

Summary of Climate Change Effects on Major Habitat Types in Washington State

Shrub-Steppe and Grassland Habitats

Produced by the Washington Department of Fish and Wildlife,
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CLIMATE CHANGE EFFECTS ON SHRUB-STEPPE AND GRASSLAND HABITATS IN WASHINGTON STATE

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PREFACE

This paper is a reference document—a “science summary”— for the Ecosystems, Species, and Habitats Topic Advisory Group (TAG), which is one of four topic groups working with Washington state agencies to prepare a statewide *Integrated Climate Change Response Strategy*. The climate change response strategy was initiated in 2009 by the state legislature (SB 5560) to help the state adapt to climate change.

The purpose of this paper is to provide TAG members with information on the potential effects of climate change in shrub-steppe and grassland ecosystems. The paper summarizes and organizes relevant literature regarding observed changes, future projections, and implications for biological communities to inform the assessment of priorities and the development of recommendations to the Washington State legislature about possible adaptation responses.

This document draws primarily from peer-reviewed studies, synthesis reports, and government publications. This document is for discussion purposes only and is not intended to be published or cited. In most cases, this document uses language taken directly from the cited sources. Readers should refer to and cite the primary sources of information. Please note that we accepted information as it was presented in synthesis reports. In cases where we accepted the interpretation of primary information as it was stated in a secondary source, we have provided the following note in the footnote: “Information as cited in [secondary source].”

This summary reports central findings from published literature and does not address all the inherent complexity and uncertainty that may be present in ecological and climatic systems. This is especially true of future climate projections, which are often based on multi-model ensembles that do not perfectly capture the complexity of Washington’s unique climate systems and geographic variability. Future projections are valuable primarily to identify a directional trend and a sense of magnitude.

This paper is a joint production of National Wildlife Federation and Washington Department of Fish & Wildlife. This draft benefitted from the review and input of WDFW scientists (George Wilhere, Matt Vander Haegen, Kurt Merg and Mike Schroeder), DNR scientists (Rex Crawford), NWF scientists (Doug Inkley) and external experts (Sonia Hall, The Nature Conservancy; and Julie Conley, South Central Washington Shrub-Steppe/Rangeland Partnership).

We must emphasize that this discussion draft is neither comprehensive nor complete. In this complex and rapidly evolving field, we do not expect that we have identified all of the most up-to-date data or presented the full complexity of climate projections. In addition, there are many gaps in knowledge, especially regarding climate change effects on specific habitats or species. Still, we hope that this provides a starting point for discussion, and that readers will augment this with additional data to advance our understanding of climate impacts and responses.

INTRODUCTION

This report summarizes literature on the effects of climate change on shrub-steppe and grassland ecosystems, with a focus on Washington State where possible. This report is divided into five sections:

First, this *Introduction* provides a roadmap of the report's organization. It briefly describes shrub-steppe and grassland ecosystems in eastern Washington (including sagebrush steppe, Palouse Prairie, and Pacific Northwest Bunchgrass communities), lists some of the ecosystem functions and services these ecosystems supply, and summarizes land use change in the region.

Second, *Global and Regional Climate Trends* provides information on the current climatic characteristics of eastern Washington, as well as changes in three major physical environmental variables (CO₂, temperature, and precipitation) that affect shrub-steppe and grassland ecosystems.

Third, *Climate Change Effects on Washington's Shrub-Steppe and Grassland Ecosystems* discusses three major climate change effects on shrub-steppe and grassland ecosystems:

- **Changes in species composition, distribution, and community dynamics**
- **Changes in ecosystem productivity**
- **Changes in disturbance regimes**

Each effect appears as a separate sub-section in which we provide information on observed climate-related changes, projected effects, and a discussion of the implications of those predictions and existing knowledge gaps.

Finally, *Appendix 1* provides an excerpt on Grassland and Shrubland Habitats from *Setting the Stage: Ideas for Safeguarding Washington's Fish and Wildlife in an Era of Climate Change* by Glick and Moore (2009). This excerpt describes key climate change impacts to grassland and shrubland habitats and potential management actions discussed at a stakeholder workshop in February 2009, as well as supplemental research undertaken by National Wildlife Federation.

ECOSYSTEM CHARACTERISTICS

SHRUB-STEPPE

Shrub-steppe in the intermountain region of western North America is often labeled as a “cold” desert biome; however, only small areas of the intermountain lowlands are deserts in the global sense.¹ Rather, the area is better described as relatively well-vegetated semidesert scrub or shrub-steppe that occupies lower elevations in the basins, valleys, lower plateaus, foothills, and lower mountain slopes in this region.² Because these “lowlands” generally occur around 3000 feet in elevation, cool average temperatures prevail.³

The dominance of winter precipitation, combined with either fine-textured or rocky soils, is the main reason for the dominance of shrub vegetation in this ecosystem.⁴ Soils are an important component of shrub-steppe ecosystems and influence plant community composition. The variable composition, texture, and depth of soils affect drainage, nutrient availability, and rooting depth and results in a variety of climax communities.⁵ In eastern Washington, the soils are characterized by loess and volcanic tephra (material ejected during eruptions) covering basaltic plains.⁶ For example, much of the interior Columbia Basin is underlain by basaltic flows, and the soils vary from deep accumulations of loess-derived loams to shallow, rocky soils in areas where glacial floods scoured the loess from underlying basalt.⁷ Sandy soils cover extensive areas in the west central and southern parts of the basin, and are the result of glacial outwash and alluvial and wind-blown deposition.⁸

Woody species of *Artemisia* (sagebrush) are the most characteristic and widespread vegetation dominants in the intermountain lowlands,⁹ and plants can have a relatively long lifespan of up to approximately 100 years.¹⁰ Sagebrush steppe habitats in Washington State are described further below.

Sagebrush Steppe

Sagebrush steppe occurs where there is a co-dominance of sagebrush with perennial bunchgrasses.¹¹ For example, Vander Haegen et al. (2000) describe the sagebrush steppe habitat of the Columbia Basin

¹ Information as cited in West and Young (2000), *Intermountain Valleys and Lower Mountain Slopes*. Chapter 7 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

² West and Young (2000), *Intermountain Valleys and Lower Mountain Slopes*. Chapter 7 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

³ Ibid.

⁴ Information as cited in West and Young (2000), *Intermountain Valleys and Lower Mountain Slopes*. Chapter 7 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

⁵ Information as cited in Vander Haegen et al. (2000), *Shrubsteppe Bird Response to Habitat and Landscape Variables in Eastern Washington, U.S.A.* (primary literature)

⁶ Information as cited in West and Young (2000), *Intermountain Valleys and Lower Mountain Slopes*. Chapter 7 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

⁷ Information as cited in Vander Haegen et al. (2000), *Shrubsteppe Bird Response to Habitat and Landscape Variables in Eastern Washington, U.S.A.* (primary literature)

⁸ Ibid.

⁹ West and Young (2000), *Intermountain Valleys and Lower Mountain Slopes*. Chapter 7 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

¹⁰ Information as cited in Welch (2005), *Big Sagebrush: A Sea Fragmented into Lakes, Ponds, and Puddles*. (USFS technical report)

as covered by a dominant overstory of sagebrush (*Artemisia* spp.) with an understory of intermixed bunch grasses, forbs (herbaceous plants that are not grasses), and the ubiquitous invasive annual grass *Bromus tectorum* (cheatgrass).

In Washington State, Welch (2005) describes big sagebrush (*Artemisia tridentata*) habitat as beginning a few miles east of the Snake and Columbia Rivers and extending west to the Cascades and north along the Columbia and Okanogan rivers.¹² There are three sub-species of big sagebrush, including basin (*A. tridentata* spp. *tridentata*), Wyoming (*A. tridentata* spp. *wyomingensis*), and mountain (*A. tridentata* spp. *vaseyana*).¹³ Wyoming big sagebrush steppe is the most widespread, occurring throughout the Columbia Plateau.¹⁴ Mountain big sagebrush steppe occurs in the mountains of eastern Washington.¹⁵ Other shrub dominants also occur in Washington, including bitterbrush steppe (primarily along the eastern slope of the Cascades) and three-tip sagebrush steppe (in the northern and western Columbia Basin).¹⁶ Some common species of native shrubs, bunchgrasses, and forbs found in the sagebrush steppe community are listed in Table 1 below. Many sites also support non-native plants such as cheatgrass or crested wheatgrass (*Agropyron cristatum*).¹⁷

Table 1: Characteristic native shrub-steppe vegetation of eastern Washington and Oregon. Vegetative community composition varies with factors such as elevation, precipitation, and disturbance in a given region. The common species of shrubs and bunch grasses were listed by Crawford and Kagan in Chappell et al. (2001). Common forb species were noted in a study of the Columbia Basin by Vander Haegen et al. (2000).

Shrubs	Bunch grasses	Forbs
Big sagebrush (<i>Artemisia tridentata</i>)	Sandberg blue grass (<i>Poa secunda</i>)	Balsam root (<i>Balsamorhiza</i> spp.)
Three-tip sagebrush (<i>Artemisia tripartita</i>)	Bluebunch wheatgrass (<i>Pseudoroegneria spicata</i>)	Lupines (<i>Lupinus</i> spp.)
Silver sagebrush (<i>Artemisia cana</i>)	Idaho fescue (<i>Festuca idahoensis</i>)	Phlox (<i>Phlox</i> spp.)
Stiff sagebrush (<i>Artemisia rigida</i>)	Needle and thread grass (<i>Stipa</i> spp.)	Desert buckwheat (<i>Eriogonum</i> spp.)
Low sagebrush (<i>Artemisia arbuscula</i>)	Bottlebrush squirreltail (<i>Elymus elymoides</i>)	
Green rabbitbrush (<i>Chrysothamnus viscidiflorus</i>)	Threadleaf sedge (<i>Carex filifolia</i>)	
Tobaccobrush (<i>Ceanothus velutinus</i>)	Basin wildrye (<i>Leymus cinereus</i>)	
Antelope bitterbrush (<i>Purshia tridentata</i>)		
Short-spine horsebrush (<i>Tetradymia spinosa</i>)		

¹¹ West and Young (2000), *Intermountain Valleys and Lower Mountain Slopes*. Chapter 7 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

¹² Welch (2005), *Big Sagebrush: A Sea Fragmented into Lakes, Ponds, and Puddles*. (USFS technical report)

¹³ Chappell et al. (2001), *Wildlife Habitats: Descriptions, Status, Trends, and System Dynamics*. Chapter 2 in: *Wildlife-Habitat Relationships in Oregon and Washington*. (book chapter)

¹⁴ Ibid.

¹⁵ Ibid.

¹⁶ Ibid.

¹⁷ Ibid.

GRASSLANDS

Grasslands around the globe occur in climates with high light intensity, warm temperatures, and at least one annual dry season.¹⁸ In the United States, grasslands are the largest natural biome, covering more than 125 million hectares of land.¹⁹ North American grasslands contain approximately 7500 plant species from about 600 genera of grasses, as well as numerous forbs and woody plants.²⁰ Grasslands are generally dominated by three to four grass species that produce the majority of biomass in the ecosystem, while forbs and dwarf shrubs may also be seasonally important.²¹

The presence of alluvial and loessial deposits of fine sediments promote the success of native bunchgrass or agronomic crops.²² Perennial grasses thrive on rarer deep loam or sandy soils, as long as they are not excessively grazed or burned.²³ Washington's grasslands are part of the Palouse bioregion, the characteristics of which are described further below.

The Palouse Bioregion, Pacific Northwest Bunchgrass, and Palouse Prairie

The Palouse bioregion covers approximately 6,200 mi² in west central Idaho, southeastern Washington, and northeastern Oregon between the western edge of the Rocky Mountains and the Columbia River basin.²⁴ It encompasses the hills of the Palouse Prairie, the southerly Camas Prairie, and the forested hills and canyonlands of the area's rivers.²⁵

Palouse Prairie is a type of grassland dominated by remnants of native perennial grass and sagebrush species, and invasive, non-native annual grasses.²⁶ The term "Palouse Prairie" is often used to refer to the Pacific Northwest Bunchgrass vegetation type, which is an intermountain bunchgrass vegetation type that originally extended throughout southwest Canada, eastern Oregon and Washington, and parts of Idaho, Utah, and Montana.²⁷ Pacific Northwest Bunchgrass vegetation is generally characterized by

¹⁸ Sims and Risser (2000), *Grasslands*. Chapter 9 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

¹⁹ Information as cited in Sims and Risser (2000), *Grasslands*. Chapter 9 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

²⁰ Ibid.

²¹ Ibid.

²² Information as cited in West and Young (2000), *Intermountain Valleys and Lower Mountain Slopes*. Chapter 7 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

²³ West and Young (2000), *Intermountain Valleys and Lower Mountain Slopes*. Chapter 7 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

²⁴ Information as cited in Black et al. (1998), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

²⁵ Black et al. (1998), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

²⁶ Sims and Risser (2000), *Grasslands*. Chapter 9 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

²⁷ Information as cited in Sims and Risser (2000), *Grasslands*. Chapter 9 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

dominant cool-season (C₃) grasses that compose more than 80% of the flora, with the remainder being predominantly C₄ grasses (see Box 7, “C₃ vs. C₄ plants” for more information on this classification).²⁸ In this paper, we follow Tisdale (1982) and limit the use of the term “Palouse Prairie” to those grasslands restricted to the Palouse region in eastern Washington.

In southeastern Washington, Idaho fescue grasslands that were formerly widespread in the Palouse region now occur mostly in isolated, moist sites near lower treeline in the foothills of the Blue Mountains, the Northern Rockies, and the east Cascades near the Columbia River Gorge.²⁹ Bluebunch wheatgrass grassland habitats are found throughout the Columbia Basin as native grasslands in deep canyons and as fire-induced representatives in the shrub-steppe.³⁰ Sand dropseed and three-awn needlegrass grassland habitats are restricted to river terraces in the Columbia Basin and Blue Mountains.³¹ Some common native species of shrubs, bunchgrasses, and forbs found in the grassland community are listed in Table 2. Non-native annual plants are also usually present, and may include cheatgrass, medusahead (*Taeniatherum caput-medusae*), and other bromes (*Bromus* spp.).³²

Table 2: Characteristic native grassland vegetation of eastern Washington and Oregon. Note that vegetative community composition varies with factors such as elevation, precipitation, and disturbance in a given region. The common species of shrubs, bunch grasses, and forbs were listed by Crawford and Kagan in Chappell et al. (2001).

Shrubs	Bunch grasses	Forbs
Smooth sumac (<i>Rhus glabra</i>)	Bluebunch wheatgrass	Balsam root (<i>Balsamorhiza</i> spp.)
Rabbitbrush (<i>Chrysothamnus</i> spp.)	(<i>Pseudoroegneria spicata</i>)	Biscuit root (<i>Lomatium</i> spp.)
Big sagebrush (<i>Artemisia tridentata</i>)	Idaho fescue (<i>Festuca idahoensis</i>)	Buckwheat (<i>Eriogonum</i> spp.)
Common snowberry	Rough fescue (<i>Festuca campestris</i>)	Fleabane (<i>Erigeron</i> spp.)
(<i>Symphoricarpos albus</i>)	Sand dropseed (<i>Sporobolus</i>	Lupine (<i>Lupinus</i> spp.)
Nootka rose (<i>Rosa nutkana</i>)	<i>cryptandrus</i>)	Milkvetches (<i>Astragalus</i> spp.)
Succulent pricklypear (<i>Opuntia</i>	Sandberg bluegrass (<i>Poa secunda</i>)	
<i>polycantha</i>)	Three-awn needlegrass (<i>Aristida</i>	
	<i>longiseta</i>)	

ECOSYSTEM FUNCTIONS AND SERVICES

Shrub-steppe and grasslands are habitat for many species of wildlife. More than 3,000 species of mammals, birds, reptiles, fish, and amphibians live in North American grasslands,³³ and over 350 species

²⁸ Ibid.

²⁹ Chappell et al. (2001), *Wildlife Habitats: Descriptions, Status, Trends, and System Dynamics*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

³⁰ Ibid.

³¹ Ibid.

³² Ibid.

³³ Information as cited in Sims and Risser (2000), *Grasslands*. Chapter 9 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

of flora and fauna depend on sagebrush habitats for all or part of their existence.³⁴ A high proportion of the endemic and imperiled species in the western United States are found within the sagebrush distribution.³⁵ For example, the Columbia Basin population of pygmy rabbits (*Brachylagus idahoensis*) and Gunnison sage-grouse (*Centrocercus minimus*) are highly dependent on sagebrush habitats and currently are candidate species for federal listing under the Endangered Species Act.³⁶

Vander Haegen et al. (2001) provide a detailed discussion of the wildlife present in shrubland and grassland habitats in eastern Washington and Oregon. These habitats generally host a lower diversity of taxa than habitats with higher vertical structural diversity (i.e., forests), however, species may be more specialized to survive under the challenging environmental conditions present.³⁷ Because of higher vertical structural diversity, habitats with a shrub component tend to have more diverse wildlife communities than grass dominated habitats.³⁸ For example, the shrub-steppe has 49 closely associated species, whereas eastside grassland has only 34.³⁹ Intact native plant communities also have more wildlife species that are closely associated with them, compared to similar habitats that have become dominated by exotic plants (e.g., 34 species closely associated with native eastside grasslands vs. 2 with modified grasslands).⁴⁰ Table 3 depicts the number of species associated with shrub-steppe as opposed to modified grassland (i.e., non-native, annual grassland) habitats in Washington and Oregon, and provides some examples of species in each category. For more specific information on the identity, ecology, and adaptations of species in these habitats, as well as a discussion of management issues, see:

- Vander Haegen, WM, SM McCorquodale, CR Peterson, GA Green, and E Yense. 2001. Wildlife of Eastside Shrubland and Grassland Habitats. In: DH Johnson and TA O'Neil (eds.) *Wildlife-Habitat Relationships in Oregon and Washington* (Chapter 11). Corvallis: Oregon State University Press. Pp. 292 – 316.

³⁴ Connelly et al. (2004), *Conservation Assessment of Greater Sage-grouse and Sagebrush Habitats*. (unpublished report)

³⁵ Ibid.

³⁶ Information as cited in Connelly et al. (2004), *Conservation Assessment of Greater Sage-grouse and Sagebrush Habitats*. (unpublished report)

³⁷ Vander Haegen et al. (2001), *Wildlife of Eastside Shrubland and Grassland Habitats*. Chapter 11 in: *Wildlife-Habitat Relationships in Oregon and Washington*. (book chapter)

³⁸ Ibid.

³⁹ Ibid.

