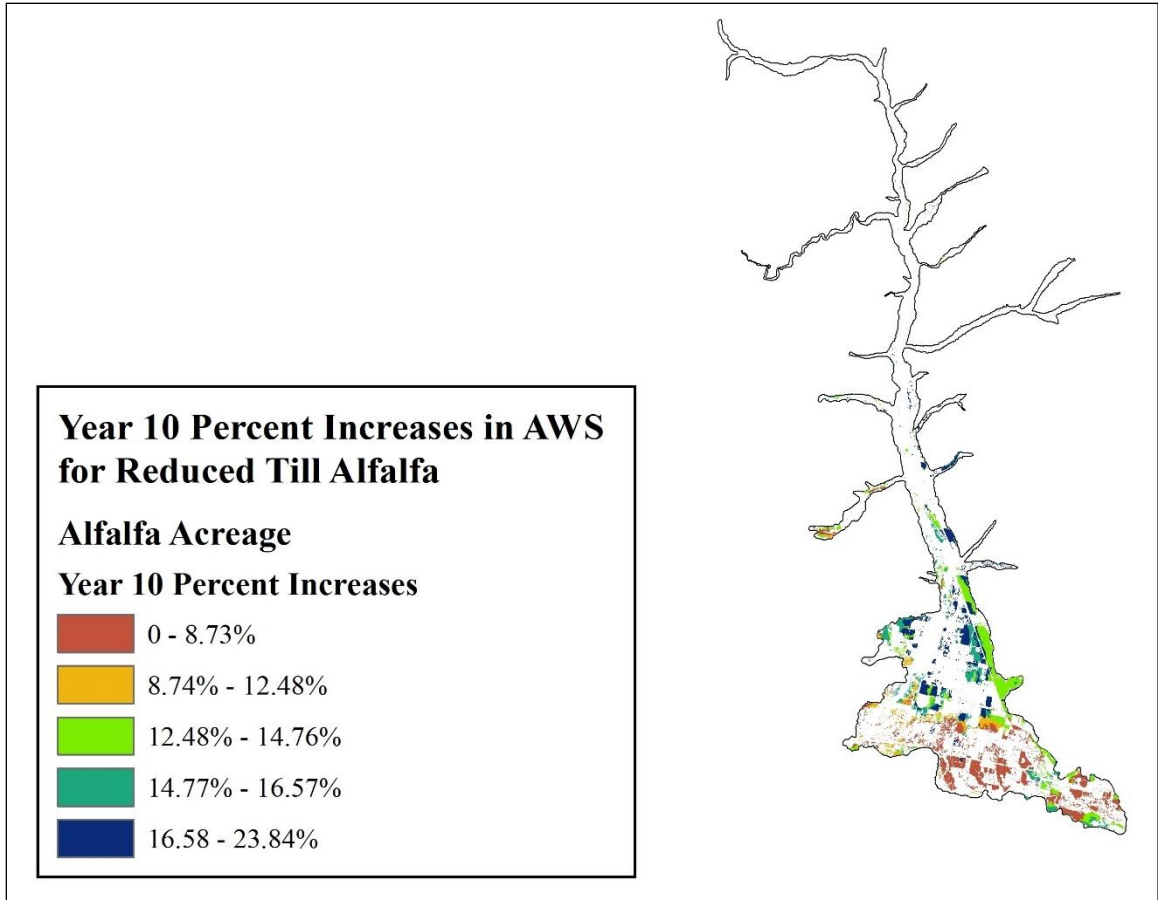


Figure 70. Year 10 percent increases in AWS for reduced till alfalfa in the WRV.

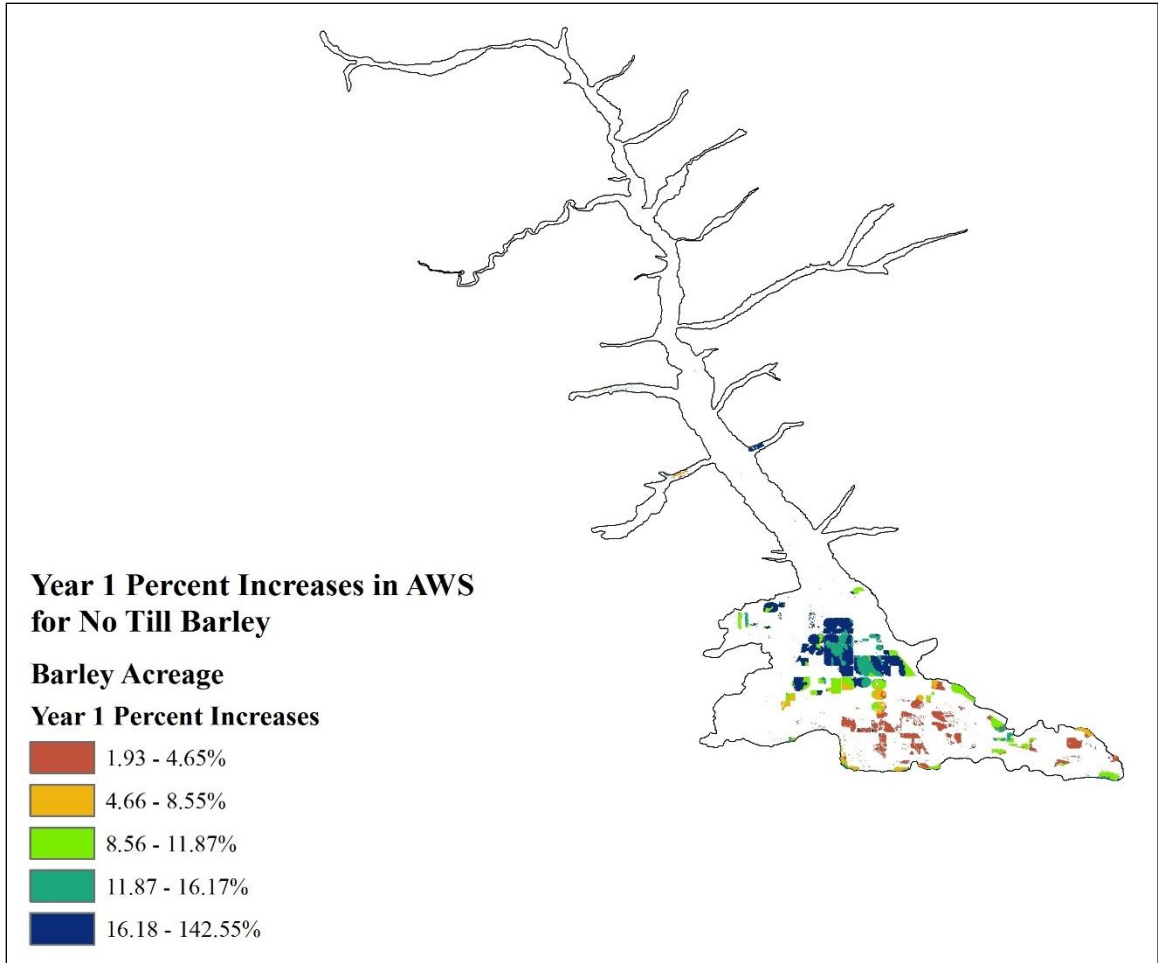


Figure 71. Year 1 percent increases in AWS for reduced till alfalfa in the WRV.

