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OREGON 2100: Projected Climatic and Ecological Changes

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ABSTRACT

Greenhouse climatic warming is underway and exacerbated by human activities. Future outcomes of these processes can be projected using computer models checked against climatic changes during comparable past atmospheric compositions. This study gives concise quantitative predictions for future climate, landscapes, soils, vegetation, and marine and terrestrial animals of Oregon. Fossil fuel burning and other human activities by the year 2100 are projected to yield atmospheric CO_2 levels of about 600-850 ppm (SRES A1B and B1), well above current levels of 400 ppm and preindustrial levels of 280 ppm. Such a greenhouse climate was last recorded in Oregon during the middle Miocene, some 16 million years ago. Oregon's future may be guided by fossil records of the middle Miocene, as well as ongoing studies on the environmental tolerances of Oregon plants and animals, and experiments on the biological effects of global warming. As carbon dioxide levels increase, Oregon's climate will move toward warm temperate, humid in the west and semiarid to subhumid to the east, with increased summer and winter drought in the west. Western Oregon lowlands will become less suitable for temperate fruits and nuts and Pinot Noir grapes, but its hills will remain a productive softwood forest resource. Improved pasture and winter wheat crops will become more widespread in eastern Oregon. Tsunamis and stronger storms will exacerbate marine erosion along the Oregon Coast, with significant damage to coastal properties and cultural resources.

Keywords: *carbon dioxide, greenhouse, Oregon, soil, vegetation, climate, mammals.*

INTRODUCTION

Oregon is central to the Pacific Northwest, and known especially for wilderness and ecological variety (Figs 1-2, Table 1). These aspects of the region are central to the concept of the Pacific Northwest as "Ecotopia" in Callenbach's (1975) utopian novel, and in Garreau's (1982) cultural geography. Oregon has been inhabited by native Americans for more than 14,920 years (Jenkins et al., 2012), but European settlement dates back to 1805, when Lewis and Clark overwintered near modern Astoria (Ambrose, 1997). Oregon's population of 3.9 million and global population of 7.1 billion (USCB, 2013) are now bringing unprecedented environmental challenges.

By the year 2100, global atmospheric CO_2 concentrations are predicted to triple, from pre-industrial levels of 280 ppmv to some 600-850 ppmv, based on fossil fuel emission scenarios SRES A1B and B1 based on business as usual with adaptive technologies and population peaking at 9 billion by 2050 (Table 2: Stocker et al., 2013; Jones, 2013). Such amounts of atmospheric CO_2 are unknown in the past two million years (Lüthi et al., 2008; Gavin et al., 2013a), but can be matched with estimates of CO_2 over the past 40 million years (Fig. 3). Among these past estimates of CO_2 are two comparable with scenarios for 2100, and both are 16.5 million years old (middle Miocene) in nearby Idaho: 852 ± 86 ppm from carbon isotopic composition of fossil soils (paleosols in the paleomagnetically dated Renova Formation; Retallack, 2009) and 612 ± 24 ppm from stomatal index of fossil *Ginkgo* leaves (in interbeds to $^{40}Ar/^{39}Ar$ dated Grande Ronde Basalt; Barry et al., 2010; Retallack and Rember, 2011). These middle Miocene estimates are comparable with those derived from foraminiferal boron isotopes, and ocean carbonate compensation depth (Royer et al., 2012; Pälike et al., 2012; Zhang et al., 2013). The marine alkenone carbon dioxide paleobarometer has been anomalously low compared with other proxies, but now has been revised to include middle Miocene CO_2 estimates of 560-410 ppm (Zhang et al., 2013). Thus Oregon's rich fossil record of middle Miocene soils, plants and animals (Orr and Orr, 2009) can illuminate the kind of climate expected within the state by the turn of this century.

Miocene Oregon was topographically similar to modern Oregon. The Oregon Coast Range had docked by 50 million years ago and early Miocene hill ranges of 20 million years ago restricted marine incursions to the present coastal strip (Orr and Orr, 2012). Cascades volcanoes have been active for 30 million years (Oligocene), as indicated by dated lavas of every age since (McBirney et al., 1974; Mertzman, 2000). A continuous eastern Oregon rain shadow since then is apparent from the appearance and persistence of calcareous paleosols in eastern Oregon (Retallack 2004, 2008). Extensional faulting in eastern Oregon filled in by voluminous flood basalts of 18 -11 Ma are notable tectonic events that maintained topographic diversity (McBirney et al., 1974; Kohn and Fremd, 2008). A computer simulation model (ECHAM5) demonstrated that middle Miocene differences in paleogeography from modern account for only a 0.7°C (1.2°F) warmer paleoclimate, and elevated CO_2 is needed for a significantly warmer (2.8-4.9°C or 5.0-8.8°F) paleoclimate (Krapp and Jungclaus, 2011). Thus Miocene paleogeographical differences have a negligible effect on computer models of global climate.

Ancient paleoclimatic records allow informed choice

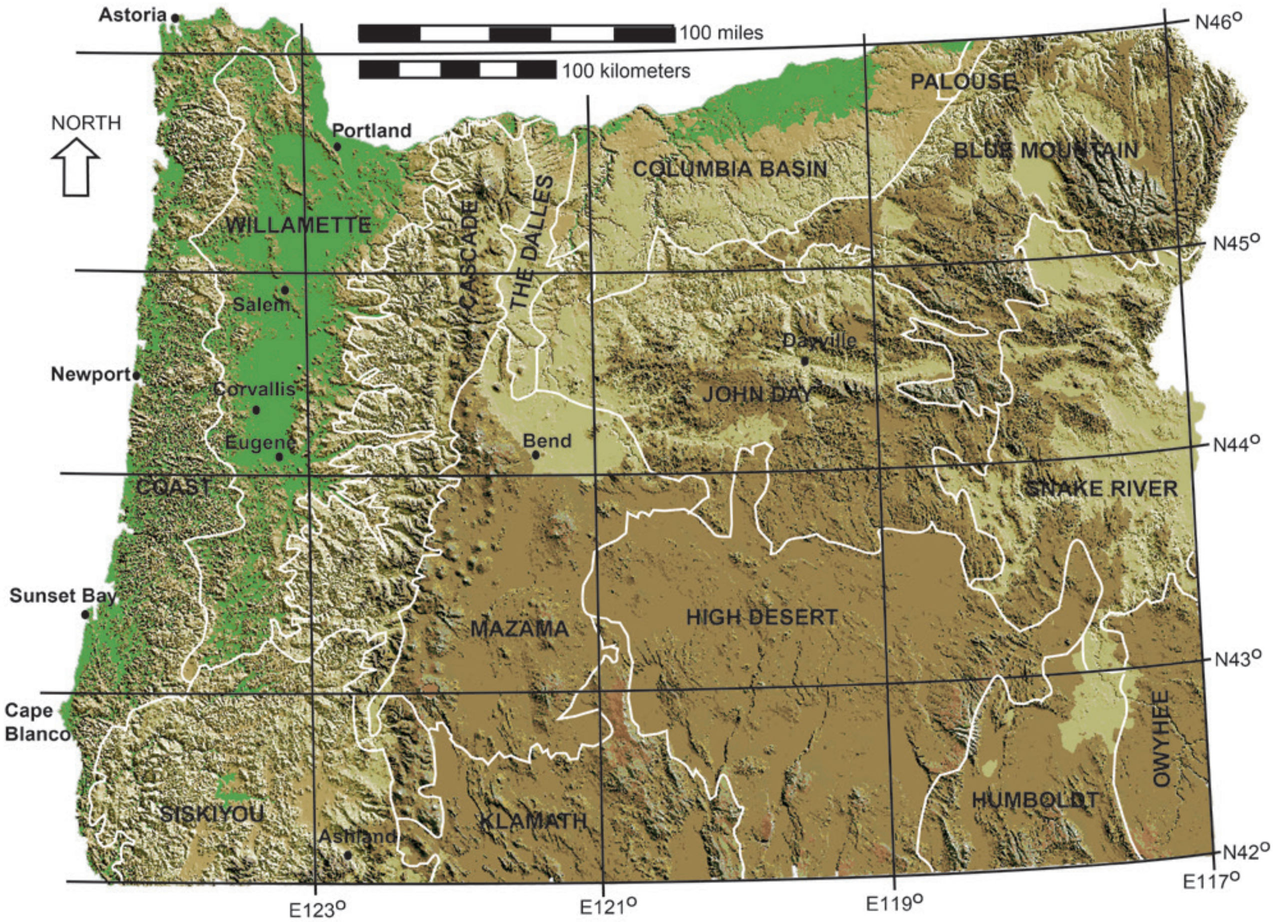

Figure 1. *Ecological provinces and mentioned localities in Oregon (after Loy et al., 2001; Thorson et al., 2003).*

of alternative climate models for Oregon's future (Fig. 4). There are now 45 global climate models listed by Stocker et al. (2013), and although they show impressive agreement, some method of selecting among them is needed. A common method is to average them, and this is the basis of predictions for individual counties of the United States (average of 33 models of the Coupled Model Intercomparison Project, CIMP5, of Puckett, 2013) and of an Oregon assessment (20 models of Mote and Salathé, 2010). An alternative approach for Oregon has been to show variance in three of the most current models (Hadley, CSIRO and MIROC of Bachelet et al., 2011). Here a third approach is taken to select models that best approximate current and past climate records, as advocated by Stocker et al. (2013). The model chosen as most likely for Oregon here is the one that best approximates vegetation and climate for that time in the past with CO_2 levels similar to those predicted for the year 2100, which appears to be the middle Miocene (Fig. 3).

Other aspects of future change in Oregon can also be addressed from the fossil record. Paleoclimatic records of the past 125,000 years place future climate change within a perspective of long term astronomical forcings by changes in Earth-orbital characteristics (Worona and Whitlock, 1995; Whitlock and Bartlein, 1997), as well as variation from glacial CO_2 levels of 180 ppm to interglacial levels of 280 ppm CO_2 (Lüthi et al., 2008). Comparable Milankovitch-paced variation in paleoclimate is clear from Oligocene and Miocene paleosol records in Oregon back as far as 30 million years old (Retallack et al., 2004; Bestland et al., 2008; Retallack, 2009). Earth's climate has already warmed beyond the envelope of variation tracking astronomical cycles of tens to hundreds of thousands of years and will duplicate conditions like those of many millions of years ago within this century (Stocker et al., 2013).

