DOI: 10.5586/aa.1673

Publication history
Received: 2016-04-09
Accepted: 2016-05-21
Published: 2016-06-30

Handling editor
Bożena Denisow, Faculty of Horticulture and Landscape Architecture, University of Life Sciences in Lublin, Poland

Authors' contributions
Both authors equally contributed to describing climate change effects on U.S. grasslands and preparing individual sections of the manuscript. Authors' order in the byline is arranged alphabetically.

Funding
This study did not involve any financial support.

Competing interests
No competing interests have been declared.

Citation
Belesky DP, Malinowski DP. Grassland communities in the USA and expected trends associated with climate change. Acta Agrobot. 2016;69(2):1673. http://dx.doi.org/10.5586/aa.1673

INVITED REVIEW

Grassland communities in the USA and expected trends associated with climate change

David Paul Belesky[1], Dariusz Piotr Malinowski[2]*

[1] Division of Plant and Soil Sciences, Davis College of Agriculture, West Virginia University, 1082 Agricultural Sciences Building, Morgantown, WV 26506-6108, United States
[2] Department of Soil and Crop Sciences, Texas A&M University System, Texas AgriLife Research and Extension Center, P.O. Box 1658 Vernon, TX 76385, United States

* Corresponding author. Email: dmalinow@ag.tamu.edu

Abstract

Grasslands, including managed grazinglands, represent one of the largest ecosystems on the planet. Managed grazinglands in particular tend to occupy marginal climatic and edaphic resource zones, thus exacerbating responses in net primary productivity relative to changes in system resources, including anthropogenic factors. Climate dynamism, as evident from the fossil record, appears to be a putative feature of our planet. Recent global trends in temperature and precipitation patterns seem to differ from long-term patterns and have been associated with human activities linked with increased greenhouse gas emissions; specifically CO_2. Thus grasslands, with their diverse floristic components, and interaction with and dependence upon herbivores, have a remarkable ability to persist and sustain productivity in response to changing resource conditions. This resistance and resilience to change, including uncertain long-term weather conditions, establishes managed grasslands as an important means of protecting food security. We review responses of grassland communities across regions of the USA and consider the responses in productivity and system function with respect to climatic variation. Research is needed to identify plant resources and management technologies that strengthen our ability to capitalize upon physiological and anatomical features prevalent in grassland communities associated with varying growing conditions.

Keywords

climate change; desertification; ecosystems; geographic regions; grasslands

Introduction

Native and improved grasslands are an important basis for U.S. food production providing a significant part of the feed requirements of ruminants used for meat and milk production [1]. Grasslands also provide an array of other services, i.e., contribute to environmental sustainability of the agroecosystems by reducing water run-off and soil erosion [2], aquifer recharge [3], conserving soil water during summer drought [4], improving soil physical and chemical properties [5], securing habitat for wildlife [6], and a variety of recreational opportunities. Native grasslands of North America occur within precipitation and temperature gradients that generally increase in magnitude from west to east and north to south, respectively [7]. High temperatures, often accompanied by sporadic precipitation events, restrict summer grassland production in the southern parts of the North American continent.

Native grasslands cover a broad expanse of the U.S. and encompass a diverse set of environmental conditions and ecological communities. The latest census data on inventory of U.S. major land uses indicate that grassland pasture and range land occupied 238 million hectares (25.9% of total land area of 0.9 billion hectares), compared with forest-use land, (263 million hectares; 28.8%), cropland (179 million hectares;

19.5%), special uses land (primarily national parks and wildlife areas; 120 million hectares; 13.1%), miscellaneous other land uses (92 million hectares, 10.1%), and urban land (24 million hectares; 2.6%) [8].

Lauenroth [9] considers two types of grasslands: the climatically determined grasslands in areas where water availability is not enough to support forests, and the anthropogenically determined grasslands located in most of the temperate regions where the potential climax community vegetation is forest and where herbaceous vegetation is maintained by domestic herbivore exploitation. There are three major categories of native grasslands in North America [10]:

- Tall grass prairie lies mainly in the eastern portion of the Midwest. The grasses here often grow to be 1.5 m tall. Average precipitation reaches 760 mm per year.
- Mixed grass prairie is found in the middle portion of the Midwestern United States. The grasses here grow to be 0.6 to 0.9 m tall. Average annual precipitation is 380 to 635 mm.
- Short grass prairie is found in the western portion of the Midwest hugging the edge of the western deserts and the Rocky Mountains. The grasses here grow to be no more than 0.6 m tall. Average annual precipitation reaches about 250 mm.

The International Vegetation Classification recognizes several grasslands types across North America: Vancouverian and Rocky Mountain grassland and shrubland; North American boreal grassland, meadow, and shrubland; Eastern North American grassland, meadow, and shrubland; Southeastern North American grassland and shrubland; Western North American interior sclerophyllous chapparal shrubland; Western North American cool semi-desert scrub and grassland; Great Plains grassland and shrubland; North America warm desert scrub and grassland; California grassland and meadow; and Caribbean central American montagne shrubland and grassland [11].

Climate, together with fire and grazing pressure, are important factors affecting grassland ecosystems worldwide and particularly in North America. Climate variability is an inherent characteristic of a large portion of the USA and extreme variability occurred several times in the past century [12]. For example, a distinct warmer and drier climate cycle occurred from 1930 to 1960, followed by a cooler and wetter climate cycle from 1970 to 2000. The recent warm climate cycle started around 2000. Climate scientists agree that the global temperature has been increased in the industrial era, likely due to human-caused elevations in atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) [13]. These factors, combined with variable solar radiation cycles, natural emissions of GHGs (volcanic activity), and other natural phenomena (i.e., El Niño Southern Oscillation), contribute to the climate variability worldwide [14]. Recent significant changes in the climatic conditions across the Southern United States began taking place around 2000 and have continued doing so [12,15]. As examples, we present here long-term climate variability and change for the Northwest (Boise, ID; latitude: 43.5667, longitude: −116.2410, elevation: 876 m), Midwest (Cincinnati, OH; latitude: 39.1033, longitude: −84.4189, elevation: 147 m), and Southwest (Vernon, TX; latitude: 39.0906, longitude: −99.3668, elevation: 383 m) regions of the USA (Fig. 1). The average mean annual temperature for Boise, ID has been increasing since late 1990's, while there has been no noticeable trend in precipitation changes. In contrast, there have been no significant changes in average annual temperature for Cincinnati, OH but the annual precipitation has been decreasing since the early 2000's. Vernon, TX has been experiencing a significant increase in average mean annual temperatures since the late 1990's accompanied by a drastic decrease in annual precipitation. The abrupt change in the weather patterns has resulted in repeated, extreme, and often long-term drought events devastating the fragile ecosystems and agricultural production in the Southwest region [16]. During the 1930 to 1940 decade, climatic changes resulted in the worst decadal drought in recent U.S. history (also known as the "dust bowl") that brought devastating consequences for American agriculture [17]. The recent climate warming cycle has already resulted in record droughts in Texas, Oklahoma, and Kansas in 2011 [18], and in California in 2014 [19] causing billions of dollars in direct agricultural losses.

Climate change alters seasonal distribution and intensity of precipitation that affect seasonal water dynamics and in consequence, grasslands productivity [20]. Some

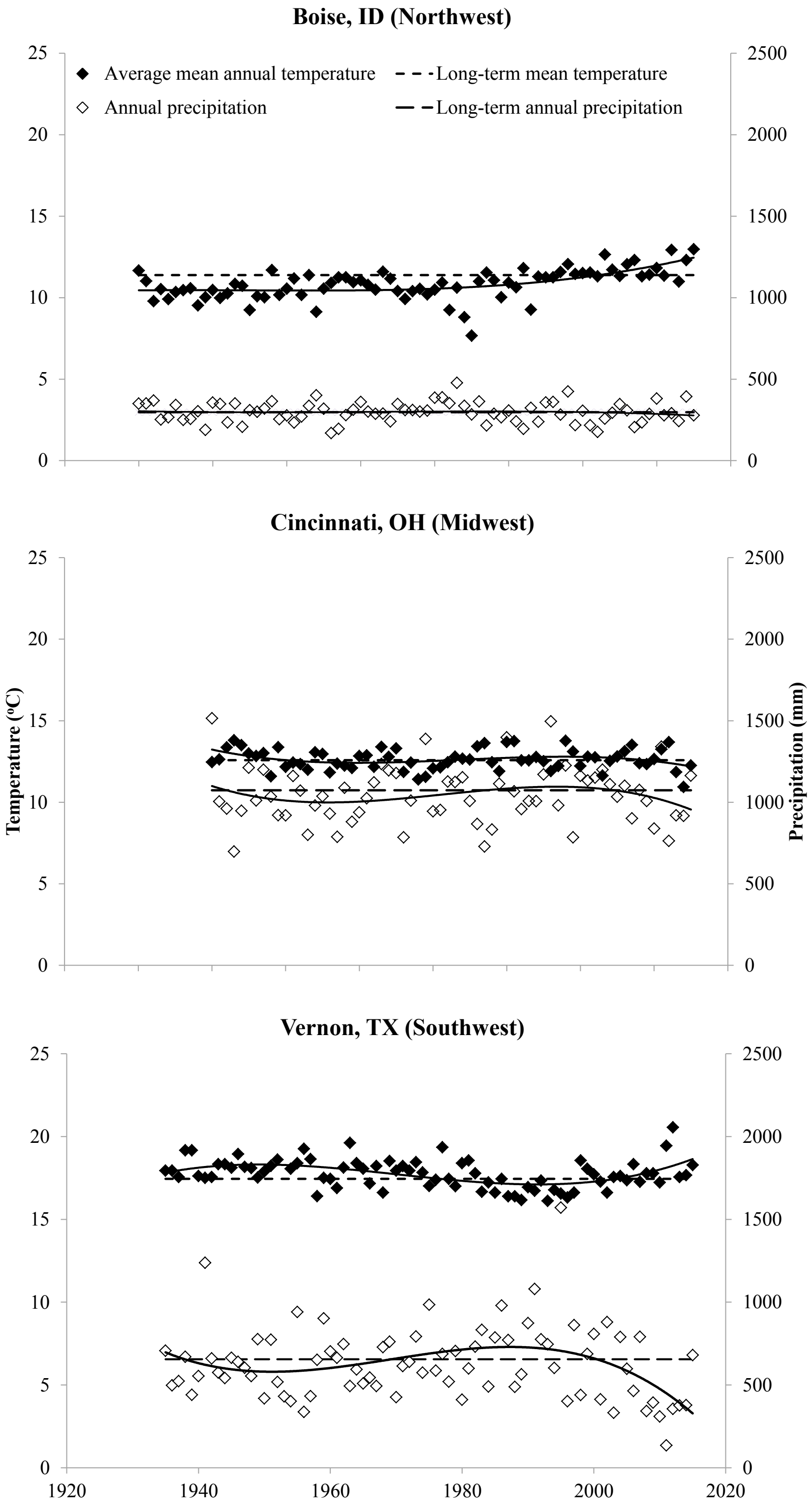

Fig. 1 Examples of long-term trends in average mean annual temperature and total annual precipitation for the Northwest, Midwest, and Southwest regions of the USA. Solid lines are 3rd degree polynomial curves fitted on the actual data. Temperature and precipitation data source [144].

areas of the globe will receive higher precipitation than other regions, and it is predicted that the intensity of rainfall will increase, while frequency will decrease, causing frequent droughts in some regions [21]. We review selected aspects of climate change effects on grasslands ecosystems in the USA and proposed mitigation strategies to maintain and protect the vital components of human existence.