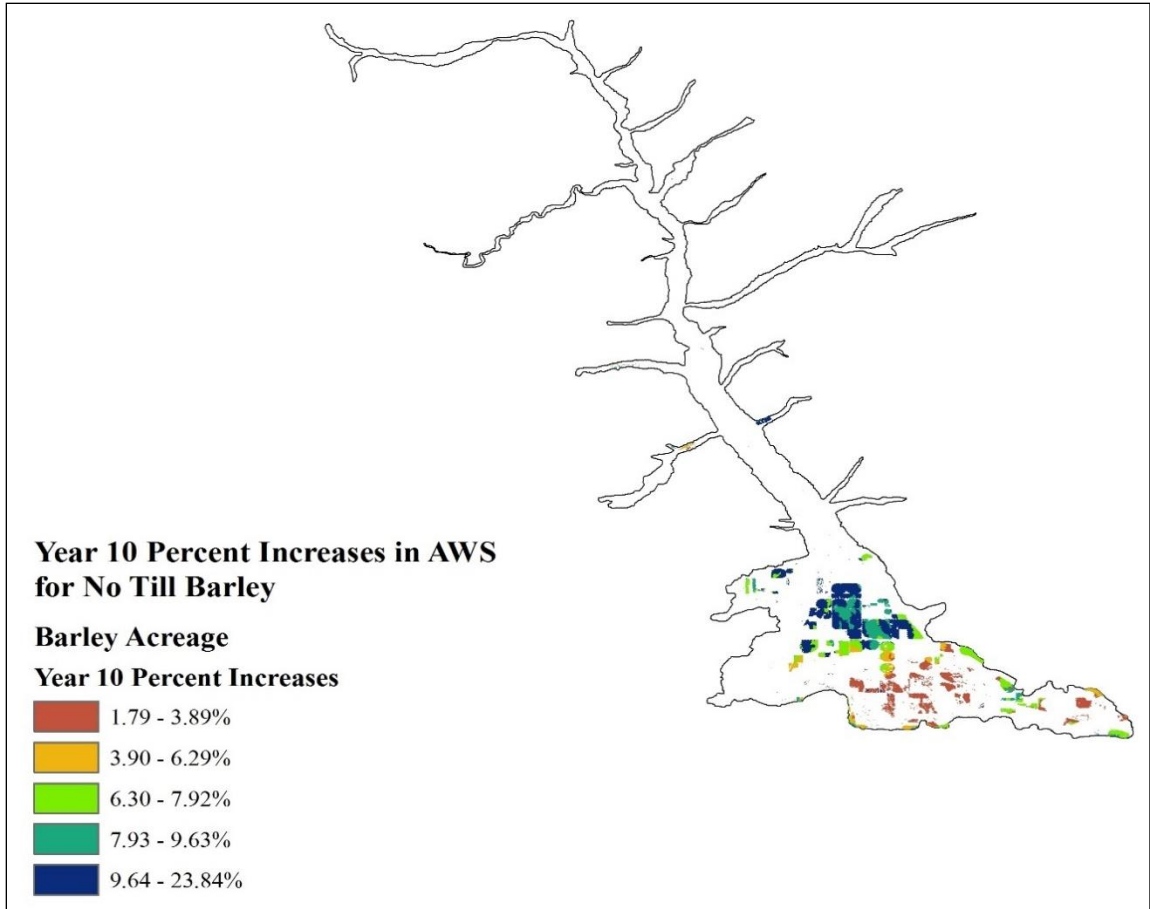


Figure 72. Year 10 percent increases in AWS for reduced till alfalfa in the WRV.

Figures 73-74 show the most conservative scenario (nominal to medium input).

Results for other scenarios are available from the author.

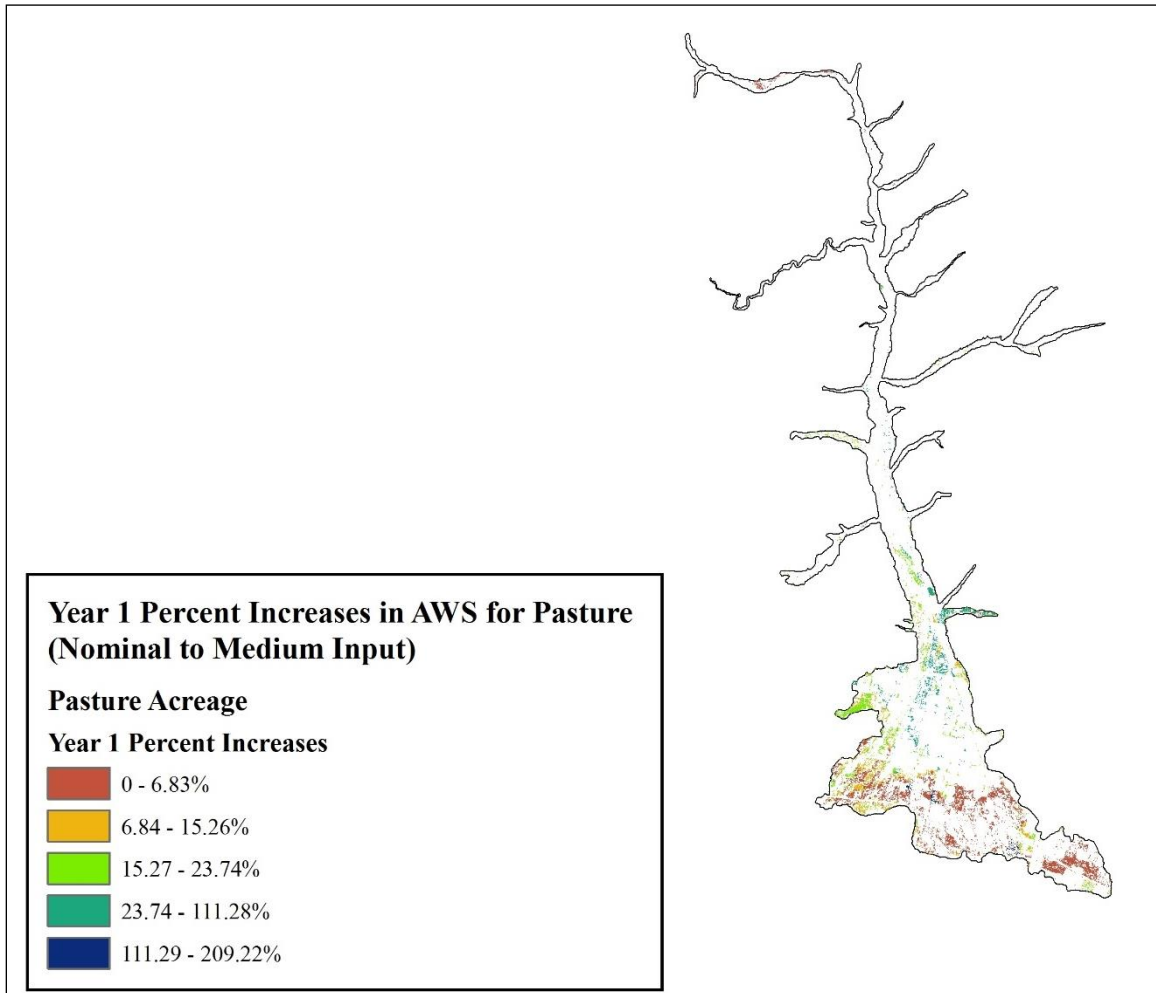


Figure 73. Year 1 percent increases in AWS for nominal to medium input pasture in the WRV.