Groundwater observations in Oregon's Miocene paleosols (Bestland et al., 2008) give indications of regional and seasonal changes in water resources relevant to the future (Tague et al., 2008). Oregon's vegetation during the middle Miocene was very different from that of today (Chaney and Axelrod, 1959) and provides a perspective on the necessary ecological transformation to come, and which of the coming onslaught of biological invasions to allow (Boersma et al., 2006).

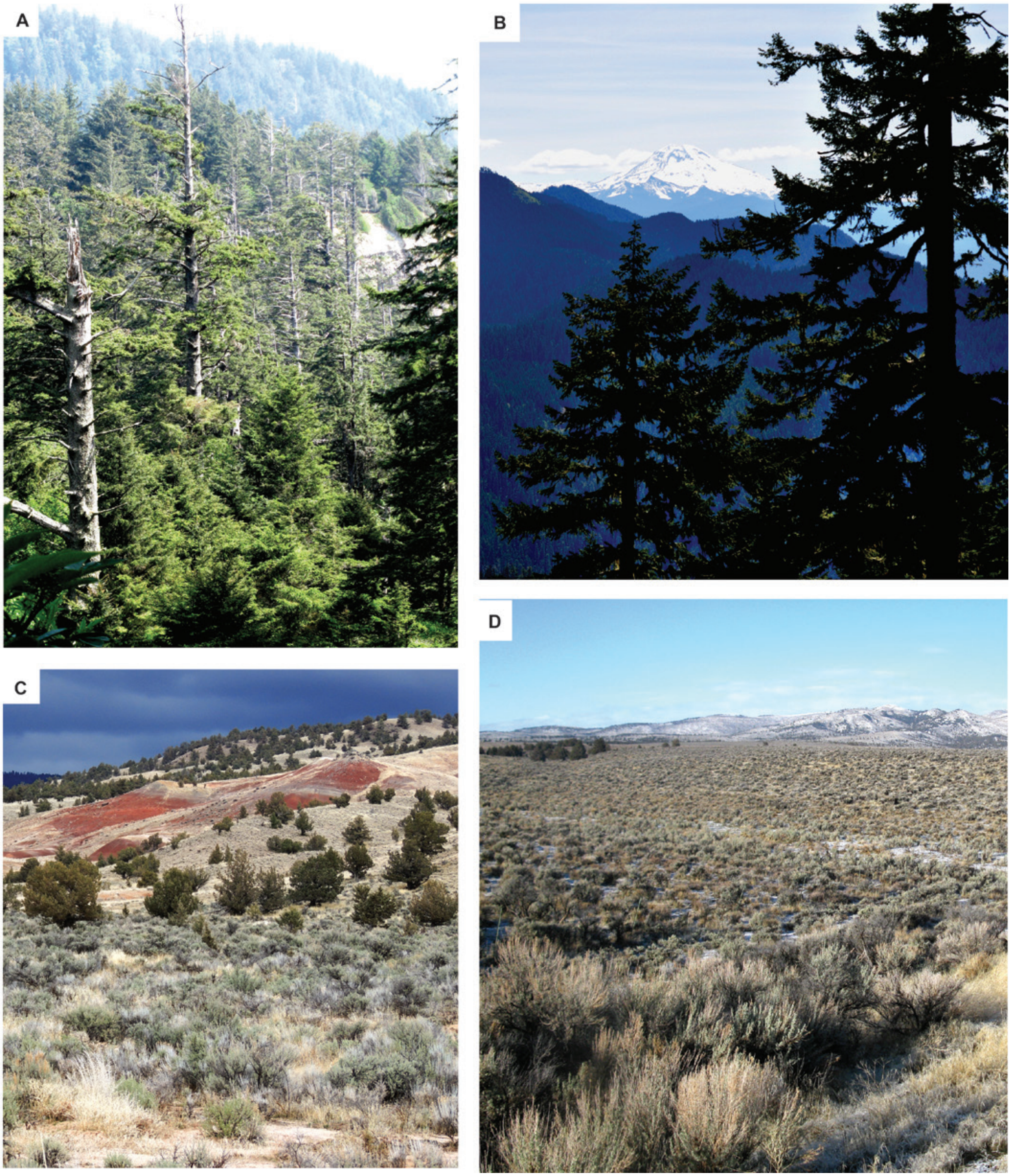

Figure 2 (left). *Modern vegetation of Oregon: A, coastal vegetation of Sitka spruce (*Picea sitchensis*) north of Cannon Beach: B, forest of Douglas fir (*Pseudotsuga douglasii*) from above Blue River looking toward South Sister: C, western juniper (*Juniperus occidentalis*) near Paulina: D, desert shrubland of sagebrush (*Artemisia tridentata*) near Glass Butte.*

TABLE 1. ECOLOGICAL PROVINCES OF OREGON

Province	Geology	Zonal Soils	Climate	Vegetation	Mammals
Blue Mountains	Permian Clover Creek and Burnt Creek Greenstones, Cretaceous Wallowa Granite, and Cenozoic Clarno, John Day and Mascall Formations	Xeralf, Alboll, Xeroll, Vitrand, Xerert Argid, Calcid,	mean January minimum −9.4°C (15.1°F), mean spring maximum 21.2°C (70.2°F), mean annual precipitation 569 mm (22.5 inches) with 54% in winter	juniper woodland, ponderosa pine forest, with local alpine vegetation	bison, mountain goat, bighorn sheep, elk, gray wolf, cougar, black bear
Cascades	Basaltic and andesitic PlioPleistocene High Cascades Volcanics	Boroll, Vitrand, Xeralf, Orthod	mean January minimum −5.8°C (21.6°F), mean spring maximum 19.9°C (58.0°F), mean annual precipitation 1842 mm (84.5 inches) with 70% in winter	Douglas fir forest, with alpine vegetation	mule deer, mountain beaver, black bear, cougar
Coast Range	Eocene Yachats, Tillamook and Goble Volcanics, and Tyee Formation	Udoll, Aquult, Humult, Udult, Xerult, Aquod	mean January minimum 1.9°C (35.4°F), mean spring maximum 15.2°C (59.4°F), mean annual precipitation 1936 mm (76.2 inches) with 55% in winter	Sitka spruce forest with salt marsh	mule deer, elk, mountain beaver, black bear
Columbia Plateau	Miocene Columbia River Basalt, and Plio-Pleistocene Palouse Silt	Xeroll, Calcid	mean January minimum −5.1°C (24.2°F), mean spring maximum 19.0°C (71.3°F), mean annual precipitation 310 mm (9.0 inches) with 62% in winter	Grassland	mule deer, coyote
Northern Basin and Range	basaltic Mio-Pliocene High Lava Plains volcanics Miocene Owhyee and Steens Basalt and Trout Creek Formation	Aquept, Aquoll, Xerert, Argid, Calcid	mean January minimum −9.5°C (12.2°F), mean spring maximum 19.8°C (68.0°F), mean annual precipitation 257 mm (10.0 inches) with 68% in winter	sagebrush	bighorn sheep, bison, pronghorn, mule deer, coyote
Eastern Cascades Slopes and Foothills	Pliocene Deschutes Formation, Early Holocene Mazama pumiceous tuffs	Xeroll, Vitrand, Calcid, Xeralf	mean January minimum −9.4°C (15.0°F), mean spring maximum 19.6°C (67.3°F), mean annual precipitation 678 mm (26.7 inches) with 72% in winter	juniper woodland, ponderosa pine forest	mule deer, coyote
Klamath Mountains	Cretaceous Ashland and Merlin Granite and Paleozoic schists and serpentinites	Xeroll, Xerult, Udalf, Xeralf, Xerert	mean January minimum −0.2°C (31.7°F), mean spring maximum 18.0°C (64.4°F), mean annual precipitation 1146 mm (45.1 inches) with 57% in winter	ponderosa pine forest, with alpine vegetation	mule deer, bison, gray wolf, cougar, black bear,
Snake River Plain	Plio-Pleistocene Idaho Group	Xeroll, Argid, Natrid, Xeralf	mean January minimum −8.9°C (16.0°F), mean spring maximum 21.8°C (71.3°F), mean annual precipitation 251 mm (9.9 inches) with 55% in winter	ponderosa pine forest and grassland	coyote
Willamette Valley	Eocene volcaniclastic Eugene Formation and Pleistocene Willamette Formation	Alboll, Aquoll, Xeroll, Humult, Udult, Aqualf, Xeralf, Xerert	mean January minimum −0.9°C (30.3°F), mean spring maximum 16.3°C (61.4°F), mean annual precipitation 1280 mm (50.4 inches) with 56% in winter	oak wooded grassland and ash swamp	mule deer, gray wolf, black bear

Note: from Huddleston (1979), Anderson et al. (1998), Verts and Carraway (1998), Loy et al., (2001) and Thorson et al. (2003).