Effects of current and predicted climate changes on grassland ecosystems in the USA

The discussion of current and predicted effects of climate change on grassland communities and their management will focus on the six major geographic regions of the United States, e.g., Southwest, West, Northwest, Midwest (including the Great Plains), Northeast (including Mid-Atlantic region), and Southeast (Fig. 2).

Southwestern grasslands

Characteristics of Southwestern grasslands. The Southwestern grassland biome is classified as temperate grasslands [22,23] and includes the following grassland types: montane grasslands, desert grasslands, Colorado Plateau grasslands, Great Basin grasslands, and Plains grasslands [24]. Temperate grasslands are located at mid-latitude and are dominated by perennial grasses and forbs. Climate is moderately dry (semiarid) with wet/dry seasons and temperature and precipitation extremes [25]. Short grasses include buffalograss (*Buchloe dactyloides*) and blue grama (*Bouteloua gracilis*). Mid grasses include little bluestem (*Schizachyrium scoparium*), needlegrass (*Stipa* spp.), western wheatgrass (*Pascopyrum smithii*), and Indian rice grass (*Achnatherum hymenoides*) [26].

Montane grasslands include the montane, subalpine and alpine meadows, valleys, and high elevation grasslands that occur throughout the Grand Canyonlands, Painted Desert, Tonto Transition, White Mountain-San Francisco Peaks, Basin and Range, Central Rio Grande Intermontane, South-Central Highlands, Sacramento-Manzano Mountain, Southern Parks and Ranges, and Upper Rio Grande Basin ecoregion

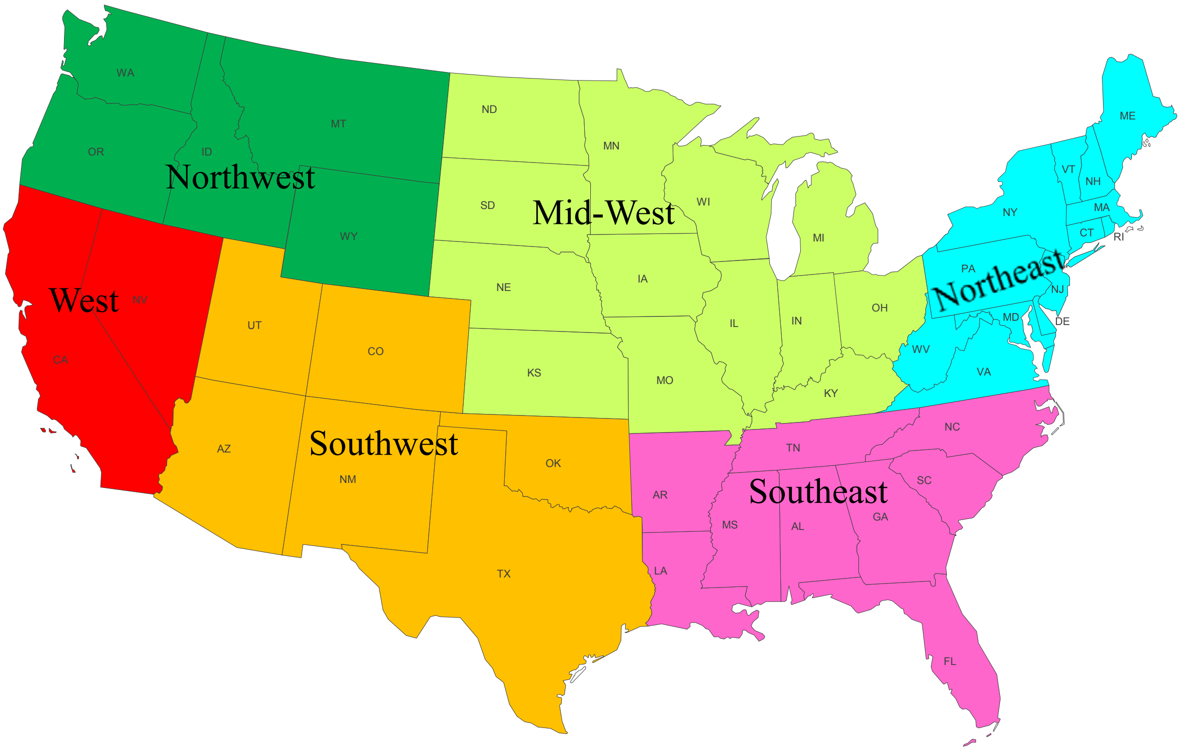

Fig. 2 Geographic regions of the USA. Map © MapResources.com.

sections [27]. Climates are extreme with mean annual temperature ranging from −3 to 7°C and mean annual precipitation (mainly as snowfall) ranging from 560 to 760 mm, of which over 50% is received during the months October through March [28]. The most common components of these grassland communities are cool-season grasses represented by subalpine Thurber fescue (*Festuca thurberi*), timber oatgrass (*Danthonia intermedia*), sheep fescue (*Festuca ovina*), and Arizona fescue (*Festuca arizonica*), introduced Kentucky bluegrass (*Poa pratensis*), tufted hairgrass (*Deschampsia caespitosa*), and a warm-season grass, screwleaf muhly (*Muhlenbergia virescens*) [29,30].

Desert grasslands occur at low elevations in arid and semi-arid environments of the Chihuahuan, Mohave, and Sonoran deserts, and are characterized by an arid climate with limited precipitation [31]. Annual precipitation ranges from less than 250 mm to 400 mm and the seasonality of precipitation differs substantially among hot deserts. These environments are characterized by very high summer temperatures (over 48°C) and relatively mild winters with frost free valley bottoms and some freezing at higher elevations. The Mojave Desert is dominated by winter precipitation and the main growing period occurs during the cool season. The Chihuahuan Desert is dominated by summer precipitation with biological activity during the warm season. The Sonoran Desert is intermediate, receiving both winter and summer precipitation, thus the growing season occurs all year long. These grasslands are composed by a combination of mixed herbaceous species with few shrub species [22], often called savannas [31]. Grasses are represented by black grama (*Bouteloua eriopoda*), tobosa (*Pleuraphis mutica*), curly mesquite (*Hilaria belangeri*), bushmuhly (*Muhlenbergia porteri*), and burrograss (*Scleropogon brevifolius*) [30]. Major shrubs that occur in association with these grasses include creosote bush (*Larrea tridentata*), velvet mesquite (*Prosopis velutina*) in Arizona, western honey mesquite (*Prosopis glandulosa* var. *torreyana*) in southern New Mexico, tarbush (*Flourensia cernua*), turpentine bush (*Ericameria laricifolia*), desert ceanothus (*Ceanothus greggii*), and soaptree yucca (*Yucca elata*).

Grasslands of the Colorado Plateau are located in northern Arizona above the Mogollon Rim and northern New Mexico in association with the Colorado Plateau and adjacent to small areas of the Rocky Mountain physiographic regions [32]. The climate of the Colorado Plateau is highly variable from north to south and from low to high elevations [33]. Average annual precipitation ranges from 136 to 668 mm. In the north, precipitation occurs mainly as infrequent summer thunderstorms. In the south, the peaks of precipitation are in the winter and again in the summer because of moisture derived from southern monsoonal weather patterns. Spring and fall are generally the driest periods. Temperatures also vary considerably, ranging from −7°C in the winter to 35°C in the summer in the southern and lower elevations. At mid and high elevations, temperatures range from −16°C in the winter to 15°C in the summer [34]. The grasslands of Colorado Plateau occur within the Grand Canyonlands, Painted Desert, Tonto Transition, White Mountains-San Francisco Peaks, Navajo Canyonlands, South-Central Highlands, Southern Parks and Ranges, and Upper Rio Grande Basin ecoregion [27]. Grasslands of the Colorado Plateau occur at high elevations and are dominated by desertscrub and shrublands represented by big sagebrush (*Artemisia tridentata*) and alder-leaf cercocarpus (*Cercocarpus montanus*), but also by juniper (*Juniperus* spp.), pinyon pine (*Pinus edulis*), ponderosa pine (*P. ponderosa*), Dogulas fir (*Pseudotsuga menziesii*), and aspen (*Populus tremuloides*) [35]. Grass species characteristic to these grasslands include western wheatgrass, needle and thread (*Hesperostipa comata*), blue grama, galleta, New Mexico feathergrass (*Hesperostipa neomexicana*), and three-awn species (*Aristida* spp).

Great Basin grasslands occur at lower elevations and are less productive than subalpine or montane grasslands but they are higher in elevation and more productive than desert grasslands [30]. This region is characterized by hot summers and moderate to cold winters. The average annual temperature ranges from 4 to 13°C. Total annual precipitation averages 125 to 500 mm with no precipitation during the summer months except in the mountains [36]. Mean monthly precipitation shows a strong winter-dominated pattern in the west, with a gradual shift eastward to more summer moisture, with less distinct wet and dry seasons compared with other deserts [37]. Sagebrush dominates the vegetation of the lower elevations of the province. Cool-season grasses are represented by Great Basin wildrye (*Elymus cinereus*), bluebunch wheatgrass (*Agropyron spicatum*), Idaho fescue (*Festuca idahoensis*), Sandberg's bluegrass (*Poa sandbergii*), bottlebrush squirreltail (*Sitanion hystrix*), Thurber's needlegrass (*Stipa thurberiana*), prairie Junegrass (*Koeleria cristata*), and the introduced annual cheatgrass (*Bromus tectorum*) [38]. Warm-season grasses are represented by blue grama (*Bouteloua gracilis*), galleta (*Pleuraphis jamesii*), Indian ricegrass, sideoats grama (*Bouteloua curtipendula*), dropseeds (*Sporobolus* spp.), and wolftail (*Lycurus phleoides*) [30].

The Plains Grasslands consist of the shortgrass, midgrass, and tallgrass prairies. These grasslands extend throughout the Great Plains physiographic province [32] and occur within the Southern High Plains, Pecos Valley, Redbed Plains, and Texas High Plains ecoregion sections [27]. Climate of these regions ranges significantly from semiarid (west) to subhumid (east) and so does the annual precipitation, ranging from 250 mm in the west to 650 mm in the east. Seventy to eighty percent of annual precipitation occurs during the months between April and September, often in a form of torrential rains causing much runoff. Evaporation is about twice as high in the Southern as in the Northern Great Plains, and water requirement of the growing vegetation is proportionally higher. The frost-free season ranges from about 100 days at the Canada border to 200 days in Texas. The majority of grasses consist of warm-season species. Grasses characteristic for the shortgrass prairie include blue grama (*Bouteloua gracilis*) and buffalo grass (*Buchloe dactyloides*) [30]. The midgrass prairie ecosystem is represented by little bluestem (*Schizachyrium scoparium*), blue grama, and plains bristlegrass (*Setaria vulpiseta*). The tallgrass prairie is dominated by big bluestem (*Andropogon gerardii*). Rare native cool-season grasses are represented by Texas bluegrass (*Poa arachnifera*) occurring in New Mexico, Kansas, Oklahoma, Texas, Illinois, Arkansas, Louisiana, Mississippi, Alabama, Georgia, Florida, South Carolina, North Carolina, and Tennessee [39], and Texas wintergrass (*Nasella leucotricha*) occurring in Texas, Oklahoma, Arkansas, and Louisiana [40]. These two cool-season grasses possess summer dormancy trait that is a characteristic of some cool-season grass ecotypes originating from the Mediterranean climate of Southern Europe and California. Summer dormancy in cool-season perennial grasses is a result of an evolutionary adaptation to long, hot and dry summers and mild winters with precipitation periods [41].