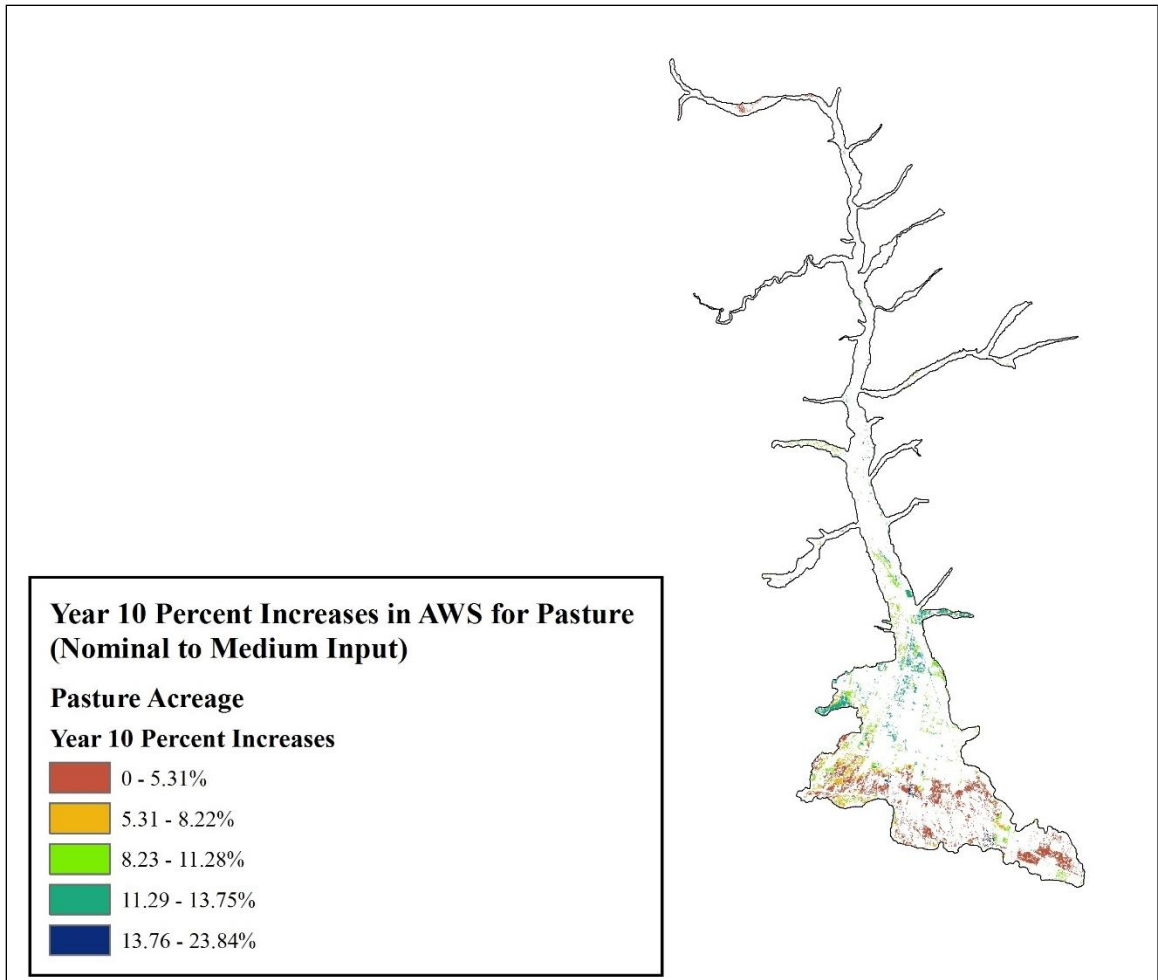


Figure 74. Year 10 percent increases in AWS for nominal to medium input pasture in the WRV.

