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Potential effects of climate change on riparian areas, wetlands, and groundwater-dependent ecosystems in the Blue Mountains, Oregon, USA

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ABSTRACT

Riparian areas, wetlands, and groundwater-dependent ecosystems, which are found at all elevations throughout the Blue Mountains, comprise a small portion of the landscape but have high conservation value because they provide habitat for diverse flora and fauna. The effects of climate change on these special habitats may be especially profound, due to altered snowpack and hydrologic regimes predicted to occur in the near future. The functionality of many riparian areas is currently compromised by water diversions and livestock grazing, which reduces their resilience to additional stresses that a warmer climate may bring. Areas associated with springs and small streams will probably experience near-term changes, and some riparian areas and wetlands may decrease in size over time. A warmer climate and reduced soil moisture could lead to a transition from riparian hardwood species to more drought tolerant conifers and shrubs. Increased frequency and spatial extent of wildfire spreading from upland forests could also affect riparian species composition. The specific effects of climate change will vary, depending on local hydrology (especially groundwater), topography, streamside micro-climates, and current conditions and land use.

Practical Implications

Riparian areas, wetlands, and groundwater-dependent ecosystems have enormous conservation value throughout western North America. These special habitats are typically biodiversity hotspots for both plants and animals. They also play a significant role in maintaining functional hydrologic regimes in watersheds and providing cool water for spawning and rearing of salmonid fish species.

Resource managers at national forests in the Blue Mountains (northeast Oregon and southeast Washington, USA) are mandated to protect riparian areas and retain their functionality. Riparian areas have been degraded by livestock grazing, water diversions, and other land uses over many decades. Although restoration of riparian areas is a priority for federal managers, competition among different users creates a complex social and political environment.

The added stress of climate change makes riparian and wetland restoration and conservation even more challenging. Some smaller habitats (e.g., near springs and streams) could disappear, whereas larger habitats, especially those with a good groundwater supply, may be more resilient to a warmer climate. Most riparian and wetland ecosystems will experience some degree of increased stress in a warmer climate, including the indirect effects of increasing wildfire and non-native species. Some changes may occur gradually and others may occur episodically (e.g., following wildfire). Long-term monitoring is needed to detect where, when, and how climate change effects occur.

Riparian areas, wetlands, and groundwater-dependent ecosystems have been classified and mapped throughout the Blue Mountains, an important first step for conservation and restoration. Impacts from land-use practices have been quantified in some locations, providing a benchmark for systems that are currently compromised. Our assessment of climate change impact and vulnerability can be used to develop restoration priorities and to identify those aquatic ecosystems that could experience the most stress from a warmer climate and altered hydrologic regimes. Maintaining a reasonable degree of hydrologic functionality and minimizing impacts from land use will contribute to building and sustaining resilience.

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1. Introduction

In the Blue Mountains, climate change will likely have significant, long-term implications for freshwater resources and associated vegetation. Climate change is expected to cause a transition from snow to rain, resulting in diminished snowpack and shifts in streamflow to earlier in the season (Leibowitz et al., 2014). Additional effects include more extreme high streamflows, more extreme low streamflows, reduced groundwater recharge, and altered nutrient dynamics and other ecosystem functions (Johnson et al., 2012; Raymondi et al., 2013). Increasing air temperatures contribute to shifts in precipitation and stream runoff patterns, and also influence fire frequency and severity (Schoennagel et al. 2017), and the duration of the fire season. Another consequence of warming temperatures is the higher frequency and severity of droughts, which have increased the susceptibility of plant species to pathogens and insect pests, leading to regional tree die-offs (Breshears et al., 2005) and changes in the distribution of vegetation.

Here, we describe the potential effects of climate change on riparian areas, wetlands, and groundwater-dependent ecosystems (GDEs) in the Malheur, Umatilla, and Wallowa-Whitman National Forests. We define riparian areas, wetlands, and GDEs, highlighting the considerable overlap among these ecosystems, then briefly describe the current condition, land use impacts, and range of plant communities that occur in these habitats. We describe potential climate-influenced changes for different vegetation assemblages, and emphasize that there is considerable uncertainty about rates and direction of change, depending on physical and biological conditions and land use effects.

2. Definitions

Riparian areas are zones of direct physical and biotic interactions between terrestrial and aquatic ecosystems (Gregory et al., 1991), and include the continuum from headwaters to the mouths of streams and rivers, the vertical dimension that extends upward into the vegetation canopy and downward into subsurface interactions, and the lateral dimension that extends to the limits of flooding on either side of a stream (Stanford and Ward, 1993).

In the Blue Mountains, riparian ecosystems occur across a broad range of climatic conditions, and geomorphic and physical features at all elevations (Crowe and Clausnitzer, 1997; Johnson, 2004; Wells, 2006). Stream sizes, landforms, valley widths, and hydrologic regimes determine the biotic communities that occur along streams. Riparian areas, wetlands, and intermittent streams are included within Riparian Habitat Conservation Areas (RHCAs), which specify minimum buffers from each side of the stream channel edge: intermittent streams (15 m), wetlands and non-fish-bearing perennial streams (46 m), and fish-bearing streams (91 m). Active management within buffers must comply with riparian management objectives designed to improve habitat conditions for fish species.