Implications of climate change on Southwestern grasslands. The Southwest is the hottest and driest region in the United States, where the availability of water has defined its landscapes, history of human settlement, and modern economy [42]. Throughout the Southwestern United States, climate models consistently project increased aridity and seasonal shifts in precipitation, along with more extreme precipitation events [43]. Recent warming in the Southwest is among the most rapid in the United States, indicating that the transition to a more arid climate is already occurring [31]. It is noteworthy that plants and animals in these environments already live near their physiological limits. The progressing tree mortality may be the most drastic example of the upcoming changes in vegetation [44]. The predicted consequences of this climate shift include fewer frost days, warmer temperatures, greater water demand by plants, animals and people, and an increased frequency of extreme weather events (heat waves, droughts, and floods). Regional annual average temperatures are projected to rise by 1.4°C to 3.1°C during 2041–2070 and by 3.1°C to 5.3°C during 2070–2099 with continued increase in global CO_2 emissions [42]. Reduced water supply will lengthen the dry season, create conditions for drought and insect outbreaks [45], and increase the frequency and intensity of wildfires. Temperatures currently considered unusually high will occur more frequently. Precipitation patterns will become more erratic and high-intensity storms will likely become more common, resulting in longer dry periods and floods. Interestingly, these model-based projections closely align with observations made in the region over the past decade, indicating an expansion of the current boundaries of southwestern deserts to the north and east [31].

Grazing systems in the Southwest have historically been based on four major forage resources, depending on particular regions: native range and grasslands, dual-use wheat (*Triticum aestivum*), and introduced cool-season and warm-season perennial grasses [46]. In the past decade, insufficient precipitation in autumn has threatened timely planting of dual-use wheat in the Southern Great Plains, resulting in a lack of forage for cattle to graze into the winter and early spring [41]. Changing climatic conditions are considered the major reason for failure of introduced traditional cool-season perennial grasses at the margin of their existence in C_4 (Hatch–Slack carbon assimilation pathway) dominated ecosystems of the Southwest [47,48]. One reason for the failure of introduced cool-season perennial grasses is their inability to adapt to increasing aridity. Temperate (continental) cool-season perennial forage grasses have been developed from germplasm originating from environments where extreme heat and prolonged droughts do not occur [49]. The future of cool-season perennial grasslands in the Southwest will depend on introduction of new cool-season grass types that will persist under the altered climatic conditions. The most promising are cool-season perennial grasses with summer dormancy trait [41]. These grasses originate from the Mediterranean Basin of Southern Europe and Northern Africa, and Mediterranean environments of California [50,51]. Summer-dormant grasses cease growth and lose green leaves during summer, regardless of soil moisture availability [52]. Growing season lasts from autumn through late spring. Summer-dormant ecotypes evolved in tall fescue (*Lolium arundinaceum*, formerly *Festuca arundinacea*) [53], orchardgrass (*Dactylis glomerata* ssp. *hispanica*) [54] and *D. glomerata* ssp. *judaica* [55], harding grass (*Phalaris acquatica*) [56], bulbous bluegrass (*Poa bulbosa*) [57], bulbous barley (*Hordeum bulbosum*) [58], and oatgrass (*Arrhenatherum palaestinum*) [59]. Four summer-dormant cool-season perennial grass species originate from the Mediterranean climate of California: big squirreltail (*Elymus multisetus*) [60], Sandberg's bluegrass (*Poa secunda* ssp. *secunda*), nodding needle grass (*Stipa cernua*), and California melicgrass (*Melica californica*) [50]. As indicated earlier in the text, two summer-dormant perennial cool-season grasses, Texas bluegrass and Texas wintergrass, evolved in environments of the Southern Great Plains of the USA that only partially resemble Mediterranean climate (hot dry summers and relatively mild and rainy winters). Native ecotypes of summer-dormant cool-season grasses are not as productive as their summer-active (temperate) counterparts, thus plant breeders have been developing cultivars of tall fescue, orchadrgrass, and harding grass with improved forage productivity to meet the nutritive requirements of grazing animals [61–63].

Projected increases in temperature and progressing desertification of arid/semiarid regions will have significant effects on livestock management systems that usually are

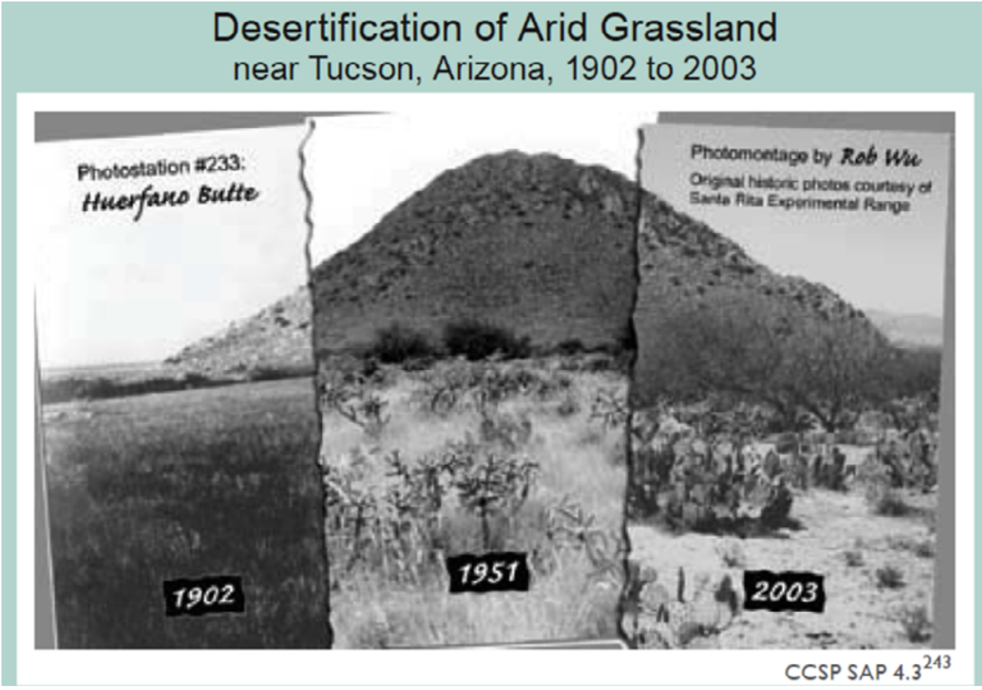

Fig. 3 The progression from grassland to desert (desertification) over a 100-year period attributed to grazing management as well as reduced rainfall in the Southwest. Reprinted from [113].

not flexible in response to fluctuations in precipitation [31]. Historically, Southwestern grasslands have been notoriously overgrazed and high stocking rates combined with long drought periods increase the potential for degradation (Fig. 3) and shrub encroachment [64]. Combined selection pressures of herbivory and progressing aridity are predicted to result in communities least responsive to grazing by introduced livestock [65]. Changing climate will not only affect the amount and nutritive value of forages, but also livestock health conditions and weight gains as a result of physiological stresses associated with higher temperatures. Invasive plant species are already a problem in overgrazed Southwestern grasslands and their spreading will continue with progressing climate change [66,67].

Western grasslands

Characteristics of Western grasslands. The Western grasslands occupy Mediterranean regions of California, and semi-arid and arid regions of Nevada. Although classified in one group, Western grasslands are very diverse and span numerous bioregions. In California, the major bioregions include:

- Southern California Coast. Elevation ranges from 0 to 912 m. Precipitation varies from 250 to 640 mm and temperatures average 16 to 18°C. The growing season lasts 250 to 360 days.
- Sonoran Desert (including parts of the Colorado Desert and Upper Sonoran Desert sections of California and Arizona, and a portion of the Chihuahuan Basin and Range Section in Arizona and New Mexico). Elevation ranges from 91 to 1064 m. Precipitation ranges from 80 to 200 mm with a bimodal pattern. Temperature averages from 16 to 24°C and winters are mild. The growing season lasts 250 to 350 days.
- Mojave Desert. Elevation ranges from −91 to 3344 m. Precipitation ranges from 80 to 250 mm. Temperature averages from 10 to 24°C. The growing season lasts 200 to 300 days.
- Central Valley (including the Sacramento and San Joaquin valleys and portions of the Bay Area bioregions). Elevation ranges from 0 to 243 m. Precipitation ranges from 130 to 760 mm. Temperature averages 13 to 19°C. The growing season lasts 230 to 350 days.

- Central California Coast. Elevation ranges from 0 to 730 m. Precipitation ranges from 350 to 1270 mm. Temperature averages 10 to 17°C. The growing season lasts 200 to 330 days.
- Sierra Nevada. Elevation ranges from 300 to 4407 m. Precipitation ranges from 500 to 2030 mm. Summers are dry with low humidity. Temperature averages 5.5 to 15.5°C. The growing season lasts 20 to 230 days.
- Northern California Coast. Elevation ranges from 0 to 912 m. Precipitation ranges from 1020 to 2540 mm. Temperature averages 10 to 13°C. The growing season lasts 250 to 310 days.
- Klamath Mountains. Elevation ranges from 456 to 2432 m. Precipitation ranges from 1020 to 3050 mm. Temperature averages 7 to 13°C. The growing season lasts 60 to 250 days.
- Modoc Plateau (including the Southern Cascade Section). Elevation ranges from 912 to 3010 m. Precipitation ranges from 300 to 760 mm. Temperature averages 7 to 11°C. The growing season lasts 70 to 140 days.
- San Francisco Bay. Mediterranean climate with maximum rainfall in winter. Precipitation ranges from 508 to 1270 mm.
- Intermountain Desert Bioregion. Summers are hot, but winters are only moderately cold. The average annual temperature ranges 4 to 13°C. Annual precipitation averages 130 to 490 mm, often falling as winter snow. Almost no rain falls during the summer months except in the mountains [27].

California's grasslands cover approximately 25% of the state, either as open grassland, oak woodland, or savanna [68]. California grasslands are among the most endangered ecosystem in the United States. These Mediterranean grasslands were once vegetated by native perennial grasses. European settlers introduced a number of exotic Mediterranean annual grass species that gradually displaced native grasses [69]. These invasive grasses, continuous overgrazing, drought, fire suppression and expanding crop cultivation destroyed the native perennial grass and forb component of the climax plant community [70], with climate change considered as the current driving factor [71]. The conversion from native perennial grassland to annual grassland is usually irreversible unless the site can be cultivated. Based on differences in abundance of native perennial grasses and in the relative dominance of annual versus perennial grasses, the California grassland has been categorized as coastal prairie and the valley grassland [72]. The coastal prairie contains both native and exotic perennial species. Characteristic species for these plant communities are California oatgrass (*Danthonia californica*) and purple needle grass (*Nassella pulchra*). Valley grasslands are dominated by annual grass species. Native perennial grasses are represented by purple needle grass, blue wildrye (*Elymus glaucus*), Sandberg bluegrass (*Poa secunda*), and alkali sacaton (*Sporobolus airoides*).