Table 3: Numbers of species generally associated with modified grasslands (i.e., shrub-steppe converted to non-native annual grassland such as cheatgrass) and shrub-steppe habitats, and the number of species that depend on shrubs as an important component of the habitat (i.e., those predicted to be lost if fire removes the shrub layer). Notes about species representatives in each category are included from Vander Haegen et al. (2001). This table is modified from Table 2 in Vander Haegen et al. (2001).

SPECIES GROUP	MODIFIED GRASSLANDS		SHRUB-STEPPE		SHRUBS ARE KEY
	Generally associated	Closely associated	Generally associated	Closely associated	
Birds	31	2	44	22	22
	Sagebrush-obligate bird species include Sage and Brewer's sparrows (<i>Amphispiza belli</i> & <i>Spizella brewer</i>), sage thrashers (<i>Oreoscoptes montanus</i>), and sage grouse (<i>Centrocercus urophasianus</i>). Vesper sparrows (<i>Pooecetes gramineus</i>) and green-tailed towhees (<i>Pipilo chlorurus</i>) are near-obligates.				
Mammals	34	0	26	27	12
	Pocket mice (<i>Perognathus</i>) and deer mice (<i>Peromyscus maniculatus</i>) are numerically dominant small mammals in eastern WA. White and black-tailed jackrabbits (<i>Lepus townsendii</i> & <i>Lepus californicus</i>), mountain cottontails (<i>Sylvilagus nuttallii</i>), pygmy rabbits (<i>Brachylagus idahoensis</i>), and several ground squirrel species (<i>Spermophilus</i> spp.) are characteristic of mid-sized mammals. Carnivores may include coyote (<i>Canis latrans</i>), badger (<i>Taxidea taxus</i>), long-tailed weasel (<i>Mustela frenata</i>), and bobcats (<i>Lynx rufus</i>) or mountain lions (<i>Puma concolor</i>) where shrub-steppe and mountains are contiguous. Large herbivores, found where free water is present, include mule deer (<i>Odocoileus hemionus</i>), pronghorn antelope (<i>Antilocapra americana</i>), and elk (<i>Cervus canadensis</i>).				
Reptiles	7	0	20	0	6
	Mohave black-collared lizard (<i>Crotaphytus bicinctores</i>), long-nose leopard lizard (<i>Gambelia wislizenii</i>), and desert horned lizard (<i>Phrynosoma platyrhinos</i>) occur only in shrub-steppe and shrubland habitats. Racer (<i>Coluber constrictor</i>), gopher snake (<i>Pituophis catenifer sayi</i>), and western rattlesnake (<i>Crotalus viridis</i>) are three of the 10 snake species that occur in shrub-steppe habitats. Painted turtles (<i>Chrysemys picta</i>) and western pond turtles (<i>Clemmys marmorata</i>) will use shrub-steppe if near permanent fresh water.				
Amphibians	10	0	9	0	1
	In shrub-steppe, long-toed and tiger salamanders (<i>Ambystoma macrodactylum</i> & <i>Ambystoma tigrinum</i>) and rough-skinned newt (<i>Taricha granulosa</i>) are present. Great Basin spadefoot toad (<i>Spea intermontana</i>), western toad (<i>Bufo boreas</i>), and Woodhouse's toad (<i>Bufo woodhousii</i>) are also common. Non-native bullfrogs (<i>Rana catesbeiana</i>) threaten native reptile and amphibian species.				
TOTAL	82	2	103	49	41

Some wildlife species may be only a minor component of arid land habitats overall, but nevertheless may be strongly associated with special habitat elements in the landscape (and may not be found in their absence).⁴¹ For example, black bears (*Ursus americanus*), beavers (*Castor canadensis*), and muskrats (*Ondatra zibethicus*) are not considered shrub-steppe species, but all may occur in larger riparian corridors that extend from forested communities into shrub-steppe.⁴² Rock outcrops, cliffs, and talus slopes may provide nesting sites for species such as peregrine falcons (*Falco peregrines*), cliff swallows (*Petrochelidon pyrrhonota*) and golden eagles (*Aquila chrysaetos*), and habitat for rock wrens (*Salpinctes obsoletus*) and yellow-bellied marmots (*Marmota flaviventris*).⁴³ Talus slopes and talus-like structures (e.g., rock piles, lava stringers) are associated with 22 species and provide refuge for small mammals such as the least chipmunk (*Tamias minimus*).⁴⁴ Caves are used by 18 species, including bobcats (*Lynx rufus*), common ravens (*Corvus corax*) and bats (*Chiroptera*).⁴⁵ Burrowing owls (*Athene cunicularia*), badgers (*Taxidea taxus*), pygmy rabbits, and some species of ground squirrels are among the species that require areas with deep soils for constructing dens and nests.⁴⁶ All amphibians are associated with standing or slow-moving water at some point during their lifecycle.⁴⁷ Abandoned buildings, wells, and trash piles may also attract wildlife as sites for nesting, foraging, or estivation.⁴⁸

In addition to functioning as habitat, temperate grasslands also contain a substantial soil carbon pool and are important for maintaining soil stability.⁴⁹ Most of the productive, arable lands [i.e., cultivated agricultural lands] in North America were once grasslands.⁵⁰ In addition, shrub-steppe and grasslands are an important component of the nation's current rangeland resources⁵¹ and provide fodder for wild and domestic animals.⁵²

⁴¹ Ibid.

⁴² Ibid.

⁴³ Ibid.

⁴⁴ Ibid.

⁴⁵ Ibid.

⁴⁶ Ibid.

⁴⁷ Ibid.

⁴⁸ Ibid.

⁴⁹ Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC Fourth Assessment Report)

⁵⁰ Sims and Risser (2000), *Grasslands*. Chapter 9 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

⁵¹ Ibid.

⁵² Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC Fourth Assessment Report)

Box 1: Wildlife Threatened by Climate Change - Greater Sage-Grouse in Washington State

The greater sage-grouse (*Centrocercus urophasianus*) is the largest species of grouse in North America, and is dependent on sagebrush (*Artemisia* spp.) for both food and cover. Sage-grouse may move more than 50 km between seasonal ranges, but in general display high fidelity to their seasonal range. Populations are characterized by relatively low productivity.

Sage-grouse in Washington reportedly declined by at least 77% from 1960 to 1999, and current populations occupy about 8% of their historic range. The Washington Fish and Wildlife Commission listed the greater sage-grouse as a threatened species in 1998. The USFWS designated the greater sage-grouse in Washington State as a candidate for endangered species listing in 2001. In March 2010 federal candidate status was extended to the entire range of the species.

Threats to Greater Sage-Grouse

Habitat fragmentation and conversion across much of the species' range are the primary contributors to population declines. Projected climate change and its associated consequences have the potential to affect greater sage-grouse and may increase its risk of extinction, as the impacts of climate change interact with other stressors such as disease and habitat degradation. Under projected future temperature conditions, the cover of sagebrush within the distribution of sage-grouse is anticipated to be reduced due to non-native grass invasions making the areas prone to destructive fires. Climate warming is also likely to increase the severity of West Nile Virus (WNV) outbreaks and to expand the area susceptible to outbreaks into areas that are now too cold for the WNV vector.

Conservation in Washington

Washington Department of Fish and Wildlife developed a species management plan for sage-grouse in 1995 (Washington State Management Plan for Sagegrouse). Washington also developed a Recovery Plan that summarizes the status of sage-grouse in Washington and outlines strategies to increase their population size and distribution to ensure the existence of a viable population of the species in the state. Washington is implementing many of the recovery tasks ahead of the final approval of the Recovery Plan.

Sources: Conley (2010), Connelly et al. (2004), Fish and Wildlife Service (2010) and sources cited therein.

LAND USE CHANGE & CLIMATE CHANGE IMPLICATIONS

The response of arid lands to climate change will be strongly influenced by interactions with non-climatic factors such as land use at local scales.⁵³ Livestock grazing, conversion to agriculture, urbanization, energy and natural resource development, habitat treatment, and even restoration activities have had both direct and indirect consequences.⁵⁴ Land use change over the past 200 years has had a much greater effect on these ecosystems than has climate change, and the vast majority of land use changes have little to do with climate or climate change.⁵⁵ Today's arid lands reflect a legacy of historic land uses, and future land use practices will arguably have the greatest impact on arid land ecosystems in the next two to five decades.⁵⁶ In the near-term, climate fluctuation and change will be important primarily as it influences the impact of changes in land use on ecosystems, and how ecosystems respond to land use.⁵⁷

In addition to traditional land uses such as agriculture and grazing, arid land response to future climate will be mediated by growing environmental pressures such as air pollution and nitrogen deposition, energy development, motorized off-road vehicles, feral pets, and invasion of non-native plants.⁵⁸ Some of these factors may reinforce and accentuate climate effects (e.g., livestock grazing); others may constrain, offset or override climate effects (e.g., atmospheric CO₂ enrichment, fire, non-native species).⁵⁹

Below are descriptions of land use history in shrub-steppe habitats and the Palouse bioregion, as well as estimates of the amount of extant habitat in each ecosystem. For more information on ways in which agricultural conversion, habitat fragmentation, livestock grazing, invasive cheatgrass, and changes in the fire regime have affected shrub-steppe plants and wildlife in eastern Washington and Oregon, see:

- Vander Haegen, WM, SM McCorquodale, CR Peterson, GA Green, and E Yense. 2001. Wildlife of Eastside Shrubland and Grassland Habitats. In: DH Johnson and TA O'Neil (eds.) *Wildlife-Habitat Relationships in Oregon and Washington* (Chapter 11). Corvallis: Oregon State University Press. Pp. 305-311

⁵³ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁵⁴ Knick et al. (2003), *Teetering on the Edge or Too Late? Conservation and Research Issues for Avifauna of Sagebrush Habitats*. (primary literature)

⁵⁵ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁵⁶ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁵⁷ Ibid.

⁵⁸ Ibid.

⁵⁹ Ibid.

Land Use History: Shrub-Steppe

Shrub-Steppe is a vegetative community consisting of one or more layers of perennial grass with a conspicuous but discontinuous over-story layer of shrubs.⁶⁰ In Washington, these communities usually contain big sagebrush in association with bunchgrasses, although other associations are found.⁶¹ Shrub-steppe communities once covered most dryland areas of eastern Washington, extending from below the forests of the Cascade slope to the prairies of the Palouse.⁶²

Sagebrush-steppe, a specific type of shrub-steppe ecosystem, is among the most imperiled ecosystems in North America.⁶³ Sagebrush once covered approximately 63 million ha in western North America,⁶⁴ and sagebrush-steppe occupied more area than any other North American semidesert vegetation type.⁶⁵ Prior to European settlement, it is estimated that 10.4 million acres of shrub-steppe existed in eastern Washington.⁶⁶ Today, estimates of the amount of original shrub-steppe habitat remaining in eastern Washington range from 40%⁶⁷ to 48%.⁶⁸

Very little sagebrush habitat now exists undisturbed or unaltered from its pre-settlement condition.⁶⁹ Across the west, land managers historically removed sagebrush from large areas for reseeding with perennial non-native grasses, principally to provide forage for livestock.⁷⁰ Agriculture, mining, powerline and natural-gas corridors, urbanization, and expansion of road networks have fragmented landscapes or completely eliminated sagebrush from extensive areas.⁷¹ For example, the mean patch size of sagebrush in Washington decreased from 13,420 ha to 3,418 ha [a reduction of 75%] and the number of patches increased from 267 to 370 between 1900 and 1990.⁷² These changes have pushed many sagebrush systems beyond thresholds from which recovery to a pre- Eurasian-settlement condition is unlikely.⁷³

In Washington, Euro-American settlers converted large tracts of sagebrush habitat into areas for agriculture and livestock grazing.⁷⁴ The most productive big sagebrush sites (sites that were highly

⁶⁰ Information as cited in Dobler et al. (1996), *Status of Washington's Shrub-Steppe Ecosystem: Extent, ownership, and wildlife/vegetation relationships*. (WDFW project report)

⁶¹ Dobler et al. (1996), *Status of Washington's Shrub-Steppe Ecosystem: Extent, ownership, and wildlife/vegetation relationships*. (WDFW project report)

⁶² Ibid.

⁶³ Information as cited in Knick et al. (2003), *Teetering on the edge or too late? Conservation and research issues for avifauna of sagebrush habitats*. (primary literature)

⁶⁴ Knick et al. (2003), *Teetering on the edge or too late? Conservation and research issues for avifauna of sagebrush habitats*. (primary literature)

⁶⁵ Information as cited in West and Young (2000), *Intermountain Valleys and Lower Mountain Slopes*. Chapter 7 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

⁶⁶ Dobler et al. (1996), *Status of Washington's Shrub-Steppe Ecosystem: Extent, ownership, and wildlife/vegetation relationships*.(WDFW project report)

⁶⁷ Ibid.

⁶⁸ Welch (2005), *Big Sagebrush: A Sea Fragmented into Lakes, Ponds, and Puddles*. (USFS technical report)

⁶⁹ Information as cited in Knick et al. (2003), *Teetering on the edge or too late? Conservation and research issues for avifauna of sagebrush habitats*. (primary literature).

⁷⁰ Ibid.

⁷¹ Ibid.

⁷² Ibid.

⁷³ Ibid.

⁷⁴ Welch (2005), *Big Sagebrush: A Sea Fragmented into Lakes, Ponds, and Puddles*.(USFS technical report)

fertile, with deep soils) were developed for agricultural use, leaving big sagebrush growing on less fertile ground, shallow soils, and steep unusable hillsides.⁷⁵ A study of Lincoln and Grant counties by Vander Haegen et al. (2000) confirmed that historically, most of the shrub-steppe in the analysis areas was on deep, loamy or sandy soils; in contrast, extant shrub-steppe occurred predominantly on shallow soils. Seventy-five percent of loamy-soil shrub-steppe in the analysis area had been converted to agriculture or other land uses.⁷⁶ The only large area of loamy-soil shrub-steppe remaining was generally unsuitable for cropland.⁷⁷

Alterations in the understory vegetation and soils have changed the composition of sagebrush communities.⁷⁸ Replacement of native perennial bunchgrasses by cheatgrass, a non-native annual grass, has profoundly altered the fire regime and led to extensive loss of large expanses of sagebrush habitats.⁷⁹ The configuration of sagebrush habitats within the larger context of the landscape has also changed.⁸⁰ The increased edge in landscapes fragmented by roads, power-lines, fences, and other linear features promotes the spread of exotic invasive species, facilitates predator movements, and isolates wildlife populations.⁸¹ For example, wind-farm development, with road networks, pipelines, and powerline transmission corridors, influences vegetation dynamics by fragmenting habitats or by creating soil conditions facilitating the spread of invasive species.⁸² Describing the biological effects of this natural resource development, Knick et al. (2003) cite that the density of sagebrush-obligate birds within 100 m of roads constructed for natural gas development in Wyoming was 50% lower than at greater distances.⁸³ This example illustrates that changes in quantity, composition, and configuration of sagebrush habitats have consequences on the ecological processes within the sagebrush ecosystem and the resources available to support wildlife.⁸⁴ In Washington, wind farm development has been focused in arid lands and seems likely to expand in the future.⁸⁵

In eastern Washington, Dobler et al. (1996) report that Grant County historically contained the greatest acreage of shrub-steppe (1,614,555 acres), although today only 35% of this habitat remains. Yakima County currently supports the largest amount of shrub-steppe, with 58% of its original acreage still

⁷⁵ Ibid.

⁷⁶ Vander Haegen et al. (2000), *Shrubsteppe Bird Response to Habitat and Landscape Variables in Eastern Washington, U.S.A.* (primary literature)

⁷⁷ Ibid.

⁷⁸ Connelly et al. (2004), *Conservation Assessment of Greater Sage-grouse and Sagebrush Habitats.* (unpublished report)

⁷⁹ Information as cited in Connelly et al. (2004), *Conservation Assessment of Greater Sage-grouse and Sagebrush Habitats.* (unpublished report)

⁸⁰ Connelly et al. (2004), *Conservation Assessment of Greater Sage-grouse and Sagebrush Habitats.* (unpublished report)

⁸¹ Information as cited in Connelly et al. (2004), *Conservation Assessment of Greater Sage-grouse and Sagebrush Habitats.* (unpublished report)

⁸² Information as cited in Knick et al. (2003), *Teetering on the Edge or Too Late? Conservation and Research Issues for Avifauna of Sagebrush Habitats.* (primary literature)

⁸³ Ibid.

⁸⁴ Information as cited in Connelly et al. (2004), *Conservation Assessment of Greater Sage-grouse and Sagebrush Habitats.* (unpublished report)

⁸⁵ Conley et al. (2010), *An Ecological Risk Assessment of Wind Energy Development in Eastern Washington.* (TNC report)

intact (857,731 acres).⁸⁶ The Yakima Training Center, the Yakama Indian Reservation, and the Hanford Site hold three of the largest blocks of shrub-steppe in Washington.⁸⁷ Other remaining shrub-steppe exists along waterways in the central Columbia Basin and the channeled scabland, where shallow soils and rock outcrops make farming difficult; fragments also exist within a matrix of agricultural lands⁸⁸ (see Table 4 for percent of habitat loss in other eastern WA counties).

The majority of remaining sagebrush habitat in the U.S. lower 48 states is managed by federal agencies;⁸⁹ however, this is not reflected in Washington State. In a study of shrub-steppe in the Columbia Basin, Dobler et al. (1996) found that 60% of remaining shrub-steppe land was privately owned. The Bureau of Indian Affairs was the only other major owner (11%).⁹⁰ Other owners of shrub-steppe land included WDNR (7%), U.S. Dept. of Defense (6%), WDFW and the U.S. Dept. of Energy (5% each) and U.S. BLM (3%).⁹¹ The USFWS, U.S. Bureau of Reclamation, USFS, and other public lands all held ownerships of 1% or less.⁹²

Table 4: Shrub-steppe acreage in Washington counties, based on Landsat data analyzed at the WDFW Remote Sensing Laboratory using plant community predictions of Daubenmire (1988). The study area was the central Columbia Basin, and did not cover some shrub-steppe areas in Okanogan and Klickitat counties. Dobler et al. (1996) completed this analysis for only 20% of the area in Okanogan county. This table is modified from Table 1 in Dobler et al. (1996).

County	Historical acreage	Remaining acreage	Percent loss
Okanogan	432,494	266,297	38
Yakima	1,488,672	857,731	42
Kittitas	581,164	323,946	44
Benton	1,032,188	502,523	51
Douglas	1,095,016	502,709	54
Chelan	201,925	76,903	62
Lincoln	1,260,032	473,674	62
Grant	1,614,555	571,830	65
Franklin	753,716	230,778	69
Adams	1,187,399	279,758	76
Walla Walla	770,017	178,037	77
TOTAL	10,417,178	4,264,186	59

Land Use History: Palouse Bioregion

⁸⁶ Dobler et al. (1996), *Status of Washington's Shrub-Steppe Ecosystem: Extent, ownership, and wildlife/vegetation relationships*. (WDFW project report)

⁸⁷ Ibid.