Wetlands are ecosystems inundated or saturated by surface water or groundwater at a frequency and duration sufficient to support vegetation typically adapted for life in saturated soil (FICWD, 1989). Wetlands can be diverse physically and biologically, varying in duration, seasonality, and depth of inundation and soil saturation. In the Blue Mountains, the dominant wetland types are palustrine, lacustrine, and riverine (Cowardin et al., 1979; Figs.1–3). Palustrine wetlands are freshwater ecosystems that include marshes, wet meadows, and forested wetlands. Lacustrine wetlands border lake shores. Riverine wetlands occur along stream channels. Most riparian areas are categorized as riverine wetlands, and all wetland and riparian areas in national forests in the Blue Mountains are managed as RHCAs.

Groundwater-dependent ecosystems (GDEs) are biotic communities whose extent and life processes depend on access to or discharge of groundwater (Springer and Stevens, 2009; USFS, 2012a,b). Many wetlands, lakes, streams, and rivers receive inflow from groundwater, which can contribute substantially to maintenance of water levels, as well as water temperature and chemistry required by native biota (Lawrence et al., 2014). In the Blue Mountains, GDEs include springs, high-elevation lakes, fens, streams, rivers (Brown et al., 2009, 2010), and riparian wetlands along gaining river reaches. Fens are peat-accumulating wetlands that are largely supported by groundwater (thus, GDEs). Groundwater is important to most watersheds in northeastern Oregon (Gannett, 1984; Brown et al., 2009).

3. Methods

To assess current condition of riparian areas and wetlands in the Blue Mountains, we reviewed the regional literature for documented impacts of past land use on seven broad riparian/wetland plant community types, and utilized information from theses, government reports and scientific journal articles. We also analyzed riparian vegetation data collected through the interagency program, PACFISH INFISH Biological Opinion Effectiveness Monitoring (PIBO; http://fsweb.r4.fs.fed.us/unit/nr/pibo/index.shtml), which monitors biological and physical components of aquatic and riparian habitats throughout the Columbia River Basin (Meredith et al., 2011; Archer et al., 2012). For 191 sites in the Blue Mountains, we assessed riparian vegetation changes in total plant cover, woody cover, and non-native species cover (2007–2011), and compared data from reference and managed sites (Coles-Ritchie et al., 2007). To evaluate current distribution of wetlands in the Blue Mountains, we summarized information from the Oregon Wetlands Geodatabase (http://oregonexplorer.info/wetlands/DataCollections/GeospatialData_Wetlands) (Figs. 1–3).

To assess the current condition of GDEs, we utilized data compiled by The Nature Conservancy (Brown et al., 2010), the National Hydrology Dataset (http://nhd.usgs.gov), and the Oregon Wetlands Geodatabase. In addition, we summarized existing inventory data; since 2008, 133 GDEs, mostly springs, have been characterized in Blue Mountains' national forests, using the GDE Inventory Field Guide (USFS, 2012a). As part of this protocol, information on management indicators is recorded to assist in identifying concerns and needs for management action. We assessed three indicators: aquifer functionality, soil integrity, and vegetation composition. In the Malheur and Wallowa-Whitman National Forests, GDE inventories targeted sites where proposals for water development could be damaging, whereas inventories in the Umatilla National Forest targeted portions of grazing allotments and watersheds with specific management concerns.

To describe the potential effects of climate change on riparian areas and wetlands in the Blue Mountains, we utilized published research that examined responses of riparian and wetland characteristics to drought and hydrologic alteration, primarily dams and diversions, focusing on studies conducted in the western USA. We also considered local knowledge from resource managers and stakeholders—summarized during a series of meetings on climate change adaptation—who have observed changes to specific resources, such as aspen and cottonwood stands over recent decades. For potential effects of climate change on GDEs, we summarized regional predictions of vulnerability (Brown et al., 2009, 2010) and relied on published, scientific literature. For these resources, there is considerable uncertainty in our projections, however, because empirical data are lacking on specific mechanisms through which climate change will influence riparian and wetland plant communities.