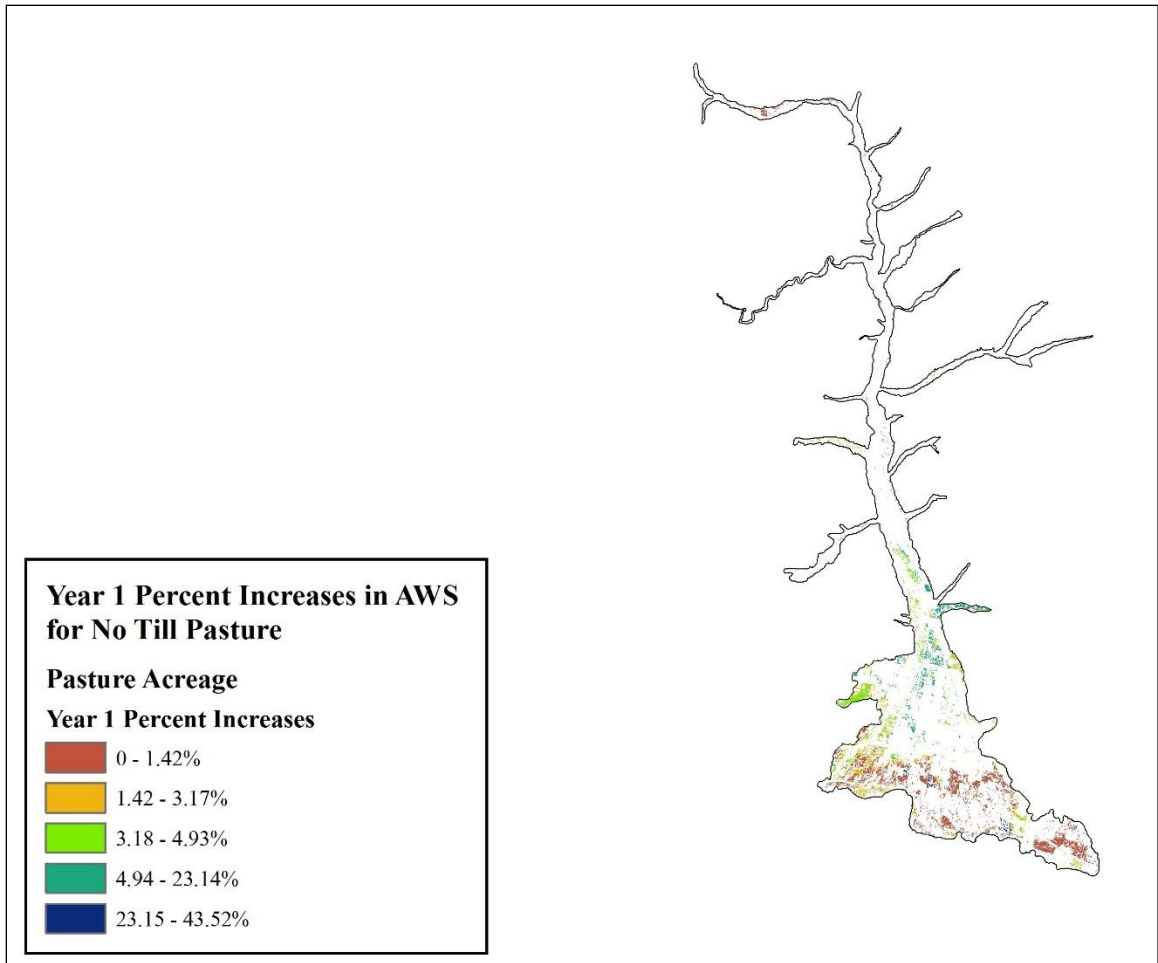


Figure 75. Year 1 percent increases in AWS for no till pasture in the WRV.

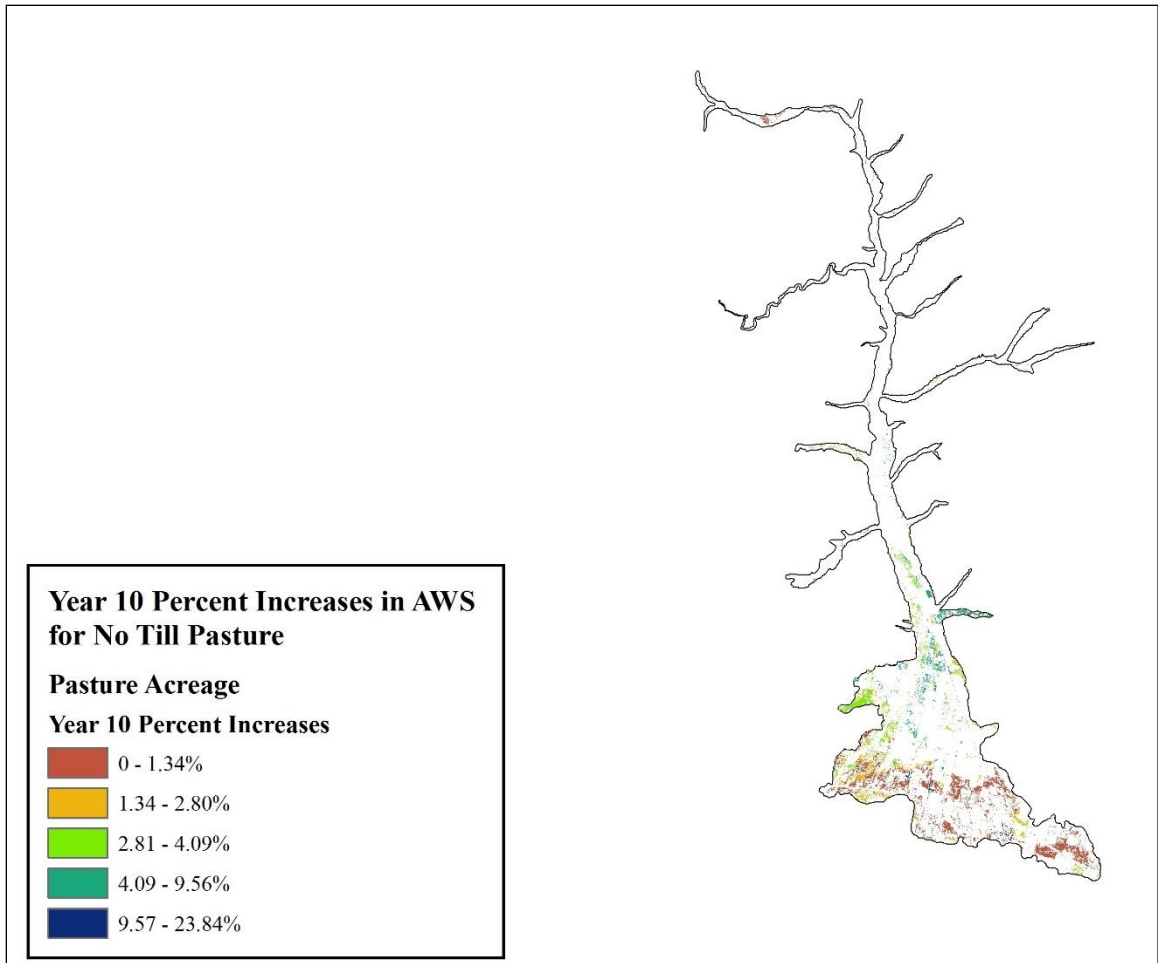


Figure 76. Year 10 percent increases in AWS for no till pasture in the WRV.

Figures 77-78 show the most conservative scenario for the Ogle shrub land benchmarks (nominal to medium input). Results for other scenarios are available from the author.