Repeated severe droughts and increasing temperature are threats to native grass species in the Mediterranean environments of California. Mediterranean annual grasses may have become dominant in the California's Central Valley because they are better adapted to withstand the summer drought than the native perennial grasses, regarding of grazing pressure [72,73]. Although climatic variation is one of the primary determinants of plant community composition in California annual grassland [74,75], effects of historic and recent climate changes may be insufficient to explain alteration of the grassland communities because the dominant species are adapted and tolerant of climate variability [76]. Lenihan et al. [71] evaluated responses of vegetation distribution, carbon, and fire to three scenarios of future climate change for California by 2100 using the MC1 Dynamic General Vegetation Model. Under three future climate scenarios, the simulated responses of the vegetation classes in terms of changes in percentage coverage were similar. Significant declines in the extent of the total cover are predicted for alpine/subalpine forest, conifer forest, mixed evergreen woodland, and shrubland vegetation classes, while mixed evergreen forest and grassland vegetation are predicted to increase in coverage. The desert vegetation class is predicted to decrease in coverage under the neutral climate change model, but increase under the moderately dry and very dry scenarios. In contrast, Byrd et al. [77] predict that grassland habitat loss due to future development could reach 37% by 2100, mostly a result of agricultural expansion. Most of the proposed scenarios project that the dry season duration will be extended resulting in prolonged drought periods. Predicted increase in atmospheric CO_2 concentration may similarly affect productivity of C_4 and C_3 grass species when soil water becomes limited [78] or favor C_4 grasses if precipitation patterns shift to the later part of the growing season [79]. Sala et al. [80] simulated the effects of five most important determinants of changes in biodiversity at the global scale, e.g., land use, climate, nitrogen deposition, biotic exchange, and atmospheric CO_2. Their analysis predicts Mediterranean and grassland ecosystems to be most sensitive to the simulated driver changes, regardless of any interactions among these drivers of change or a lack of such interactions. In contrast, deserts and alpine ecosystems will express the fewest diversity changes, because there is no single driver to which biodiversity in these biomes is extremely sensitive.

Currently, only about 1% of California grasslands are vegetated by native perennial grasses [68]. There have been extensive efforts to restore native perennial grasses in California grasslands [68,81]. Would introduced summer-dormant perennial grasses originating from the Mediterranean Basin help reduce the spreading of introduced Mediterranean annual grass species and increase native perennial grass populations? Limited research data suggest that summer-dormant cool-season grasses originating from the Mediterranean Basin and introduced to Mediterranean environments of California have very limited potential for invasiveness in native summer-dormant cool season grass dominated ecosystems when compared with introduced Mediterranean annuals [82]. Summer-dormant cool-season grasses evolved in association with annual components of Mediterranean Basin grasslands [83], suggesting they have the potential to successfully compete with annual species for limiting resources [84]. Malinowski and Pinchak [41] evidenced that introduced summer-dormant cool-season grasses were the most viable option to maintain cool-season forage production in environments affected by progressing desertification in the Southern Great Plains. Research is needed to evaluate the potential of introduced perennial summer-dormant cool-season grasses to coexist with native summer-dormant cool-season grasses in Mediterranean environments of California as a tool to reduce the competition from invasive, introduced Mediterranean annual grasses.

There are two major ecosystems in Nevada, the Great Basin in the northern and the Mojave Desert in the southern part of the state [85]. The Great Basin varies significantly in elevation, with sagebrush-dominated valleys and numerous mountain ranges. It is also described as "cold desert" with snowy cold winters and hot and dry summers. The Great Basin's vegetation zones can be grouped into several distinct types: salt desert and sagebrush grassland in the valleys, and pinyon-juniper woodland, mountain shrub, subalpine forest, and alpine tundra in high elevations (above 3230 m). Vegetation cover is typically only about 15–40% of the ground surface. The sagebrush grassland is dominated by perennial bunchgrasses such as Great Basin wild rye (*Leymus cinereus*), squirreltail (*Elymus elymoides*), needle-and-thread (*Heterostipa comata*), and Indian rice grass (*Oryzopsis hymenoides*) [86]. This ecosystem relies on a fragile balance among the timing and amount of precipitation, grazing practices, and fire frequencies. A disturbance of the balance, i.e., as a result of a disrupted pattern of precipitation cause by the changing climate, favors invasion by exotic plant species such as cheatgrass (*Bromus tectorum*) [87]. This annual grass dies out in early summer and its dry biomass increases fire frequency in these ecosystems from every 80 years to every 4 years between fire events [88]. This results in disappearance of perennial and dominant grasses and shrubs, and establishment of cheatgrass monocultures with very low forage quality for wildlife or livestock [86].

Mojave Desert in Nevada is characterized by extremely hot summer and cool winter temperatures. The vegetation is dominated by short growing desert shrubs, grasses, herbaceous flowering plants, succulents (cacti and yuccas), and rarely – trees [86]. Many annual plant species grow only in years with significant winter rains (winter annuals) or summer rains (summer annuals). Tree species include screwbean mesquite (*Prosopis pubescens*), western honey mesquite (*Prosopis glandulosa*), velvet ash (*Fraxinus velutina*), several willow species including *Salix exigua* and *Salix gooddingii*, and Fremont's cottonwood (*Populus fremontii*). The symbolic plant of the transition zone between the Mojave and Great Basin deserts is the Joshua tree (*Yucca brevifolia*), a member of the lily family that grows to 10 m height.

Implications of climate change on Western grasslands. The West is already experiencing the impacts of climate change. The period since 1950 has been hotter than any comparably long period in at least 600 years [89]. Based on projections, annual temperatures in California, Nevada and the rest of the Southwest could increase by 1.9 to 5°C with continued growth in global greenhouse gas emissions (A2 emissions scenario), with the greatest increases in the summer and fall by the end of this century [42]. Precipitation is estimated to decrease, especially in winter and spring. Such warmer and drier climate will intensify long-term droughts, affecting equilibrium of the Western ecosystems. The projected climate changes will result in conversions of Western grasslands into shrub communities [90]. Shifting climatic zones to higher elevations, combined with severe drought, will cause extensive tree death across many of the Southwestern mountainous ecosystems [44,91].

Northwestern grasslands

Characteristics of Northwestern grasslands. The Northwest geographic region of the United States is located between the Pacific Ocean and the Rocky Mountains, punctuated by the Cascade and Olympic mountain ranges. It includes the states of Washington, Oregon, Idaho, Montana, and Wyoming. The states of Washington and Oregon have a Mediterranean-type climate with relatively wet winters and dry summers. On the west slopes of the Olympic Mountains are the wettest locations in North America, where annual precipitation exceeds 5000 mm [92], supporting the region's coastal temperate rainforest. Idaho, west part of Montana, and Wyoming have semiarid climate, but because of their topographical diversity, the climate is also varied. The annual precipitation ranges from as little as 120 mm to as much as 1140 mm, both as rain and snow.

Temperatures increased across the Pacific Northwest from 1895 to 2011, with a regionally averaged warming of about 0.7°C [93]. In contrast, no significant changes in precipitation amounts have been occurring in this region. Compared to the period 1970–1990, an increase in average annual temperature of 1.8 to 5.3°C is projected by 2099, depending on the scenario of global greenhouse gas emissions [94]. It is projected that annual average precipitation in the Pacific Northwest will either decrease by 11% or increase by 12% during 2030 to 2059 and range from a 10% decrease to an 18% increase during 2070 to 2099, depending on the various greenhouse gas emission scenarios. These precipitation changes may result in low streamflow west of the Cascades and a greater extent of wildfires throughout the region [95].

Implications of climate change on Northwestern grasslands. Grassland prairies and oak savannas in western parts of the Northwest (west of the Cascades) are adapted to periodic drought and may expand under the projected warmer and drier conditions [92]. This would likely be an expansion upwards in elevation in some areas as a result of tree species mortality [95]. If the precipitation increases, sagebrush steppe systems may decline and be replaced by woodland and forest vegetation. Native grassland and shrubland ecosystems are generally adapted to frequent fires, but projected increases in fire activity may threaten fire intolerant shrubs and associated fauna. Projected climate changes will favor expansion of non-native invasive species, i.e., meadow knapweed (*Centaurea ×moncktonii*) and yellow starthistle (*Centaurea solstitialis*), that may modify the responses of grassland and shrubland ecosystems throughout the Pacific Northwest [96]. Native noxious species, i.e., western juniper (*Juniperus occidentalis*), are also projected to expand affecting the grassland and shrubland areas of eastern Oregon and Washington [97]. The response of invasive grass species to climate change may vary considerably [98]. Exotic annual grasses such as medusahead (*Taeniatherum caput-medusae*), cheatgrass (*Bromus tectorum*), and red brome (*Bromus madritensis* subsp. *rubens*) can alter fire regimes and affect persistence of a number of native components of the ecosystems [98,99].

Predicted warmer temperatures in the Pacific Northwest may increase the risk of forest damage from diseases, i.e., yellow-cedar decline and Cytospora canker of alder (*Alnus* sp.) may be high if annual precipitation decreases, while risk of forest damage from dwarf mistletoes (*Arceuthobium* sp.) and *Armillaria* root disease may be high whether precipitation increases or decreases [100]. Future increases in temperature and precipitation may lead to increased risk of sudden oak death caused by *Phytophthora ramorum* [101] and Swiss needle cast caused by *Phaeocryptopus gaeumannii* [100].

Midwest and Great Plains

Characteristics of Midwestern United States. The Midwest (Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin) represents one of the most intense areas of agriculture in the world [102]. The major agriculture production focuses on corn, soybean, livestock, vegetables, fruits, tree nuts, berries, nursery and greenhouse plants. Forestry is also an important part of the region's economy. The region encompasses the upper basin of the Mississippi River and most of the Ohio River. The Great Lakes are the largest fresh water lake system in the world, providing a major recreation area and a transportation system with access to the Atlantic Ocean [103].

Although land use in the Midwest is dominated by managed ecosystems, there are three prominent environmental gradients in native vegetation [103]. The transition from prairie to forest in southwest to northeast Minnesota is mainly driven by water availability. The south to north transition from Eastern deciduous to Northern mixed hardwood forest in Michigan and Wisconsin is a prominent landscape feature corresponding with climatic and soil gradients. The third gradient reflects the transition from Northern to boreal forest in the far north portions of the region. The Midwest has a typical continental climate with some modifications in the Great Lakes area. Total annual precipitation increases from northwest to southeast and varies from 635 mm in western Minnesota and Iowa to 1016 mm along the Ohio River. Most of the region has a summer pattern of precipitation. Temperatures vary widely from winter to summer and year-to-year. The average annual temperature varies from 3°C in northern Minnesota to 15°C in the Missouri Bootheel.

Implications of climate change on Midwestern agriculture. Climatic trends indicate that the annual mean temperature is increasing in the northern portion of Midwest at a rate of 2°C per century, while the southern part of Midwest experiences a cooling trend at the rate of 0.6°C per century [103]. The projected changes in annual mean temperature are in the range of 3 to 6°C for most of the Midwest (except for the Ohio River Valley) by the end of the twenty-first century. Total annual precipitation has increased in the region by 20% during the twentieth century and it is projected to further increase in the upper Midwest by 20–40% and decrease in the Ohio River Valley by 20% by the end of the twenty-first century. Increases in precipitation will occur mainly in the winter, spring, and fall but decreases will be prominent in the summer [93]. These climatic changes will result in a longer growing season that has already increased an average of 14 days between 1899 and 1992 [104]. Temperature extremes are projected to increase along with warmer nighttime temperatures, affecting both livestock and crops [105].