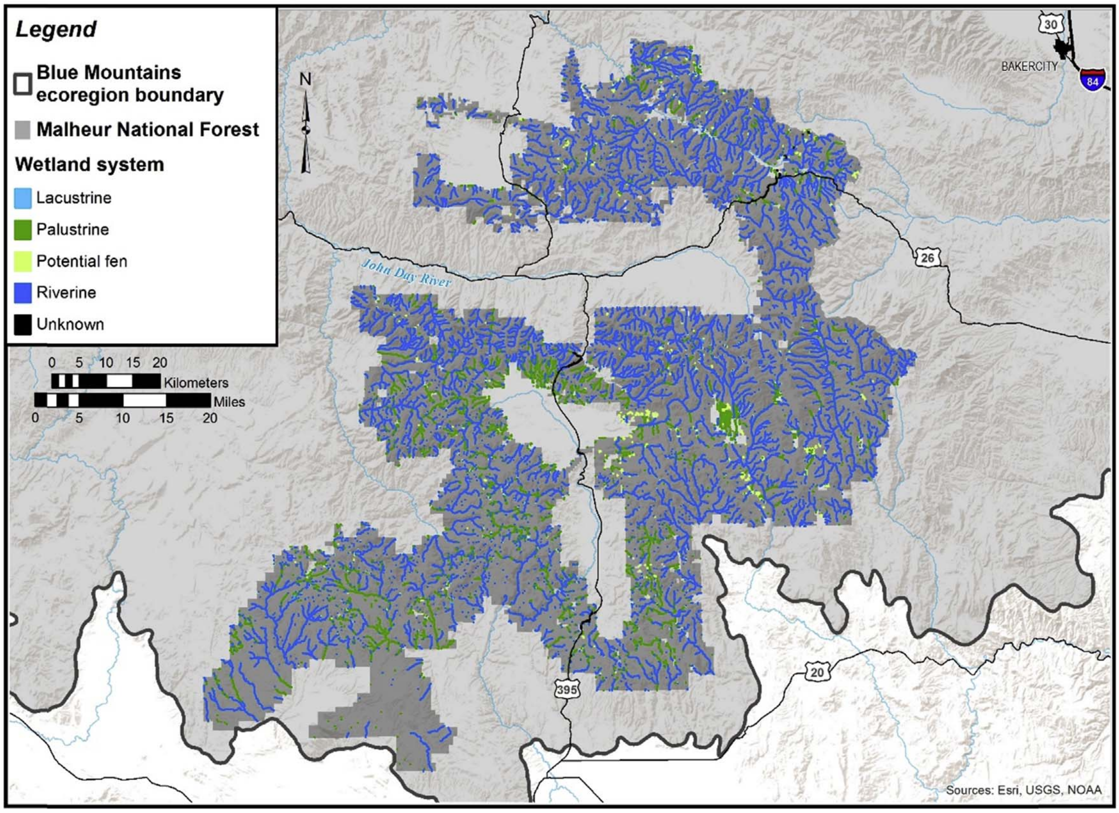

Fig. 1. Wetlands in Malheur National Forest. Source: Oregon Wetlands Geodatabase.

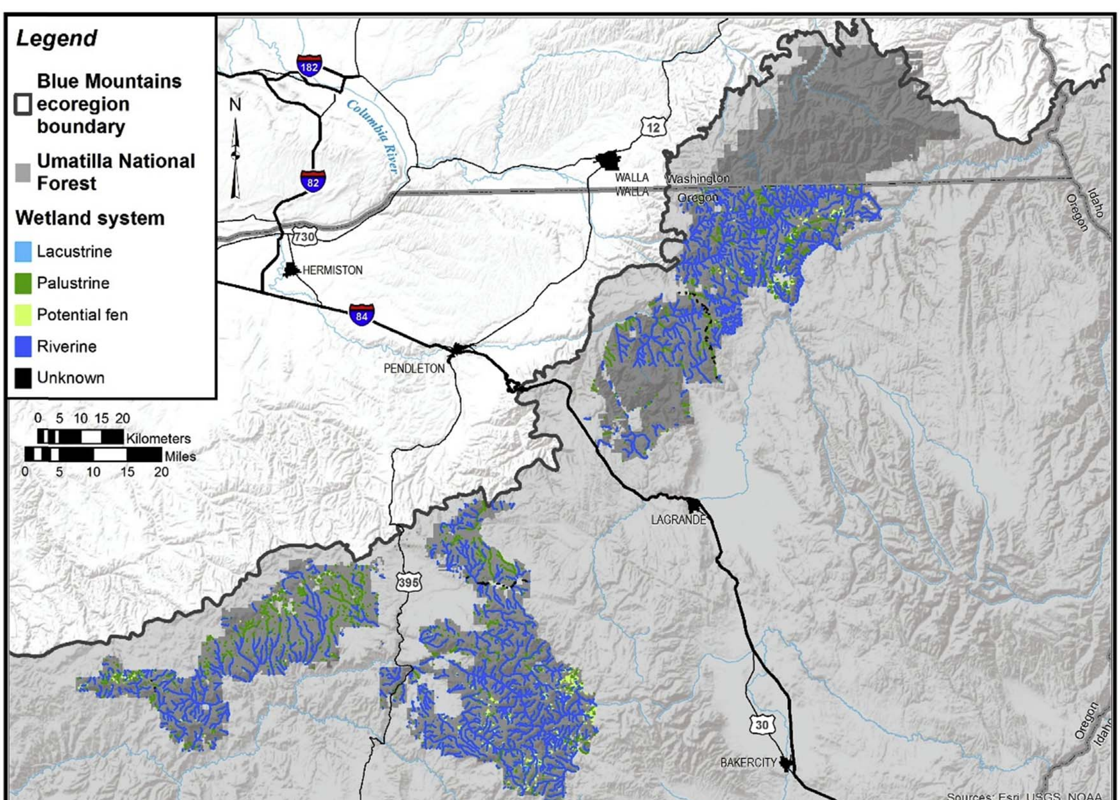

Fig. 2. Wetlands in the Oregon portion of Umatilla National Forest. Source: Oregon Wetlands Geodatabase.