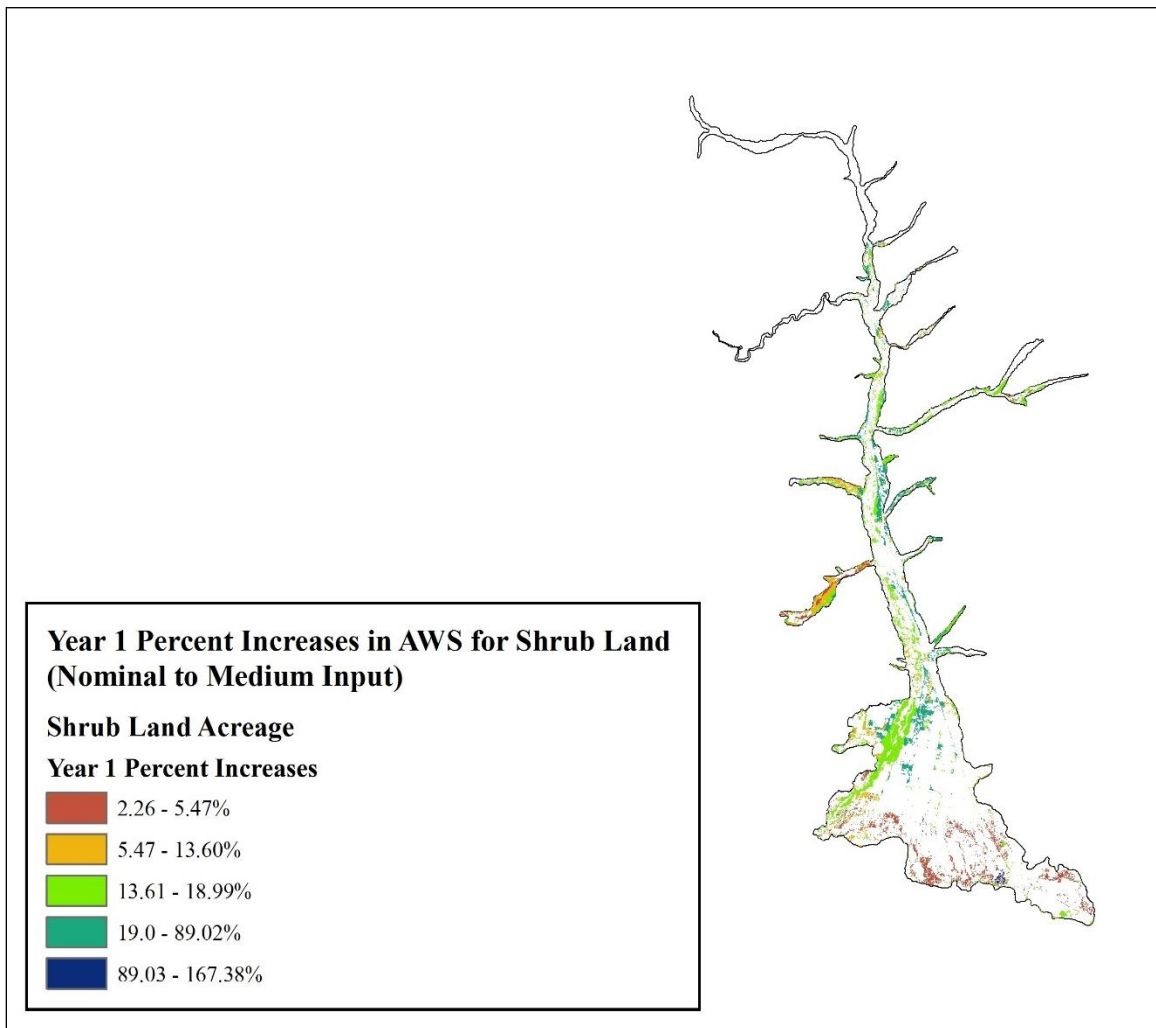


Figure 77. Year 1 percent increases in AWS for nominal to medium input shrub land in the WRV.

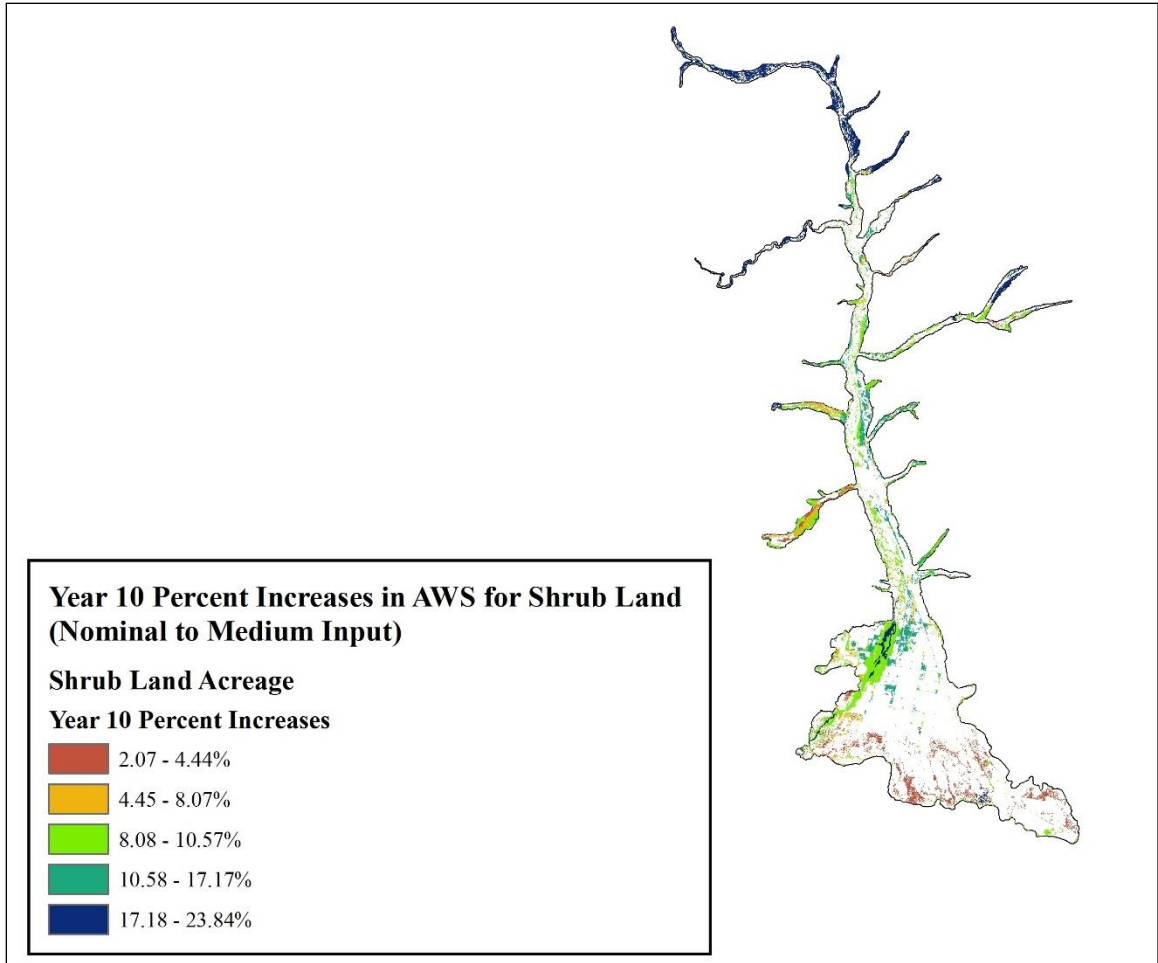


Figure 78. Year 10 percent increases in AWS for nominal to medium input shrub land in the WRV.

Ancillary Appendix 4

Impacts of Varying C Contents

As originally conceived, one aim of this thesis was to model the impacts of differing carbon contents on AWS increases. SOC:SOM ratios vary depending soil characteristics, though the scientific convention is to use a 58% content (Pribyl, A critical review of the conventional SOC to SOM conversion factor, 2010) (Franzluebbers, 2010) (Hudson, 1994). Increased attention to the CO₂ sequestration potential of agricultural lands has led some to question the conventional 58% C ratio (Pribyl, 2010). More recent estimates put the range between ~42-58% SOC (Kimble, et al., 2007). Pribyl, (2010) found that in almost all cases reviewed that an assumption of 50% would be more accurate. The differing C content lead to the following SOC: AWS relationships: 1) 42% SOC: 1.554% increase in AWS; 2) 50% SOC: 1.85% increase in AWS; 3) 58% SOC: 2.146% increase in AWS.