⁸⁸ Ibid.

⁸⁹ Knick et al. (2003), *Teetering on the Edge or Too Late? Conservation and Research Issues for Avifauna of Sagebrush Habitats*. (primary literature)

⁹⁰ Dobler et al. (1996), *Status of Washington's Shrub-Steppe Ecosystem: Extent, ownership, and wildlife/vegetation relationships*. (WDFW project report)

⁹¹ Ibid.

⁹² Ibid.

Prior to Euro-American settlement, bunchgrasses dominated the Palouse bioregion; however, most of the original perennial grass prairie was gone by 1900.⁹³ The conversion of more than 94% of the areas occupied by native landcover types makes the ecosystems of the Palouse bioregion some of the most endangered in the United States.⁹⁴ The World Wildlife Fund estimates that conversion to agriculture has destroyed more than 99% of the Palouse grasslands; the only two remaining large blocks of relatively intact habitat are located in the Hell's Canyon and Coulee Dam National Recreation Areas in eastern Washington.⁹⁵

Agriculture has affected both soil and water in the Palouse bioregion. Breaking the original perennial grass cover left the soil vulnerable to erosion by wind and water;⁹⁶ in fact, the Palouse region has one of the highest soil erosion rates in the country.⁹⁷ Intensification of agriculture has affected both water quantity and quality as well. Replacing perennial grasses with annual crops altered the hydrology and caused more intense erosion, loss of perennial prairie streams, and lowering of the water table.⁹⁸ As early as the 1930s soil scientists were noting significant downcutting of regional rivers.⁹⁹

As a result of habitat loss, several once common animal species, including ferruginous hawk (*Buteo regalis*), white-tailed jack rabbit (*Lepus townsendii*), and sharp-tailed grouse (*Tympanuchus phasianellus*), are rare and survive only as small relict populations in isolated fragments of habitat.¹⁰⁰ Six globally rare plant species are endemic to the Palouse region,¹⁰¹ and the integrity of remaining habitats for these and other species are low.¹⁰²

⁹³ Black et al. (1998), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

⁹⁴ Information as cited in Black et al. (1998), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

⁹⁵ World Wildlife Fund (2001), *Palouse Grasslands (NA0813)*. (website)

⁹⁶ Black et al. (1998), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

⁹⁷ Information as cited in Black et al. (1998), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

⁹⁸ Black et al. (1998), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

⁹⁹ Information as cited in Black et al. (1998), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

¹⁰⁰ Black et al. (1998), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

¹⁰¹ Information as cited in Black et al. (1998), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

¹⁰² Black et al. (1998), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

GLOBAL AND REGIONAL CLIMATE TRENDS

CLIMATE AND THE GREENHOUSE EFFECT

The IPCC Third Assessment Report defines *climate* as the “average” weather, in terms of the mean and its variability over a certain time period and in a certain area.¹⁰³ Earth’s climate system is described as an interactive system consisting of the atmosphere, hydrosphere (fresh and saline liquid waters), cryosphere (ice sheets, glaciers, snow fields), biosphere (e.g., vegetation), and the land surface (e.g., soils).¹⁰⁴ The climate system is influenced by a variety of external forces – the most important of which is the sun.¹⁰⁵ Human activities, such as the burning of fossil fuels, are also considered an external force that affects the climate system.¹⁰⁶

The sun provides a nearly constant flow of shortwave radiation toward Earth that is received at the top of the atmosphere.¹⁰⁷ Although this directly raises temperatures and produces surface warming, warming also occurs as a result of the greenhouse effect.¹⁰⁸ The lower atmosphere acts like a blanket that traps heat underneath it, absorbing and radiating back to the Earth some of the heat emitted by the surface and thereby warming the Earth.¹⁰⁹ Changes in the atmospheric concentration of greenhouse gases and in land cover interact with solar radiation to alter the balance of energy retained in Earth’s atmosphere.¹¹⁰ Warming as a result of the greenhouse effect influences air temperatures and precipitation patterns on global, regional, and local scales. For more background information on the climate system and a more thorough review of natural and human-induced climate variations, see:

- Baede, APM, E Ahlonsou, Y Ding, and D. Schimel. 2001. The Climate System: an Overview. In: Climate Change 2001: The Scientific Basis. IPCC Third Assessment Report. Available online at http://www.grida.no/publications/other/ipcc_tar/.

CURRENT CLIMATIC CHARACTERISTICS OF EASTERN WASHINGTON

Eastern Washington is part of the large inland basin between the Cascade and Rocky Mountains. The Rocky Mountains shield the northeastern portion of the basin from cold air masses traveling south from Canada,¹¹¹ and the Cascade Mountains shield the western portion of the basin from the comparatively mild winter and cooler summer maritime air masses.¹¹² This produces a climate with a mixture of continental and marine characteristics.¹¹³ The rainshadow that develops on the eastern side of the

¹⁰³ Baede et al. (2001), *The Climate System: an Overview*. (IPCC Third Assessment Report)

¹⁰⁴ Ibid.

¹⁰⁵ Ibid.

¹⁰⁶ Ibid.

¹⁰⁷ Strahler and Strahler (2005), *Physical Geography: Science and Systems of the Human Environment*. (book)

¹⁰⁸ Ibid.

¹⁰⁹ Ibid.

¹¹⁰ Baede et al. (2001), *The Climate System: an Overview*. (IPCC Third Assessment Report)

¹¹¹ Washington Regional Climate Center (n.d.), *Climate of Washington*. (website)

¹¹² Ibid.

¹¹³ Ibid.

Cascade crest is key in creating climatic conditions that favor shrub-steppe and grassland habitats in the intermountain lowland landscapes in eastern Washington.¹¹⁴

All regions of eastern Washington share the same general climatic pattern: warm summers with little precipitation, followed by cold winters during which most of the annual precipitation falls.¹¹⁵ Summer precipitation generally falls from intermittent thunder or hailstorms, while winter precipitation may be rain or snow.¹¹⁶ In general, snow begins to accumulate on the ground in December and can last from days to months, depending upon the region.¹¹⁷ Higher elevations receive more precipitation (both rain and snow) than lower elevations.¹¹⁸ In an average winter, frost in the soil can be expected to reach a depth of 10 to 20 inches.¹¹⁹

Although the region shares the same general climatic patterns, average temperatures and precipitation characteristics in eastern Washington vary broadly with elevation and topography. For example, the east slope of the Cascade Range exhibits an average of approximately 400 inches of winter season snowfall near its peak, while areas at lower elevations (~2,000 feet above sea level) receive an average of only 75 inches. Different climatic characteristics for five regions of eastern Washington are summarized in Table 5, while descriptions of each region are given below.

- *Cascade Range – eastern slope*: This region includes the summit eastward for 25 – 75 miles, as well as the area south from the Canadian border to the Columbia River. It is characterized by rapid changes in the amount of precipitation as one moves eastward and to lower elevations. Several large irrigation reservoirs are located in valleys along the eastern slope of the Cascades. Snowmelt provides irrigation water for orchards and other agricultural areas in the Okanogan, Wenatchee, Methow, Yakima, and Columbia River valleys.
- *Okanogan – Big Bend*: This region includes fruit producing valleys along the Okanogan, Methow, and Columbia Rivers, grazing land along the southern Okanogan highlands, the Waterville Plateau, and part of the channeled scablands.
- *Central Basin*: This region includes the Ellensburg valley and the central plains area in the Columbia basin south from the Waterville Plateau to the Oregon border and east to near the Palouse River.
- *Northeastern*: This region includes the northeastern and higher elevations of the Okanogan highlands, the Selkirk Mountains, and the lower elevations southward to the vicinity of the Spokane River.
- *Palouse – Blue Mountains*: This region includes counties along the eastern border of Washington from Spokane south to the Oregon border and west to near Walla Walla.

¹¹⁴ West and Young (2000), *Intermountain Valleys and Lower Mountain Slopes*. Chapter 7 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

¹¹⁵ Washington Regional Climate Center (n.d.), *Climate of Washington*. (website)

¹¹⁶ *Ibid.*

¹¹⁷ *Ibid.*

¹¹⁸ *Ibid.*

¹¹⁹ *Ibid.*

Table 5: Climatic characteristics for five broad regions of eastern Washington; information summarized from the Western Regional Climate Center (WRCC, n.d.).

REGION	Elevation range (ft. above sea level)	Average Temp. (avg. min – avg. max)	Average annual precipitation	Average winter season snowfall	Average snowfall accumulation & duration
Cascade Range/ East Slope	2000 ft. – summit	Jan. 15°F - 35°F	22 - 92 in.* *(Cle Elum – Stampede Pass, ~2000 ft. – 4,000 ft.)	75 in. (2,000 ft.) - 400 in. (summit)	24 – 60 in. No duration given
		July 45°F - 80°F			
Okanogan/ Big Bend	1000 – 3000 ft.	Jan. 15°F - 32°F	11 – 16 in.	30 – 70 in.	10 – 40 in. 3 – 4 months
		July 50°F - 90°F			
Central Basin	400 - 1800 ft.	Jan. 15°F - 30°F	7 – 15 in.	10 – 35 in.	<15 in. Days – 2 months
		July 50°F - 90°F			
Northeastern	2000 - 6000 ft.	Jan. 15°F - 30°F	17 – 28 in.	40 – 80 in.	15 – 30 in. (at lower elevations) 4 months
		July 45°F - 90°F			
Palouse/ Blue Mountains	1000 - 6000 ft.	Jan. 20°F - 38°F	10 - 40 in.	20 – 40 in.	No amount given Days – 2 months
		July 55°F - 85°F			

Shrub-steppe and grasslands ecosystems occupying lower elevations receive precipitation largely during winter and spring when evaporation and transpiration are minimal; in contrast, summer storms are generally high-intensity, short-lived events that contribute relatively little water to soils.¹²⁰ Crawford and Kagan describe eastern Washington’s grasslands as occurring from 500 to 6,000 feet in elevation, in habitats that are generally hot and dry.¹²¹ Annual precipitation in these habitats totals between 8 and 20 inches, with only 10% falling between July and September.¹²² Additionally, snow accumulation in these habitats is generally low (1 – 6 inches), and occurs in January and February.¹²³ Shrub-steppe also generally occupies hot, dry environments, although variants exist in cool, moist areas with some snow accumulation in climatically dry mountains.¹²⁴ Shrub-steppe elevation range is wide (300-9000 feet) with most habitat occurring between 2,000 and 6,000 feet.¹²⁵

¹²⁰ West and Young (2000), *Intermountain Valleys and Lower Mountain Slopes*. Chapter 7 in: *North American terrestrial vegetation*. 2nd edition. (book chapter)

¹²¹ Chappell et al. (2001), *Wildlife Habitats: Description, Status, Trends, and System Dynamics*. Chapter 2 in: *Wildlife-Habitat Relationships in Oregon and Washington*. (book chapter)

¹²² Ibid.

¹²³ Ibid.

¹²⁴ Ibid.

¹²⁵ Ibid.

CO₂ CONCENTRATIONS – GLOBAL TRENDS

Today's atmospheric carbon dioxide (CO₂) concentrations are approximately 385 parts per million (ppm).¹²⁶ Over the past 800,000 years, atmospheric CO₂ concentrations have varied between about 170 and 300 ppm.¹²⁷ Today's concentrations are approximately 30 percent higher than the earth's highest level of CO₂ over that time period.¹²⁸

TEMPERATURE – GLOBAL AND REGIONAL TRENDS AND PROJECTIONS

Global average temperature has risen approximately 1.5°F since 1900, and is projected to rise another 2°F to 11.5°F by 2100.¹²⁹

In the Pacific Northwest, Mote and Salathé (2009) project that annual temperatures will increase 2.2°F on average by the 2020s and 5.9°F by the 2080s; these projections are compared to 1970 - 1999 and averaged across all climate models.¹³⁰

McWethy et al. (2010) include the northeastern portion of Washington State in their summary of regional climate trends in the northern U.S. Rocky Mountains. The authors state that over the course of the 20th century, the instrumental record in the northern Rockies showed a significant increase in average seasonal, annual, minimum, and maximum temperatures.¹³¹ Regional average annual temperatures increased 2 - 4°F from 1900 to 2000.¹³² In general, seasonal and annual minimum temperatures increased at a faster rate than maximum temperatures.¹³³ In particular, summer and winter seasonal average minimum temperatures increased significantly faster than the season's average maximum temperatures, reducing seasonal, daily temperature ranges.¹³⁴

Central and southeastern Washington are included in the summary of regional climate trends for the Upper Columbia Basin. For most of the Upper Columbia Basin, average annual temperatures increased 1.2 – 1.4°F from 1920 to 2003.¹³⁵ Average temperatures have increased as much as 4°F in parts of the region and increases have been more pronounced at higher elevations.¹³⁶ During the mid-20th century, average and daily minimum temperatures increased more in the winter and spring than in other seasons

¹²⁶ Information as cited in Karl et al. (2009) *Global Climate Change Impacts in the United States*. (U.S. government report)

¹²⁷ Ibid.

¹²⁸ Ibid.

¹²⁹ Ibid.

¹³⁰ Mote and Salathé (2009), *Future Climate in the Pacific Northwest*. Chapter 1 in: *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. (CIG 2009)

¹³¹ Information as cited in McWethy et al. (2010), *Climate and terrestrial ecosystem change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and future perspectives for natural resource management*. (NPS report)

¹³² Ibid.

¹³³ Ibid.

¹³⁴ Ibid.

¹³⁵ Ibid.

¹³⁶ Ibid.

and more than maximum temperatures.¹³⁷ During the second half of the 20th century, minimum and maximum temperatures increased at similar rates.¹³⁸

Stöckle et al. (2009) report a range of climate projections for eastern Washington based on two general climate models: PCM1 (which projects less warming and more precipitation for eastern Washington) and CCSM3 (which projects more warming and less precipitation).¹³⁹ Both models project increases in annual temperature, although the amount of increase varies; the projections are summarized in Table 6. Overall, the changes for the average maximum and minimum temperatures are similar to those projected for average temperatures.¹⁴⁰ The projected warming trend will increase the length of the frost-free period throughout the state; this will continue the trend observed from 1948 to 2002, during which the frost-free period has lengthened by 29 days in the Columbia Valley.¹⁴¹

Table 6: Projected increases in average annual temperature at three locations in eastern Washington under two general climate models (CCSM3 and PCM1). Projections were made for three timeframes (2020s, 2040s, and 2080s) and compared against baseline temperatures from 1975-2005. Table modified from Stöckle et al. (2009).

Location in eastern WA / Timeframe of Projection	Increase in Temperature for Each GCM As Compared with Baseline (1975-2005) Temperature			
	CCSM3		PCM1	
LIND	°Celsius	°Fahrenheit	°Celsius	°Fahrenheit
2020s	1.4	2.5	0.8	1.4
2040s	2.3	4.1	1.7	3.1
2080s	3.2	5.8	2.6	4.7
PULLMAN				
2020s	1.7	3.1	1.1	2.0
2040s	2.7	4.9	2.0	3.6
2080s	3.5	6.3	2.9	5.2
SUNNYSIDE				
2020s	1.7	3.1	1.3	2.3
2040s	2.7	4.9	2.2	4.0
2080s	3.5	6.3	3.0	5.4

¹³⁷ McWethy et al. (2010), *Climate and terrestrial ecosystem change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and future perspectives for natural resource management*. (NPS report)

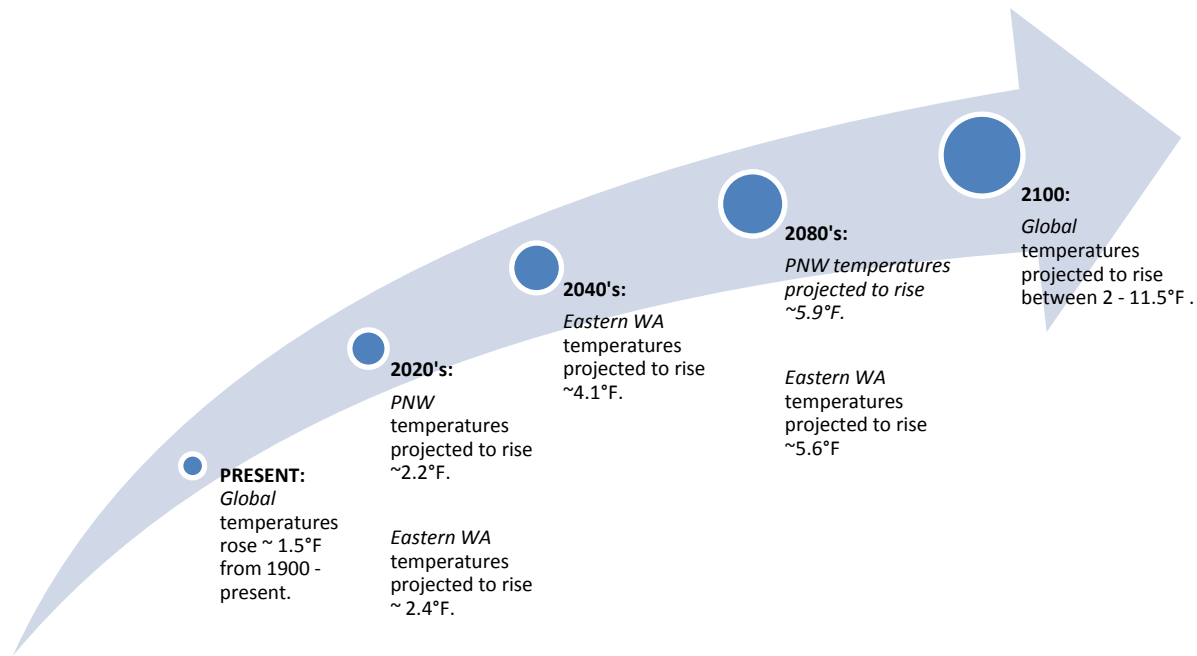
¹³⁸ Information as cited in McWethy et al. (2010), *Climate and terrestrial ecosystem change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and future perspectives for natural resource management*. (NPS report)

¹³⁹ Stöckle et al. (2009), *Assessment of climate change impact on eastern Washington agriculture*. Chapter 5 in: *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. (CIG 2009)

¹⁴⁰ Ibid.