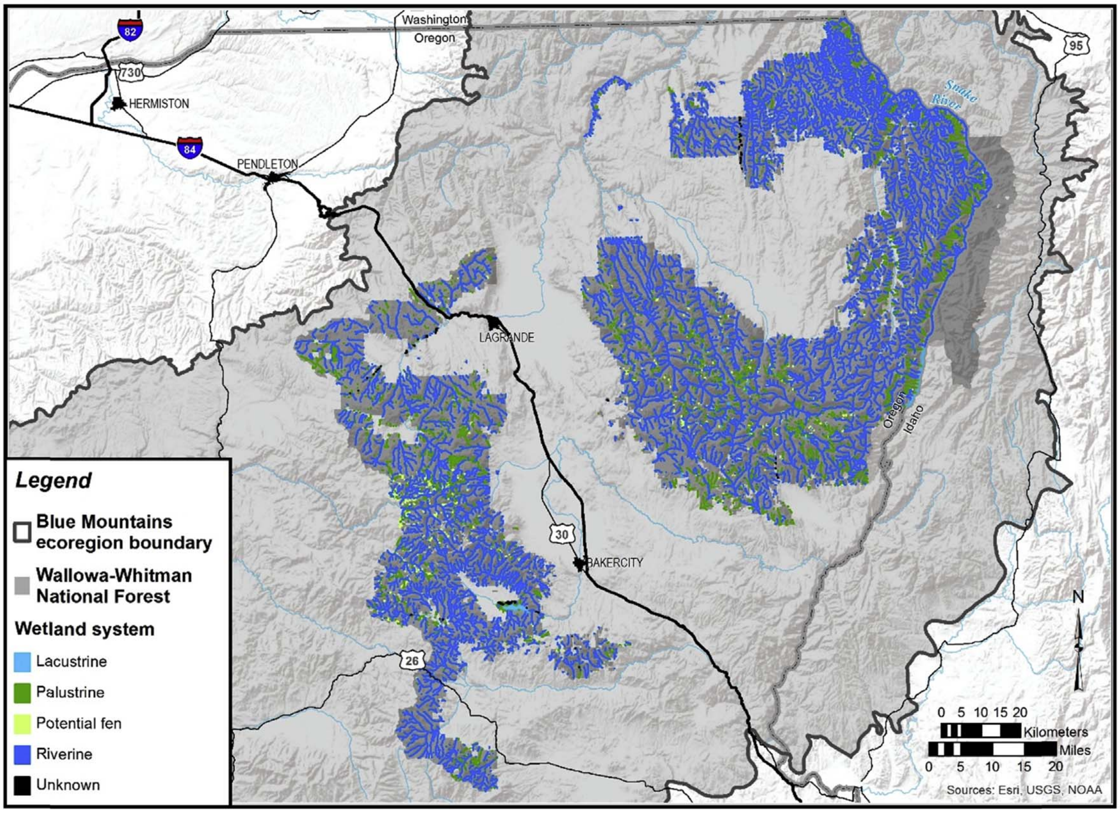

Fig. 3. Wetlands in Wallowa-Whitman National Forest. Source: Oregon Wetlands Geodatabase.

4. Results and discussion

4.1. Current resource conditions

4.1.1. Riparian areas

Conifer-dominated riparian areas, which occur at high to moderate elevations along first- and second-order streams and in confined valley bottoms are valued for maintenance of riparian microclimates, wildlife habitat, and sources of large instream wood (Powell et al., 2007). Dominant species include subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), and lodgepole pine (*Pinus contorta* var. *latifolia*). "Warm riparian forests" can include Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), or western white pine (*Pinus monticola*). These vegetation types have been affected by past forest harvest, mining, grazing, road building, fire exclusion, and invasive species (Wickman, 1992; Parks et al. 2005) (Table 1). Natural disturbances include wildfire, forest insects, fungal pathogens, landslides, and debris flows (Luce et al., 2012).

Riparian and wetland aspen plant communities are uncommon and small (usually < 1 hectare in size), but provide valued habitat throughout the Blue Mountains region. Most wetland and riparian quaking aspen (*Populus tremuloides*) communities in this area are associated with herbaceous species (Swanson et al., 2010). Aspen communities have been affected by fire suppression and herbivory by livestock and native ungulates (Bartos and Campbell, 1998; Shinneman et al., 2013). They are currently threatened by herbivory and conifer encroachment, especially in meadows (Table 1). Many stands are declining, without signs of regeneration, and are susceptible to a broad range of insects and fungal pathogens (Swanson et al., 2010).

Cottonwood-dominated riparian areas are dominated by black cottonwood (*Populus trichocarpa*), and occur along different valley types in the Blue Mountains, which range from high-gradient valleys to moderately confined or open, low-gradient valleys (Crowe and Clausnitzer, 1997). In the mid-1800s, cottonwood-dominated riparian areas along wide valley bottoms at low-mid elevations were settled and used widely for livestock production, due to availability of productive forage and proximity to water (Dwire et al., 1999). Decline of cottonwood and willows (*Salix* spp.) has been attributed primarily to livestock grazing (McIntosh et al., 1994; Beschta and Ripple, 2005), including conversion to pastures by modifying stream channels, removing woody species, and planting with non-native grasses. Wood cutting and hydrologic modification of streams for agriculture and irrigation have also reduced the abundance of hardwood species in riparian areas. Streamflow alterations and livestock grazing may have contributed to low recruitment of cottonwoods (Beschta and Ripple, 2005) (Table 1).

Willow-dominated riparian areas are most extensive at low-mid elevations. Willows provide shade and organic matter for streams, bank stability, sediment retention, and habitat for many vertebrate species (Kauffman et al., 2001). At least seven species of willows are found in the Blue Mountains (Crowe and Clausnitzer, 1997). Historical removal of American beaver (*Castor canadensis*) contributed to reduction of willow-dominated riparian areas (McAllister, 2008), and functioning beaver dams are still infrequent in the Blue Mountains (Swanson et al., 2010). Willow-dominated riparian areas have been heavily affected by livestock grazing and elk (*Cervus elaphus*) browsing ((Brookshire et al., 2002). Flow alteration has altered species composition downstream of water diversions (Caskey et al., 2014).