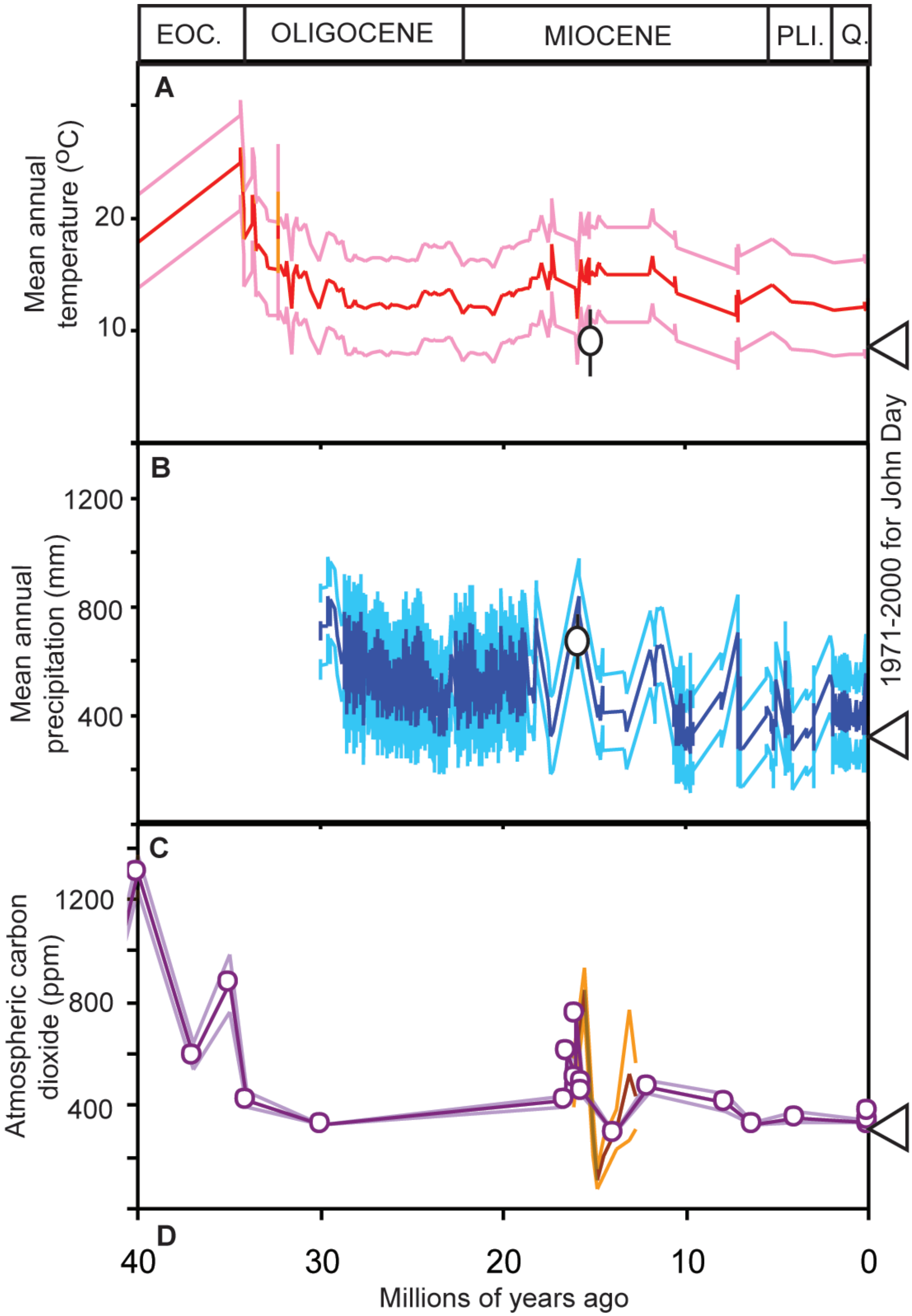

Figure 3. *Paleoclimatic records from paleosols (red, blue and orange lines) and paleobotany (open symbols and purple lines of C) in eastern Oregon for the past 40 million years: A, mean annual temperature: B, mean annual precipitation: C, atmospheric carbon dioxide levels (error envelopes are standard error: from Retallack, 2009, 2013a; Retallack and Rember, 2011; Gallagher and Sheldon, 2013). Arrows to right are historic (1971-2000) values for John Day, Oregon.*

TABLE 2. HUMAN CO2 EMISSION SCENARIOS USED FOR FUTURE CLIMATE MODELING

IPCC Label	Description of emission scenario	CO_2 predicted by 2100	Global rise in temperature 1999-2099	Sea level rise (m) 1999-2099
SRES A1B (<RCP 6.0, >RCP4.5)	Rapid economic growth, global population peaks mid-century (9 billion in 2050), rapid introduction of new and more efficient technologies: balance across all energy sources	~850 ppm	2.8 (1.7-4.4) °C 5.0(3.1-7.9) °F	0.21-0.48
SRES B1 (≈RCP 4.5)	Global environmental sustainability, global population peaks mid-century (9 billion in 2050), service and information economy, introduction of clean and resource-efficient technologies	~600 ppm	1.8(1.1-2.9) °C 3.2(1.9-5.2) °F	0.18-0.38
SRES A2 (≈RCP 8.5)	Regionally oriented economic development, continuously increasing population (15 billion people in 2100), slow technological change	~1250 ppm	3.4(2.0-5.4) °C 6.1(3.6-9.7) °F	0.23-0.51

Note: froms Bachelet et al., (2011), with old (RSES) and new (RCP) scenarios of International Panel on Climate Change (IPCC)) from Stocker et al. (2013).

This review summarizes a large amount of climate change research to provide a concise narrative and guide to published work on changes to the natural environment expected in Oregon due to ongoing greenhouse warming. Political and social changes of the future are not a part of this review, though they are clearly of relevance for projecting future greenhouse gas emissions and a variety of mitigation scenarios.

CLIMATE

Oregon during the twentieth century had a cold temperate climate, humid in the west and semiarid in the east, although quite varied for each ecological province (Table 1). Most climatic computer models agree that higher atmospheric CO_2 will result in a wetter and warmer climate for Oregon (Fig. 4: Mote and Salathé, 2010; Bachelet et al., 2011), as for many parts of the world (Stocker et al., 2013). How much warmer and wetter can be informed by proxy evidence for Oregon's paleoclimate of 16 million years ago (middle Miocene) which was the most recent time when atmospheric CO_2 reached levels like those anticipated by 2100 (Table 2). For example, middle Miocene (15.7 million years old by $^{40}Ar/^{39}Ar$ technique) bauxitic paleosols like those formed in the Salem Hills (Fig. 5A; Martin et al., 2013; Liu et al., 2013) now require mean annual temperatures of at least 17°C (63°F) and mean annual precipitation of at least 1100 mm (43.3 inches; Retallack, 2010). Comparable paleoclimatic estimates come from leaf shape analysis of a middle Miocene (13.1 million years old by 40Ar/39Ar technique) fossil flora from nearby Molalla: mean annual temperature 14.0 ± 1.7°C (57.2 ± 3.1°F) and mean annual precipitation 1871 ± 32 mm (73.7 ± 1.3 inches; Wolfe et al., 1997; Yang et al., 2011). Both paleosol and paleobotanical estimates are warmer, wetter and more seasonal than current means for the Willamette Valley (Table 1). More specifically for Salem, close to both bauxitic paleosols and Molalla fossil plants, climate from 1971-2000 had mean annual temperature of 11.4°C (52.6°F) and mean annual precipitation of 1016 mm (40 inches), and difference between lowest monthly summer mean precipitation and highest winter mean of 150 mm (5.9 inches: NOAA, 2002). The difference between this past and projected climate inferred from middle Miocene paleosols for the central Willamette Valley is a warming of 5.6°C (10.1°F), and precipitation increase of 84 mm (3.4 inches).

In central Oregon, intrabasaltic greenhouse paleosols of 16.3 million years ago in the John Day Fossil Beds National Monument of central Oregon (Fig. 5B) have been dated by the K-Ar method on basalt (Sheldon, 2003; Bestland et al., 2008). These distinctive red Alfisol profiles show chemical weathering comparable with modern soils formed under mean annual temperature of 13.9 ± 2.1 °C (57.0 ± 3.8 °F; Gallagher and Sheldon, 2013) and mean annual precipitation of 750 ± 180 mm (29.5 ± 7.1 inches; Sheldon, 2003; Retallack, 2008). The nearby Mascall fossil flora (Fig. 6) of a diatomaceous lake dated to 15.8 million years old (by $^{40}Ar/^{39}Ar$ technique; Tedford et al. 2004), has leaf shapes indicative of mean annual temperature 8.7 ± 1.7 °C (47.6 ± 3.1 °F), and mean annual precipitation 621 ± 32 mm (24.4 ± 1.3 inches; Yang et al., 2011). From 1971 to 2000 nearby John Day experienced mean annual temperature of 9.3°C (48.4°F), and mean annual precipitation of 344 mm (13.5 inches; NOAA, 2002). The difference between the historic and paleosol-