¹⁴¹ Information as cited in Stöckle et al. (2009), *Assessment of climate change impact on eastern Washington agriculture*. Chapter 5 in: *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. (CIG 2009)

Figure 1: Summary of projected temperature changes globally, in the Pacific Northwest, and in eastern Washington. Increases in PNW temperature are compared to a baseline of temperatures from 1970-1999. Increases in Eastern WA temperature are compared to a baseline of temperature data from 1975-2005, and are averaged across the two GCMs reported above (PCM1 & CCSM3). All increases reported as compared to a given baseline – *not* in addition to a previous increase. Figure created by NWF report authors and compiled from Karl et al. (2009), McWethy et al. (2010), Mote & Salathé (2009), & Stöckle et al. (2009).



PRECIPITATION – REGIONAL PROJECTIONS

Mote and Salathé (2009) state that projected changes in overall annual precipitation for the Pacific Northwest (averaged across all climate models) are small: +1 to +2%.¹⁴² However, some of the models projected an enhanced seasonal cycle in precipitation, with changes toward wetter winters and drier summers.¹⁴³

- **Drier summers:** For summer months, a majority of models projected decreases in precipitation, with the average declining 16% by the 2080s.¹⁴⁴ Some models predicted reductions of as much as 20-40% in summer precipitation; these percentages translate to 3- 6 cm over the summer season (June/July/August).¹⁴⁵
- **Wetter winters:** A majority of models projected increases in winter precipitation, with an average value reaching +9% (about 3 cm) by the 2080s under the higher-emissions modeling scenario (A1B); this value is small relative to interannual variability.¹⁴⁶ Although some of the

¹⁴² Mote and Salathé (2009), *Future Climate in the Pacific Northwest*. Chapter 1 in: *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. (CIG 2009)

¹⁴³ Ibid.

¹⁴⁴ Ibid.

¹⁴⁵ Ibid.

¹⁴⁶ Ibid.

models predicted modest reductions in fall or winter precipitation, others showed very large increases (up to 42%).¹⁴⁷ [For information on A1B and B1 emissions scenarios, see Box 2]

Snowpack in the Pacific Northwest is highly temperature sensitive and long-term records show that April 1 snowpack has already declined substantially throughout the region.¹⁴⁸ Snover et al. (2005) cite information that April 1 snowpack (measured as snow water equivalent, or SWE) has declined markedly almost everywhere in the Cascades since 1950.¹⁴⁹ These declines exceeded 25 percent at most study locations, and tended to be largest at lower elevations.¹⁵⁰ Stoelinga et al. (in press) examined snowpack data over an even longer time period (1930-2007) and concluded that snowpack loss occurred at a rate of approximately 2.0% per decade, yielding a 16% loss over nearly 80 years.¹⁵¹

Relative to late 20th century averages (1971-2000), Elsner et al. (2009) project that April 1 SWE will decrease by 27-29% across the state by the 2020's, 37-44% by the 2040's, and 53-65% by the 2080's.¹⁵² However, a study by Stoelinga et al. (in press) predicts that cumulative loss of Cascade spring snowpack from 1985-2025 will be only 9%.¹⁵³

High annual and decadal variability make it difficult to identify long-term precipitation trends for specific regions within the Pacific Northwest. According to McWethy et al. (2010), general patterns during the end of the 20th century indicate that areas within the northern Rockies (a region which includes northeastern Washington) experienced modest but statistically insignificant decreases in annual precipitation.¹⁵⁴ Although rising temperatures throughout the West have generally led to an increasing proportion of precipitation falling as rain rather than snow,¹⁵⁵ the prevalence of winter temperatures that are well below freezing may make the northern Rockies region less sensitive to small temperature changes that affect the number of freezing days.¹⁵⁶

The upper Columbia Basin is also characterized by high decadal variability in precipitation.¹⁵⁷ Between 1930 and 1995, increases in precipitation ranged from 13 – 38%,¹⁵⁸ but these trends are not statistically

¹⁴⁷ Ibid.

¹⁴⁸ Information as cited in Karl, et al. (2009), *Global Climate Change Impacts in the United States*. (U.S. government report)

¹⁴⁹ Information as cited in Snover et al. (2005), *Uncertain Future: Climate change and its effects on Puget Sound*. (CIG 2005)

¹⁵⁰ Ibid.

¹⁵¹ Stoelinga et al. (in press), *A New Look at Snowpack Trends in the Cascade Mountains*.

¹⁵² Elsner et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*. Chapter 3 in: *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. (CIG 2009)

¹⁵³ Stoelinga et al. (in press), *A New Look at Snowpack Trends in the Cascade Mountains*. (primary literature)

¹⁵⁴ Information as cited in McWethy et al. (2010), *Climate and terrestrial ecosystem change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and future perspectives for natural resource management*. (NPS report)

¹⁵⁵ Ibid.

¹⁵⁶ Ibid.

¹⁵⁷ McWethy et al. (2010), *Climate and Terrestrial Ecosystem Change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and Future Perspectives for Natural Resource Management*. (NPS report).

¹⁵⁸ Information as cited in McWethy et al. (2010), *Climate and Terrestrial Ecosystem Change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and Future Perspectives for Natural Resource Management*. (NPS report).

significant depending on the area and time interval measured.¹⁵⁹ Overall, variability in winter precipitation has increased since 1973.¹⁶⁰ Spring snowpack and SWE declined throughout the Upper Columbia Basin in the second half of the 20th century.¹⁶¹ The decline was most pronounced at low and mid-elevations, and declines of more than 40% were recorded for some parts of the region.¹⁶² Declines in snowpack and SWE are associated with increased temperatures and declines in precipitation during the same period.¹⁶³ The timing of peak runoff shifted 2-3 weeks earlier for much of the region during the second half of the 20th century,¹⁶⁴ and the greatest shifts occurred in the mountain plateaus of Washington, Oregon, and western Idaho.¹⁶⁵

Specifically for eastern Washington, climate scenarios project that annual precipitation will increase by about 10% to 14% and 8% to 10% for the CSSM3 and PCM1 projections, respectively, but with the spring-summer precipitation becoming a smaller fraction of the total increase.¹⁶⁶ The changes in evapotranspiration are roughly similar to precipitation changes but with a larger proportion of the increase during the spring-summer period.¹⁶⁷

Table 7: Summary of climate projections for the Rocky Mountains and Upper Columbia Basin. Table found in Ashton (2010) Table 1, based on information in McWethy et al.,(2010).

Climate Variable	General Change Expected	Range of Change Expected	General pattern	Confidence
Temperature	Increase	1.5–2.1°C (2.7°–3.4°F)	Increases slightly greater in the summer	High
Precipitation	No change	2–5% increase in winter, 0–4% decrease in summer	Increase in winter, decrease in summer	Moderate for winter; low for summer
Drought	Increase in frequency and severity	Varies with magnitude of temperature and evaporation change	Greatest impact in summer	High
Temperature Extreme Events	Increase of warm events, decrease of cold events	Varies with magnitude of temperature change	Increase in frequency and length of hot events	High
Precipitation Extreme Events	Potential for decreased frequency coupled with increased intensity	Uncertain	Potential for more intense spring and summer floods	Uncertain

¹⁵⁹ McWethy et al. (2010), *Climate and Terrestrial Ecosystem Change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and Future Perspectives for Natural Resource Management*. (NPS report)

¹⁶⁰ Information as cited in McWethy et al. (2010), *Climate and Terrestrial Ecosystem Change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and Future Perspectives for Natural Resource Management*. (NPS report).

¹⁶¹ McWethy et al. (2010), *Climate and Terrestrial Ecosystem Change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and Future Perspectives for Natural Resource Management*. (NPS report)

¹⁶² Information as cited in McWethy et al. (2010), *Climate and Terrestrial Ecosystem Change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and Future Perspectives for Natural Resource Management*. (NPS report)

¹⁶³ Ibid.

¹⁶⁴ Ibid.

¹⁶⁵ Ibid.

¹⁶⁶ Stöckle et al. (2009), Assessment of climate change impact on eastern Washington agriculture. Chapter 5 in: *The Washington Climate Change Impacts Assessment: Evaluating Washington’s Future in a Changing Climate*. (CIG 2009)

¹⁶⁷ Ibid.

Box 2: A1B and B1 Emissions Scenarios

The A1B and B1 emissions scenarios are two of many emissions scenarios used by the International Panel on Climate Change (IPCC) to model climate change effects in futures with different levels of fossil fuel reliance. In *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. (WACCIA (CIG 2009)), the Climate Impacts Group chose A1B as the higher emissions scenario and B1 as the low emissions scenario to analyze 21st Century Pacific Northwest climate.

The A1B scenario represents a future of rapid economic growth in which energy sources are balanced between fossil and non-fossil fuels (with the assumption that energy use efficiency will improve with the introduction of new technologies).

The B1 scenario represents a future in which global economies are less material-intensive and based more on information and services. Clean and resource-efficient technologies are introduced and an emphasis is placed on economic, social, and environmental sustainability.

The WACCIA (CIG 2009) notes that recent CO₂ emissions have exceeded even the high end emission scenario used by the IPCC (A1F1).

Weighted Average Approach to Climate Projections

In the WACCIA, Mote and Salathé (2009) base their temperature and precipitation predictions for Washington on both the common practice of presenting a range of projected changes from multiple climate model ensembles, as well as a reliability ensemble averaging (REA) approach. The latter approach is a weighted average prediction -- each model's output for seasons and decades is weighted by its bias and distance from the all-model average; this approach may produce better results for the future than an unweighted average by giving more weight to models that perform well in simulating 20th century climate. For more details on this approach, including graphical presentations of the average and range of values, see Mote and Salathé (2009).

Sources: IPCC (2007) *AR4, Working Group 1: The Scientific Basis. Section F.1 Box 5.*, Mote and Salathé (2009), CIG (2009).

CLIMATE CHANGE EFFECTS ON WASHINGTON'S SHRUB-STEPPE AND GRASSLAND ECOSYSTEMS

Slight changes in temperature and precipitation can substantially alter the composition, distribution, and abundance of species in arid lands, and the products and services they provide.¹⁶⁸ For example, observed and projected decreases in the frequency of freezing temperatures, lengthening of the frost-free season, and increased minimum temperatures can alter plant species ranges and shift the geographic and elevational boundaries of many arid lands.¹⁶⁹ The extent of these changes will also depend on changes in precipitation and fire.¹⁷⁰ Increased drought frequency could also cause major

¹⁶⁸ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

¹⁶⁹ Ibid.

¹⁷⁰ Ibid.

changes in vegetation cover.¹⁷¹ Losses of vegetative cover coupled with increases in precipitation intensity and climate-induced reductions in soil aggregate stability will dramatically increase potential erosion rates.¹⁷² Transport of eroded sediment to streams coupled with changes in the timing and magnitude of minimum and maximum flows can affect water quality, riparian vegetation, and aquatic fauna.¹⁷³

This section describes major climate change effects on Washington's shrub-steppe and grassland ecosystems, including:

- Changes in species composition, distribution, and community dynamics
- Changes in ecosystem productivity
- Changes in disturbance regimes

CHANGES IN SPECIES COMPOSITION, DISTRIBUTION, AND COMMUNITY DYNAMICS

Ecosystem function and species composition of grasslands are likely to respond mainly to precipitation change and warming in temperate systems.¹⁷⁴ Changes in mean temperature will affect levels of physiological stress and water requirements during the growing season.¹⁷⁵ Similarly, minimum winter temperatures may strongly influence species composition and distribution.¹⁷⁶ Species have different requirements for growth and different abilities to adapt to changes in temperature and precipitation regimes. For example, plants that can access water in deep soil or in groundwater depend less on precipitation for growth and survival, but such plants may be sensitive to precipitation changes that affect the recharge of deep water stores.¹⁷⁷

Although climate influences community composition and dynamics at broad spatial scales, topography, soils, and landforms control local variation in ecosystem structure and function within a given elevational zone (i.e., moisture/temperature regime).¹⁷⁸ Communities transition from desert scrub and grassland to savanna, woodland, and forest along strong elevation gradients.¹⁷⁹ Topography influences water balance, air drainage, night temperatures, and routing of precipitation.¹⁸⁰ Soil texture and depth affect water capture, water storage, and fertility.¹⁸¹ These factors strongly interact with precipitation to

¹⁷¹ Ibid.

¹⁷² Ibid.

¹⁷³ Ibid.

¹⁷⁴ Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC Fourth Assessment Report, section 4.4.3)

¹⁷⁵ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

¹⁷⁶ Ibid.

¹⁷⁷ Ibid.

¹⁷⁸ Ibid.

¹⁷⁹ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

¹⁸⁰ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

¹⁸¹ Ibid.

limit plant production and control species composition.¹⁸² To predict vegetation response to climate change, it is necessary to understand these complex relationships among topography, soil, soil hydrology, and plant response.¹⁸³

In addition to temperature, precipitation, and landscape position, rising atmospheric CO₂ may also contribute to alterations in plant community dynamics and composition. Enhanced photosynthesis and plant productivity as a result of elevated atmospheric CO₂ is a possible effect of climate change known as “CO₂ fertilization.” Elevated CO₂ influences plant productivity and soil water balance in most grassland types, with woody species (i.e., trees and shrubs) showing higher responsiveness to enhanced CO₂ than herbaceous species.¹⁸⁴ These differential effects of rising atmospheric CO₂ on woody relative to herbaceous growth forms are considered very likely to occur.¹⁸⁵

The fertilization effect of increased CO₂ concentrations could significantly alter competitive interactions among plant species.¹⁸⁶ Higher concentrations of atmospheric CO₂ and increasing temperature are predicted to increase the competitive ability of C₃ versus C₄ plants in water-limited systems (see Box 3 “C₃ vs. C₄ plants” for descriptions of these functional types).¹⁸⁷ In some cases, enhanced atmospheric CO₂ may also benefit non-native C₃ species over native C₃ species. For example, the arid Great Basin is dominated by C₃ plants, and here, CO₂ enrichment favors cheatgrass – a non-native, annual C₃ species – over the native C₃ plants.¹⁸⁸ Elevated CO₂ concentrations may also increase a plant’s water-use efficiency, which in turn may enhance its tolerance of drought conditions.¹⁸⁹ This enhanced drought tolerance is particularly significant when attempting to project the response of arid vegetation to climate change.¹⁹⁰

¹⁸² Ibid.

¹⁸³ Ibid.

¹⁸⁴ Information as cited in Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC Fourth Assessment Report, section 4.4.3)

¹⁸⁵ Ibid.

¹⁸⁶ Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC Fourth Assessment Report, section 4.4.3)

¹⁸⁷ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

¹⁸⁸ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

¹⁸⁹ Information as cited in Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC Fourth Assessment Report, section 4.4.3)

¹⁹⁰ Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC Fourth Assessment Report, section 4.4.3)

Note that the direct climate change effects of CO₂ fertilization and increasing average temperatures may have contrasting influences on dominant functional types.¹⁹¹ Trees and C₃ grasses may benefit from rising CO₂ but not from warming, whereas C₄ grasses may benefit from warming but not from CO₂ fertilization.¹⁹² This may mean that uncertain, non-linear, and rapid changes in ecosystem structure and carbon stocks could occur.¹⁹³

Box 3: C₃ vs. C₄ Plants

All plants have small openings on their leaves called “stomata”. These openings allow plants to capture atmospheric CO₂ and bring it into their cells, where it is used for photosynthesis. The different ways in which CO₂ is incorporated into plant photosynthesis distinguishes C₃ from C₄ plants.

Most plants conduct photosynthesis through the C₃ pathway, although some plants adapted for arid conditions use the alternative C₄ pathway. The differences between these two pathways, and their implications for plant ecology, are described below.

Photosynthetic Pathways

“C₃” plants incorporate CO₂ into a 3-carbon photosynthetic compound. An enzyme called RUBISCO is involved both in capturing CO₂ and in facilitating its use in the rest of the photosynthetic process.

“C₄” plants incorporate CO₂ into a 4-carbon photosynthetic compound. They use a different enzyme – PEP carboxylase – to capture CO₂. This enzyme then delivers the CO₂ to RUBISCO for use in photosynthesis.

RUBISCO is interesting in that it is not specific to CO₂ – it will also capture oxygen, which is useless for photosynthesis. When PEP carboxylase delivers CO₂ right to RUBISCO, it avoids this wasteful occurrence.

Photosynthetic Adaptations to Arid Conditions

Under cool, moist conditions and normal lighting, C₃ plants conduct photosynthesis more efficiently than C₄ plants because they require fewer enzymes and no specialized cell structures. However, under high light intensity and high temperatures, C₄ plants photosynthesize more efficiently than C₃ plants.

Why is this so? When plants open their stomata to capture CO₂, they also lose water (another necessary component of photosynthesis) through evaporation. Because C₄ plants have special cell structures and an enzyme that delivers CO₂ right to RUBISCO, they can capture plenty of CO₂ for photosynthesis – then close their stomata and avoid water loss. Because RUBISCO sometimes collects oxygen instead of CO₂, C₃ plants have to leave their stomata open longer to capture the same amount of CO₂ as C₄ plants. Therefore, they end up losing more water than C₄ plants.

* Source: Pima Community College (2000)

¹⁹¹ Ibid.

¹⁹² Ibid.

¹⁹³ Ibid.

Non-Native Plants: Cheatgrass Invasions in Washington State

Annual plants are a major source of plant diversity in North American deserts, but non-native annuals are rapidly displacing native annuals.¹⁹⁴ In arid lands of the United States, non-native grasses often act as “transformer species” in that they change the character, condition, form, or nature of a natural ecosystem over substantial areas.¹⁹⁵ A site’s suitability for invasion by non-native plants –its “invasibility” – varies across elevation gradients; land use and climate also influence the probability, rate, and pattern of non-native species invasion.¹⁹⁶ Changes in ecosystem susceptibility to invasion by non-native plants may be expected with changes in climate, CO₂, and nitrogen deposition.¹⁹⁷ For example, high CO₂ concentrations appear to benefit non-native grasses and weeds more so than native species.¹⁹⁸

Cheatgrass is an example of a non-native, invasive species of particular concern in the western United States because it readily invades shrub-steppe and grassland habitats (see Box 4, “History of Cheatgrass Invasion” for more information on cheatgrass introduction and spread in Washington).¹⁹⁹ Once established, cheatgrass is extremely difficult to eradicate.²⁰⁰ In disturbed areas, cheatgrass can gain a head start over native perennial grass seedlings because its seeds can germinate earlier in autumn and in colder winter temperatures, and it is better able to produce root growth in winter.²⁰¹ It also has high root and shoot growth rates, as well as high leaf area and root length per unit biomass relative to the seedlings of native perennial grasses.²⁰² Cheatgrass competition acting on seedling-stage perennial grasses inhibits the recruitment of perennial grasses into cheatgrass communities by greatly reducing survival to adult stage, adult growth, and flowering, which all combine to reduce seed availability.²⁰³ Although cheatgrass has an early size advantage over seedlings of perennials, established perennial plants are likely to be better competitors against cheatgrass because they can access deep soil moisture that is largely unavailable to cheatgrass, and they may suppress cheatgrass abundance.²⁰⁴

¹⁹⁴ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

¹⁹⁵ Ibid.