Other woody-dominated riparian areas (deciduous shrubs and trees) comprise floristically diverse communities throughout the Blue Mountains, including those dominated by water birch (*Betula occidentalis*), four species of alder (*Alnus* spp.), and a wide range of shrub species. Some woody plant communities are the result of hydrologic modification that has converted willow-dominated areas to communities dominated by shrub species that are more tolerant of low soil moisture. Woody-dominated riparian areas have also been affected by livestock grazing, herbivory from native ungulates, and conversion to pastures and other agricultural uses (Table 1).

Herbaceous-dominated riparian areas occur over a wide elevation

Table 1
Stressors in riparian and wetland ecosystems (modified from Theobald et al., 2010).

Stressor	Direct and indirect causes	Potential effects	Systems most affected by climate change
Changes in flow regime and dewatering	Surface water: dams, diversions, land use changes, climate change Groundwater: pumping, land use change, climate change	Water stress in vegetation Shifts in plant species composition Homogenization of riparian area and simplification of biota Isolation of floodplain from stream Altered stream-riparian organic matter exchange and trophic dynamics Altered floodplain biogeochemistry Altered channel structure Decreased lateral extent of riparian area	Cottonwood, aspen, willow, and herbaceous-dominated communities located along low-gradient, wide valley bottoms
Channelization	Bank hardening Levee construction Structural changes in channel-deepening Berm development Meander cutoff	Isolation of floodplain from stream Altered fluvial processesAltered hydraulics (aquatic habitat and channel forms) Altered floodplain biogeochemistry	Cottonwood, aspen, willow, and herbaceous-dominated communities located along low-gradient, wide valley bottoms
Conversion of floodplains to other uses	Removal of woody riparian vegetation	Elimination of cottonwood, aspen, willow, and herbaceous communities Reduced extent of riparian area, thus reducing ecosystem services	Cottonwood, aspen, willow, and herbaceous-dominated communities located along low-gradient, wide valley bottoms
Invasive species	Altered physical and ecological processes that facilitate establishment and spread	Displacement of native species Formation of monocultureAltered site characteristics (e.g., biogeochemistry, soil properties, water balance) Shifts in community composition Altered habitat structure	Nearly all riparian and wetland communities, especially those that occur in drier environments Potential increase in tamarisk in Hells Canyon
Changes in sediment delivery to channel	Offroad vehicle useRoads (drainage, gravel application) Livestock and herbivore trampling Altered vegetative cover in watershed and along channel Direct mechanical effects on channel, dams, and diversions	Shifts in channel and floodplain form (through increased or decreased delivery to channel)Altered channel processes (e.g., incision and aggradation)	Nearly all riparian and wetland communities, although direct causes and severity will differ
Herbivory	Grazing by cattle and wild ungulates	Bank trampling and compaction Altered cover and composition of vegetation Stream capture Nutrient inputs	Aspen, cottonwood, willow and herbaceous communities are the most heavily impacted
Wildfire and fuels, fire exclusion	Fuel buildup from non-native species and fire exclusion Reduced flooding Slower decomposition	Increased frequency and intensity of fires Loss of fire-intolerant taxa Altered structure of riparian vegetation and habitat quality and distribution Riparian areas could serve as refugia for some upland species	Conifer-dominated riparian communities with tree species similar to adjacent uplands
Insects and disease	Fire exclusion and past harvest activities have resulted in susceptible stand structure	Altered fuel loads and distribution associated with increased canopy mortality	Conifer-dominated riparian plant associations with tree species similar to adjacent uplands

range from alpine to lower montane, and are mostly dominated by sedge species (*Carex* spp., *Eleocharis* spp., others). These communities are found primarily in moderately confined to wide valley bottoms, usually along low-gradient stream segments. Herbaceous-dominated meadows have been affected by heavy elk grazing at mid elevations and by livestock grazing at all elevations (Skovlin and Thomas, 1995). Altered species composition and density have been caused by conversion of natural meadows to pasture in some floodplains. Water diversions and ditches have affected channel characteristics, seasonal water supply and water tables (McIntosh et al., 1994). In some meadows, hydrologic alteration and livestock grazing have caused drier conditions and increased dominance by non-native grasses and grazing-tolerant native species (Johnson et al., 1994) (Table 1).

Subalpine and alpine riparian areas and wetlands include communities that are dominated by (1) willow species in glacial valleys, (2) shrub species in low-gradient valleys and the upper terminus of glacial valleys, (3) graminoid species in low-gradient valleys and fens, and (4) sedges and forbs associated with headwater springs (Wells, 2006). These communities have been affected by livestock grazing and ungulate browsing, but are in better condition than similar low-elevation communities.

Analysis of riparian vegetation data collected through the PIBO program (2007–2011) across a range of riparian plant communities showed significantly lower total cover and woody cover for managed sites relative to reference sites, as well as higher non-native species cover and lower ratings for wetland functionality. This documented pattern of degraded habitat and continued spread of non-native species could contribute to further reductions in the biological integrity of riparian areas.