The dominant natural vegetation of the western and northern Midwest consists of C_3 perennial grasses. Also majority of cultivated grasses, i.e., wheat and perennial ryegrass (*Lolium perenne*), are C_3 grasses. It is predicted that C_3 perennial grasses will be replaced by C_4 perennial grasses as a result of increasing temperature [106]. Model simulations project much more drastic effects on the temperate continental coniferous forest and mixed forest than native grasslands of the Midwest [103]. The northern hardwood forests are likely to undergo a conversion to temperate deciduous forests and savannas. The future of grasslands in the Midwest may be more dependent on agricultural policies and economic conditions than climate [107].

Characteristics of Great Plains grasslands. The Great Plains is the largest grassland province in North America, occupying 172 million hectares [108]. The Great Plains is a region covered in prairie, steppe, and grassland, located west of the Mississippi River tallgrass prairie states and east of the Rocky Mountains in the United States and Canada. It covers parts of the states of Wyoming, Montana, Nebraska, North Dakota, South Dakota, Colorado, Kansas, Oklahoma, Texas, and New Mexico, and the Canadian provinces of Alberta, Manitoba, and Saskatchewan. As outlined in our publication, the Great Plains region is located in the western part of the Midwest and the eastern part of the Northwest, and from Canada in the north to Texas in the south (Fig. 2). The Great Plains region consists of relatively flat plains that increase in elevation from 0 to over 1525 m at the base of mountain ranges along the Continental Divide [109]. Vegetation varies from forest in the mountains of western Montana and Wyoming, to extensive rangelands throughout the Plains, marshes along Texas Gulf Coast, and desert landscapes in far West Texas [110]. The climax vegetation of the Great Plains is mixed prairie but most range is now characterized by the short grasses due to long history of close grazing. The most abundant grasses are blue grama (*Bouteloua gracilis*) and buffalograss (*Buchloe dactyloides*) [111]. Central and northern environments of the Great Plains are dominated by western wheatgrass (*Pascopyrum smithii*) and needlegrasses (*Stipa* sp.). Less dominant grasses are greasegrass (*Tridens flavus*) and sideoats grama (*Bouteloua curtipendula*).

The United States Geological Survey divides the Great Plains in the United States into ten physiographic subdivisions [112]:

- Coteau du Missouri or Missouri Plateau, glaciated – located in east-central South Dakota, northern and eastern North Dakota and northeastern Montana;
- Coteau du Missouri, unglaciated – located in western South Dakota, northeastern Wyoming, southwestern North Dakota and southeastern Montana;
- Black Hills – located in western South Dakota;
- High Plains – located in southeastern Wyoming, southwestern South Dakota, western Nebraska (including the Sand Hills), eastern Colorado, western Kansas, western Oklahoma, eastern New Mexico, and northwestern Texas (including the Llano Estacado and Texas Panhandle);
- Plains Border – located in central Kansas and northern Oklahoma (including the Flint, Red and Smoky Hills);
- Colorado Piedmont – located in eastern Colorado;
- Raton section – located in northeastern New Mexico;
- Pecos Valley – located in eastern New Mexico;
- Edwards Plateau – located in south-central Texas;
- Central Texas section – located in Central Texas.

The climate is highly diverse as a result of the region's large north-south extent and increasing elevation from east to west. Great Plains experience multiple weather extremes, including floods, droughts, severe storms, tornadoes, hurricanes, and winter storms. Precipitation ranges from 250 mm in the northwest to 1250 mm along the eastern region boundary in East Texas [109]. Annual average temperatures range from less than 5°C in the mountains of Wyoming and Montana to more than 21°C in South Texas, with extremes ranging from −57°C in Montana to 49°C in North Dakota and Kansas. Most of the precipitation (70–80%) falls in the months between April and September and in the form of torrential rains with much runoff. Evaporation is about twice as high in the Southern as in the Northern Great Plains, and water requirement of the growing vegetation is proportionally higher. The frost-free season ranges from about 100 days at the Canada border to 200 days in Texas. Daylength varies dramatically from north to south in summer, resulting in a rapid growth of vegetation in the north and total seasonal yields similar to those further south.

Implications of climate change on Great Plains grasslands. Climate change impacts on agriculture and ecosystems will vary across the highly diverse region of the Great Plains. Over 80% of the land area in the Great Plains is utilized by agriculture, consisting in almost equal proportions of crop and livestock production [109]. Agriculture in this region has been heavily dependent on withdrawals of water from the High Plains Ogallala aquifer at rates that have already been shown to be unsustainable [113]. In the long-term, climate change impacts will have detrimental effects increasing variability in crop and agricultural production [114]. Climate change projections indicate that future precipitation patterns will vary across the region. In northern states, the amount of winter and spring precipitation and the number of days with heavy downpours and snowfall are projected to increase [89,109]. Central part of the Great Plains is projected to experience drier summers in some areas. Southern states, including

Texas and Oklahoma, are also projected to experience longer periods of drought. The average annual temperatures in the Northern and Central Great Plains have increased by about 1.1°C over the last century, with larger increases in minimum than in maximum temperatures and more pronounced winter warming [115]. Maximum temperatures reach more than 38°C in the Southern Plains and 35°C in the Northern Plains for at least 7 days a year [109]. The number of days over 38°C is projected to double in the northern and quadruple in the southern part of Great Plains by mid-century, regardless of greenhouse gas emission scenarios [93]. Similar increases are expected in the number of nights with minimum temperatures higher than 27°C in the south and 15°C in the north, except for mountain regions. Model projections for the Great Plains include annual temperature increases of 1.6 to 2.2°C by 2030 and 3.7 to 6.1°C by 2090; an increase in heat events (3 or more days ≥41°C); more hot days (number of days ≥41°C); and an increase in the number of growing degree days, as compared with the period from 1961–1990 [115]. As a consequence, the growing season in the Great Plains will be extended by mid-century by an average of 24 days relative to the 1971–2000 average. The Great Plains is already experiencing warmer winters, and further temperature increases are projected for this season. The dormancy period for winter crops is shortening, which will reduce yields and grazing season of some important livestock feed crops, such as winter wheat (*Triticum aestivum*) [116], and increase the potential for damage by spring freezes [109,114]. Continued livestock production and associated water usage in this region will exacerbate water shortages as climate change impacts continue.

Productivity of native grasslands in the Northern Great Plains is highly dependent on winter and early spring precipitation patterns, thus predicted changes in the seasonality of precipitation will have large impacts on these vegetation communities [117,118]. Increased variability in precipitation patterns will increase plant water stress and affect photosynthesis, aboveground productivity, and soil CO_2 flux resulting in altered carbon storage [119]. In the Northern Great Plains, increased precipitation and CO_2 concentration will result in higher net primary productivity of native grasslands, but digestibility of forage grasses may be reduced under these conditions [120,121]. Increasing temperature during summer months will shift the plant composition of mixed C_3 and C_4 grasslands towards warm-season species [122] and increase the potential for invasion of these temperate grasslands by subtropical C_4 species [123–125]. An eastward shift in the east-west forest-grass ecotone will also occur in response to changes primarily in precipitation, but also in temperature, resulting in a reduction in forest and an increase in grassland area in the central United States [126].

Northeast

The Northeast is a geographical region of the United States bounded to the north by Canada, to the east by the Atlantic Ocean, to the south by the Southern United States, and to the west by the Midwestern United States. The Northeastern United States covers the states of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania, Maryland, Washington DC, Virginia, and West Virginia. The northeastern states possess a wide range of climates [127]. Annual precipitation varies from over 1270 mm in the coastal areas to 800 mm in the western part of Pennsylvania and New York. Annual mean temperatures range from 10°C in Connecticut south to Maryland, and 4°C in most of New York state, New England, and northern Pennsylvania. During winter, frequent storms bring bitter cold and frozen precipitation, especially to the north. Summers are warm and humid, especially to the south.

The Northeast landscape is dominated by forest, grasslands, coastal zones, beaches and dunes, and wetlands. Anthropogenic grasslands are considered the dominant representatives of grasslands in this region. The long-term precipitation patterns, latitude and elevation, and mild temperatures sustain forest growth as the climax vegetation. Forest clearing and occasionally fire can create opportunity for establishment of grassland communities that can be sustained by management, i.e., mowing or grazing. Temperature and precipitation patterns are influenced by latitude, elevation and proximity to the Atlantic Ocean and the Great Lakes [128], consequently these vary most dramatically from north to south. Rain shadow areas in the Appalachian Mountains, coupled with shallow, rocky soils, further influence season-long grassland production patterns. Soil as a function of regional geology also influences the types and distribution of grass community production. Soils in the northern portions of the region tend to be derived from glaciated material, and southwards from weathered sedimentary and metamorphic materials, in situ or transported by water and gravity. Temperature and precipitation gradients favor forest biomes, but slight changes in either temperature or precipitation could shift conditions enough to favor development of naturalized grasslands. The general climate patterns for the Northeastern United States favor cool-season, temperate origin species in the northern portion and warm-season, temperate to subtropical species in the southern part (Southeast). The Mid-South is considered a transition zone where both cool-season and warm-season temperate species thrive depending on temperatures during the year.

Many cool-season, temperate origin grasses such as Kentucky bluegrass (*Poa pratensis*) and other bluegrasses (*Poa* sp.), orchardgrass (*Dactylis glomerata*), redtop (*Agrostis alba*) and other bentgrasses (*Agrostis* sp.), timothy (*Phleum pratense*), smooth bromegrass (*Bromus inermis*), and reed canarygrass (*Phalaris arundinacea*) are used commonly or found naturalized in pastures and meadows. In the Mid-South or the transition zone, tall fescue (*Lolium arundinaceum*, formerly known as *Festuca arundinacea*) is the predominant grass, with some bluegrass, bentgrass, and orchardgrass depending upon location and weather patterns. Tall fescue has remarkable adaptability to a range of challenging growing conditions including droughty soils, soil acidity, relatively high temperatures and pests [129]. Consequently, tall fescue is the dominant cool-season species growing throughout the transition zone of the Eastern USA. Much of the tall fescue is infected with *Neotyphodium coenophialum*, an endophytic fungus which causes tall fescue toxicity in consuming herbivores [129]. The exceptional resilience attributed to tall fescue seems to be associated with the presence of the fungal endophyte. The mutualistic relationship between host grass and fungal symbiont appears to confer a range of physiological and biochemical features that translate into tolerance of environmental and biological stressors. Many novel host–endophyte associations have been developed to minimize the deleterious influences of the associations on livestock performance. These associations, while beneficial in terms of livestock performance, might succumb to additional environmental stresses allowing a resurgence of naturalized host–endophyte lines that persist in naturalized grassland and low-input pasture. The main tall fescue cultivar, "Kentucky 31", was planted extensively throughout the transition zone, starting in the 1950s. Recently, with increasing understanding of the toxicity issue, new cultivars are available with nontoxic novel endophytes and are recommended for use in new or replacement plantings. Other grasses are used to a limited extent for forage within the region and include perennial ryegrass, annual ryegrass (*L. multiflorum*), and crabgrass (*Digitaria* sp.). Many legumes are important in pastures and meadows of the Eastern USA. In symbiosis with *Rhizobium* bacteria in root nodules, they fix atmospheric N and improve forage quality through their lower cell wall fiber content than grasses at similar maturity stages. Several different genotypes of white clover (*Trifolium repens*) constitute the primary legume mixed with grasses in pastures from Maine south to Georgia. Other perennial cool-season legumes used include red clover (*T. pratense*), birdsfoot trefoil (*Lotus corniculatus*), forage soybean (*Glycine max*), alfalfa (*Medicago sativa*) and alsike clover (*T. hybridum*).