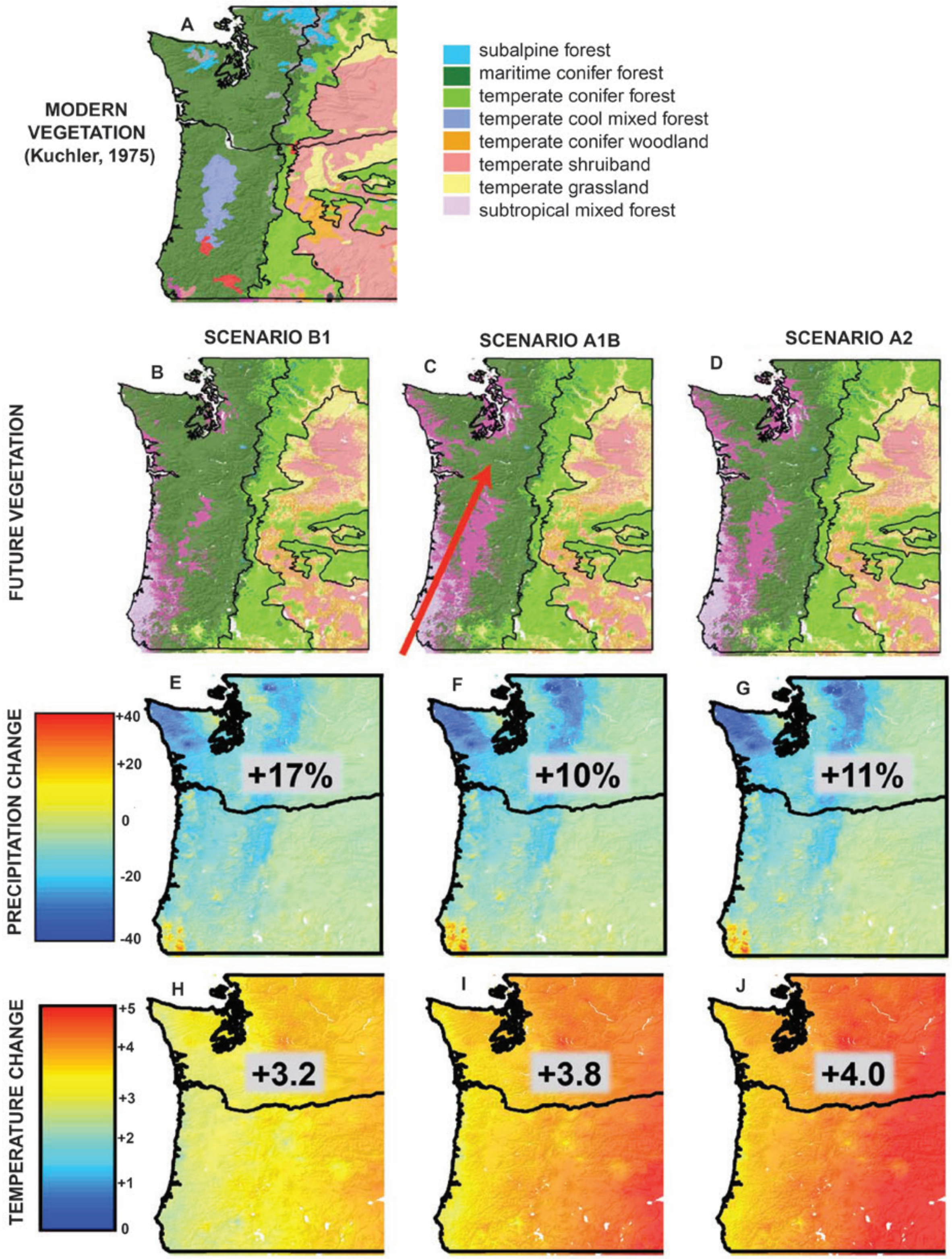

Figure 4. *Late twentieth century vegetation (A) and projected changes by 2100 in vegetation using computer model MC1 (B-D) and climate using computer model MIROC (E-J), mean monthly precipitation (mm;E-G), and maximum monthly temperature (°C; H-J) under three different emission scenarios (Table 2). Black lines in panels A-D are 1000 and 1400 m contours (3281 and 4593 feet). This figure is modified from other choices presented by Bachelet et al. (2011).*

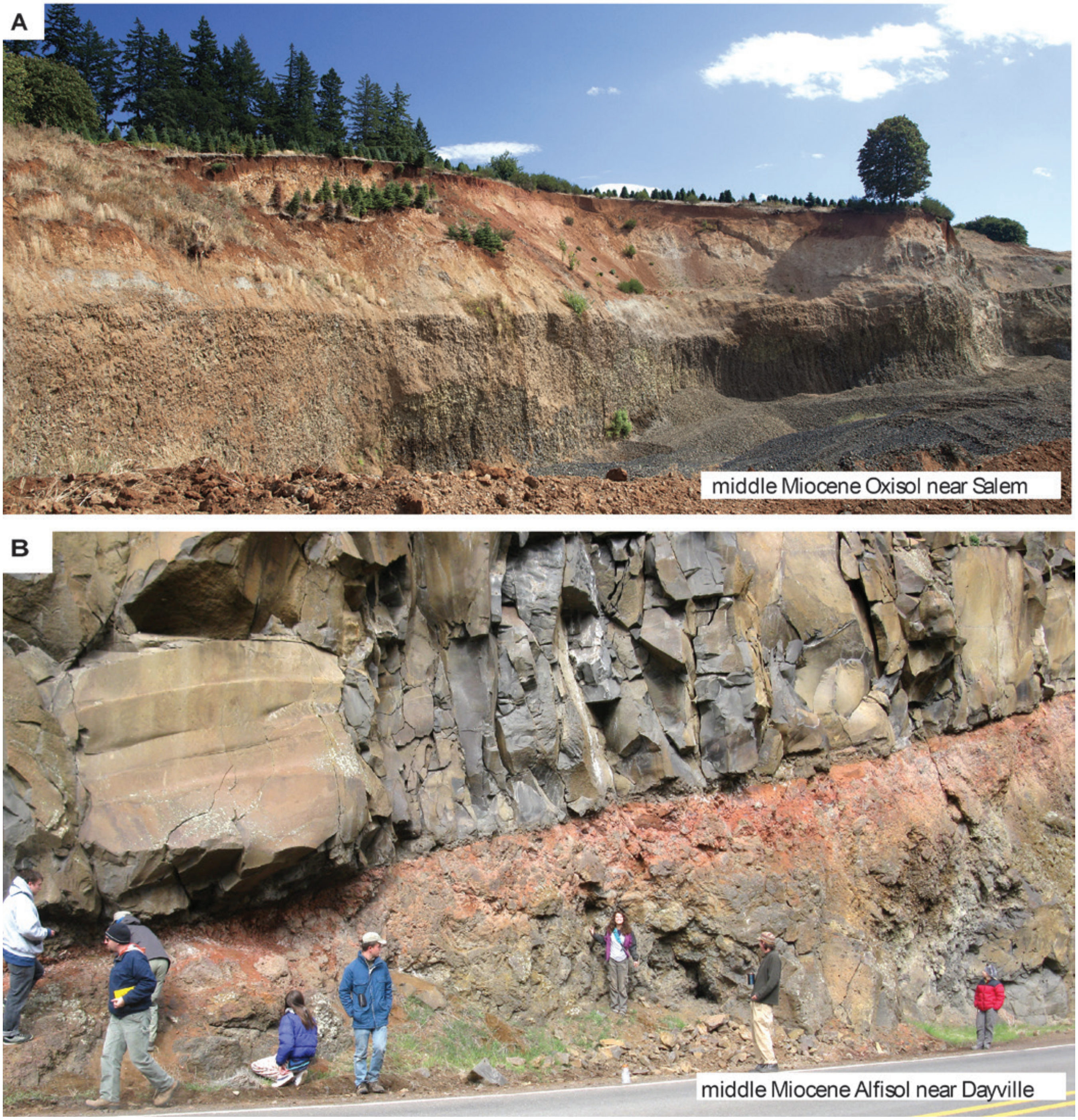

Figure 5. *Middle Miocene fossil soils (paleosols) of paleoclimates warmer and wetter than today: A, bauxitic Oxisol within Columbia River Basalt in PDP Quarry, south of Enchanted Forest, near Salem (photo by Marli Miller, used with permission): B, Alfisol within Columbia River Basalt in Picture Gorge. The Oxisol is 10 m thick, and although exhumed here, is overlain by the basalt of Silver Falls in the hills behind (Liu et al., 2013).*

projected climate for the central Blue Mountains is a warming of 6.7°C (10.2°F), and precipitation increase of 416 mm (16.4 inches).

Comparable changes of climate in the Pacific Northwest are projected by climate models (Fig. 4), although some models predict only 1-2% enhancement in precipitation (Mote and Salathé, 2010). Three emission scenarios are shown here (Fig. 4; Table 2), because this is the most unpredictable component of future projections. Emission scenario A1B is a middle path between emission scenario A2, which is more or less business as usual, and the B1 scenario, which may be unreasonably optimistic about green technological advances. Emission scenario A1B with the MIROC 3.2 medium resolution model (middle column of Fig. 4) and MC1 vegetation model is most like both the amount of CO_2 in the atmosphere, as well as the rise in temperature and precipitation seen in the middle Miocene. This validates the independent MIROC atmospheric and MC1 vegetation models with a time in the past when they acted as predicted. Other models do not match experience with observed past CO_2, climate, and vegetation. This combination of A1B emission scenario and MIROC and MC1 models predicts warming of 4.2°C (7.6°F) and precipitation increases of 60 mm/yr (2.4 inches/yr) for the Willamette Valley, but 4.8°C (8.6°F) and 216 mm/yr (8.5 inches/yr) for the central Blue Mountains (Bachelet et al., 2011), within error envelopes for Miocene paleosol-based estimates given above. The computer model extends results to show less warming in the Coast Range and Cascades, and much greater increases in precipitation in the southwestern Klamath Mountains (Fig. 4). Other computer models applied to the Pacific Northwest by Bachelet et al. (2011) give lower temperature increase but much higher rainfall (CSIRO model), and comparable temperature but reduced precipitation (Hadley model). Computer models of climate change have made enormous strides in resolution within the past decade (Jones, 2013), and local application to the Pacific Northwest is updated by two active research groups with informative web sites (CIG, 2013; MAPSS, 2013).

GROUNDWATER

Increased rainfall and high groundwater overall predicted by computer models for Oregon's future (Fig. 4) are supported by evidence in middle Miocene rocks for extensive lacustrine diatomaceous shales and poorly drained paleosols (Bestland et al., 2008; Liu et al., 2013). A lack of evidence for middle Miocene glaciation is compatible with computer models showing that Oregon's few remaining glaciers will be gone and snowpack greatly diminished by 2100 (Moore et al., 2009). This will greatly reduce water supply of the McKenzie River which currently dominates fresh water into the Willamette Valley through springs and snowmelt from the High Cascades (Tague et al., 2008; Sproles et al., 2013). All parts of Oregon will have more water than currently from heavy fall and late spring rains, but the McKenzie River will join other Oregon Rivers in having a late summer low stage in which water temperatures may be dangerous for salmon and other fish (Mote et al., 2003). Peak flow, when dams currently store water, will come earlier in the year, more toward April rather than July, and this will require storage adjustments to meet late summer demands (Chang and Jung, 2010). Water demand for irrigation in eastern Oregon will be offset by widespread increased rainfall (Fig. 4E-G), that will leach soil salts resulting in fewer harmful crystals in the soil. Some irrigation districts may no longer be necessary, but others will be threatened by increased evaporation and soil salinity (Coakley et al., 2010).