¹⁹⁶ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

¹⁹⁷ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

¹⁹⁸ Ibid.

¹⁹⁹ Bradley (2009), *Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity*. (primary literature)

²⁰⁰ Ibid.

²⁰¹ Information as cited in Humphrey and Schupp (2004), *Competition as a barrier to establishment of a native perennial grass (*Elymus elymoides*) in alien annual grass (*Bromus tectorum*) communities*.(primary literature)

²⁰² Ibid.

²⁰³ Humphrey and Schupp (2004), *Competition as a barrier to establishment of a native perennial grass (*Elymus elymoides*) in alien annual grass (*Bromus tectorum*) communities*. (primary literature)

²⁰⁴ Information as cited in Humphrey and Schupp (2004), *Competition as a barrier to establishment of a native perennial grass (*Elymus elymoides*) in alien annual grass (*Bromus tectorum*) communities*. (primary literature)

Observed Changes

Climate change may alter precipitation regimes by affecting the timing, frequency, and intensity of precipitation events.²⁰⁵ Precipitation exerts primary control of plant productivity and composition in semi-arid and arid land plant communities.²⁰⁶ The frequency and seasonal distribution of precipitation play a major role in the availability of water within soil profiles, strongly influencing arid land plant composition and dynamics.²⁰⁷ Winter precipitation is more likely to percolate deeper into the soil profile, unlike summer precipitation that may evaporate before infiltrating.²⁰⁸ In the northern Great Basin of the U.S., the majority of annual precipitation is received during the winter and early spring. This climatic regime favors growth and development of deep-rooted shrubs and cool season plants using the C₃ photosynthetic pathway.²⁰⁹

Bates et al. (2006) assessed vegetation response to altered timing of precipitation during a seven-year experiment in an *Artemisia tridentata* spp. *wyomingensis* community in the northern Great Basin, near Burns, Oregon. Using rainout shelters, the authors manipulated precipitation regimes for specific areas of grasses and shrubs at four locations. Precipitation regimes were altered such that plants in the “winter” treatment received 80% of their precipitation between October and March, while those in the “spring” treatment received 80% of their precipitation between April and July.²¹⁰ Control treatments received precipitation according to long-term (50-year) distribution patterns.²¹¹ The authors found that big sagebrush exhibited no response to precipitation changes in terms of its cover and density.²¹² Big sagebrush did have higher reproductive success and heavier shoot weights with the application of increased precipitation in the “spring” treatment; however, this did not result in the recruitment of new plants.²¹³ Herbaceous plants exhibited lower biomass, cover, and density under the “spring” treatment, likely due to reduced soil water availability during the most active growth period (April-May).²¹⁴ Effective precipitation was less in the “spring” treatment because the soils never became thoroughly wet.²¹⁵

The productivity of cold desert C₃ species of the Great Basin is keyed to the recharging of soil moisture during winter.²¹⁶ Bates et al. (2006) state that a long-term shift to a spring/summer dominated precipitation pattern would likely lead to the forb component being lost or severely reduced, with the potential to reduce ecosystem biodiversity.²¹⁷ However, a shift in precipitation to spring/summer is not predicted for Washington State. Rather, a slight increase in annual precipitation is projected for eastern

²⁰⁵ Information as cited in Bates et al. (2006), *The effects of precipitation timing on sagebrush steppe vegetation*. (primary literature)

²⁰⁶ Ibid.

²⁰⁷ Ibid.

²⁰⁸ Ibid.

²⁰⁹ Ibid.

²¹⁰ Bates et al. (2006), *The effects of precipitation timing on sagebrush steppe vegetation*. (primary literature)

²¹¹ Ibid.

²¹² Ibid.

²¹³ Ibid.

²¹⁴ Ibid.

²¹⁵ Ibid.

²¹⁶ Information as cited in Bates et al. (2006), *The effects of precipitation timing on sagebrush steppe vegetation*. (primary literature)

²¹⁷ Bates et al. (2006), *The effects of precipitation timing on sagebrush steppe vegetation*. (primary literature)

Washington, with a greater percentage of precipitation falling in winter (see earlier section on precipitation projections). This simply accentuates the historical precipitation pattern.

Bates et al. (2006) conclude that a shift in precipitation that does not stray far from historical patterns is unlikely to cause major disruptions to ecosystem composition or productivity. Thus, increases in winter precipitation, combined with summer drought, appear unlikely to cause major changes to vegetation composition or productivity of *A. tridentata* communities in the northern Great Basin.²¹⁸

The invasion of non-native species such as cheatgrass may cause major changes in vegetation composition and productivity. Climatically-suitable cheatgrass habitat exists in eastern Oregon and Washington and generally already hosts extensive cheatgrass populations.²¹⁹ Low elevation sites become more susceptible to cheatgrass invasion with an increase in soil moisture variability and a reduction in perennial herbaceous cover.²²⁰ In a 45-year study of cold desert sagebrush steppe, abundance of native species was found to be an important factor influencing community resistance to invasion.²²¹

Future Projections

Increases in winter temperatures have been predicted for large regions of western North America.²²² In southern Washington, a shift from below-freezing to above-freezing mean monthly temperatures may occur.²²³ Such a shift will change the duration and magnitude of below-freezing temperatures, which will have significant impacts on many species in the western U.S.²²⁴ For example, warm-temperate plant species that were previously limited by freezing temperatures may be able to spread northward, along with warm-temperate pests and pathogens.²²⁵

Changes in climate will affect the nature of elevational zonation, with arid land communities potentially moving upward in elevation in response to warmer and drier conditions.²²⁶ Experimental data suggest shrub recruitment at woodland-grassland ecotones is favored by increases in summer precipitation, but unaffected by increases in winter precipitation.²²⁷ Greater temperatures and higher rates of evapotranspiration predicted to co-occur with drought could increase mortality for the dominant woody

²¹⁸ Ibid.

²¹⁹ Information as cited in Bradley (2009), *Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity*. (primary literature)

²²⁰ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²²¹ Ibid.

²²² Shafer et al. (2001), *Potential changes in the distributions of western North America tree and shrub taxa under future climate scenarios*. (primary literature)

²²³ Ibid.

²²⁴ Ibid.

²²⁵ Ibid.

²²⁶ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²²⁷ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

vegetation typical of North American desert, and create opportunities for the establishment of non-native annual grasses.²²⁸

The potential range of the native woody shrub big sagebrush is simulated to shift northward and contract significantly in response to increases in the mean temperature of the coldest month (MTCO).²²⁹ Increases in the MTCO could indirectly affect the potential range of big sagebrush if increases in transpiration rates during the winter months, combined with changes in the precipitation regime, result in increased soil moisture stress during the year.²³⁰ Increases in the frequency of fires under future climate scenarios would also facilitate the simulated potential range contractions, because big sagebrush does not re-sprout following fire events.²³¹

Warming and CO₂ fertilization may have opposite effects on savanna and grassland dominant functional types, with CO₂ fertilization favoring woody C₃ plants and warming favoring C₄ herbaceous types.²³² North American forest vegetation types could spread with up to 7.2°F (4°C) warming; but with greater warming, forest cover could be reduced by savanna expansion of up to 50% (partly due to the impacts of fire).²³³ One study found that for arid systems, CO₂-induced changes to plant water balance yielded a greater plant response than the direct effects of CO₂ fertilization.²³⁴

CO₂ enhancement of C₃ woody plant seedling growth, as compared to growth of C₄ grasses, may facilitate woody plant establishment.²³⁵ Reduced transpiration rates from grasses under higher CO₂ may also allow greater soil water recharge to depth, and favor shrub seedling establishment.²³⁶ Changes in both plant growth and the ability to escape the seedling-fire-mortality constraint are critical for successful shrub establishment in water-limited grasslands.²³⁷

Interactions with other facets of global change may constrain growth form and photosynthetic pathway responses to CO₂ fertilization. For example, increasing temperature and rainfall changes may override the potential benefits of rising CO₂ for C₃ relative to C₄ grasses.²³⁸ Increased winter temperatures could also lengthen the C₄ growing season.²³⁹ Greater primary production as a result of elevated CO₂,

²²⁸ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²²⁹ Shafer et al. (2001), *Potential changes in the distributions of western North America tree and shrub taxa under future climate scenarios*. (primary literature)

²³⁰ Ibid.

²³¹ Information as cited in Shafer et al. (2001), *Potential changes in the distributions of western North America tree and shrub taxa under future climate scenarios*. (primary literature)

²³² Information as cited in Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC Fourth Assessment Report, section 4.4.3)

²³³ Ibid.

²³⁴ Shafer et al. (2001), *Potential changes in the distributions of western North America tree and shrub taxa under future climate scenarios*. (primary literature)

²³⁵ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²³⁶ Ibid.

²³⁷ Ibid.

²³⁸ Information as cited in Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC Fourth Assessment Report, section 4.4.3)

²³⁹ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

combined with increased abundance of non-native grass species, may alter fire frequencies.²⁴⁰ Nitrogen deposition may also favor grassland physiognomies over shrublands.²⁴¹ Predicted changes in C₃ versus C₄ dominance, or changes in grass versus shrub abundance in water-limited ecosystems, will require an understanding of multi-factor interactions of global change that the scientific community does not yet possess.²⁴²

Changes in community composition as a result of cheatgrass invasion depend on the future climate. A decrease in spring precipitation could reduce cheatgrass climatic habitat because cheatgrass would not have adequate water resources during its growing season.²⁴³ In contrast, decreased summer precipitation may make perennials less viable and favor early season annuals like cheatgrass.²⁴⁴ One study (Bradley 2009) presented a median climate change scenario in an effort to identify the most likely future for cheatgrass. This scenario depicted the majority of eastern Washington maintaining its current climatic suitability for cheatgrass, with a small area (a portion of 1 or 2 counties) gaining climatic suitability.²⁴⁵

Discussion

If climatic conditions become unsuitable for a plant, potential migration to areas with a more suitable climate can only occur via the dispersal and establishment of the next generation of individuals.²⁴⁶ Evidence suggests that vegetative range adjustments are episodic in response to climatic conditions, occurring rapidly when conditions are suitable and slowly or not at all otherwise.²⁴⁷ Migration rates, changes in disturbance regimes, and interactions with other species will all be important factors in determining the distribution of species under future climates, as will transient changes in the range and viability of diseases, pests, and mutualists.²⁴⁸ From the magnitude of simulated potential range changes, it is clear that competitive interactions between species will change as climate changes, which could affect the viability of some species.²⁴⁹ Changing species distributions may bring a species into contact with other taxa with which it has never interacted, and entirely new competitive interactions may result.²⁵⁰ Conversely, climate change may eliminate an important predator, allowing a species to greatly

²⁴⁰ Ibid.

²⁴¹ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²⁴² Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²⁴³ Bradley (2009), *Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity*. (primary literature)

²⁴⁴ Ibid.

²⁴⁵ Ibid.

²⁴⁶ Shafer et al. (2001), *Potential changes in the distributions of western North America tree and shrub taxa under future climate scenarios*. (primary literature)

²⁴⁷ Information as cited in McWethy et al. (2010), *Climate and terrestrial ecosystem change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and future perspectives for natural resource management*. (NPS report)

²⁴⁸ Information as cited in Shafer et al. (2001), *Potential changes in the distributions of western North America tree and shrub taxa under future climate scenarios*. (primary literature)

²⁴⁹ Shafer et al. (2001), *Potential changes in the distributions of western North America tree and shrub taxa under future climate scenarios*. (primary literature)

²⁵⁰ Ibid.

expand its range.²⁵¹ Perhaps the most significant interspecies interaction will be with humans due to the impact of our land-use activities on habitat and species distributions and abundances.²⁵²

Non-native plant invasions, promoted by enhanced nitrogen deposition (e.g., from burning fossil fuels) and increased anthropogenic disturbance, will have a major impact on how arid land ecosystems respond to climate and climate change.²⁵³ Because established non-native annual and perennial grasses can generate massive, high-continuity fine-fuel loads that predispose arid lands to fires more frequent and intense than those with which they evolved, desert scrub, shrub-steppe, and desert grassland/savanna biotic communities may be quickly and radically transformed into monocultures of invasive grasses over large areas.²⁵⁴

Knowledge Gaps

- Predictions of future primary production in shrub-steppe and grassland ecosystems of eastern Washington. Will longer dry seasons and less water storage in snow result in decreased productivity of native plant species?
- Effects of climate change on other invasive plants such as knapweed, starthistle, medusahead. Are there species other than cheatgrass that might also increase, perhaps even having greater effects than cheatgrass?
- Information on whether other species (e.g., *Poa bulbosa*) are becoming invasive.
- Information on how invasive species may be dominating and replacing other invasive species (i.e., information on the rate and composition of community changes). For example, a reviewer cited information that *Ventenata dubia*, an exotic, winter-annual grass, has been reported as increasing in dominance in areas formerly dominated by cheatgrass.

Reviewer Comments

- A WDFW reviewer commented: “One of my biggest concerns is that if you look at Washington, conversion of habitats is not uniform. A substantial amount of 'aridlands' has been converted for production of crops. I believe it is useful to make it clear that any change in climate (regardless of direction) is likely to have a much larger effect on habitats that have already been altered (i.e., the aridlands).”

CHANGES IN ECOSYSTEM PRODUCTIVITY

Productivity refers to the rate of biomass (organic matter) produced by an individual organism or a community, measured as either energy or organic matter produced per unit area. Plants use the energy from sunlight to convert atmospheric CO₂ and water to organic sugars through photosynthesis. Plants “fix” carbon when they convert it from an inorganic form (e.g., CO₂) to an organic form (e.g., glucose).

²⁵¹ Ibid.

²⁵² Information as cited in Shafer et al. (2001), *Potential changes in the distributions of western North America tree and shrub taxa under future climate scenarios*. (primary literature)

²⁵³ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²⁵⁴ Ibid.

Within arid ecosystems, year-to-year variations in plant growth are related to rainfall, with water as the primary factor limiting plant growth.²⁵⁵ Factors such as soil texture, depth, and landscape position also affect soil moisture availability and determine plant growth in local conditions.²⁵⁶ Although grasslands may tend to support higher aboveground net primary production (ANPP) than shrub-dominated systems, grasslands also demonstrate higher interannual variation.²⁵⁷ Increases in temperature and changes in the amount and seasonal distribution of precipitation in cold deserts can be expected to have a dramatic impact on the dominant vegetation, net primary production, and carbon storage in arid lands.²⁵⁸

Woody plant community elimination as a result of fire and invasion of annual grasses may also affect carbon storage in arid lands.²⁵⁹ First, carbon is lost through the volatilization of carbon stored in shrub biomass during fires; if burned, these woody communities are unlikely to regenerate.²⁶⁰ Second, net carbon exchange (NCE) is lower in invasive grass communities than in native shrubland, reducing carbon accumulation rates.²⁶¹ Third, conversion from a woody to annual life form will likely affect patterns of belowground carbon storage.²⁶² Shallow soils may have increased carbon content as brome density increases, while shrub-dominated systems have extensive rooting systems at 1-2m depths and may store more carbon in deep soils.²⁶³ Additionally, decreased vegetative cover on burned landscapes may increase topsoil erosion, leading to losses of shallow soil carbon.²⁶⁴

Observed Changes

Changing amounts and variability of rainfall may strongly control temperate grassland responses to future climate change (see earlier section on precipitation projections).²⁶⁵ For example, a temperate grassland near Lethbridge, in Alberta, Canada fixed roughly five times as much carbon in a year with 30% higher rainfall, while a 15% rainfall reduction led to a net carbon loss.²⁶⁶ Non-linear responses in net primary productivity (NPP) to increasing rainfall variability are possible; ecosystem models of mixed C₃/C₄ grasslands showed an initially positive relationship between NPP and increasing rainfall

²⁵⁵ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²⁵⁶ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²⁵⁷ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²⁵⁸ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²⁵⁹ Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

²⁶⁰ Information as cited in Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

²⁶¹ Ibid.

²⁶² Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

²⁶³ Information as cited in Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

²⁶⁴ Ibid.

²⁶⁵ Information as cited in Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC Fourth Assessment Report, section 4.4.3)

²⁶⁶ Ibid.

variability.²⁶⁷ However, greater variability ultimately reduced NPP even if the rainfall total was kept constant.²⁶⁸ Empirical results for C₄ grasslands confirm a similar relationship between NPP and rainfall variability.²⁶⁹

A study by Bradley et al. (2006) compared carbon storage in adjacent plots of invasive grassland and native shrubland in north-central Nevada, where dominant sagebrush and bunchgrass species included *Artemisia tridentata* and *Poa secunda*. The authors estimated that the loss of aboveground carbon associated with the loss of sagebrush ecosystems (e.g., as a result of fire and conversion to grassland systems) was 440 +/- 180 gC/m² (SE).²⁷⁰ The authors note that woody, nonphotosynthetic vegetation is a critical component of carbon storage in semiarid systems, and that the loss of woody vegetation in these areas is likely permanent, as cheatgrass dominates immediately following fires and competes effectively with native species for resources.²⁷¹

The effect of woody elimination on belowground carbon storage is highly uncertain.²⁷² The loss of vegetation on burned landscapes may increase soil erosion and lead to a loss of shallow soil carbon.²⁷³ However, Bradley et al. (2006) found inconsistent results in the top 10 cm of soil, suggesting that fire and cheatgrass invasion had not resulted in a loss of shallow soil carbon thus far at their study site. Elsewhere, shallow (30 cm) soil carbon appeared to increase with higher cheatgrass density, although the trend was not significant.²⁷⁴

Shallow soils are likely not the only soil carbon pools affected by woody elimination.²⁷⁵ Sagebrush rooting depth can reach 2 m,²⁷⁶ much deeper than annual grasses.²⁷⁷ Accordingly, studies in other semiarid sites have shown that shrub systems store the same or significantly more soil organic carbon than grasslands, particularly between 1 and 2 m depths.²⁷⁸

Future Projections

²⁶⁷ Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC Fourth Assessment Report, section 4.4.3)

²⁶⁸ Information as cited in Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC Fourth Assessment Report, section 4.4.3)

²⁶⁹ Ibid.

²⁷⁰ Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

²⁷¹ Information as cited in Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

²⁷² Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

²⁷³ Information as cited in Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

²⁷⁴ Ibid.