Implications of climate change on Northeastern grasslands. Similar to other regions of the USA, the projected temperature increase in the Northeast will be highly dependent on global emissions of greenhouse gases [127]. Under increasing greenhouse gas emission (A2 scenario), the mean annual temperatures are projected to increase by 2.4°C to 5.6°C by the 2080s. If the greenhouse gas emissions should not increase (B1 scenario), the projected temperature increase will range from 1.7°C to 3.3°C. Regardless of the greenhouse emission scenarios, the frequency, intensity, and duration of heat waves are expected to increase, with larger increases under higher emissions [89]. The number of days per year with temperatures above 32°C will significantly increase throughout much of the southern portion of the region, including Maryland and Delaware, and southwestern West Virginia and New Jersey. Long-term precipitation records show an increasing trend for the Northeast. For example, the average annual precipitation of 1040 mm for New England has increased by 95 mm (9%) over the last century [130]. Despite this trend toward more precipitation, longer periods without rainfall and longer growing seasons are more frequent, resulting in a drier growing season, especially during the summer months, when temperatures and evapotranspiration are high [131]. By the end of the century, the average annual precipitation is expected to increase by 7% under the low emissions (B1) scenario and 14 % under the high emissions (A2) scenario.

The broad range of plant resources occurring in grasslands provides a means to respond to dynamic weather patterns and resource conditions. The carbon assimilation pathways that exist in grasses might provide an additional resource to mitigate atmospheric CO_2 enrichment. Grasses with the C_4 metabolic pathway appear to have evolved from plants adapting to high light intensities, high temperatures, and restricted moisture availability [132]. Species having this metabolic pathway tend to dominate tropical and subtropical regions. They are considerable more N-use and water-use efficient than are C_3 species. Much of the grassland in the Mid-South (the transition zone) is a mélange of C_3 and C_4 species that shift with respect to frequency in the sward as a function of seasonal temperature patterns and precipitation. Consequently, any benefit in productivity that might be realized from elevated atmospheric CO_2 concentrations might be lost in C_3 species at higher temperatures where C_4 species thrive. It is difficult to make a general recommendation for grasslands management since the production goal along with the location will dictate what needs to be grown. Seasonal patterns of productivity can be complementary with cool-season temperate species achieving optimal production and nutritive value in spring and again in late summer or early autumn, while warm-season temperate or subtropical species reach peak production during mid-summer. Changing temperature and precipitation patterns could then in fact, increase the reach of the transition zone into more northern latitudes of the Northeast.

Southeast

The Southeastern United States covers the states of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, and South Carolina. The geological provinces of the southeastern humid region, extending west from the Atlantic Ocean, include the Coastal Plain, the Piedmont, the Appalachian Province (the Blue Ridge Mountains, the Great Valley and Ridge region, and the Appalachian Mountains), the Allegheny and Cumberland Plateaus, and the central lowlands [128]. The Southeastern region of the United States has a humid subtropical climate, but southern Florida has a tropical monsoon climate and significantly warmer winters. Most of the region experiences mild winters and hot, humid summers. The average annual temperature ranges from 15 to 21°C [36]. The growing season lasts for 200 to 300 days, with frost occurring nearly every winter. Annual precipitation ranges from 1020 to 1530 mm and is almost evenly distributed throughout the year with slight peaks in midsummer or early spring due to increased frequency of thunderstorms. Precipitation exceeds evaporation, but summer droughts occur. Changing agricultural practices in the Southeastern U.S. show a decline in cropland while pasture acreage remains relatively stable [133].

The natural vegetation of the Southeastern United States is a mosaic of forest coastal plain savannas, Piedmont prairies, limestone glades and barrens in the central portion of the region, canebrakes, and isolated prairie [134]. All of the economically important forage species used in the Southeast are not native to the region, nor are they native to other regions of the USA [135]. Warm-season and tropical grasses are very adapted to the climate of the Southeast. These include various land-race sources of bermudagrass (*Cynodon* sp.) as well as improved cultivars selected from naturalized populations. Other important species include johnsongrass (*Sorghum halepense*), bahiagrass (*Paspalum notatum*), and dallisgrass (*P. dilatatum*) occurring widely in the deeper south part of the region. In Florida, several subtropical species are prevalent, including limpograss (*Hemarthria altissima*), *Desmodium*, and *Pennisetum* species. Winter annual grasses sown include rye (*Secale cereale*), wheat and annual ryegrass.

Summer annual grasses are also sown to amplify production in mid-season and include forage-type sorghum (*S. bicolor*), pearl millet (*P. glaucum*), and foxtail millet (*Setaria italica*). Forage legumes are represented by crimson clover (*T. incarnatum*), berseem clover (*T. alexandrinum*), arrowleaf clover (*T. vesiculosum*), and perennial peanut (*Arachis hypogea*).

Implications of climate change on Southeastern grasslands. Since 1970, the average annual temperature in the Southeast region have increased by about 1.1°C, with the greatest warming occurring during the summer [136]. Temperatures are projected to increase by 2.2 to 4.4°C by the end of the century. The number of days with temperature over 35°C will significantly increase while the number of days with frost or freeze during winter will decrease. Temperatures in the inland areas of the Southeast are projected to increase more than these along the coasts. Natural cycles, including the El Niño Southern Oscillation, tropical weather systems, and differences in atmospheric pressure across key regions of the Earth, are anticipated to drive short-term temperature fluctuations. There is less confidence in projections of future precipitation patterns because the Southeast is located in the transition zone between projected wetter conditions to the north and drier conditions to the southwest, many of the model projections show only small changes relative to natural variations [136]. Generally, the models project drier conditions in the far southwest of the region and wetter conditions in the far northeast of the region [93]. One climate characteristic specific for this region is predicted increase in sea level that will affect portions of the Southeast that are highly vulnerable to seas level rise [136].

Silvopastoral grazing system dominates the Northeast and Southeast regions of the USA. Projected warming trend of the climate may cause northern forest tree species to decline, i.e., eastern hemlock (*Tsuga canadensis*), red spruce (*Picea rubens*), and sugar maple (*Acer saccharum*). The habitat is projected to become more suitable for southern species such as eastern red cedar (*Juniperus virginiana*) and loblolly pine (*Pinus taeda*). A major transition in forest composition is not expected until 2040 to 2069 [137]. Warming will also reduce the abundance of tall fescue, the major component of the Southeast grasslands, regardless of projected precipitation patterns [138]. The persisting endophyte-infected tall fescue will have higher concentrations of toxic alkaloids which may exacerbate fescue toxicosis in grazing cattle.

Conclusions

The climate has been changing many times in the Earth's history. What differentiates the current change is a close link to human activities resulting in a rapidly increasing rate of greenhouse gas emissions [139]. The rapidly progressing greenhouse effect is causing an increase in Earth's average temperature, resulting in climate anomalies and abnormal weather patterns worldwide. The last time humans caused a drastic disruption of climate patterns in North America was the Dust Bowl era in the 1930's as a result of deleterious agricultural practices in the 1920's applied to meet increasing demand for food in the USA [113]. It is estimated that about 41 million hectares of the Great Plains were affected by wind erosion and drought and contributed significantly to the Great Depression [140]. The Dust Bowl dramatically demonstrated the effects of poor land-use practices combined with weather variability and change on ecosystems functions. A similar scenario is apparent today. Depletion of water resources in the Great Plains due to unsustainable water usage is likely to be exacerbated by future changes in temperature and precipitation that appear to be linked with human activity [141]. The impacts of recent and future climate changes will vary across the USA. Southern and southwestern, and to some extent southeastern regions are already experiencing accelerated increase in temperature and decrease in precipitation, resulting in repeated and severe droughts. This desertification process will continue in the next decades and will dramatically change the flora and fauna of these environments. The northern, northwestern, and northeastern regions are likely to experience less dramatic shifts in climatic patterns. Many of the regions already affected by progressing droughts are important sources of agricultural production to supply millions of citizens. Future climate conditions will require carefully planned responses to predicted local climate stressors, i.e., adjusting planting patterns in response to altered crop yields and crop species, introducing drought-tolerant varieties, and restricting trade to protect food security [114]. Genetic improvement of both forage crops for managed grasslands and grazing ruminants will be an integral part of future grassland agriculture [128]. Adaptive actions must be taken to secure food production, consumption, research, and education to avoid economic losses posed by changing climate [142,143]. For pastures and rangelands, science-based solutions will help producers and agribusiness make decisions about implementing new technologies to help reduce risk associated with progressing climate change.

Acknowledgments

The authors would like to express their acknowledgements to David Jones and Bryan Hope of Texas AgriLife Research and Extension Center at Vernon, TX for compiling weather data sets used for this presentation.

References

1. O'Mara FP. The role of grasslands in food security and climate change. Ann Bot. 2012;110:1263–1270. http://dx.doi.org/10.1093/aob/mcs209
2. Brady NC, Weil RR. The nature and properties of soils. 11th ed. Upper Saddle River, NJ: Prentice-Hall, Inc.; 1996.
3. Kemp DR, Michalk DL. Towards sustainable grassland and livestock management. J Agric Sci. 2007;145:543–564. http://dx.doi.org/10.1017/S0021859607007253
4. Hanselka CW, Livingston SD, Bade D. Renovation practices to improve rainfall effectiveness on rangeland and pastures. College Station, TX: Texas Agricultural Extension Service, Texas A & M University System; 1993.
5. Dormaar JF, Naeth MA, Willms WD, Chanasyk DS. Effect of native prairie, crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.] and Russian wildrye (*Elymus junceus* Fish.) on soil chemical properties. Journal of Range Management. 1995;48:258–263. http://dx.doi.org/10.2307/4002430
6. Duebbert HF, Jacobson ET, Higgins KF, Podoll EB. Establishment of seeded grasslands for wildlife habitat in the Prairie Pothole Region. Washington, DC: U.S. Fish and Wildlife Service; 1981. (Special Scientific Report, Wildlife; vol 234).
7. Pieper RD. Grasslands of central North America. In: Suttie JM, Reynolds SG, Batello C, editors. Grasslands of the world. Rome: Food and Agricultural Organization of the United Nations; 2005. p. 221–263. (Plant Production and Protection Series; vol 34).
8. Lubowski RN, Vesterby M, Bucholtz S, Baez A, Roberts M. Major uses of land in the United States, 2002. Washington, DC: U.S. Department of Agriculture; 2006. (Economic Information Bulletin; vol 14).
9. Lauenroth WK. Grassland primary production: North American grasslands in perspective. In: French NR, editor. Perspectives in grassland ecology. New York, NY: Springer; 1979. p. 3–24. (Ecological Studies; vol 32).
10. Lauenroth WK, Milchunas DG, Dodd JL, Hart RH, Heitschmidt RK, Rittenhouse LR. Effects of grazing on ecosystems of the Great Plains. In: Vavra M, Laycock WA, Pieper RD, editors. Ecological implications of livestock herbivory in the West. Denver, CO: Society for Range Management; 1994. p. 69–100.
11. Dixon AP, Faber-Langendoen D, Josse C, Loucks CJ, Morrison J. Distribution mapping of world grassland types. J Biogeogr. 2014;41:2003–2019. http://dx.doi.org/10.1111/jbi.12381
12. Nielsen-Gammon JW. The changing climate of Texas. In: Schmandt J, Clarkson J, North GR, editors. The impact of global warming on Texas. 2nd ed. Austin, TX: University of Texas Press; 2011.
13. Periman R, Dawe C, Rickel B, Unthank A, Green C, Jemison R, et al. Southwestern region climate change trends and forest planning. Washington, DC: U.S. Department of Agriculture Forest Service; 2010.