SOILS

Middle Miocene greenhouse spike soils of Oregon show stunning differences from modern soils. Ultisols are the most deeply weathered soils now forming in western Oregon (Huddleston, 1979; Lindeburg et al., 2013), including the Jory clay loam important to Oregon vineyards (Schreiner, 2005), and now the official state soil of Oregon (Oregon State Legislature, 2011). Oxisols are deeply weathered tropical soils not currently forming in the conterminous United States, yet they formed on basalt of the Ginkgo flow dated as 15.7 million years old by $^{40}Ar/^{39}Ar$ technique (Fig. 5A; Retallack, 2010; Liu et al., 2013; Martin et al., 2013). Oregon intrabasaltic Oxisols extending from Salem north to Vancouver, Washington, are weathered to aluminum ore (bauxite) to depths of 18 m, with additional weathering to 49 m (Allen, 1948; Liu et al., 2013). In eastern Oregon, Columbia River basalts and overlying tuffs dated at 16.3 to 15.8 million years old by K-Ar and $^{40}Ar/^{39}Ar$ techniques include fossil Alfisols, Mollisols and Histosols (Fig. 5B: Sheldon, 2003, 2006; Tedford et al., 2004; Bestland et al., 2008). These paleosols contrast with Aridisols dominant in the John Day region today (Huddleston, 1979; Doescher et al., 1984). Middle Miocene range extensions of deeply weathered soils in both eastern and western Oregon explain the rapid drawdown of the greenhouse spike of 16 million years ago (Sheldon and Tabor, 2013), as carbon from atmospheric carbon dioxide was reallocated by weathering to bicarbonate in groundwater and organic matter of plants (Retallack, 2010). Comparable facilitation of deep weathering with deep rooted and fast growing plants will be important for mitigating future greenhouse CO_2 levels (Kiely, 2010).

Oxisol, Alfisol and Histosol paleosols of the middle Miocene (Fig. 5) formed during some 100,000 years between eruption of lava flows (Sheldon, 2003, 2006;

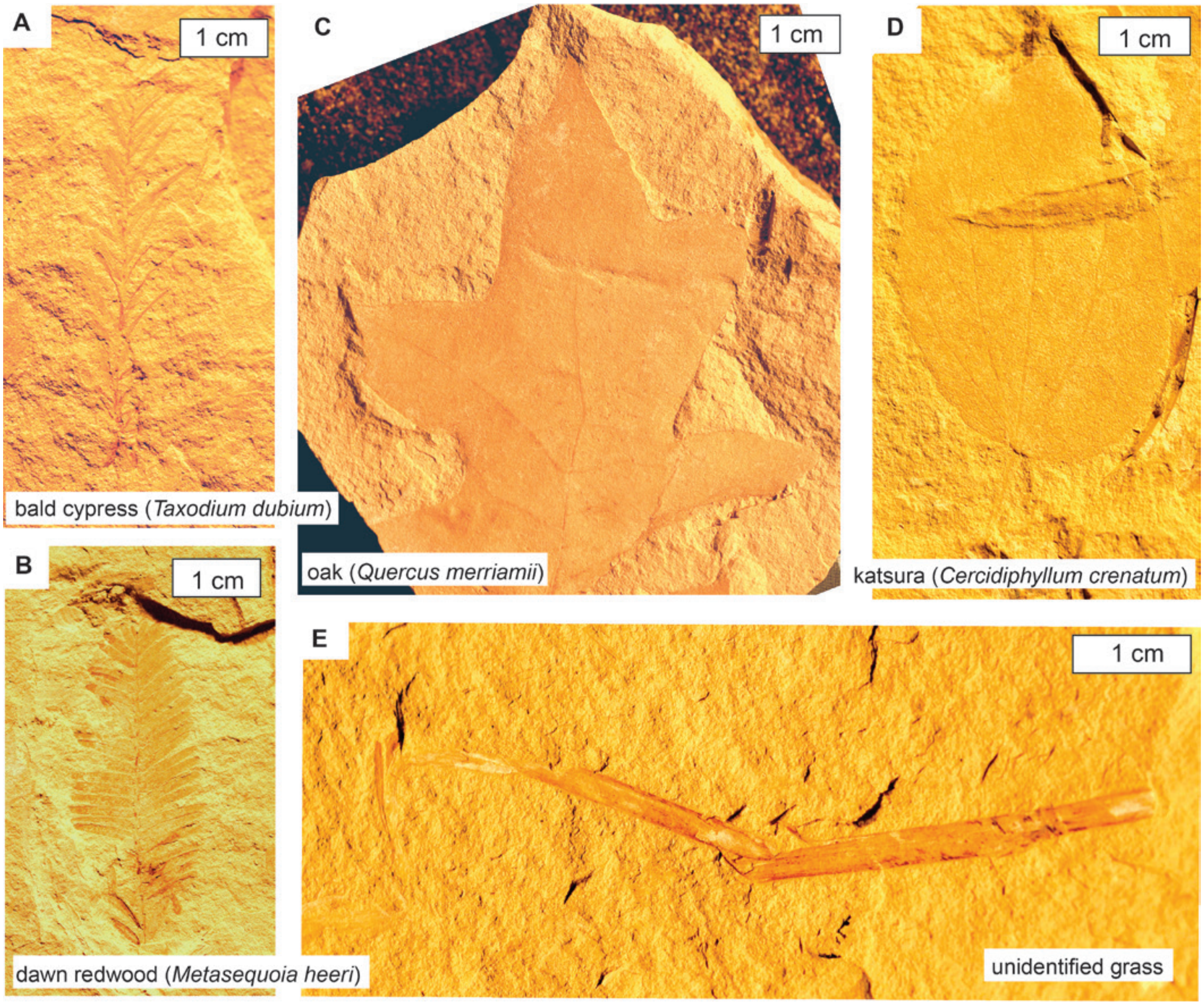

Figure 6. *Middle Miocene (15.8 million year old) fossil plants of the Mascall Formation from a paleoclimate warmer and wetter than currently near Dayville: A-B, swamp cypresses; C-D deciduous angiosperms: E unidentified grass fragments. Specimens in Condon Collection Museum of Natural and Cultural History are F-117186 (A), F-117185 (B), F-117183 (C), F-117006B (D), F-111408A (E).*

Liu et al., 2013), but rates of soil formation are too slow to allow development to the same extent between now and 2100 (Retallack, 2001). The paleosols represent an increased rate and depth of humid-warm weathering compared with the present, and these weathering rate changes will precede full development of soils with a degree of chemical weathering adjusted to the new climate. Such soils will provide uniquely higher soil mineral fertility, productivity and perhaps decomposition, compared with soils adjusted over thousands of years to comparable climatic belts, as revealed by heating and elevated CO_2 experiments (Pendall et al., 2004).

The effectiveness of soils for food production and carbon sequestration will also be interrupted by rare and catastrophic resurfacing events to produce soils lacking humus and supportive microbial communities. For example, a large magnitude (Richter scale 9) earthquake on the subduction zone fault, expected within the next century, will level much construction on insecure foundations in western Oregon, and also destroy coastal infrastructure with a devastating tsunami spreading marine sand inland (Kelsey et al., 2005). Storm and tsunami damage will also destroy middens and other archeological sites along the Oregon coast, with consequent loss of information on early human adaptations to Oregon (Erlandson, 2012). Loss of Oregon coastal land due to anticipated sea level rise is to some extent offset by ongoing tectonic uplift of the Coast Range. For example, long term uplift rate at

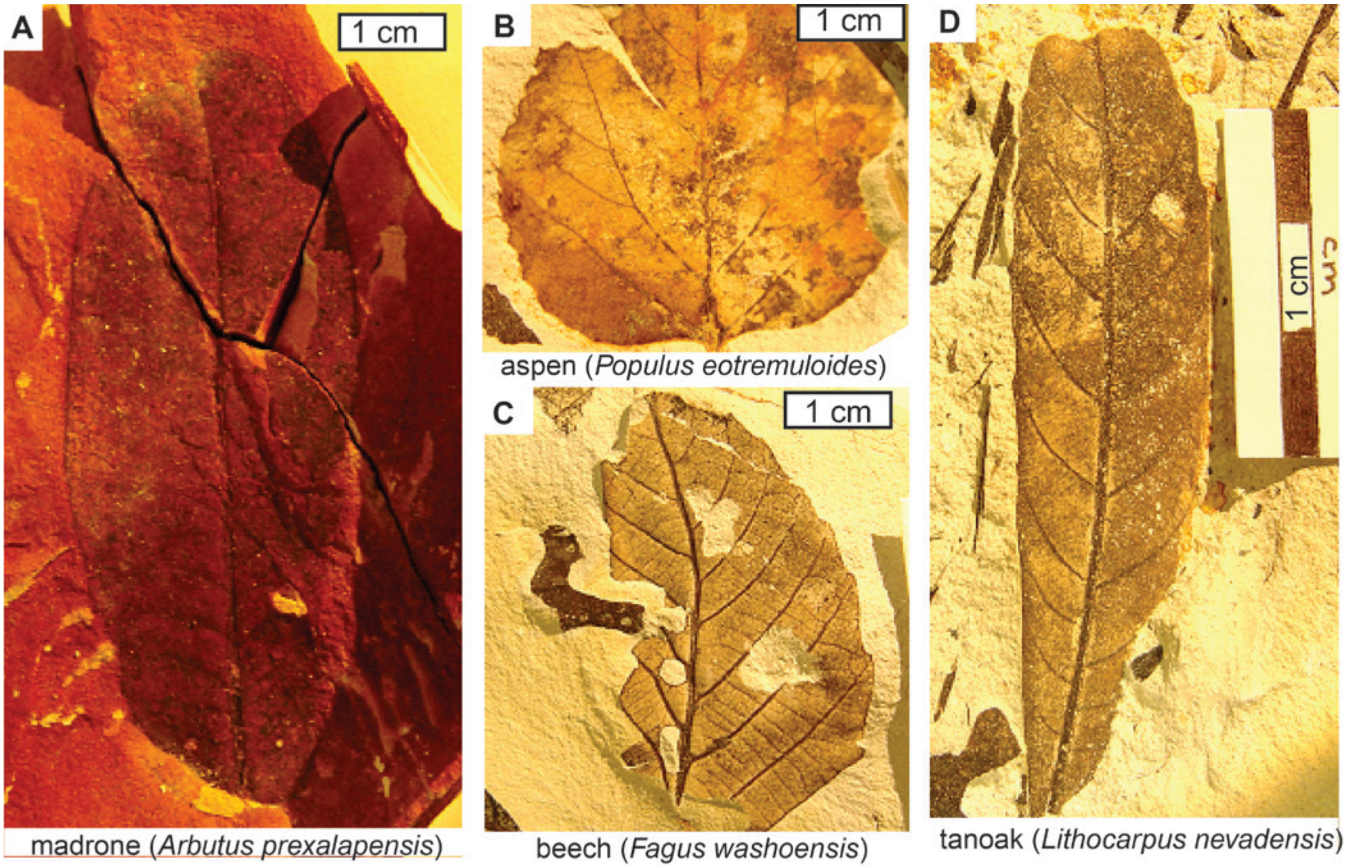

Figure 7. *Early Miocene (18.2 million year old) fossil plants of the sandstone of Floras Lake from a paleoclimate more like that of northern California than currently near Cape Blanco. Specimens in Condon Collection Museum of Natural and Cultural History are F-115014B (A), F-38119A (B), F-42078 (C), F-42088 (D) (photo credits: L. F. Emerson).*