²⁷⁵ Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

²⁷⁶ Information as cited in Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

²⁷⁷ Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

²⁷⁸ Information as cited in Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

Projected increases in precipitation variability coupled with changes in species composition would be expected to further increase the already substantial variation in arid land plant production.²⁷⁹ Carbon stocks are very likely to be greatly reduced under more frequent disturbance, especially by fire.²⁸⁰ On balance, grasslands are likely to show reduced carbon sequestration due to increased soil respiratory losses through warming, fire regime changes, and increased rainfall variability.²⁸¹

If climate change causes the semi-arid shrub-steppe to become hotter and drier it may affect soil C and N cycling and precipitate changes in soil processes and microbial and plant community structure.²⁸² Smith et al. (2002) used an elevation gradient as an analog of climate change to analyze the influence of climate on soil microbial activity and soil properties in a shrub-steppe community on the Hanford Site in eastern Washington. This elevation gradient simulated the temperature and precipitation changes anticipated for the region in the next century.²⁸³ The authors collected soil at 25 sites over a 500 m elevation, and found that soil pH decreased over the transect.²⁸⁴ In contrast, soil ammonium, nitrate, total carbon, total nitrogen, and nitrification potential increased with increasing elevation.²⁸⁵

Based on their results, Smith et al. (2002) state that predicted changes in temperature and precipitation over the next 100 years may cause soil pH and ammonium to increase and nitrification potential to decrease.²⁸⁶ Total C, N, and microbial biomass concentrations would be expected to decrease as primary productivity was inhibited by lower available precipitation and increased evapotranspiration.²⁸⁷ Such a change could shift the controlling factors of the ecosystem to abiotic factors.²⁸⁸ The changes in the cycling of N and to some extent C due to climate change could alter the microbial and plant community structure and function of this ecosystem and cause it to move in the direction of desertification.²⁸⁹

Discussion

Arid lands have low NPP and only small increases in net productivity are expected under future scenarios of warmer, drier climates.²⁹⁰ Because soil organic matter is inversely related to mean annual

²⁷⁹ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²⁸⁰ Parry et al. (2007), *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. (IPCC Fourth Assessment Report, section 4.4.3)

²⁸¹ *Ibid.*

²⁸² Smith et al. (2002), *Soil properties and microbial activity across a 500m elevation gradient in a semi-arid environment*. (primary literature)

²⁸³ *Ibid.*

²⁸⁴ *Ibid.*

²⁸⁵ *Ibid.*

²⁸⁶ *Ibid.*

²⁸⁷ *Ibid.*

²⁸⁸ *Ibid.*

²⁸⁹ *Ibid.*

²⁹⁰ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

temperature in many arid regions, anticipated increases in regional temperature may lead to a loss of soil carbon to the atmosphere, exacerbating increases in atmospheric carbon dioxide.²⁹¹

Knowledge Gaps

- Washington-specific studies on observed and projected changes in NPP in aridlands.
- The soil carbon dynamics of shrub elimination for both shallow and deep soils need further investigation.

CHANGES IN DISTURBANCE REGIMES

In shrub-steppe and grasslands, disturbances such as fire and grazing are superimposed against the backdrop of climate variability, climate change, and spatial variation in soils and topography.²⁹² Temperature and precipitation play important roles in determining how plant communities respond to a given type and intensity of disturbance.²⁹³ In turn, the frequency and intensity of a disturbance will determine the relative abundance of annual, perennial, herbaceous, and woody plants on a site.²⁹⁴ An increase in the frequency of extreme climate events (e.g., drought) as a result of climate change would make arid systems increasingly susceptible to major changes in vegetation cover.²⁹⁵

In particular, the climate-driven dynamic of the fire cycle is likely to remain the single most important feature controlling future plant distribution in U.S. arid lands.²⁹⁶ Field experiments and contemporary patterns in natural settings suggest that the response of non-native plants to climate change will be especially important in the dynamics of arid land fire cycles, and that changes in climate that promote fires will exacerbate land cover change in arid and semi-arid ecosystems.²⁹⁷

Little information is available on the fire regimes of northern intermountain steppe vegetation before the arrival of Euro-American settlers.²⁹⁸ Dry coniferous forests experienced frequent low-intensity fires, many of which resulted from human activities.²⁹⁹ It is likely that some of these natural and anthropogenic fires also burned steppe vegetation, but the frequency and timing of those fires are not precisely known.³⁰⁰ Soon after Euro-Americans arrived in the region, fires may have become more frequent, but eventually fire suppression in uplands and the cessation of burning by Native Americans probably reduced the frequency of fire at moderate elevations.³⁰¹ Although dry forests were negatively

²⁹¹ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²⁹² Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

²⁹³ Ibid.

²⁹⁴ Ibid.

²⁹⁵ Ibid.

²⁹⁶ Ibid.

²⁹⁷ Ibid.

²⁹⁸ Weddell et al. (2001), *Fire in Steppe Vegetation of the Northern Intermountain Region*. (Idaho BLM technical bulletin)

²⁹⁹ Ibid.

³⁰⁰ Ibid.

³⁰¹ Ibid.

impacted by fire suppression, the evidence for a similar situation in steppe communities, which have much lower fuel loads, is less compelling.³⁰²

Estimates of fire-return intervals range from 10 to 70 years for presettlement fire regimes in big sagebrush/bunchgrass ecosystems with mixed-severity and stand-replacement fires.³⁰³ These fires are thought to have occurred primarily between July and September, with the middle to end of August being the period of the most extreme fire conditions.³⁰⁴ Fuel loading in sagebrush ecosystems varies with species composition, site condition, and precipitation patterns; some sites support fuels that burn readily in some years, and other sites generally cannot carry fire.³⁰⁵

The conversion of the shrub-dominated steppes of the western U.S. to a cheatgrass dominated landscape during the 20th century provides an example of how invasive-induced increases in the fire cycle can significantly alter plant communities.³⁰⁶ The tendency for wildfire to promote initial replacement of basin big sagebrush by cheatgrass was recognized as early as 1914,³⁰⁷ and vast areas of sagebrush shrublands have been converted to cheatgrass in the past century.³⁰⁸

The increase in fine fuels associated with cheatgrass invasion can lead to a higher incidence of fire.³⁰⁹ Cheatgrass can colonize open spaces between perennial, native shrubs with a fine, flammable material that increases the frequency of fire events.³¹⁰ Cheatgrass invasion promotes more frequent fires by increasing the biomass and horizontal continuity of fine fuels that persist during the summer lightning season and by allowing fire to spread across landscapes where fire was previously restricted to isolated patches.³¹¹

³⁰² Black et al. (1999), *Biodiversity and Land-Use History of the Palouse Bioregion: Pre-European to Present*. Chapter 10 in: *Perspectives on the Land-Use History of North America: A Context for Understanding our Changing Environment*. (book chapter)

³⁰³ Information as cited in Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³⁰⁴ *Ibid.*

³⁰⁵ *Ibid.*

³⁰⁶ Information as cited in Ziska et al. (2005), *The impact of recent increases in atmospheric CO₂ on biomass production and vegetative retention of Cheatgrass (Bromus tectorum): implications for fire disturbance*. (primary literature)

³⁰⁷ Information as cited in Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³⁰⁸ *Ibid.*

³⁰⁹ Information as cited in Bradley (2009), *Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity*. (primary literature)

³¹⁰ Information as cited in Ziska et al. (2005), *The impact of recent increases in atmospheric CO₂ on biomass production and vegetative retention of Cheatgrass (Bromus tectorum): implications for fire disturbance*. (primary literature)

³¹¹ Information as cited in Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

Box 4: History of Cheatgrass Invasion in Washington State

Prior to 1850, the Columbia Plain supported a perennial bunchgrass-dominated steppe. Beginning in the 1850s and continuing sporadically for the next 20 years, gold and silver strikes were reported north and east of the Columbia Plain. Euro-American settlers began to use the region as an open range for cattle that were driven annually to the mines, via the Okanogan River Valley. Local overgrazing and consequent soil surface alteration resulted.

By 1890, homesteading and farming began to occur on the Columbia Plain. By 1901, authors writing about the area reported that bunchgrasses were practically exterminated over large areas and their places occupied more or less by weedy annual plants.

Cheatgrass (*Bromus tectorum*) arrived in the interior Pacific Northwest in 1889, likely first as a grain contaminant. It was also deliberately introduced at least once during the turn of the century search for new grasses for the overgrazed range. From 1905 – 1914, cheatgrass became widespread and locally abundant in the region. Its spread was accelerated by the development of the railroad system and by the transport of contaminated grains such as alfalfa seed. By 1930, *B. tectorum* seems to have occupied its current range.

Source: Mack (1981)

In cold desert shrub steppe, cheatgrass is often most abundant under shrubs, resulting in rapid consumption of the shrub during fire and mortality of native plants and seed banks; the higher availability of nutrient resources in the vicinity of shrubs enables greater biomass and seed production of cheatgrass in the post-fire period.³¹² Thus, the rate and extent of invasion of cold desert sagebrush-steppe by cheatgrass may initially be a function of the cover and density of sagebrush plants and the fertile areas they create.³¹³

Because cheatgrass is fire-adapted, increasing fire frequency favors its establishment and spread.³¹⁴ For example, cheatgrass is better adapted to recover and thrive in the postfire environment³¹⁵ than are most native species in Great Basin sagebrush communities.³¹⁶ Sagebrush does not re-sprout after burning, and many other native perennial plants are top-killed and are slow to recover after a fire.³¹⁷ Species in sagebrush steppe and bunchgrass habitat that are not adapted to frequent burning include bluebunch wheatgrass, Idaho fescue, and rough fescue, which may be susceptible to fire injury and lack persistent seed banks.³¹⁸ More frequent fires can lead to a virtually irreversible loss of native shrubs and

³¹² Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³¹³ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³¹⁴ Ziska et al. (2005), *The impact of recent increases in atmospheric CO₂ on biomass production and vegetative retention of Cheatgrass (*Bromus tectorum*): implications for fire disturbance*. (primary literature)

³¹⁵ Information as cited in Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³¹⁶ Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³¹⁷ Information as cited in Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³¹⁸ Ibid.

grasses, which reduces ecosystem carbon storage and threatens the habitat of sagebrush obligate species.³¹⁹

- For a detailed discussion of cheatgrass fire ecology and fire effects, including further references, see: Zouhar, Kris. 2003. *Bromus tectorum*. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). <http://www.fs.fed.us/database/feis/>

In addition to fire disturbances, arid lands can also be slow to recover from severe livestock grazing impacts.³²⁰ The plant communities of the Great Basin and Intermountain West evolved with few large herbivores, and thus domestic livestock use of these plant communities is considered a deviation from the historical disturbance regime;³²¹ the historical disturbance regime for these communities would have been periodic fires without domestic livestock grazing.³²² Grazing by domestic livestock has been identified as a causal agent of cheatgrass invasion by reducing the ability of the native plant communities to resist invasion and by dispersing cheatgrass seeds.³²³ However, cheatgrass has also been found in plant communities that have experienced minimal or no domestic livestock grazing.³²⁴

Although insects are an important food base in western arid lands,³²⁵ they also represent a third potential source of disturbance.³²⁶ The majority of insects in western shrub steppe habitats are primary consumers, and at times they may become so numerous as to completely defoliate sagebrush (e.g., the sagebrush moth, *Aroga websteri*), or to compete with domestic livestock for forage (e.g., the migratory grasshopper, *Melanoplus sanguinipes*, and Mormon cricket, *Anabrus simplex*).³²⁷ The ecological and economic effects of such outbreaks may be far-reaching because intense and widespread herbivory can lead to complex changes in plant community structure and dynamics, population levels of other animals (for example, insectivorous predators), and rates of nutrient cycling.³²⁸

In the upper Columbia Basin, the National Park Service monitors changes in the incidence of sagebrush moth infestations and the rate of tent caterpillar (*Malacosoma fragile*) infestation in bitterbrush

³¹⁹ Information as cited in Bradley (2009), *Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity*. (primary literature)

³²⁰ Information as cited in Knick et al. (2003), *Teetering on the Edge or Too Late? Conservation and Research Issues for Avifauna of Sagebrush Habitats*. (primary literature)

³²¹ Information as cited in Davies et al. (2009), *Interaction of historical and nonhistorical disturbances maintains native plan communities*. (primary literature)

³²² Davies et al. (2009), *Interaction of historical and nonhistorical disturbances maintains native plan communities*. (primary literature)

³²³ Information as cited in Davies et al. (2009), *Interaction of historical and nonhistorical disturbances maintains native plan communities*.(primary literature)

³²⁴ Ibid.

³²⁵ Information as cited in United States Department of Energy (2001), *Appendix C: Hanford Biological Resources in a Regional Context*. In: *Hanford site Biological Resources Management Plan*. (U.S. government report)

³²⁶ United States Department of Energy (2001), *Appendix C: Hanford Biological Resources in a Regional Context*. In: *Hanford site Biological Resources Management Plan*. (U.S. government report)

³²⁷ United States Department of Energy (2001), *Appendix C: Hanford Biological Resources in a Regional Context*. (U.S. government report)

³²⁸ Information as cited in Bentz et al. (2008), *Great Basin Insect Outbreaks*.(USFS technical report)

communities as two key indicators of impaired ecosystem health.³²⁹ Mesic, low sagebrush communities in the Interior Columbia Basin (an area that includes *Artemisia rigida/Poa secunda* communities in eastern Washington) are described as susceptible to the sagebrush moth, which can cause small patches of high mortality.³³⁰

Observed Changes

Cheatgrass invasion has altered fire regimes in arid ecosystems. For example, because cheatgrass cures by early July and remains flammable throughout the summer dry season, the wildfire season may begin earlier and extend later into the fall.³³¹ The size of fires has also increased with the spread of cheatgrass.³³² Climatic conditions favoring the growth of nonnative annual grasses provide fuels that contribute to extensive fire spread the subsequent fire season.³³³ Fires ignited in cheatgrass stands may spread to adjacent sagebrush-bunchgrass steppe and forests.³³⁴

With cheatgrass infestation, fire-return intervals were as short as 5 years on some Great Basin sagebrush sites, where presettlement fire-return intervals were in the range of 30 to 110 years.³³⁵ Wind-blown cheatgrass seeds can swiftly recolonize burned areas, creating a cheatgrass monoculture with a total loss of shrub biomass.³³⁶ Even without repeated fires, cheatgrass has been observed dominating previously burned areas and preventing shrub regrowth.³³⁷

Low-elevation sites, which are relatively dry and experience wide variations in soil moisture, appear to be more vulnerable to cheatgrass invasion than higher elevation sites with more stable soil moisture.³³⁸ Cheatgrass plants tend to be larger and more fecund in the postfire environments than on unburned sites, potentially leading to subsequent increases in density with favorable climatic conditions.³³⁹ A few studies and modeling efforts suggest that cheatgrass may decline in the long term after fire on some sagebrush sites, as the increased fire interval provides more opportunity for perennial species to establish and reproduce.³⁴⁰

³²⁹ National Parks Service, Inventory and Monitoring (2004), *Upper Columbia Basin Network Vital Signs Monitoring Priorities*. (website)

³³⁰ Information as cited in Bunting et al. (2002), *Altered Rangeland Ecosystems in the Interior Columbia Basin*. (USFS technical report)

³³¹ Information as cited in Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³³² Ibid.

³³³ Ibid.

³³⁴ Ibid.

³³⁵ Information as cited in Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³³⁶ Information as cited in Bradley et al. (2006), *Invasive grass reduces aboveground carbon stocks in shrublands of the Western U.S.* (primary literature)

³³⁷ Ibid.

³³⁸ Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³³⁹ Information as cited in Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³⁴⁰ Ibid.

The long-term abundance of cheatgrass after fire appears to be related to precipitation patterns.³⁴¹ At a site in Utah that burned in 1981, short-term increases in cheatgrass occurred in both burned and unburned sites, coinciding with above average precipitation;³⁴² however, cheatgrass cover declined to trace amounts 11 years after fire on all sites, coinciding with drought.³⁴³ Cheatgrass cover then increased during a wetter period over the following seven years on burned and unburned sites.³⁴⁴ Thus, cheatgrass dominated the postfire community for a few years, after which the perennial grasses (primarily bluebunch wheatgrass, Indian ricegrass, and Sandberg bluegrass) recovered and began to dominate, especially in ungrazed areas.³⁴⁵

Cheatgrass has also been recorded to increase with increased precipitation in the absence of fire.³⁴⁶ At the Jordan Crater Research Natural Area in southern Oregon (a pristine sagebrush site with no fire or other disturbance), cheatgrass abundance at the study site increased from 0 to 10 percent over a 14 year period; this increase was attributed to abundant precipitation in the final year of the study.³⁴⁷

Davies et al. (2009) examined the interaction between fire and grazing disturbances in the Northern Great Basin Experimental Range near Burns, Oregon. Interestingly, they found that the long-term exclusion of grazers did not produce the expected effect of shifting vegetative dominance from shrubs to native forbs and perennial grasses.³⁴⁸ Rather, it decreased the ability of the native herbaceous community to tolerate fire.³⁴⁹ Burning resulted in a substantial cheatgrass invasion and a large increase in non-native annual forbs in the treatment designed to most closely match pre-settlement disturbance regimes.³⁵⁰

Light to moderate livestock grazing may indirectly act to prevent cheatgrass invasion by reducing litter accumulation, thereby decreasing the amount of fine fuels available to facilitate fire.³⁵¹ Although arid lands may have relatively low fuel loads, these ecosystems may still need fuel-reducing disturbances to prevent negative community shifts following fire.³⁵² However, the level of grazing pressure is critical,³⁵³ because heavy grazing can change habitat features such as plant species diversity and biomass or water and nutrient cycling; this in turn facilitates the spread of invasive plants and degrades habitat for other

³⁴¹ Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³⁴² Information as cited in Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³⁴³ Ibid.

³⁴⁴ Ibid.

³⁴⁵ Ibid.

³⁴⁶ Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³⁴⁷ Information as cited in Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report chapter)

³⁴⁸ Davies et al. (2009), *Interaction of historical and nonhistorical disturbances maintains native plant communities*. (primary literature)

³⁴⁹ Ibid.

³⁵⁰ Ibid.

³⁵¹ Ibid.

³⁵² Ibid.

³⁵³ Ibid.

species (e.g., birds).³⁵⁴ A study of severe livestock grazing impacts found that at least 45 years of protection were required for detectable recovery of herbaceous perennial understory cover in cold desert sagebrush steppe.³⁵⁵ Development of warmer, drier climatic conditions would be expected to further slow rates of recovery.³⁵⁶

Davies et al. (2009) concluded that nonhistorical disturbances may be needed to promote community resistance and resilience in the face of changing environments and land uses, since invasive species and perhaps climate change have produced conditions where fuel loads within the natural range of variability can result in severe negative responses to fire.