For demonstrative purposes, this Appendix provides the results of applying these differing C contents to: 1) the time needed to reverse drought vulnerability; 2) impacts on non-irrigated recharge on shrub land in the ESP; and 3) impacts on total recharge for no till Barley. I chose to focus on no till Barley because this is the crop applicable to the financial analysis.

While an imperfect analysis because C sequestration studies measured C directly, assumptions of the C content could become relevant in a variety of contexts. For instance, if policymakers decide to prioritize certain conservation practices – e.g., mulch

till or compost – and make assumptions regarding either sequestration, soil building, or AWS, they will necessarily assume a C content.

As these results show the effects vary depending upon the parameter being examined and baseline SOC AWS values. For instance, for reversing drought vulnerability, except no till pasture, the maximum difference is five years (Table 25). In most cases, however, the difference is one to two years (Table 25). For the impacts on non-irrigated recharge, varying the C content has significant impacts, sometimes more than 1000% in Year 5, though the impacts in Year 1 are much less – generally 30% or less (Table 26). Finally, for the impacts on total recharge of no till barley, the effect is minimal (~4% or less) (Table 27).

Table 25. Impacts of C content on time needed to reverse drought vulnerability (mean values).

Crop/Land Use Type	Year (58% C Content)	Year (50% C Content)	Year (42% C Content)
Pasture			
Conant Degraded to High Input	Year 6	Year 7	Year 9
Conant Nominal to High Input	Year 7	Year 8	Year 11
Conant Degraded to Medium Input	Year 7	Year 9	Year 12
Conant Nominal to Medium Input	Year 9	Year 11	Year 14
No Till Pasture	+35 Years	+35 Years	+Year 35
Shrub Land			
Conant Degraded to High Input	Year 3	Year 3	Year 4
Conant Nominal to High Input	Year 3	Year 4	Year 5
Conant Degraded to Medium Input	Year 5	Year 5	Year 7
Conant Nominal to Medium Input	Year 5	Year 7	Year 8

^a Results like underestimated because improved AWS benchmark comes only from top 30 cm.

Table 26. Impacts of C content on non-irrigated recharge for shrub land in the ESP (mean values).

Scenario	Year 1	Year 5	Year 10
Conant Degraded to High (58% C)	226.92%	2443.35%	8450.69%
Conant Degraded to High (50% C)	195.62%	1746.38%	5248.51%
Conant Degraded to High (42% C)	164.32%	1207.36%	3148.62%
Conant Nominal to High (58% C)	201.71%	2099.45%	7162.70%
Conant Nominal to High (50% C)	173.88%	1511.92%	4495.96%
Conant Nominal to High (42% C)	146.06%	1054.01%	2728.94%
Conant Degraded to Medium (58% C)	126.07%	1140.23%	3651.03%
Conant Degraded to Medium (50% C)	108.68%	847.93%	2401.76%
Conant Degraded to Medium (42% C)	91.29%	612.10%	1533.88%
Conant Nominal to Medium (58% C)	100.85%	853.32%	2639.59%
Conant Nominal to Medium (50% C)	86.94%	644.63%	1778.81%
Conant Nominal to Medium (42% C)	73.03%	473.21%	1165.49%

Table 27. Impact of C content on total recharge for no till barley in the ESP (mean values).

Impact	Year 1	Year 5	Year 10 (Cumulative)
NT Barley (58% C)	1.08%	6.37%	15.24%
NT Barley (50% C)	0.93%	5.27%	12.01%
NT Barley (42% C)	0.78%	4.24%	9.23%

Ancillary Appendix 5

Concentrated Animal Feed Operations, Fertilized Acreage, and Nitrate Pollution

An additional threat to water supply in the ESP is the existing and growing number of dairy concentrated animal feed operations (CAFOs) and continued use of nitrogen-based fertilizers. Nutrients are a leading cause of surface- and ground-water impairment in Idaho (Idaho Department of Environmental Quality, 2014), though the actions of state officials have generally reduced impairments (Idaho Department of Environmental Quality, 2014). Though state officials are undertaking a comprehensive study to determine sources and contribution to nutrient pollution, nutrient-impaired groundwater areas and CAFOs – particularly those where enforcement actions have been initiated – are in close proximity (Figure 79 and 80). Logically, these are also correlated with heavily-fertilized areas (Figure 81) (US Department of Agriculture, National Agricultural Statistics Service, 2007). Surface waters are also impaired (Figure 82 and Figure 83).

To be clear, CAFOs are unlikely to degrade soil health (nutrient concentrations excepted), as animal activity is concentrated around processing facilities from birth on. In fact, CAFOs may indirectly benefit soil health because the manure can be sold as compost (Mann, 2016). Further, little evidence suggests that conservation tillage practices would reduce fertilizer runoff (Shiptalo, Owens, Bonta, & Edwards, 2013), though it is a common best management practice utilized for groundwater pollution

mitigation (Idaho Department of Water Quality; Idaho Soil Conservation Commission; Lewis Soil Conservation District, 2008).