Sunset Bay, Oregon, was 0.007 inches/year (0.17 mm/yr: Retallack and Roering, 2012), comparable with Oregon long-term coastal stream incision rates of 0.08 inches/yr (0.2 mm/yr: Personius, 1995). Since the last great earthquake some 314 years ago, geodetic uplift has been 0.13 inches/yr (3.4 mm/yr) for the area around Coos Bay, and this rate exceeds current location-specific sea level rise of 0.09 inches/yr (2.3 ± 0.2 mm/yr: Burgette et al., 2009). However this long term uplift was undone within a few hours by as much as three feet (one meter) of coastal subsidence around Sunset Bay during the large subduction zone earthquake of AD 1700, although this subsidence declined rapidly inland (Leonard et al., 2004). Another earthquake of this magnitude together with predicted sea level rise by 2100 of 8-55 inches (20-140 cm: Rahmsdorf, 2007, 2010) will take more than the next century for long-term tectonic uplift to compensate.

Eruptions of Mt Hood and South Sister could provide local soil resurfacing crises on the scale of the 1980 eruption of Mt St Helens (Lipman and Mullineaux, 1981). Much of the Eastern Cascades, Basin and Range, and Blue Mountains ecological provinces of central Oregon (Fig. 1) have thick pumiceous soils (Anderson et al., 1998) from the cataclysmic eruption that formed Crater Lake some 7,700 years ago (by radiocarbon dating; Klug et al., 2002). From a soil perspective, ash blankets and tsunamis are like mine spoils, because they create nutrient-rich and potentially toxic, but biologically depleted soils which take as many as 30 years of microbial and humus accumulation for productive recovery in humid temperate climates (Frouz and Nováková, 2005). Volcanic and seismic resurfacing events will interrupt food production and reduce potential carbon sequestration in soils and ecosystems.

VEGETATION

With changing local climate and soils, Oregon's plant communities will move as existing plants die and new ones sprout in more favorable ends of their climatic zones. This will not be a rapid process judging from observations of vegetation adjustment to climatic warming during the transition from glacial to modern conditions some 11,000 years ago in the Olympic Mountains of Washington. Pollen revealed regional changes from mountain hemlock (*Tsuga mertensiana*) to Douglas fir (*Pseudotsuga menziesii*) a century before this transition was recorded in the same core by locally derived megafossil needles. The local transition was effected by fire, and ecosystem inertia appears to have delayed local vegetation response by as much as a century (Gavin et al., 2013a). Comparable delayed response to climatic warming 11,000 years ago is also likely for arrival of Douglas fir in the Oregon Coast Range (Long et al., 2007).

Existing wilderness areas will be vital as refuges and pathways for future plant migrations. Oregon's modern vegetation is characterized by conifers such as Sitka spruce (*Picea sitchensis*: Fig. 2A) on the Coast Range, Douglas fir (*Pseudotsuga menziesii*: Fig. 2B) in the lower Cascade Range, and ponderosa pine (*Pinus ponderosa*) forests in uplands of eastern Oregon. These conifer forests contrast with oak (*Quercus garryana*) savanna in the Willamette Valley and juniper (*Juniperus occidentalis*: Fig. 2C) and sagebrush (*Artemisia tridentata*) desert in eastern Oregon (Fig 2D: Küchler, 1975; Loy et al., 2001). These biomes have been stable, like Oregon's climate, for the past 6000 years (Worona and Whitlock, 1995; Blinnikov et al., 2002; Long et al., 2007).

In contrast, vegetation revealed by the 15.8 million year old Mascall Formation of eastern Oregon (dated by $^{40}Ar/^{39}Ar$ technique: Tedford et al. 2004), included humid deciduous broadleaf forests with oak, sweet gum, and swamp cypresses (Fig. 6), like forests of historic Tennessee (Chaney and Axelrod, 1959). There is also evidence from fossil mammals and soils in the Mascall Formation for extensive open grassland in eastern Oregon during the middle Miocene (Bestland et al., 2008). In western Oregon, immediately below Grande Ronde Basalts dated by $^{40}Ar/^{39}Ar$ technique at 16.3 million years old (Barry et al., 2010), early-middle Miocene humid deciduous broadleaf forests and swamp cypresses are represented by the Eagle Creek flora in what is now the Columbia River Gorge (Chaney, 1918). The lower Astoria Formation of the central Oregon Coast, dated magnetostratigraphically at 16.6 million years old (Prothero et al. 2001), has yielded fossil cones of an extinct pine (*Pinus berglundii*) like California's knobcone (*Pinus attenuata*) and Bishop pines (*Pinus muricata*: Miller, 1992). Cape Blanco on the southern Oregon Coast exposes a volcanic tuff dated at 18.2 million years old using the $^{40}Ar/^{39}Ar$ technique, and containing a fossil flora most like that of the northern Central Valley of California (Fig. 7; Emerson, 2009). These various fossil plant collections fall on the three warm spikes of the local paleosol-based paleoclimatic curve (Fig. 3). As guide for the future, only these general kinds of vegetation will return to Oregon, not the same Miocene genera and species, because Oregon's warmer climate will recruit mainly garden, greenhouse, and invasive species already here, or close at hand (Boersma et al., 2006).

Miocene-like maps of vegetation for the year 2100 emerge from global circulation model MIROC with an

Figure 8. *Formerly endangered but now recovering birds (A,B,) and sea lion (C): ; (A) marbled murrelet (*Brachyramphus marmoratus, *2006 photo from U.S. Fish and Wildlife); (B) tufted puffin (*Fratercula cirrhata*), (C) Steller sea lion (*Eumetopias jubatus*).*

emission scenario such as A1B and a vegetation model such as MC1 (Bachelet et al., 2011). This shows Miocene-like spread of subtropical mixed forest in southeastern coastal Oregon and throughout the Willamette-Puget lowlands, as well as a mid-elevation zone of grasslands between upland forest and lowland sagebrush in eastern Oregon (Fig. 4B-D). In contrast, other climate models run with MC1 by Bachelet et al (2011) show different vegetation: coastal retreat of maritime conifer forest (Hadley model), expansion of eastern desert shrubland (CSIRO), and very limited range of subtropical and temperate hardwoods (Hadley and CSIRO). Miocene and model comparisons suggest that vegetation will gain biomass and productivity in all parts of Oregon. In eastern Oregon large areas of sagebrush scrub will be replaced by sod grasslands, and marshes and fens by swamp woodlands. In western Oregon conifer species will migrate uphill as the Willamette Valley and other lowlands accommodate more broadleaf evergreen trees. Other factors such as fire will also affect plant distribution (Gavin and Hu, 2006), primarily by accelerating vegetation transitions in their aftermath (Gavin et al. 2013a). Increased plant biomass, together with increased propensity for drought, more marked in western than eastern Oregon, will bring increased size and frequency of wildfire (Higuera et al., 2010), and simple fire suppression will not be an adequate management strategy (Whitlock et al., 2003). Catastrophic large fires not only destroy biomass but promote soil erosion (Colombarioli and Gavin, 2010).

Change of Oregon's climate toward Miocene conditions will enable invasion of new plant species, including native species from the south and escaped cultivated plants. The diversity of middle Miocene fossil floras is much higher than in geologically younger fossil floras (Chaney and Axelrod, 1959; Retallack, 2004; Emerson, 2009). This elevated diversity may have been due to a greenhouse paleoclimate enabling invasion of new plants and animal vectors and their pathogens from the south (Willis and MacDonald, 2011). Mass extinctions of plants, particularly wetland plants, is found during past spikes of CO_2 greater than 2000 ppmv CO_2 (Retallack, 2007, 2013b), which is unlikely for the foreseeable future (Stocker et al., 2013). The transition to grassland projected by Bachelet et al. (2011) has already begun in eastern Oregon, with invasive grasses such as cheatgrass (*Bromus tectorum*), medusahead rye (*Taeniotherium caputmedusae*) and orchard grass (*Dactylis glomerata*). In the Willamette Valley blackberry (*Rubus armeniacus*), shining cranesbill (*Geranium lucidum*) and spurge laurel (*Daphne laureola*) are spreading in well drained soils and water primrose (*Ludwigia* spp) and watermilfoil (*Myriophyllum spicatum*) are choking waterways (Boersma et al., 2006; Dennehy et al., 2011). Some 28-36% of the world's terrestrial ecosystems are novel, in the sense that human and climatic alterations are now irreversible (Perring and Ellis, 2013). Future spread of novel ecosystems with climate change will require difficult management decisions, for example, on whether to conserve diversity or function (Hulvey et al., 2013).