During a rangeland workshop conducted in August 2000 for the Interior Columbia Basin Ecosystem Management Project, insects were not listed as a significant cause of changes in composition and function in Interior Columbia Basin arid lands (significant causes included agricultural development, past livestock grazing, invasive species, and increased fire occurrence).³⁵⁷ However, incidents of widespread insect outbreaks have been recorded in the Great Basin (south of Washington State). For example, Great Basin tent caterpillar infestations periodically infest bitterbrush, causing defoliation and sometimes death.³⁵⁸ The stress inflicted by the caterpillars on the shrubs can result in significant loss of foliage and seed production, and the accumulations of tent caterpillar webs and debris have a negative influence on herbivore preference for the browse.³⁵⁹

The most prominent insect outbreaks in the Great Basin have involved grasshoppers (*Caelifera*) and Mormon crickets (*Anabrus simplex*), including a recent epidemic of Mormon crickets in Nevada and Utah.³⁶⁰ The sagebrush moth also infested thousands of hectares of sagebrush stands in the Great Basin in the 1960s and early 1970s, and another outbreak occurred in Nevada between 2004 and 2006.³⁶¹ Climate is generally believed to play a key role in determining the timing of insect outbreaks on Great Basin rangelands, but the exact mechanisms are not well understood.³⁶² Climate can have both direct effects on the metabolism of ectothermic insects and indirect effects on factors such as food quality and predation.³⁶³

Future Projections

By virtue of their significant influence on fire regimes and hydrology, non-native invasive plants in arid lands will very likely trump direct climate impacts on native vegetation where invasives gain

³⁵⁴ Information as cited in Knick et al. (2003), *Teetering on the Edge or Too Late? Conservation and Research Issues for Avifauna of Sagebrush Habitats*. (primary literature)

³⁵⁵ Ibid.

³⁵⁶ Ibid.

³⁵⁷ Bunting et al. (2002), *Altered Rangeland Ecosystems in the Interior Columbia Basin*. (USFS technical report)

³⁵⁸ Information as cited in Clements and Young (2001), *Antelope bitterbrush seed production and stand age*. (primary literature)

³⁵⁹ Clements and Young (2001), *Antelope bitterbrush seed production and stand age*. (primary literature)

³⁶⁰ Information as cited in Bentz et al. (2008), *Great Basin Insect Outbreaks*. (USFS technical report)

³⁶¹ Ibid.

³⁶² Bentz et al. (2008), *Great Basin Insect Outbreaks*. (USFS technical report)

³⁶³ Ibid.

dominance.³⁶⁴ For plant communities in the Great Basin and Intermountain regions, the temperature increases predicted by general circulation models³⁶⁵ may create the potential for increased annual grass establishment into areas where it is still a minor component of the *A. tridentata* ecosystem.³⁶⁶ There are also indications that cheatgrass is more competitive with native species under elevated CO₂ levels.³⁶⁷ A warmer environment coupled with a winter precipitation regime and greater CO₂ levels would likely permit invasion and dominance by cheatgrass, particularly if fire disturbances increase.³⁶⁸

If environmental conditions stimulate biomass production in fire-tolerant invasives such as cheatgrass, a subsequent increase in the rate of fuel accumulation could mean that minimum fuel thresholds would be reached sooner between burns.³⁶⁹ Overall, more time would be spent proportionally above a minimum fuel threshold, leading to greater fire frequency if ignition probabilities remained unchanged.³⁷⁰ Greater biomass production by the end of the life-cycle would also increase total available fuel, so that once a fire did occur, flame intensity, fire temperature, and rate of spread would increase.³⁷¹ Increases in intensity would, in turn, increase the probability that fire will damage the overstory or seedbank.³⁷² This result, combined with greater fire frequency, would reduce the number of nonfire-adapted plants that reach reproductive maturity, potentially resulting in a decrease in species and structural diversity of the community.³⁷³

As the areal extent of fire-prone non-native grass communities increases, low elevation arid ecosystems will likely experience climate-fire synchronization where none previously existed; spread of low elevation fires upslope may constitute a new source of ignition for forest fires.³⁷⁴ Exurban development has been and will continue to be a major source of both ignitions and non-native species introductions by escape from horticulture.³⁷⁵ Rising temperatures, decreases in precipitation and a shift in seasonality and variability, and increases in atmospheric CO₂ and nitrogen deposition, coupled with invasions of non-native annual species, is likely to accelerate the grass-fire cycle in arid lands and promote development of near monoculture stands of invasive plants.³⁷⁶

³⁶⁴ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³⁶⁵ Information as cited in Bates et al. (2006), *The effects of precipitation timing on sagebrush steppe vegetation*. (primary literature)

³⁶⁶ Bates et al. (2006), *The effects of precipitation timing on sagebrush steppe vegetation*. (primary literature)

³⁶⁷ Information as cited in Bates et al. (2006), *The effects of precipitation timing on sagebrush steppe vegetation*. (primary literature)

³⁶⁸ Bates et al. (2006), *The effects of precipitation timing on sagebrush steppe vegetation*. (primary literature)

³⁶⁹ Ziska et al. (2005), *The impact of recent increases in atmospheric CO₂ on biomass production and vegetative retention of Cheatgrass (*Bromus tectorum*): implications for fire disturbance*. (primary literature)

³⁷⁰ Ibid.

³⁷¹ Ibid.

³⁷² Ibid.

³⁷³ Ibid.

³⁷⁴ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³⁷⁵ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³⁷⁶ Ibid.

Discussion

Climate is a key factor dictating the effectiveness of resource management plans and restoration efforts in arid lands.³⁷⁷ Precipitation (and its interaction with temperature) plays a major role in determining how plant communities are impacted by, and how they respond to, a given type and intensity of disturbance.³⁷⁸ Chronic disturbance will affect rates of ecosystem change in response to climate change because it reduces vegetation resistance to slow, long-term changes in climate.³⁷⁹ Plant communities dominated by long-lived perennials may exhibit considerable biological inertia, and changes in community composition may lag behind significant changes in climate.³⁸⁰ Because conditions required for seed germination and establishment are largely independent of conditions required for subsequent plant survival, species established under previous climate regimes may persist in novel climates under which they did not germinate.³⁸¹ Disturbances such as fire and grazing can therefore create opportunities for species better adapted to the current conditions to establish.³⁸² Given the episodic nature of desert plant establishment and the high susceptibility of the new community structure to additional fire, it will likely be exceedingly difficult to recover current native plant dominance in the future.³⁸³

Disturbances in arid lands can also destabilize sites and quickly reduce their ability to capture and retain precipitation inputs.³⁸⁴ Long-term reductions in plant cover by severe grazing and short-term reductions caused by fire create opportunities for accelerated rates of wind and water erosion.³⁸⁵ Soil erosion affects species composition in ways that can further reduce plant production and cover.³⁸⁶ This is the fundamental basis for desertification, a long-standing concern in many U.S. arid lands.³⁸⁷ Desertification involves the expansion of deserts into semi-arid and subhumid regions, and the loss of productivity in arid zones.³⁸⁸ A long-standing controversy continues in determining the relative contribution of climatic and anthropogenic factors as drivers of desertification.³⁸⁹ Local fence line contrasts argue for the

³⁷⁷ Ibid.

³⁷⁸ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³⁷⁹ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³⁸⁰ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³⁸¹ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³⁸² Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³⁸³ Ibid.

³⁸⁴ Ibid.

³⁸⁵ Ibid.

³⁸⁶ Ibid.

³⁸⁷ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³⁸⁸ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³⁸⁹ Ibid.

importance of land use (e.g., changes in grazing and fire regimes); vegetation change in areas without observable change in land use argue for climatic drivers.³⁹⁰

In sagebrush steppe habitats, the accelerating frequency of large wildfires and vegetation response has resulted in extensive rehabilitation efforts to control erosion, return stability to the system and, in some cases, reestablish a shrubland landscape.³⁹¹ When considering restoration plans, it is important to note that the effects of successive disturbances depend upon the impact of the preceding disturbance on the community.³⁹² Returning ecosystems to “historical” or “pre-European settlement” conditions by reintroducing historical disturbance is probably a simplistic view of ecosystem dynamics.³⁹³ The effects of the prior disturbance on plant communities will determine if the successive disturbance effects are compounded or mediated.³⁹⁴ Overall, restoration will be difficult, expensive, and may require decades or even centuries.³⁹⁵ Not all areas previously dominated by sagebrush can be restored because alteration of vegetation, nutrient cycles, topsoil, and disturbance processes have pushed some areas past critical thresholds from which recovery is unlikely.³⁹⁶

Knowledge Gaps

- Effects of varying levels of grazing on community trajectory with climate change.
- Information on pest disturbances, such as Aroga moth. Insect lifecycles may respond to climate change, and changes in insect populations may be another important disturbance factor in sagebrush ecosystems in the future.
- *In situ* studies of herbivory with studies of CO₂-induced changes in digestibility, changes in the time to productive maturity and root : shoot ratios.
- Studies of changes in plant decomposition as a result of changes in C:N ratios with atmospheric CO₂ increase, and how this may affect fuel accumulation.
- Information on the response of other nonnative species described as postfire invaders in sagebrush ecosystems, including Kentucky bluegrass, Russian-thistle, tumble mustard, flixweed tansymustard (*Descurainia sophia*), leafy spurge, rush skeletonweed, knapweeds (*Centaurea* spp.), jointed goatgrass (*Aegilops cylindrica*), Mediterranean sage (*Salvia aethiopsis*), and medusahead.³⁹⁷

³⁹⁰ Ibid.

³⁹¹ Information as cited in Knick et al. (2003), *Teetering on the edge or too late? Conservation and research issues for avifauna of sagebrush habitats*. (primary literature)

³⁹² Davies et al. (2009), *Interaction of historical and nonhistorical disturbances maintains native plant communities*. (primary literature)

³⁹³ Ibid.

³⁹⁴ Ibid.

³⁹⁵ Information as cited in Knick et al. (2003), *Teetering on the edge or too late? Conservation and research issues for avifauna of sagebrush habitats*. (primary literature)

³⁹⁶ Ibid.

³⁹⁷ Information as cited in Rice et al. (2008), *Fire and Nonnative Invasive Plants in the Interior West Bioregion*. (USFS technical report)

SENSITIVE SHRUB-STEPPE AND GRASSLAND SUB-HABITATS

RIPARIAN SYSTEMS

Springs, rivers and floodplain (riparian) ecosystems commonly make up less than 1% of the landscape in arid regions of the world.³⁹⁸ However, these areas are highly productive ecosystems embedded within upland ecosystems of much lower productivity.³⁹⁹ For this reason, these areas attract human settlement and also provide essential habitat for wildlife migration and breeding, threatened and endangered species, and aridland vertebrate species.⁴⁰⁰

Riparian vegetation in arid lands can occur at scales from isolated springs to ephemeral and intermittent watercourses and perennial rivers.⁴⁰¹ Rivers, riparian zones, and certain types of springs in arid lands are dynamic ecosystems that react to changing hydrology, geomorphology, human utilization, and climate change.⁴⁰² As such, spring, river and riparian ecosystems will likely prove to be responsive components of arid landscapes to future climate change.⁴⁰³

Eastern Washington and Oregon host riparian and wetland habitats that are dominated by woody plants, and occur between 100 – 9,500 ft in elevation.⁴⁰⁴ Riparian habitats appear along perennial and intermittent rivers and streams, in impounded wetlands, and along lakes and ponds.⁴⁰⁵ Eastside lowland willow and other riparian shrublands are the major riparian types at lower elevations, while black cottonwood riparian habitats occur at low to middle elevations.⁴⁰⁶ White alder riparian habitats are restricted to perennial streams at low elevations in dry climatic zones in Hells Canyon, the Malheur River drainage, and western Klickitat and southcentral Yakima counties.⁴⁰⁷

The native riparian vegetation in the shrub-steppe region of the Columbia Basin is characterized by a mosaic of shrubby thickets with patches of deciduous trees and grass/forb-dominated plant communities.⁴⁰⁸ However, conifer trees, including ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*), are widely scattered in eastern Washington riparian areas and were likely more common historically than at present.⁴⁰⁹ They are currently restricted to canyons or valleys with

³⁹⁸ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

³⁹⁹ Ibid.

⁴⁰⁰ Ibid.

⁴⁰¹ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁴⁰² Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁴⁰³ Ibid.

⁴⁰⁴ Chappell et al. (2001), *Wildlife Habitats: Description, Status, Trends, and System Dynamics*. Chapter 2 in: *Wildlife-Habitat Relationships in Oregon and Washington*. (book chapter)

⁴⁰⁵ Ibid.

⁴⁰⁶ Ibid.

⁴⁰⁷ Ibid.

⁴⁰⁸ Knutson and Naef (1997), *Management Recommendations for Washington's Priority Habitats: riparian*. (WDFW report)

⁴⁰⁹ Ibid.

steep rocky walls along mid- to high-gradient streams where they are inaccessible to harvest and where microclimates are conducive to supporting trees.⁴¹⁰

A diversity of shrub and deciduous tree species occurred historically and still occur in some places, and they include snowberry (*Symphoricarpos albus*), wild rose (*Rosa woodsii*), black hawthorn (*Crataegus douglasii*), hackberry (*Celtis occidentalis*), parsnip (*Pastinaca sativa*), common chokecherry (*Prunus virginiana*), bittercherry (*Prunus emarginata*), mock orange (*Philadelphus lewisii*), red osier dogwood (*Cornus stolonifera*), water birch (*Betula occidentalis*), willow, black cottonwood (*Populus trichocarpa*), and quaking aspen (*Populus tremuloides Michx*).⁴¹¹ Succulent herbs of the ground layer include sticky geranium (*Geranium viscosissimum*), northern bedstraw (*Galium boreale*), fescue (*Festuca*), waterleaf (*Hydrophyllaceae*), and bracken fern (*Pteridium aquilinum*).⁴¹² Shrub thickets are exceedingly rich in wildlife species and numbers and historically consisted of a diverse mixture of plant communities along the smaller streams and rivers in the Columbia Basin, but examples of such undisturbed systems are now rare due to the impacts of grazing and cultivation.⁴¹³ Small, intermittent streams and draws may naturally have little or no characteristic riparian vegetation.⁴¹⁴ Instead, they consist of largely upland plant species, including big sagebrush, bitterbrush (*Purshia tridentate*), rabbitbrush (*Chrysothamnus nauseosus*), and spiny hopsage (*Grayia spinosa*).⁴¹⁵

This habitat is tightly associated with stream dynamics and hydrology.⁴¹⁶ Flood cycles occur within 20-30 years in most riparian shrublands although flood regimes vary among stream types.⁴¹⁷ Fires recur typically every 25-50 years but fire can be nearly absent in colder regions or on topographically protected streams.⁴¹⁸ The presence of woody and herbaceous vegetation assists in moderating stream temperature, sedimentation, water quality and quantity, and debris flows downstream.⁴¹⁹

Grazing and trampling is a major influence in altering structure, composition, and function of this habitat; some portions are very sensitive to heavy grazing.⁴²⁰ For example, in many eastern Washington riparian areas, the regeneration of palatable shrubs and trees and associated herbage has been

⁴¹⁰ Information as cited in Knutson and Naef (1997), *Management Recommendations for Washington's Priority Habitats: riparian*. (WDFW report)

⁴¹¹ Knutson and Naef (1997), *Management Recommendations for Washington's Priority Habitats: riparian*. (WDFW report)

⁴¹² Ibid.

⁴¹³ Information as cited in Knutson and Naef (1997), *Management Recommendations for Washington's Priority Habitats: riparian*. (WDFW report)

⁴¹⁴ Knutson and Naef (1997), *Management Recommendations for Washington's Priority Habitats: riparian*. (WDFW report)

⁴¹⁵ Ibid.

⁴¹⁶ Chappell et al. (2001), *Wildlife Habitats: Description, Status, Trends, and System Dynamics*. Chapter 2 in: *Wildlife-Habitat Relationships in Oregon and Washington*. (book chapter)

⁴¹⁷ Ibid.

⁴¹⁸ Ibid.

⁴¹⁹ Knutson and Naef (1997), *Management Recommendations for Washington's Priority Habitats: riparian*. (WDFW report)

⁴²⁰ Chappell et al. (2001), *Wildlife Habitats: Description, Status, Trends, and System Dynamics*. Chapter 2 in: *Wildlife-Habitat Relationships in Oregon and Washington*. (book chapter)

suppressed by decades of unmanaged overgrazing.⁴²¹ Overgrazing has also caused the replacement of native plants with more grazing-resistant non-native plant communities of bluegrass and exotic weeds such as thistle (*Asteraceae*), teasel (*Dipsacus fullonum*), dandelion (*Taraxacum officinale*), and reed canarygrass (*Phalaris arundinacea*).⁴²² Remnant cottonwoods and other deciduous trees are occasionally found, but these are usually mature trees tall enough to be out of reach of browsing livestock.⁴²³ Tree seedlings and saplings are notably absent in many of these riparian areas.⁴²⁴

Approximately 40% of riparian shrublands occurred above 3,280 ft in elevation before 1900; now nearly 80% is found above that elevation.⁴²⁵ This change reflects losses to agricultural development, roading, dams and other flood-control activities. The current riparian shrublands contain many exotic plant species and generally are less productive than historically.⁴²⁶

Climate Change Effects on Arid land Riparian Ecosystems

Although climate change can potentially impact arid land river and riparian ecosystems through a variety of mechanisms and pathways, three are particularly important.⁴²⁷ The first is the impact of climate change on water budgets.⁴²⁸ The second is competition between native and non-native species in a changing climate; and the third is the role of extreme climate events (e.g., flood and droughts) in a changing climate.⁴²⁹ Extreme events have always shaped ecosystems, but the interactions of a warmer climate with a strengthened and more variable hydrologic cycle are likely to be significant structuring agents for riverine corridors in arid lands.⁴³⁰

First, climate change may result in alterations in the volume and timing of surface waters in arid regions.⁴³¹ For example, under the A1B and B1 emissions scenarios, Elsner et al. (2009) project that spring peak streamflow in the Yakima River will shift approximately four weeks earlier by the 2040s (to mid to late April) and that increased winter streamflow will result in a second peak that is typically characteristic of lower-elevation transient watersheds. By the 2080s, a significant shift in the hydrologic characteristics of the watershed is projected, as the spring peak is lost and peak streamflow is projected

⁴²¹ Knutson and Naef (1997), *Management Recommendations for Washington's Priority Habitats: riparian*. (WDFW report)

⁴²² Ibid.

⁴²³ Ibid.

⁴²⁴ Information as cited in Knutson and Naef (1997), *Management Recommendations for Washington's Priority Habitats: riparian*. (WDFW report)

⁴²⁵ Chappell et al. (2001) *Wildlife Habitats: Description, Status, Trends, and System Dynamics*. Chapter 2 in: *Wildlife-Habitat Relationships in Oregon and Washington*. (book chapter)

⁴²⁶ Ibid.