4.1.2. Wetlands

The number of wetlands in national forests of the Blue Mountains is shown in Table 2 (wetlands in the Washington state portion of Umatilla National Forest are not shown). Current condition of riparian and wetland ecosystems differs considerably depending on location and land use history. As described above, riparian and wetland communities at low-mid elevations have been the most impacted by land use (McIntosh et al., 1994; Crowe and Clausnitzer, 1997) (Table 1).

4.1.3. Groundwater-dependent ecosystems

Steep elevation gradients, bedrock, and glacial landforms influence the distribution, characteristics, and water chemistry of GDEs in the Blue Mountains. The number of currently mapped springs in national forests is shown in Table 2. Most springs are unnamed, and many may not be perennial, especially during dry years. Springs play a key role as groundwater discharge zones that deliver cool water to streams, support summer streamflow, and may deliver relatively warm water during winter (Winter, 2007; Lawrence et al., 2014). Most streams and rivers

Table 2
Number of springs (named and unnamed) and wetlands for Malheur, Umatilla, and Wallowa-Whitman National Forests.[a]

National forest	Springs			Wetlands				
	Named	Unnamed	Total	Palustrine	Lacustrine	Riverine	Total	Potential fens
Malheur	389	2462	2851	4405	8	4648	9061	1132
Umatilla	268	381	649	2472	5	1780	4257	568
Wallowa-Whitman	273	1635	1908	5419	77	4886	10,382	1037
Total	930	4478	5408	12,296	90	7314	23,700	2737

[a] The number of springs was derived from the National Hydrography Database. The number of wetlands was derived from the Oregon Wetlands Geodatabase (excludes national forest land in Washington and Idaho). This database identified "potential fens" if a wetland occurred near a spring, so overlap exists between number of palustrine wetlands and number of potential fens.

Table 3
Area of different wetland types and percentage of forest area for Malheur, Umatilla, and Wallowa-Whitman National Forests.[a]

National forest	Palustrine		Lacustrine		Riverine		Potential fens[b]	
	hectares	*%*	*hectares*	*%*	*hectares*	*%*	*hectares*	*%*
Malheur	4552	0.7	62	< 0.001	1963	0.3	967	0.150
Umatilla	2091	0.5	104	< 0.001	1669	0.4	556	0.001
Wallowa-Whitman	3897	0.4	1447	0.01	4458	0.5	619	0.060
Total	10,540		1613		8090		2142	

[a] Wetland area derived from the Oregon Wetlands Geodatabase and excludes national forest land in Washington and Idaho.
[b] Potential fens are classified primarily as palustrine wetlands and are included in the area calculated for palustrine wetland area.

in the Blue Mountains are at least partially groundwater dependent, and 59% of annual streamflow in semiarid mountains of eastern Oregon is attributable to groundwater discharge (Santhi et al., 2008). The influence of groundwater on stream temperature is especially important for cold-water fish habitat.

The Oregon Wetlands Geodatabase identified "potential fens" if a wetland occurred near a spring (Tables 2 and 3; Figs.1–3), inferring that groundwater is an important water source. Because characterization based on remotely sensed information can be inaccurate and incomplete, fens frequently remain undetected, and numbers shown (Table 2) are likely under-estimates. Although fens occupy a very small portion of the Blue Mountains landscape (Table 3), they contribute substantially to regional biodiversity. Analysis of information collected as part of GDE inventories on the Umatilla National Forest showed that 56% of GDEs had reduced aquifer functionality, largely due to groundwater extraction. Water diversions that withdraw water emerging from spring habitat or an adjacent stream are present at many locations, with an average of 93% of available water being diverted. Soil was altered in 24% of GDEs, mostly through ground disturbance or soil compaction. Upland plant species cover was higher than expected in 18% of GDEs, suggesting that hydric species may have been replaced because of altered hydrology. Trails by animals or people were found in 44% of GDEs, grazing/browsing by livestock in 36% of sites, and grazing/browsing by wildlife in 16% of sites. Functionality of severely impacted GDEs is low and may be decreasing. GDE inventories for Malheur and Wallowa-Whitman National Forests (not shown) revealed similar patterns. A study in watersheds adjacent to Wallowa-Whitman National Forest documented reduced groundwater supply and contaminated groundwater from pesticides and fertilizers (Brown et al., 2009).

4.2. Potential climate change effects

4.2.1. Riparian areas and wetlands

A warmer climate in the Blue Mountains region is projected to alter snow accumulation, timing, and rate of melt, thus affecting streams in a number of ecologically significant ways. Earlier spring snowmelt will lead to higher peak streamflows in winter (Mote et al., 2005) and lower streamflows in summer (Luce and Holden, 2009). The most extreme trajectory for certain resources is complete loss of the ecosystem and valued functions, which may occur for smaller springs and wetlands, and headwater stream segments. Shifts in riparian vegetation and reduced area occupied by riparian communities are expected in response to altered streamflow and lower streamside soil moisture independent of streamflow. For example, Ponderosa pine (*Pinus ponderosa*) and upland shrubs may be increasing in areas previously dominated by riparian woody species in response to channel incision and decreasing soil moisture (Table 1). Reduced width of riparian areas, increased severity and frequency of drought, and higher demands for water could reduce the difference in soil moisture between streamside and upland habitats. Reduced riparian extent could affect vegetation composition and structure, with negative feedbacks for the quantity and quality of ecosystem services provided by riparian vegetation (e.g., wildlife habitat, recreational value, shade over streams). Here, we describe the most likely climate change effects on dominant riparian and wetland plant communities in the Blue Mountains.