Oregon has unusually extensive historic and restorable rangelands and forests (Fig. 2), but will see expansion of novel ecosystems of human influence like those of more densely settled parts of the world (Vitousek et al., 1997). Some invading plants will be useful for pasture improvement and landscape stabilization (Kiely 2010), versus noxious weeds targeted for eradication (Boersma et al., 2006). Not all invaders are necessarily destructive. The northward migration of coast redwood (*Sequoia sempervirens*) is already underway: one tree grew as far north as Waldport in the mid Holocene some 1700 years ago (radiocarbon years calibrated for secular variation; Gavin et al., 2013b). Coast redwood is already widely planted in urban areas of Oregon. Reassessment of coast redwood growth has shown that this species has responded to the past century of warming temperatures with increased growth (Sillett, 2013). Spread of coast redwood would provide both watershed stabilization and a timber resource, as is clear from regrowth since annexation in 1978 to Redwoods National Park, of the clear-cut Redwood Creek, in northern California (Belous, 1984).

Other ecosystem services including pasture improvement and carbon storage may come from eradication of low-nutrition grasses such as cheatgrass (*Bromus tectorum*), and replacement with nutritious, fast-growing grasses better adapted to withstand grazing by Eurasian livestock and increasing precipitation (Retallack, 2013a). Such pasture improvement by introduced species, and techniques such as planned grazing, pasture cropping and contour coppicing (Butterfield et al, 2006) also build reserves of carbon in the soil (Sanderman et al., 2010). Buried carbon is a marketable commodity within global carbon trading schemes, and in pilot studies carbon farming has added to farm income (Kiely, 2010).

The ecosystem service of coastal sand stabilization is provided by marram grass (*Ammophila arenaria*), introduced to dunes near San Francisco in AD 1869. Marram grass was already widespread in Oregon by the 1930's (Wiedemann and Pickart, 2008), threatening native dune plants and nesting of the western snowy plover (*Charadrius alexandrinus*; Colwell et al., 2005). Like the native dune grass *Leymus mollis* and many tropical grasses, *Ammophila* has endophytic bacterial symbionts allowing nitrogen fixation in nutrient-poor substrates (Dalton et al., 2004). In addition, marram grass has aggressive phalanx-style propagation from rhizomes (Wiedmann and Pickart, 2008). *Ammophila* thus provides ecosystem services, stabilizing large areas of the coastal sand from increased human traffic and increasingly destructive storms, although at a cost to native biodiversity.

The Miocene fossil record of the Pacific Northwest also reveals that invasions of plants from warmer climates of the south comes with increased risk of insect predation and plant pathogens (Fornash, 2007). Port Orford Cedar root rot (*Phytophora lateralis*) and sudden oak death (*Phytophora ramorum*) are already present in Oregon and moving north (Boersma et al., 2006). Related water molds (Oomycota) have devastated native vegetation in summer-dry, hot southwestern Australia (Shearer et al., 2004). Gypsy moth (*Lymantria dispar*) was introduced to Boston in 1868-9 for possible silk production, and reached Portland, Oregon, by 1979, locally defoliating oaks (*Quercus garryana*) and a variety of other deciduous trees. With global warming, the distribution of gypsy moths in North America may move northward into Canada (Vanhanen et al., 2007). Biological controls and insecticides will continue to control such pests of the timber economy (Boersma et al., 2006).

Kinds and distribution of crops will change, but economic effects will be limited because of the unusual diversity of Oregon's agricultural enterprises, which will further diversify with warming climate. Oregon's most valuable five agricultural products of nursery products, hay, grass seed, cattle and milk will be sustainable

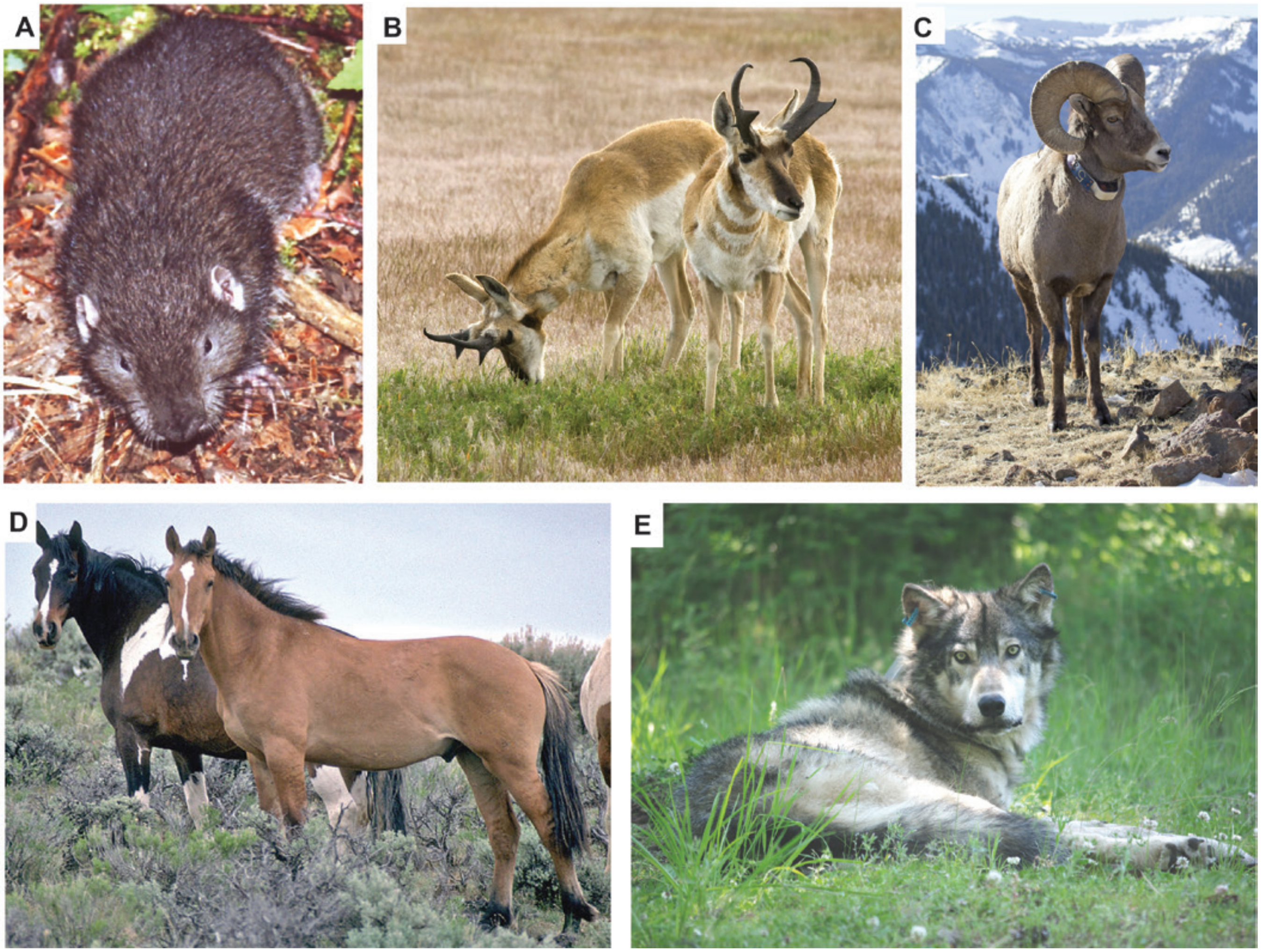

Figure 9. *Oregon "wildlife": (A) mountain beaver or sewellel (*Aplodontia rufa*) in Olympic National Park, Washington (photo courtesy of Mike Habeck); (B) pronghorn (*Antilocapra americana*) from near Pendleton (photo courtesy of Nick Myatt and Oregon Department of Fish and Wildlife): (C) Rocky Mountain bighorn sheep* (Ovid canadensis) *upper Lostine Creek, Wallowa Mountains (photo courtesy of Nick Myatt and Oregon Department of Fish and Wildlife): (D) "Kiger stallions"* (Equus ferus), *commercially valuable wild horses, on Steens Mountain (2012 photo courtesy of Albert Herring and Wikimedia), (C) GPS-collared released gray wolf (*Canis lupus*) number OR-14 on Weston Mountain (2012 photo of Oregon Department of Fish and Wildlife).*

under climate change of the scope anticipated (Coakley et al., 2010). Large areas of eastern Oregon will become suitable for winter wheat cropping and greater yields result from increases in rainfall and atmospheric carbon dioxide (Izaurralde et al., 2003). Pinot Gris and Pinot Noir vines may produce better quality and more wine with warming predicted by mid-century, but conditions will approach their limit for production of palatable wines by 2100 (Jones, 2007). More vines for heat-tolerant Syrah, Cabernet Sauvignon and raisins may be planted in Oregon as supplies from California and Australia dry up. Winter frost in Oregon will become inadequate to stimulate flowering of temperate fruits and nuts, such as apples and filberts, which will do better in Washington and British Columbia (Luedeling et al., 2011).

MARINE ANIMALS

Future changes to marine life of Oregon can be assessed from the fossil record of Oregon's central coastal Astoria Formation, dated at 16.6 million years old by magnetic stratigraphy (Prothero et al., 2001) and formed during a peak of atmospheric CO_2 (Fig. 3) like that expected by 2100 (Table 2). Fossil sea shells of this time were diverse, because of range extensions northward into Oregon of cockles (*Anadara*) and fig shells (*Ficus*), now found no further north than Baja California (Moore, 1963). Similarly in the future, northward migration of shellfish may also include departure to British Columbia of the main catch of Dungeness crab (*Cancer magister*), which was already declining in southern compared with northern California by 1980 (Wild, 1980). Abalone (five species in all, but mainly *Haliotis rufescens*, *H. corrugata* and *H. cracherodi*) and sea urchin (*Strongylocentrotus franciscanus*) fisheries of California were commercially exhausted by 2000, and are already shifting northward to Oregon as the ocean warms (Murray et al., 1999). Existing marine reserves will be essential to facilitate northward migration, as well as insurance against local disturbances, such as oil spills and storms (Allison et al., 2003). Coastal islands and sea stacks now serve as vital refuges to most of Oregon's seals, sea lions (Fig. 8C: Pearson and Verts, 1970), and seabirds (Fig. 8A-B: Naughton et al., 2007). Whales have also rebounded with legal protections. The main population of gray whales (*Eschrictius robustus*) which migrate annually along the Oregon Coast between Baja California and the Bering Sea has now recovered to about 18,000 animals after a low during peak-whaling in 1900 of 1500-1900 animals (Swartz et al., 2006).