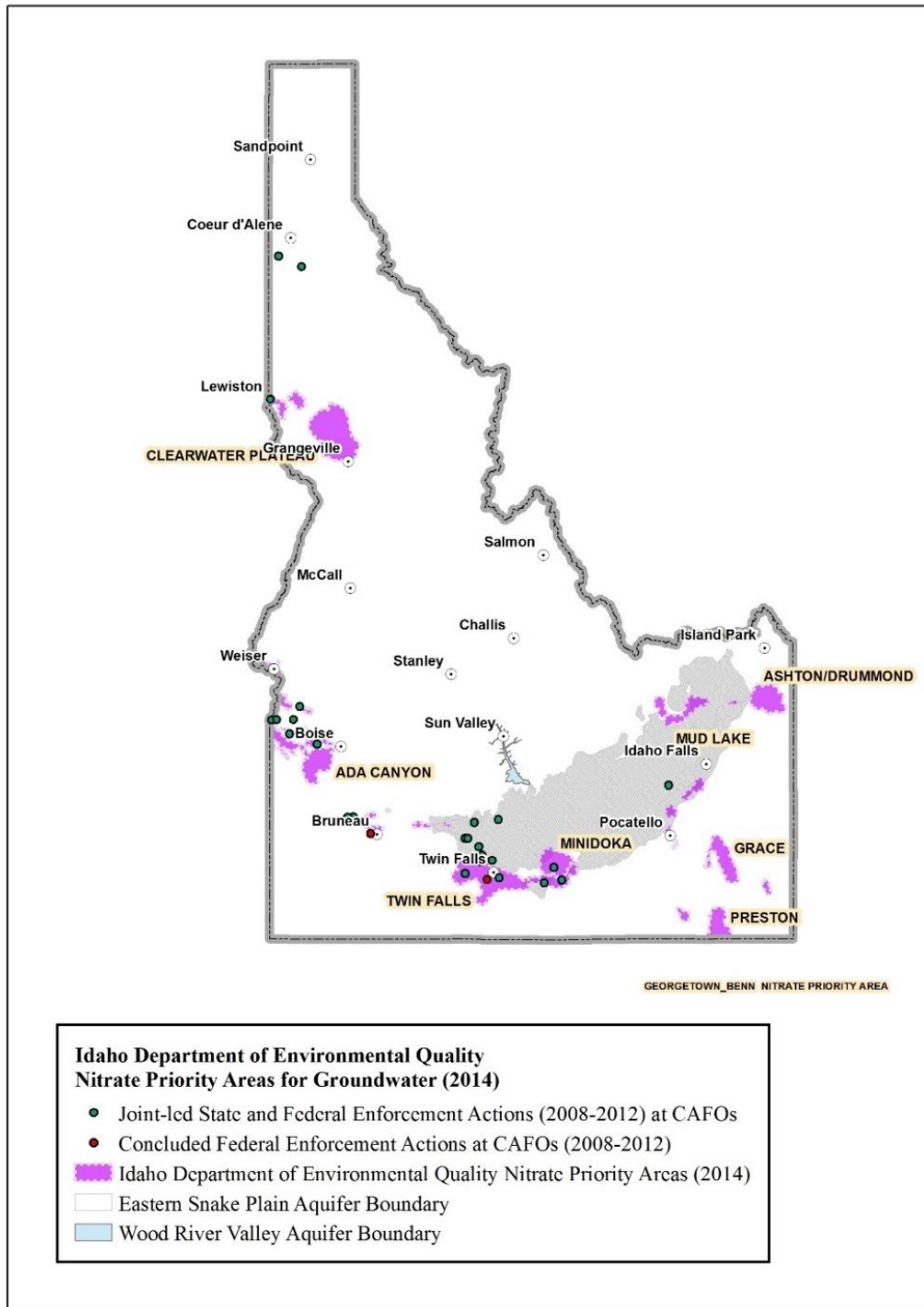


Figure 79. Map showing locations of enforcement actions at concentrated animal feed operations and Idaho Groundwater Priority Areas for Nitrate (Sadler, n.d.; Idaho Enterprise Open Data Portal, n.d.).

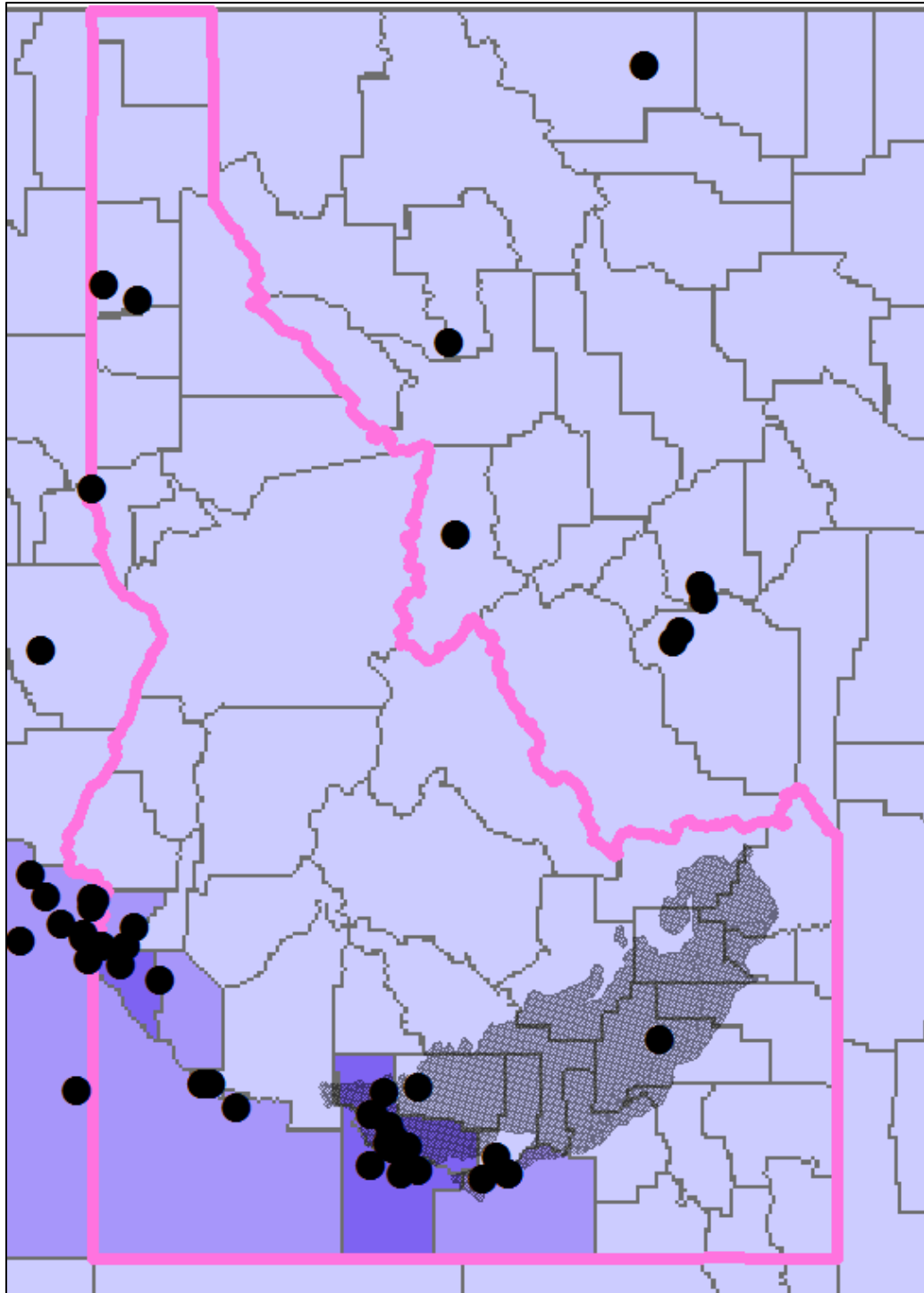


Figure 80. Map showing density of concentrated animal feed operations and enforcement sections (USDA, 2007; Sadler, n.d.).

*Darker colors indicate higher density of concentrated animal feed operations.