14. Morgan JA. Raising atmospheric CO_2 and global climate change: responses and management implications for grazing lands. In: Raynolds SG, Frame J, editors. Grasslands: developments, opportunities, perspectives. Enfield, NH: Food and Agriculture Organization of the United Nations, Rome Italy and Science Publishers, Inc.; 2005. p. 235–260.

15. Nielsen-Gammon JW, Zhang F, Odins AM, Myoung B. Extreme rainfall in Texas: patterns and predictability. Physical Geography. 2005;26:340–364. http://dx.doi.org/10.2747/0272-3646.26.5.340

16. Combs S. The impact of the 2011 drought and beyond. Austin, TX: Texas Comptroller of Public Accounts; 2012.

17. Cook BI, Seager R, Smerdon JE. The worst North American drought year of the last millennium: 1934. Geophys Res Lett. 2014;41:7298–7305. http://dx.doi.org/10.1002/2014GL061661

18. Nielsen-Gammon JW. The 2011 Texas drought. A briefing packet for the Texas legislature. College Station, TX: Office of the State Climatologist Report; 2011.

19. Dybas C, Than K. The National Science Foundation [Internet]. Cause of California drought linked to climate change. 2014 [cited 2016 Apr 8]. Available from: http://www.nsf.gov/news/news_summ.jsp?cntn_id=132709&WT.mc_id=USNSF_52&WT.mc_ev=click

20. Giorgi R, Meehl GA, Kattenberg A, Grassl H, Mitchell JFB, Stouffer RJ, et al. Simulation of regional climate change with global coupled climate models and regional modelling techniques. In: Watson RT, Zinyowerra MC, Moss RH, Dokken DJ, editors. The regional impacts of climate change: an assessment of vulnerability. New York, NY: Cambridge University Press; 1998. p. 427–437.

21. Campbell BD, Stafford Smith DM, McKeon GM. Elevated CO_2 and water supply interactions in grasslands: a pasture and rangelands management perspective. Glob Chang Biol. 1997;3:177–187. http://dx.doi.org/10.1046/j.1365-2486.1997.00095.x

22. French NR. Perspectives in grassland ecology: results and applications of the US/IBP grassland biome study. New York, NY: Springer; 1979. http://dx.doi.org/10.1007/978-1-4612-6182-7

23. Coupland RT. Natural grasslands, introduction and Western Hemisphere. Amsterdam: Elsevier; 1992. (Ecosystems of the World; vol 8A).

24. Finch DM. Assessment of grassland ecosystem conditions in the Southwestern United States. Volume 1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2004. (General Technical Report RMRS; vol GTR-135-1).

25. Sims PL. Grasslands. In: Barbour MG, Billings WD, editors. North American terrestrial vegetation. New York, NY: Cambridge University Press; 1988. p. 265–286.

26. Odum EP. Fundamentals of ecology. 3rd ed. Philadelphia, PA: Saunders; 1971.

27. McNab H, Avers PA. Ecological subregions of the United States. Section descriptions. Washington, DC: U.S. Department of Agriculture, Forest Service; 1994.

28. Ford PL, Potter DU, Pendleton R, Pendleton B, Robbie WA, Gottfried GJ. Southwestern grassland ecology. In: Finch DM, editor. Assessment of grassland ecosystem conditions in the Southwestern United States. Volume 1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2004. p. 18–48. (General Technical Report RMRS; vol GTR-135-1).

29. Fletcher R, Robbie WA. Historic and current conditions of Southwestern grasslands. In: Finch DM, editor. Assessment of grassland ecosystem conditions in the Southwestern United States. Volume 1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2004. p. 120–129. (General Technical Report RMRS; vol GTR-135-1).

30. Robbie WA. Grassland assessment categories and extent. In: Finch DM, editor. Assessment of grassland ecosystem conditions in the Southwestern United States. Volume 1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2004. p. 11–17. (General Technical Report RMRS; vol GTR-135-1).

31. Archer SR, Predick KI. Climate change and ecosystems of the Southwestern United States. Rangelands. 2008;30:23–28. http://dx.doi.org/10.2111/1551-501X(2008)30[23:CCAEOT]2.0.CO;2

32. Fenneman NM. Physiographic divisions of the United States. Ann Assoc Am Geogr. 1928;18:261–353. http://dx.doi.org/10.1080/00045602809357034

33. Hereford R, Webb RH, Graham S. Precipitation history of the Colorado Plateau Region, 1900–2000. United States Geological Survey Fact Sheet 119-02 [Internet]. Washington,

DC: United States Department of Interior; 2002 [cited 2016 Jun 7]. Available from: http://pubs.usgs.gov/fs/2002/fs119-02/fs119-02.pdf

34. Schwinning S, Belnap J, Bowling DR, Ehleringer JR. Sensitivity of the Colorado Plateau to change: climate, ecosystems, and society. Ecol Soc. 2008;13:28.
35. Tuhy JS, Comer P, Dorfman D, Lammert M, Humke J, Cholvin B, et al. A conservation assessment of the Colorado Plateau Ecoregion. Moab, UT: The Nature Conservancy, Moab Project Office; 2002.
36. Bailey RG. Description of the ecoregions of the United States. Washington, DC: United States Department of Agriculture; 1980. (Miscellaneous Publication; vol 1391).
37. Turner RM. Cold-temperate desertlands. In: Brown DE, editor. Biotic communities: Southwestern United States and Northwestern Mexico. Salt Lake City, UT: University of Utah Press; 1994. p. 145–155.
38. Ganskopp D, Bohnert D. Nutritional dynamics of 7 northern Great Basin grasses. Journal of Range Management. 2001;54:640–647. http://dx.doi.org/10.2307/4003664
39. Read JC, Anderson SJ. Texas bluegrass. In: Casler MD, Duncan RR, editors. Turfgrass biology, genetics, and breeding. Hoboken, NJ: John Wiley and Sons; 2003. p. 61–66.
40. Amme D. Nasella notes. Grasslands. 2003;13:1–5.
41. Malinowski DP, Pinchak WE. Summer dormancy trait as a strategy to provide perennial cool-season grass forage alternatives in southern latitude environments affected by climate change. Agron J. 2015;107:1227–1234. http://dx.doi.org/10.2134/agronj14.0628
42. Garfin G, Franco G, Blanco H, Comrie A, Gonzalez P, Piechota T, et al. Southwest. In: Melillo JM, Richmond TC, Yohe GW, editors. Climate change impacts in the United States. Washington, DC: U.S. Government Printing Office; 2014. p. 462–486. http://dx.doi.org/10.7930/J08G8HMN
43. Thomey ML, Ford PL, Reeves MC, Finch DM, Litvak ME, Collins SL. Climate change impacts on future carbon stores and management of warm deserts of the United States. Rangelands. 2014;36:16–24. http://dx.doi.org/10.2111/RANGELANDS-D-13-00045.1
44. van Mantgem PJ, Stephenson NL, Byrne JC, Daniels LD, Franklin JF, Fule PZ, et al. Widespread increase of tree mortality rates in the Western United States. Science. 2009;323:521–524. http://dx.doi.org/10.1126/science.1165000
45. Chen CC, Gillig D, McCarl BA. Effects of climatic change on a water dependent regional economy: a study of the Texas Edwards aquifer. Clim Change. 2001;49:397–409. http://dx.doi.org/10.1023/A:1010617531401
46. Northup BK, Phillips WA, Mayeux HS. A modified forage system for stocker production in the Southern Great Plains, USA. In: Omara FP, editor. Proceedings of the 20th International Grassland Congress; 2005 Jun 26 – Jul 1; Dublin, Ireland. Wageningen: Wageningen Academic Publishers; 2005. p. 469.
47. Malinowski DP, Hopkins AA, Pinchak WE, Sij JW, Ansley RJ. Productivity and survival of defoliated wheatgrasses in the Rolling Plains of Texas. Agron J. 2003;95:614–626. http://dx.doi.org/10.2134/agronj2003.0614
48. Gillen RL, Berg WA. Response of perennial cool-season grasses to clipping in the Southern Plains. Agron J. 2005;97:125–130. http://dx.doi.org/10.2134/agronj2005.0125
49. Barnes RF, Miller DA, Nelson JC. Forages. Vol. I. An introduction to grassland agriculture. 5th ed. Ames, IA: Iowa State University Press; 1995.
50. Laude HM. The nature of summer dormancy in perennial grasses. Bot Gaz. 1953;114:284–292. http://dx.doi.org/10.1086/335770
51. Vegis A. Dormancy in higher plants. Annu Rev Plant Physiol. 1964;15:185–224. http://dx.doi.org/10.1146/annurev.pp.15.060164.001153
52. Volaire F, Norton M. Summer dormancy in perennial temperate grasses. Ann Bot. 2006;98:927–933. http://dx.doi.org/10.1093/aob/mcl195
53. Craven KD, Clay K, Schardl CL. Systematics and morphology. In: Fribourg HA, Hannaway DA, West CP, editors. Tall fescue online monograph [Internet]. Corvallis, OR: Oregon State University Extension Service, The University of Tennessee Agricultural Experiment Station and University of Arkansas, College of Agricultural, Food and Life Sciences; 2010 [cited 2016 Jun 7]. Available from: http://forages.oregonstate.edu/tallfescuemonograph/morphology/abstract
54. Copani V, Testa G, Lombardo A, Cosentino SL. Evaluation of populations of *Dactylis*

glomerata L. native to Mediterranean environments. Crop Pasture Sci. 2012;63:1124–1134. http://dx.doi.org/10.1071/CP12276