Remarkable episodes of marine anoxia plagued the central Oregon Coast during the El Niño years from 2002 to 2006 (Barnard et al., 2011). These have been attributed to unprecedented upwelling due to unusually warm water and strong seasonal onshore breezes, which brought dead zones into shallow water three or four times each summer (Pierce et al., 2005; Hales et al., 2006). During these summer anoxic events, waves on central Oregon beaches were unusually green with phytoplankton blooms, and delivered dead and dying crabs to crowds of seagulls. Underwater cameras revealed dead fish and crabs over a wide area of the central Oregon Coast (Grantham et al., 2004), but during intervening weeks and winter months the anoxic zone retreated to deeper water allowing biological recolonization (Barth et al., 2007). These marine anoxia events reduced summer mysid (*Holmesimysis sculpta*) populations, and in those years of poor food supply Oregon's summer-resident gray whales (*Eschrichtius robustus*) were in poor condition (Newell and Cowles, 2006). Episodes of anoxia have abated since 2006 in a La Niña decadal cooling of the equatorial Pacific Ocean (Kosaka and Xie, 2013). Comparable anoxia may explain carbonaceous shale beds with articulated fossil crabs and starfish (Orr and Orr, 2009) in 17 million year old parts of the Astoria Formation (Prothero et al., 2001) of the central Oregon Coast (Retallack, 2011). Marine anoxia may be a persistent problem with increasing atmospheric CO_2, even on Oregon's wave-swept coasts.

Marine acidification with rising atmospheric CO_2 is more a problem for coral reefs than for Oregon's silicate shorelines, but even in the Pacific Northwest acidification will suppress coralline algae and planktotrophic larvae of molluscs and crustaceans (Doney et al., 2009). Troubling early economic impacts of acidification were the collapse between 2005 and 2009 in production of hatchery larvae of Pacific oyster (*Crassostrea gigas*). Solutions for such a large and global problem as ocean acidification will be difficult and expensive (Adelsman and Binder, 2012), but in the interim less vulnerable oyster species will be imported as replacements (Miller et al., 2009). The middle Miocene fossil record of the Astoria Formation lacks resolution to quantify slight pH changes that critically affect larval recruitment, but middle Miocene warming did not result in northward migration of tropical reefs. Ahermatypic corals, marine algae, tubeworms and large foraminifera in middle Miocene marine fossil assemblages of central Oregon (Moore, 1963) are evidence of limited northward migration of marine organisms from warmer waters of Baja California.

In addition to these climatic effects, Oregon's coast will experience marine invertebrate biodiversity loss due to human population growth and pollution, and has unique problems arising from public access. The entire Oregon Coast was declared a public highway by Governor Oswald West in 1913, with beach access assured under Governor Tom McCall in 1967 (Schwantes, 2003). Beachcombers take seashells, especially dead snail shells important to hermit crabs (Abrams, 1987). Stripping of grazing intertidal snails and limpets leaves rock platforms covered in dangerously slippery algae and cyanobacteria, especially in cold wet seasons (Cubit, 1984). Public education programs will be essential for marine invertebrate conservation. The Oregon seafood industry will continue to require policing for catch seasons and limits, but will inevitably be drawn into global decline in fishery resources (Jackson et al., 2001).

TERRESTRIAL ANIMALS

High CO_2 levels and warmer climate of the middle Miocene (Fig. 3) did not have adverse effects on fossil mammals of the Mascall Formation of eastern Oregon (Orr and Orr, 2009), dated at 15.8 Ma by $^{40}Ar/^{36}Ar$ (Prothero et al., 2001). These faunas of the Barstovian Mammal Age included grazing horses and antelope, and predators of evolutionary grade comparable with modern mammals. Also present were elephants and rhinoceroses (Tedford et al., 2004), lacking in the modern fauna of North America since Pleistocene megafaunal extinctions (Barnosky et al., 2004). Missing in the middle Miocene were hypergrazers, such as monodactyl horses (*Pliohippus spectans*), which evolved by Plio-Pleistocene (Retallack et al., 2002). A notable feature of middle Miocene faunas of the Barstovian mammal age is high biological diversity in most ecological categories (Janis et al., 2000; Hopkins, 2007). This may have been an adaptation to an unusually diverse array of habitats revealed by paleosols in the Mascall Formation (Bestland et al., 2008), but also is in part due to immigration of mammals from elsewhere, even as far afield as Europe and Asia (Webb et al., 1995).

The future diversity of mammals in a warming world will be different because of humans (Barnosky et al., 2011). Oregon's large animals in particular are increasingly managed. Spreading farms and ranches were responsible for extinction of bison (*Bos bison*) and gray wolf (*Canis lupus*) in Oregon by 1950 (Van Vuren and Bray, 1985; Verts and Carraway, 1998). Gray wolves recently reintroduced to Idaho have wandered widely through Oregon (Fig. 9E; Carroll et al., 2011). A herd of bison have become naturalized in the Eagle Cap Wilderness, after escape from local ranches. Reintroduction of bighorn sheep to Oregon has continued since 1954 (Oregon Department of Fish and Wildlife, 2003). Wild horses (Fig. 9D) are not controlled by hunting tags, but by roundup of excess animals for sale (Oregon Bureau of Land Management, 2013). In eastern Oregon, spreading grassland will encourage proliferation of deer and wild horses, and domestic cattle and sheep. These are unlikely to affect the abundance of pronghorn (*Antilocapra americana*: Fig. 9B), which are geographically restricted due to their preferred diet of plants in sagebrush communities (McInnis and Vavra, 1987). Iconic Oregon creatures such as mountain beaver (*Aplodontia rufa*: Fig. 9A) will suffer from human trapping to prevent forestry damage in Douglas fir plantations (Borrecco and Anderson, 1980). Many native birds and small mammals will be imperiled by feral cats, as in comparable climatic regions of Australia (Dickman, 1996), because of declining winter snow and isolation of native carnivores in preserves (Crooks and Soulé, 1999).

Changes in terrestrial vertebrates independent of human activities can no longer be assessed by field studies, but computer models give some constraints. Lawler et al. (2009) provided a computer modeled assessment of land mammal, bird, and amphibian turnover expected with range changes induced by ten climate change models and the three emission scenarios of Table 2 by 2100. Oregon suffered less turnover than the mountains of Central and South America and the high Arctic, however turnover was still significant (10-20%) in mountain regions of Oregon "wilderness".

Insects, amphibians, reptiles and birds are also strongly affected by human activity and climatic change. Invasive species in the Pacific Northwest with significant ecological effects include earthworms (*Lumbricus terrestris*, *L. rubellus*), American bullfrogs (*Rana catesbiana*), and European starlings (*Sturnus vulgaris*). These successful invasions have been considered responsible for decline in native giant earthworms (*Driloleirus americanus*, *D. macelfreshii*), western pond turtles (*Emys marmorata*), and northern flicker (*Colaptes auratus*), respectively. Invasive Asian bush mosquito (*Ochlerotatus japonica*) and Asian tiger mosquito (*Aedes albopictus*) are carriers of lethal parasites and West Nile Virus (Boersma et al., 2006).

Even without introduced species and other human modifications, climate change effects on insects are complex. The rule of thumb that insects will move north to track the climate proved true for Anise swallowtail butterflies (*Papilio zelicaon*), which have a variety of herbaceous garden host plants in the Pacific Northwest, but not for duskywing butterflies (*Erynnis propertius*), which are limited to the vicinity of host oaks (*Quercus garryana*: Pelini et al., 2009). The leading and trailing edges of northward and upward migrating ponderosa pine (*Pinus ponderosa*) will become increasingly vulnerable to bark beetles (*Dendroctonus ponderosae*), because bark beetle outbreaks are projected to increase with climatic warming (Bentz et al. 2010). Such complexities of climate change are strong arguments for preservation of large tracts of historic and restorable ecosystems, which still cover large areas of Oregon.

CONCLUSIONS

Oregon's projected climate change by 2100 is milder than other parts of the world, with less than half the increases in temperature and precipitation expected elsewhere (Stocker et al., 2013). Loss of glaciers and diminished snowpack will change the seasonal pattern of water availability, particularly in the McKenzie River watershed (Moore et al., 2009). Oregon's mountainous topography means that some historical ecosystems will find refuge by moving uphill with global warming, as they did during warming from the last ice age (Long et al., 2007). Sea level rise will have a minor effect on Oregon's largely cliffed coast (Retallack and Roering, 2012), compared with lowland regions of the world such as Bangladesh (Stocker et al., 2013). With increases in warmth and precipitation, vegetation will gain biomass and productivity (Bachelet et al., 2011), and will tap more deeply into the mineral nutrition of soils (Pendall et al., 2004). This will intensify agricultural production in western Oregon lowlands, and spread dryland grazing and cropping to larger areas of eastern Oregon (Coakley et al., 2010). The combination of invasive species and pathogens (Boersma et al., 2006) and catastrophic fires (Gavin and Hu, 2006) are likely to tip local ecosystems in unpredictable ways. Greater weathering and agricultural production on land will lead to problems of aquatic eutrophication and marine anoxia (Barnard et al., 2011), which together with global overfishing (Jackson et al., 2001), will imperil seafood production. Land mammals of Oregon will become increasingly dependent on human management, and even wilderness areas will not be immune to extinctions (Lawler et al., 2009). By the year 2100, Oregon will be warm temperate and humid to subhumid, a less extreme change than in other parts of the world (Stocker et al., 2013), and its worst environmental problems are more likely to be political and economic than ecological. The many geopolitical instabilities caused by climate change are beyond the scope of this review.

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