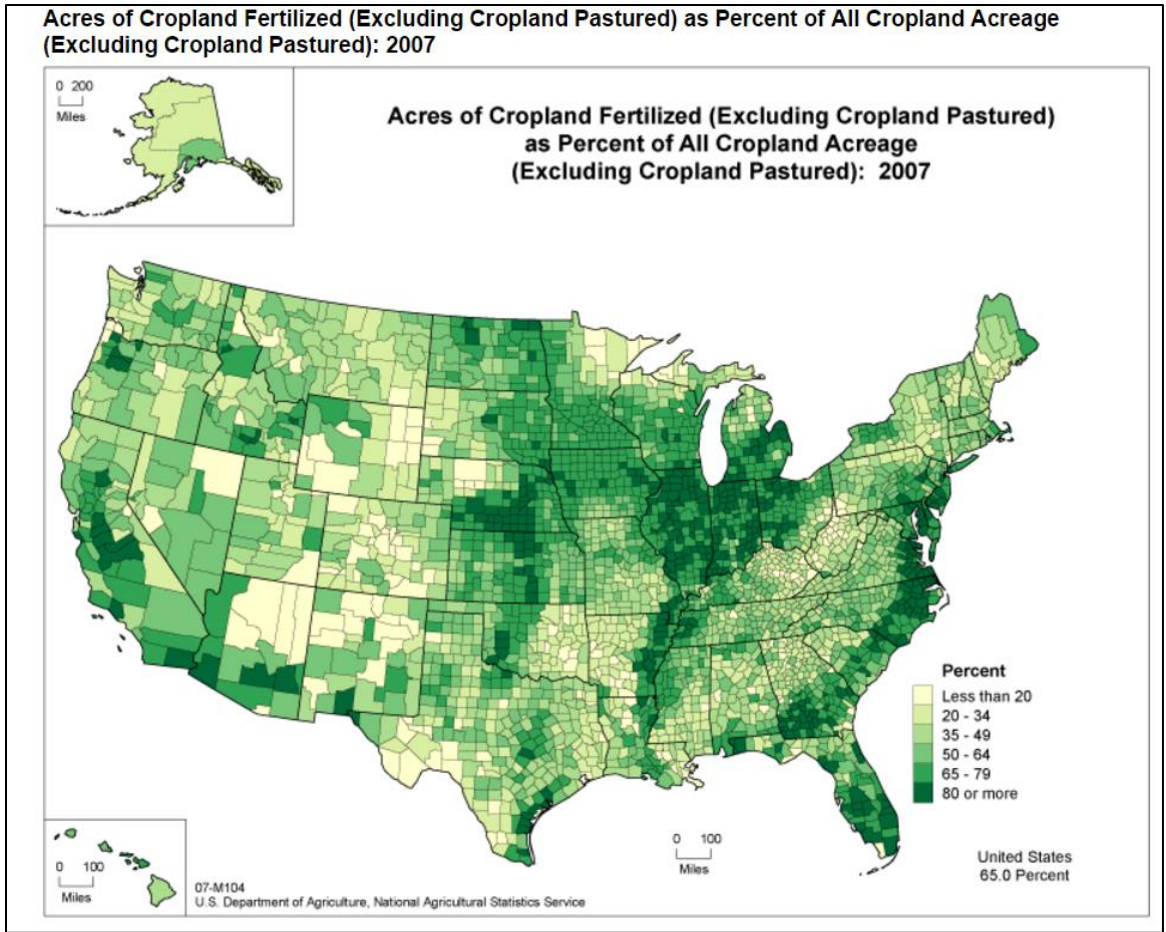


Figure 81. Concentration of fertilized acres in the U.S. (2007) (USDA, 2007).

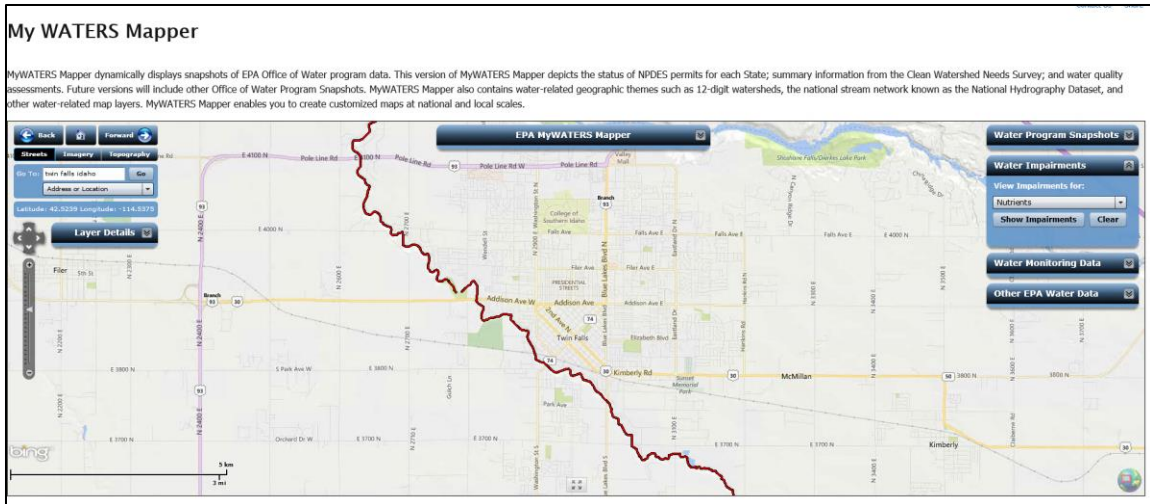


Figure 82. Example of a nutrient- impaired water way from agricultural sources (Twin Falls, Idaho) (U.S. Environmental Protection Agency, n.d.).

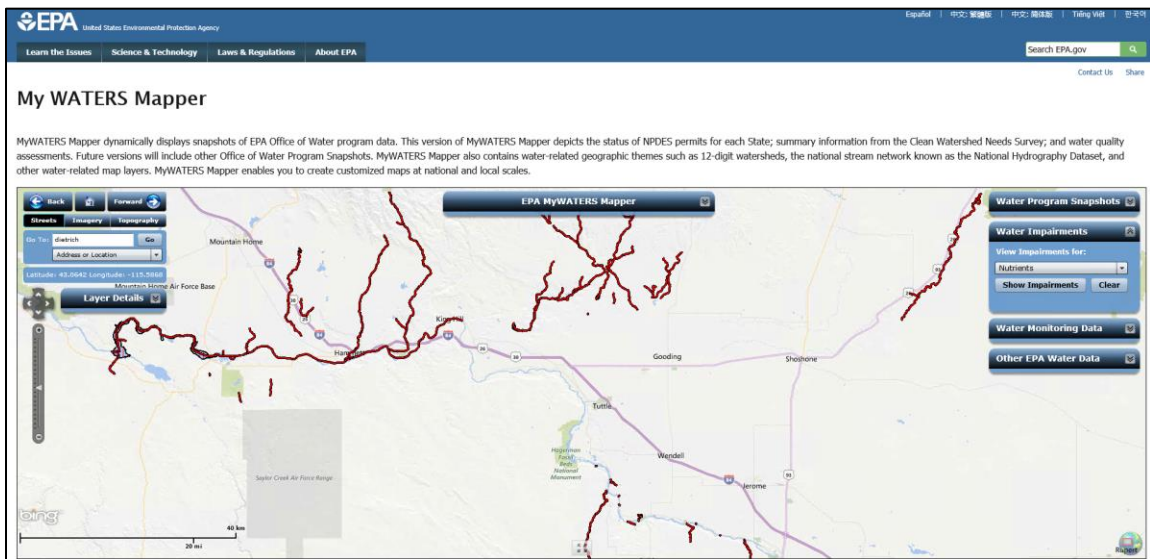


Figure 83. Example of a nutrient-impaired water way from agricultural sources (Eastern Snake Plain) (U.S. Environmental Protection Agency, n.d.).