⁴²⁷ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁴²⁸ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁴²⁹ Ibid.

⁴³⁰ Ibid.

⁴³¹ Ibid.

to occur in the winter near mid-February - more characteristic of rain dominant watersheds.⁴³² Vano et al. (2009) note that if climate change results in the predicted earlier snowmelt runoff and reduced summer flows, increased water delivery curtailments to water right holders are likely to result in the Yakima River Reservoir system. Without adaptations, for IPCC A1B global emission scenarios, water shortages increase to 27% (13% to 49% range) in the 2020s, to 33% in the 2040s, and 68% in the 2080s.⁴³³ For IPCC B1 emissions scenarios, shortages occur in 24% (7% to 54%) of years in the 2020s, 31% in the 2040s and 43% in the 2080s.⁴³⁴

Riparian zone evapotranspiration is sensitive to the length of the growing season, and climate warming will lengthen the period of time that riparian plants actively respire, and also increase the growing season for agricultural crops dependent on riparian water.⁴³⁵ The net result of climate warming is greater depletion of water along the riverine corridor.⁴³⁶

Second, effects of climate change on aquatic organisms in arid lands are not well known.⁴³⁷ Introductions of non-native fish and habitat modification have caused the extinction of numerous endemic species, subspecies and populations of fishes, mollusks and insects since the late 1800s.⁴³⁸ Declines in abundance or distribution have been attributed to (in order of decreasing importance) water flow diversions, competitive or predatory interactions with non-native species, livestock grazing, introductions for sport fisheries management, groundwater pumping, species hybridization, timber harvest, pollution, recreation and habitat urbanization.⁴³⁹ It is likely that projected climate changes will exacerbate these existing threats via effects on water temperature, sedimentation, and flows.⁴⁴⁰

Third, extreme climatic events are thought to strongly shape arid and semi-arid ecosystems worldwide.⁴⁴¹ Fluvial systems and riparian vegetation are especially sensitive to the timing and magnitude of extreme events, particularly the timing and magnitude of minimum and maximum flows.⁴⁴² The ecohydrology of arid-land rivers and riparian zones will certainly respond to altered

⁴³² Elsner et al. (2009), *Implications of 21st century climate change for the hydrology of Washington State*. Chapter 3 in: *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. (CIG 2009)

⁴³³ Vano, et al. (2009), *Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA*. Chapter 3 in: *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate*. (CIG 2009)

⁴³⁴ Ibid.

⁴³⁵ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁴³⁶ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁴³⁷ Ibid.

⁴³⁸ Ibid.

⁴³⁹ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁴⁴⁰ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁴⁴¹ Information as cited in Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁴⁴² Ibid.

precipitation patterns, and the highly variable climate that characterizes arid lands is likely to become increasingly variable in the future.⁴⁴³ Changes in patterns of erosion may be one important result of changes in the timing and magnitude of precipitation events and runoff; specific information regarding erosion and its potential impacts is highlighted in Boxes 5 and 6.

Aridland river and riparian ecosystems will very likely be negatively impacted by decreased streamflow, increased water removal, and greater competition from non-native species.⁴⁴⁴ Riparian ecosystems will likely contract, and in the remainder, aquatic ecosystems will be less tolerant of stress.⁴⁴⁵ The combination of increased droughts and floods, land use and land cover change, and human water demand will amplify these impacts.⁴⁴⁶

⁴⁴³ Ibid.

⁴⁴⁴ Ryan and Archer (2008), *Land Resources: Forests and Arid Lands*. In: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity*. (U.S. government report)

⁴⁴⁵ Ibid.

⁴⁴⁶ Ibid.

Box 5: Changing Patterns of Erosion in Aridlands – Part 1: Water Erosion

Erosion by wind and water has a strong impact on ecosystem processes in arid regions. Erosion impacts the ability of soils to support plants and can deplete nutrient-rich surface soils, thus reducing the probability of plant establishment and recruitment.

Water Erosion and Climate

Water erosion primarily depends on the erosivity of precipitation events (rainfall rate, storm duration, and drop size) and the erodibility of the surface (infiltration rate, slope, soil, and vegetation cover). Climate change may impact all of these except slope. For instance, it is well established that the amount of soil that is detached (and hence eroded) by a particular depth of rain is related to the intensity at which this rain falls.

The intensity of rainfall is a function of climate, and therefore may be impacted by climate change. The frequency of heavy precipitation events has increased over most land areas, including the United States; climate models project additional increases in the frequency of heavy precipitation, and thus highly erosive events.

Effects of Climate Change and Water Erosion on Aridland Environments and Ecosystems

Warming climate may also be responsible for changes in surface soils themselves, with important implications for the erodibility of soils by water. In particular, higher temperatures and decreases in soil moisture, such as those predicted in many climate change scenarios, have been shown to decrease the size and stability of soil aggregates, thus increasing their susceptibility to erosion.

By far the most significant impact of climate change on water erosion is via its effects on vegetation cover. Vegetation conversion to annual grasses or weedy forbs can result in loss of soil nutrients, siltation of streams and rivers, and increased susceptibility to flooding. Conversion of grasslands to shrublands appears to result in significantly greater erosion. One study found that shrubland areas (as opposed to grassland areas) are more prone to develop rills, which are responsible for significant increases in overall erosion rates. Episodes of water erosion are often associated with decadal drought-interdrought cycles because depressed vegetation cover at the end of the drought makes the ecosystem vulnerable to increased erosion when rains return.

Observations and Projections of Change

U.S. arid regions have already experienced dramatic increases in erosion rates due to widespread losses of vegetation cover. These changes have created conditions where anticipated increases in precipitation intensity, coupled with reductions in soil aggregate stability due to net warming and drying, will likely increase potential erosion rates dramatically in coming decades.

* Source: Ryan and Archer (2008) and sources cited therein.

Box 6: Changing Patterns of Erosion in Aridlands – Part 2: Wind Erosion

The susceptibility of soil to wind erosion is determined by both the erodibility of the surface soil and the amount of vegetation present to disrupt wind flows and shelter the surface from erosion. For soils, increased temperatures and drought occurrence will result in lower relative humidity in arid lands. Because the top few millimeters of soil are in equilibrium with soil moisture in the overlying air, the decrease in relative humidity may result in soils that require less wind power to initiate erosion. Increased drought occurrence throughout the western United States can further lead to lower soil moisture content, which can also increase the erodibility of the soil.

Changes in Aridland Environments and Effects on Wind Erosion

Long-term and ongoing vegetation changes in arid regions, namely the conversion of grasslands to shrublands, have dramatically increased wind erosion and dust production due to increased bare areas in shrublands compared to the grasslands they replaced. Even short-term changes in vegetation cause significant changes in the wind erodibility of the land surface.

Consequences of Increased Wind Erosion

Large-scale conversion of grasslands to shrublands, coupled with anticipated changes in climate in the coming decades, and increases in wind speed, temperature, drought frequency, and precipitation intensity, contribute to greater wind erosion and dust emission from arid lands. In arid regions, erosion has been shown to increase sediment delivery to large rivers (e.g., the Rio Grande), and can change the flow conditions of those rivers. Transport of eroded sediment to streams can change conditions in waterways, impacting water quality, riparian vegetation, and water fauna.

* Source: Ryan and Archer (2008) and sources cited therein.

VERNAL POOLS

Vernal pools are seasonal pools occurring in Mediterranean-type climates within which grow concentric zones of vegetation.⁴⁴⁷ Vernal pools are typically formed in shallow depressions where soils have impermeable hardpans, or are underlain by impermeable bedrock.⁴⁴⁸ Vernal pools fill with water from winter rains (and snowmelt in colder climates) and gradually dry during late spring and early summer through evapotranspiration.⁴⁴⁹

In eastern Washington, Björk and Dunwiddie (2004) found vernal pools in Adams, Douglas, Grant, Lincoln, Okanogan, and Spokane Counties, where they were all limited to the flat, impervious basalt bedrock exposed by the Missoula Floods. The pools were concentrated in three distinct regions

⁴⁴⁷ Crowe et al. (1994), *Vegetation Zones and Soil Characteristics in Vernal Pools in the Channeled Scabland of Eastern Washington*. (primary literature)

⁴⁴⁸ Ibid.

⁴⁴⁹ Ibid.

delineated by the Missoula Flood channels.⁴⁵⁰ The greatest concentration of pools was in the central channel, in and around the Swanson Lakes Wildlife Management Area.⁴⁵¹

Björk and Dunwiddie (2004) described the vernal pools they examined in Washington as typically small and shallow, formed on large expanses of exposed clay with little surface cover.⁴⁵² Vernal pools had shallow and relatively inorganic soils, low to moderate alkalinity and salt concentration, and minimal thatch and soil-organic matter.⁴⁵³ Björk and Dunwiddie (2004) found that pool hydrology varied seasonally with precipitation, and differed between years and between vernal pools of different sizes. In 1997, most vernal pools began to dry at the end of May, though very large pools retained standing water through June.⁴⁵⁴ In contrast, in 1998, nearly all vernal pools were fully desiccated by the middle of April.⁴⁵⁵ Small pools were the first to fill with the onset of autumn rains, while large pools did not fill until midwinter, when rainwater and snow melt accumulated during warm Pacific storms.⁴⁵⁶

Most of the Columbia Plateau vernal pools are within a shrub-steppe mosaic composed of sagebrush and various codominant grasses and forbs.⁴⁵⁷ Although many sites were only moderately disturbed, with minimal cover of non-natives, perhaps half of the pools are surrounded by floral communities significantly altered by non-native taxa.⁴⁵⁸ Several floristic elements appear to be unique to the Columbia Plateau pools.⁴⁵⁹ At least two dozen taxa that have not been documented in vernal pools elsewhere are common in the core flora, although many of these taxa do occur in other habitats.⁴⁶⁰ In Washington, many of the core native taxa are found almost exclusively in vernal pools.⁴⁶¹ The core native flora (those plants that were common, persistent, and tolerant of vernal pool hydrologic regimes) was predominantly annual (63%, or 111 native species), with abundant graminoids and composites.⁴⁶² Sixty-one perennial, native core taxa were present, as well as three core, woody species.⁴⁶³

Kulp and Rabe (1984) documented free-swimming invertebrate communities in five vernal pools in the channeled scablands in eastern Washington, and found a relatively low number of taxa compared to a nearby lake ecosystem. They hypothesized that the lower number of taxa could be the result of a low diversity of microhabitats within the pools, which generally lack large aquatic plants.⁴⁶⁴ In addition,

⁴⁵⁰ Björk and Dunwiddie (2004), *Floristics and Distribution of Vernal Pools on the Columbia Plateau of Eastern Washington*. (primary literature)

⁴⁵¹ *Ibid.*

⁴⁵² *Ibid.*

⁴⁵³ *Ibid.*

⁴⁵⁴ *Ibid.*

⁴⁵⁵ *Ibid.*

⁴⁵⁶ *Ibid.*

⁴⁵⁷ *Ibid.*

⁴⁵⁸ *Ibid.*

⁴⁵⁹ *Ibid.*

⁴⁶⁰ *Ibid.*

⁴⁶¹ *Ibid.*

⁴⁶² Björk and Dunwiddie (2004), *Floristics and Distribution of Vernal Pools on the Columbia Plateau of Eastern Washington*. (primary literature)

⁴⁶³ *Ibid.*

⁴⁶⁴ Kulp and Rabe (1984), *Free-Swimming Invertebrate Communities of Vernal Pools in Eastern Washington*. (primary literature)

organisms must be adapted to cope with the seasonal dry phase of vernal pools.⁴⁶⁵ Examples of free-swimming invertebrates present in Washington's vernal pools included species of copepods, seed shrimps (*Newnhamia insolita*), water fleas (*Daphnia*), clam shrimps, fairy shrimps (*Anostraca*), mosquitoes (*Culicidae*), diving beetles (*Thermonectus*), water striders (*Gerris remigis*), rotifers (*Rotifera*), and water mites (*Hydracarina*).⁴⁶⁶

Vernal pools on the Columbia Plateau appear to be less threatened than comparable pools in California because they occur mostly in basalt-bedrock landscapes, where most development and agriculture would be impractical.⁴⁶⁷ Hence, it appears that there has been little outright eradication of pools.⁴⁶⁸ Threats from non-native species also have been less pronounced on the Columbia Plateau.⁴⁶⁹ Although non-native taxa have had a major impact on the landscape surrounding many vernal pools on the Columbia Plateau, few sites are completely dominated by non-natives and observations suggest that vernal pools have been less invaded than surrounding communities.⁴⁷⁰

- We could find no published information on the potential effects of climate change on vernal pool ecosystems in Washington State. However, a reviewer commented that higher temperatures and associated evapotranspiration make it likely that vernal pools will less frequently contain water and more quickly dry up when they do contain water. The increased intensity of storm and drought events will also result in greater extremes of vernal pools from very dry to very large in extent.

⁴⁶⁵ Information as cited in Kulp and Rabe (1984), *Free-Swimming Invertebrate Communities of Vernal Pools in Eastern Washington*. (primary literature)

⁴⁶⁶ Kulp and Rabe (1984), *Free-Swimming Invertebrate Communities of Vernal Pools in Eastern Washington*. (primary literature)

⁴⁶⁷ Björk and Dunwiddie (2004), *Floristics and Distribution of Vernal Pools on the Columbia Plateau of Eastern Washington*. (primary literature)

⁴⁶⁸ Ibid.

⁴⁶⁹ Ibid.

⁴⁷⁰ Ibid.

APPENDIX 1: Setting the Stage – Grassland and Shrubland Habitats

Excerpts from a 2009 report coauthored by Patty Glick and Lydia Moore of National Wildlife Federation.

Grassland and Shrubland Habitats

Grassland and Shrubland Habitats		
<p>Key Impacts</p> <ul style="list-style-type: none"> Altered hydrology including floods and drought Increasing fires Expansion of invasive species Changes in land use Loss of endemics and species diversity 	<p>Potential Management Actions</p> <ul style="list-style-type: none"> Increase water use efficiency Protect and restore habitat Change agricultural practices to reduce the need for water Change land use management Raise public awareness 	<p>Information Gaps</p> <ul style="list-style-type: none"> Migration patterns Species interactions Post-fire ecosystem restoration

Key Impacts

- Altered hydrology.** Permanent and seasonal changes in water abundance will have impacts on grassland and shrubland habitats. Floods and droughts are already ecosystem stressors and they will become more frequent with climate change, with projections showing an increase in frequency and severity of both winter flooding summer droughts.³² Ephemeral pools and year round reservoirs in some areas may no longer adequately supply freshwater to ecosystems.³³ Drought will interact with other stressors, such as fire and insects, to further increase grassland vulnerability.³⁴



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- Increasingly frequent and severe fires.** Increased frequency of droughts will cause more frequent and severe wildfires.³⁵ Changes in the natural balance of fires could result in the loss of species – including fire dependant species if fires become too hot, severe, and frequent.
- Expansion of invasive species.** Invasive species are already a significant problem for grassland systems and are projected to become worse. As temperatures increase, species will tend to migrate northward where possible in an effort to adapt to changing climate conditions.³⁶ Many invasive plant species will be able to take advantage of systems that have been weakened by extreme events such as wildfires.³⁷
- Changes in land use.** Existing habitat is becoming more fragmented as eastern Washington communities expand. Possible human migration north due to changes in climate will cause further development

and habitat fragmentation, decreasing wildlife corridors and posing a problem for species that need to migrate in adaptive response to climate change. Current grazing practices and mono-crop agriculture are causing changes in the biological elements of the soil. Because soil is the underlying basis of everything else, problems and changes in the soil can impact the whole ecosystem.

- Loss of endemics and species diversity.** As diverse species respond to climate change in different ways, important connections between pollinators, breeding birds, insects, and other wildlife and the plants on which they depend will become disrupted.³⁸ These shifts can result in changes in the food web, broken or altered predator-prey relationships, and species extinction through the inability of some species to adapt.

Potential Management Actions

- Increase water use efficiency.** Irrigation infrastructure should be updated to conserve water more efficiently. Water storage needs to be sited and managed properly to provide the maximum benefit to humans and wildlife.
- Protect and restore habitat.** Site-specific research is needed to determine which areas will have the fewest negative impacts in order to prioritize the healthiest areas where conservation efforts will be most effective. Setting aside these lands for wildlife through acquisitions and easements will allow conservation efforts to focus on improving hydrology connectivity, reseeding areas after fires, and prescribing burns to control invasive species.
- Change agricultural practices to reduce the need for water.** Converting agricultural practices to be less water intensive will reduce the quantity of water diverted from rivers and streams. The most water

consumptive crops should be identified and converted to less water intensive crops through incentives and other programs with farmers.

- **Change land use management.** Land protection through conservation easements will facilitate the restoration of riparian and grassland habitat and will allow conservation measures that aggressively control and monitor invasive species. Easements will enable planned disturbances like prescribed fires and flooding events. Prescribed fire management would allow seasonal brush control to prevent larger fires and aggressively control invasive species while simultaneously promoting fire dependant natives. Pre-planned flooding events would decrease erosion damage and allow certain areas to become temporarily inundated, encouraging natural flow regimes. Long-term monitoring and study would be needed to evaluate the success of pre-planned flooding and prescribed burns.
- **Raise public awareness.** The public must be educated about the benefits of changes in land use management like prescribed burns and pre-planned flooding events in order to gain the public support required for success. In addition to education, incentives are necessary to encourage farmers and cattle ranchers to participate in conservation measures on agricultural and grazing land.

Information Gaps

- **Migration patterns.** Due to the complexity of ecosystems, it is not understood how climate change will affect species migrations. New species will expand their range northward and it is not known which species those will be or what impact they will have.
- **Species interactions.** There are too many variables in ecosystems to accurately predict all of the keystone species and how they will be affected by a changing climate. Likewise, plant/animal and predator/prey relationships will change in response to climate change and more research is needed to predict what these changes will be.
- **Post-fire ecosystem restoration.** Research around post-fire ecosystem restoration is needed to properly manage prescribed burns in a climate friendly manner. Long-term monitoring of prescribed burns and flooding is necessary to determine changes in soils and ecosystems in order to identify the success and failure of new management practices.

ADAPTATION IN ACTION: RECONNECTING WASHINGTON'S SHRUB-STEPPE HABITATS.

Scientists with the Nature Conservancy have been working with a modeling tool called ClimateWizard to measure habitat connectivity of the remaining shrub-steppe in central and eastern Washington as the basis for establishing common priority areas for conservation in the face of climate change. ClimateWizard is a tool developed by researchers at the Nature Conservancy, the University of Washington, and the University of Southern Mississippi to help “downscale” scenarios of projected changes in temperature and precipitation due to global warming.



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