Conifer-dominated riparian areas will be increasingly affected by wildfires and insect outbreaks in a warmer climate. A study of fire history in upland and riparian forests in the Blue Mountains showed that fires in riparian areas were only slightly less frequent than in uplands of the same forest type (Olson, 2000), and a study of fuel characteristics and potential for crown fire in paired upland-riparian stands in the Blue Mountains suggested that high-severity fire could extend downslope into valley bottoms (Williamson, 1999). In the future, fuel conditions in riparian areas may indeed be conducive to crown fires during hot, dry weather. Warmer temperatures are projected to promote insect outbreaks in forested areas by increasing water stress in host trees while conferring physiological advantages to insects (Bale et al., 2002). Although streamside trees appear to be more resistant to insect outbreaks (Dwire et al., 2015), this resistance could weaken in a warmer climate. As fire- and insect-caused mortality transform the structure of dry forests, adjacent riparian forests could also be affected. In some watersheds, riparian areas may serve as important refugia for certain upland species.

Riparian and wetland aspen plant communities in the Blue Mountains are already experiencing stress, since many aspen stands have been declining in number, area, and stem density (Swanson et al., 2010). Similar dieback has been observed in other locations in western North America, and although the cause for this decline is unclear, it may be related to low soil moisture in severely affected stands (Worrall et al., 2013). Warmer temperatures are expected to reduce soil moisture, groundwater, and summer streamflow, which would have a detrimental effect on the productivity, vigor, and spatial extent of aspen communities.

Cottonwood-dominated riparian areas depend on seasonal flooding for regeneration of black cottonwood and on baseflow for stand maintenance (Lite and Stromberg, 2005), so any alteration of hydrologic characteristics could affect this species. Many cottonwood stands already have minimal regeneration because of livestock grazing. Potential competition from non-native tamarisk (*Tamarix* spp.) may become more threatening. Tamarisk has displaced native cottonwoods throughout the West by altering local water tables (Merritt and Poff, 2010). Although tamarisk is not currently present in the Blue Mountains, riparian habitat for tamarisk will probably increase in the Pacific Northwest as the climate continues to warm (Kerns et al., 2009). Even without tamarisk, it is likely that cottonwood will become less dominant in riparian areas if increased drought or additional flow modification alter stream flows and groundwater.

Willow-dominated riparian areas are maintained by floods, adequate streamflow, shallow subsurface drainage, and American beaver activities (Demmer and Beschta, 2008). A warmer climate could affect groundwater and streamflow that redistributes fine textured soils for germination and establishment (Karrenberg et al., 2002), including clonal species that depend on flow characteristics for appropriate propagation substrates. Altered flood frequency and duration could affect the long-term maintenance of willow populations (Stromberg et al., 2010). If higher air temperatures and lower streamflows decrease soil and foliar moisture, willow communities may become more susceptible to wildfires.

Other shrub-dominated riparian areas could increase in spatial extent. The displacement of native species that are tolerant of extended soil saturation, such as willows and sedges, by more drought tolerant species is likely, although highly dependent on the physiological tolerances of the individual species. Conifer species, which already encroach in some riparian areas, could become more dominant in some shrub-dominated riparian areas, especially at lower elevations where soils are typically drier.

Herbaceous-dominated riparian areas contain species that are typically sensitive to height of the water table (Dwire et al., 2006). In a warmer climate, the water table could become lower and more variable, and other hydrologic characteristics could change with more frequent droughts. The spatial extent of wet meadows could diminish, with dominance shifting from sedges to grass and shrub species that are more competitive in lower soil moisture environments. Altered species composition and vegetation cover could in turn affect water quality by reducing infiltration of runoff and weakening streambank stability, thus contributing sediment to adjacent streams.

4.2.2. Groundwater-dependent ecosystems

In the Pacific Northwest, increased warming will influence the amount, timing, and distribution of runoff, as well as groundwater recharge and discharge (Waibel et al., 2013). Snowpack is the main source of groundwater recharge in the Blue Mountains. Higher temperatures can reduce the longevity of snowpack and decrease the length of time aquifer recharge can occur, potentially leading to faster runoff and less groundwater recharge. Little is known about how the shift from snow-dominated to rain-dominated hydrologic regimes will occur in many watersheds (Safeeq et al., 2013, 2014) or how this transition will influence groundwater recharge rates and amounts (Earman and Dettinger, 2011). In the Blue Mountains, the biggest declines in snowpack are projected to occur in mid elevations, although effects on available groundwater will vary depending on local topography and land use.

In the Blue Mountains, igneous and metamorphic rocks have low permeability and porosity, providing low groundwater discharge, so GDEs with this geology are less vulnerable to changes in temperature and precipitation. In contrast, aquifers in sedimentary or basalt formations, which have high permeability and porosity, provide higher discharges to GDEs and are recharged more frequently, making them more sensitive to a warmer climate. Small, unconfined aquifers may respond more rapidly to climate change than large, confined aquifers (Healy and Cook, 2002).

Groundwater storage can moderate surface water response to precipitation (Maxwell and Kollet, 2008), and altered connectivity between groundwater and surface water could directly affect streamflows, associated wetlands, and other GDEs (Earman and Dettinger, 2011). Changes in groundwater and surface water will also vary depending on location within the watershed and stream network, as well as future land use. Effects of climate change on GDEs will depend on changes in groundwater levels and recharge rates, as influenced by the size and position of groundwater aquifers (Aldous et al., 2015). GDEs supported by small, local groundwater systems exhibit more variation in temperature and nutrient concentrations than regional systems (Bertrand et al., 2012), so larger systems will likely be more resilient to climate change.

As noted above for wetland and riparian ecosystems, land use and management activities are impacting GDEs and may foreshadow responses to changing climate. In the Umatilla National Forest, 45% of surveyed springs are subjected to water withdrawals. In fens, development of peat soils over time depends on stable hydrological conditions. Reduced groundwater can cause cracking of peat soils, peat subsidence, cessation of peat accumulation, and secondary changes in hydrology (Kværner and Snilsberg, 2011), leading to significant changes in plant species composition and ecosystem processes.

5. Management context and applications

Riparian areas and wetlands are protected under the U.S. Clean Water Act, which regulates the use and modification of floodplains and wetlands. Current management objectives for riparian areas in the Blue Mountains are informed by the aquatic strategies PACFISH and INFISH that are jointly implemented by the U.S. Forest Service and Bureau of Land Management (USFS and USDI BLM, 1995). Riparian goals in PACFISH and INFISH are intended to protect native fish and their aquatic habitat and address water quality, stream channel integrity, instream flow, natural timing and variability of water-table elevation, and diversity and productivity of riparian plant communities. Maintenance and restoration of riparian vegetation focus on instream and riparian large wood, thermal regulation (stream shading), and protection from erosion. Riparian management objectives include targets for improvement or maintenance of stream characteristics such as pool frequency, water temperature, instream large wood loads, width:depth ratios, and bank stability, thus providing benchmarks for management actions that can be applied in RHCAs.

Management activities in RHCAs must meet standards and guidelines that limit timber harvest, so timber sales, fuel management, and forest restoration projects are typically excluded from riparian areas, wetlands, and GDEs. A negative outcome of these restrictions may be an increase in fuel loading (Messier et al., 2012) and more uniform forest structure. Therefore, if fuel treatments are being planned for upland forests, inclusion of adjacent riparian areas could potentially reduce overall fire hazard in some treated watersheds (Arkle and Pilliod, 2010; Dwire et al., 2016). RHCA standards and guidelines also require modified grazing practices to attain management objectives. As a result, fencing of riparian, wetlands, and GDEs within grazing allotments has become increasingly common as a means of reducing damage within and adjacent to water sources. Ongoing riparian monitoring efforts provide a consistent approach for assessing riparian conditions and the effects of management practices (Burton et al., 2011; Archer et al., 2012).

Certain goals for stream-riparian restoration could potentially be realized through reintroduction of beaver, which has been suggested as an adaptation action to climate change to improve watershed resilience (or simply allowing beaver to recolonize selected watersheds. The hydrological effects of beaver dams can extend well beyond the pond boundaries, both upstream and downstream within the fluvial corridor, and influence surface and sub-surface runoff, seepage, and storage during both high-and-low-flow periods. Benefits include retention and redistribution of sediment and organic matter, expansion of the extent of flooded soils and maintenance of high water tables, which supports willows and other valued riparian plant taxa, and contributes to the persistence of riparian wetlands.

National forests in the Blue Mountains are in the early stages of identifying and understanding groundwater resources, yet GDEs are regarded as critical components of watershed assessments and planning. As forest management plans are updated to incorporate adaptations to climate change, current strategies may require revisions to redefine desired future conditions of RHCAs, foster additional inventory and protection of GDEs, and refocus management objectives.

6. Conclusions

In the Blue Mountains, past land use and management have significantly impacted aquatic ecosystems and may already be compromising their resilience to the gradual influence of climate change (Kauffman et al., 2004; Magee et al., 2008; McAllister, 2008). The current condition of riparian areas, wetlands, and GDEs differs considerably depending on location and land use history, although most areas at low-mid elevations have consistently been the most altered (McIntosh et al., 1994; Crowe and Clausnitzer, 1997; Table 1). In the Blue Mountains, the largest declines in snowpack are predicted to occur at mid elevations, thus influencing streamflows, groundwater recharge, and soil moisture, and putting additional stress on the most impacted aquatic environments. Documented declines in the areal extent and vigor of cottonwood and aspen communities could foreshadow the future of other riparian community types, particularly those dominated by willows. Those areas that have been heavily impacted by land use are also more vulnerable to flooding and wildfire (Dwire and Kauffman, 2003), whereas less degraded areas may be more resilient to climate-related stressors (Luce et al., 2012).

Including climate change as a consideration in resource management will mostly refine and prioritize, rather than transform, current practices in riparian areas, wetlands, and GDEs (Peterson and Halofsky, 2017). Plant communities adjacent to small springs and narrow, ephemeral streams are expected to be among the first areas affected by altered hydrology as the climate continues to warm, and timely adaptation may be necessary to maintain their functionality. Regardless of the size of these water-associated habitats, their biological diversity is disproportionately high compared to drier habitats, thus meriting high priority for conservation.

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