55. McKell CM, Perrier ER, Stebbins GL. Responses of two subspecies of orchardgrass (*Dactylis glomerata* subsp. *lusitanica* and *judaica*) to increasing soil moisture stress. Ecology. 1960;41:772–778. http://dx.doi.org/10.2307/1931811
56. Oram RN. Ecotypic differentiation for dormancy levels in oversummering buds of *Phalaris aquatica* L. Bot Gaz. 1983;144:544–551. http://dx.doi.org/10.1086/337409
57. Ofir M. Seasonal changes in the response to temperature of summer-dormant *Poa bulbosa* L. bulbs. Ann Bot. 1986;58:81–89.
58. Ofir M. Effects of induction level on morphogenetic aspects of onset of summer dormancy and flowering in *Hordeum bulbosum* L. Israel Journal of Botany. 1981;30:173–180.
59. Kigel J, Konsens I, Rosen N, Rotem G, Kon A, Fragman-Sapirb O. Relationships between flowering time and rainfall gradients across Mediterranean–desert transects. Isr J Ecol Evol. 2011;57:91–109. http://dx.doi.org/10.1560/IJEE.57.1-2.91
60. Volaire F, Norton MR, Lelièvre F. Summer drought survival strategies and sustainability of perennial temperate forage grasses in Mediterranean areas. Crop Sci. 2009;49:2386–2392. http://dx.doi.org/10.2135/cropsci2009.06.0317
61. Culvenor RA. Breeding and use of summer-dormant grasses in Southern Australia, with special reference to *Phalaris*. Crop Sci. 2009;49:2335–2346. http://dx.doi.org/10.2135/cropsci2009.06.0321
62. Hopkins AA, Bhamidimarri S. Breeding summer-dormant grasses for the United States. Crop Sci. 2009;49:2359–2362. http://dx.doi.org/10.2135/cropsci2009.06.0329
63. Lelièvre F, Volaire F. Current and potential development of perennial grasses in rainfed Mediterranean farming systems. Crop Sci. 2009;49:2371–2378. http://dx.doi.org/10.2135/cropsci2009.06.0324
64. Turnbull L, Wainwright J, Ravi S. Vegetation change in the Southwestern USA: patterns and processes. In: Mueller EN, Wainwright J, Parsons AJ, Turnbull L, editors. Patterns of land degradation in drylands. Understanding self-organised ecogeomorphic systems. Dordrecht: Springer; 2014. p. 289–313. http://dx.doi.org/10.1007/978-94-007-5727-1_11
65. Milchunas DG. Responses of plant communities to grazing in the Southwestern United States. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2006. (General Technical Report RMRS; vol GTR-169).
66. Hayes GF, Holl KD. Cattle grazing impacts on annual forbs and vegetation composition of mesic grasslands in California. Conserv Biol. 2003;17:1694–1702. http://dx.doi.org/10.1111/j.1523-1739.2003.00281.x
67. Loeser MRR, Sisk TD, Crews TE. Impact of grazing intensity during drought in an Arizona grassland. Conserv Biol. 2007;21:87–97. http://dx.doi.org/10.1111/j.1523-1739.2006.00606.x
68. Barry S, Larson S, George M. California native grasslands: a historical perspective. Grasslands. 2006;16:7–11.
69. Brossard CC, Randall JM, Hoshovsky MC. Invasive plants of California's wildlands. Berkeley, CA: University of California Press; 2000.
70. Baker HG. Sources of the naturalized grasses and herbs in California. In: Huenneke LF, Mooney HA, editors. Grassland structure and function: California annual grassland. Dordrecht: Kluwer Academic Publishers; 1989. p. 29–38. http://dx.doi.org/10.1007/978-94-009-3113-8_3
71. Lenihan JM, Bachelet D, Neilson RP, Drapek R. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. Clim Change. 2008;87(1 suppl):S215–S230. http://dx.doi.org/10.1007/s10584-007-9362-0
72. D'Antonio C, Bainbridge S, Kennedy C, Bartolome J, Reynolds S. Ecology and restoration of California grasslands with special emphasis on the influence of fire and grazing on native grassland species. Berkeley, CA: University of California, Department of Integrative Biology and Department of Environmental Science, Policy, and Management; 2000.
73. Hamilton JG, Holzapfel C, Mahall BE. Coexistence and interference between a native perennial grass and non-native annual grasses in California. Oecologia. 1999;121:518–526. http://dx.doi.org/10.1007/s004420050958
74. Talbot MW, Biswell HH, Hormay AL. Fluctuations in the annual vegetation of California. Ecology. 1939;20:394–402. http://dx.doi.org/10.2307/1930392

75. Jackson RD, Bartolome JW. A state-transition approach to understanding nonequilibrium plant community dynamics in Californian grasslands. Plant Ecol. 2002;62:49–65. http://dx.doi.org/10.1023/A:1020363603900

76. Jackson RD, Bartolome JW. Grazing ecology of California grasslands. In: Stromberg MR, Corbin JD, D'Antonio C, editors. California grasslands: ecology and management. Berkeley, CA: University of California Press; 2007. p. 197–206. http://dx.doi.org/10.1525/california/9780520252202.003.0017

77. Byrd KB, Flint LE, Alvarez P, Casey CF, Sleeter BM, Soulard CE, et al. Integrated climate and land use change scenarios for California rangeland ecosystem services: wildlife habitat, soil carbon, and water supply. Landsc Ecol. 2015;30:729–750. http://dx.doi.org/10.1007/s10980-015-0159-7

78. Samarakoon AB, Gifford RM. Elevated CO_2 effects on water use and growth of maize in wet and drying soils. Aust J Plant Physiol. 1996;23:63–74. http://dx.doi.org/10.1071/PP9960063

79. Owensby CE, Ham JM, Knapp AK, Auen LM. Biomass production and species composition in a tallgrass prairie ecosystem after long-term exposure to elevated atmospheric CO_2. Glob Chang Biol. 1999;5:497–506. http://dx.doi.org/10.1046/j.1365-2486.1999.00245.x

80. Sala OE, Chapin III, FS Armesto JJ, Berlow E, Bloomfield J, Dirzo R, et al. Global biodiversity scenarios for the year 2100. Science. 2000;287:1770–1774. http://dx.doi.org/10.1126/science.287.5459.1770

81. Stromberg MR, D'Antonio CM, Young TP, Wirka J, Kephart PR. California grassland restoration. In: Stromberg MR, Corbin JD, D'Antonio CM, editors. Ecology and management of California grasslands. Berkeley, CA: University of California Press; 2007. p. 254–280. http://dx.doi.org/10.1525/california/9780520252202.003.0021

82. Vaughn KJ, Biel C, Clary JJ, de Herralde F, Aranda X, Evans RY, et al. California perennial grasses are physiologically distinct from both Mediterranean annual and perennial grasses. Plant Soil. 2011;345:37–46. http://dx.doi.org/10.1007/s11104-011-0757-3

83. Naveh Z. Mediterranean grasslands in California and Israel. Journal of Range Management. 1960;13:302–306. http://dx.doi.org/10.2307/3894785

84. Fernández Alés R, Laffarga JM, Ortega F. Strategies in Mediterranean grassland annuals in relation to stress and disturbance. J Veg Sci. 1993;4:313–322. http://dx.doi.org/10.2307/3235589

85. Chambers JC, Miller JR. Great Basin riparian ecosystems – ecology, management and restoration. Covelo: Island Press; 2004.

86. Weisberg P. Online Nevada Encyclopedia [Internet]. Nevada vegetation overview. Reno, NV: Nevada Humanities; 2010 [cited 2016 Jun 7]. Available from: http://www.onlinenevada.org/articles/nevada-vegetation-overview

87. Pellant M. Cheatgrass: the invader that won the West. Boise, ID: U.S. Department of the Interior, Bureau of Land Management; 1996.

88. Melgoza G, Nowak RS, Tausch RJ. Soil water exploitation after fire: competition between *Bromus tectorum* (cheatgrass) and two native species. Oecologia. 1990;83:7–13. http://dx.doi.org/10.1007/BF00324626

89. Walsh J, Wuebbles D, Hayhoe K, Kossin J, Kunkel K, Stephens G, et al. Our changing climate. In: Melillo JM, Richmond TC, Yohe GW, editors. Climate change impacts in the United States. Washington, DC: U.S. Government Printing Office; 2014. p. 19–67. http://dx.doi.org/10.7930/J0KW5CXT

90. Nevada Department of Wildlife [Internet]. Nevada Wildlife Action Plan. 2012 [cited 2016 Jun 7]. Available from: http://www.ndow.org/Nevada_Wildlife/Conservation/Nevada_Wildlife_Action_Plan

91. Breshears DD, Cobb NS, Rich PM, Price KP, Allen CD, Balice RG, et al. Regional vegetation die-off in response to global-change-type drought. Proc Natl Acad Sci USA. 2005;102:15144–15148. http://dx.doi.org/10.1073/pnas.0505734102

92. Dalton MM, Mote PW, Snover AK, editors. Climate change in the Northwest: implications for our landscapes, waters, and communities. Washington, DC: Island Press; 2013. http://dx.doi.org/10.5822/978-1-61091-512-0

93. Kunkel KE, Stevens LE, Stevens SE, Sun L, Janssen E, Wuebbles D, et al. Regional climate trends and scenarios for the U.S. National Climate Assessment: part 6. Climate of the Northwest U.S. Washington, DC: U.S. Department of Commerce; 2013 [cited 2016 Jun 7]. (NOAA Technical Report; vol

NESDIS 142-6). Available from: http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-6-Climate_of_the_Northwest_U.S.pdf

94. Mote P, Snover AK, Capalbo S, Eigenbrode SD, Glick P, Littell J, et al. Northwest. In: Melillo JM, Richmond TC, Yohe GW, editors. Climate change impacts in the United States. Washington, DC: U.S. Government Printing Office; 2014. p. 487–513. http://dx.doi.org/10.7930/J04Q7RWX

95. Littell JS, Oneil EE, McKenzie D, Hicke JA, Lutz JA, Norheim RA, et al. Forest ecosystems, disturbance, and climatic change in Washington State, USA. Clim Change. 2010;102:129–158. http://dx.doi.org/10.1007/s10584-010-9858-x

96. Dennehy C, Alverson ER, Anderson HE, Clements DR, Gilbert R, Kaye TN. Management strategies for invasive plants in Pacific Northwest prairies, savannas, and oak woodlands. Northwest Sci. 2011;85:329–351. http://dx.doi.org/10.3955/046.085.0219

97. Rogers BM, Neilson RP, Drapek R, Lenihan JM, Wells JR, Bachelet D, et al. Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest. J Geophys Res Biogeosci. 2011;116:1–13. http://dx.doi.org/10.1029/2011JG001695

98. Bradley BA, Oppenheimer M, Wilcove DS. Climate change and plant invasions: restoration opportunities ahead? Glob Chang Biol. 2009;15:1511–1521. http://dx.doi.org/10.1111/j.1365-2486.2008.01824.x

99. Chambers JC, Pellant M. Climate change impacts on Northwestern and intermountain United States rangelands. Rangelands. 2008;30:29–33. http://dx.doi.org/10.2111/1551-501x(2008)30[29:cciona]2.0.co;2

100. Stone JK, Coop LB, Manter DK. Predicting effects of climate change on Swiss needle cast disease severity in Pacific Northwest forests. Can J Plant Pathol. 2008;30:169–176. http://dx.doi.org/10.1080/07060661.2008.10540533

101. Sturrock RN, Frankel SJ, Brown AV, Hennon PE, Kliejunas JT, Lewis KJ, et al. Climate change and forest diseases. Plant Pathol. 2011;60:133–149. http://dx.doi.org/10.1111/j.1365-3059.2010.02406.x

102. Hatfield J. Agriculture in the Midwest [Internet]. Ann Arbor, MI: The Great Lakes Integrated Sciences and Assessments (GLISA) Center; 2012 [cited 2016 Jun 7]. Available from: http://glisa.msu.edu/docs/NCA/MTIT_Agriculture.pdf

103. Easterling DR, Karl TR. Potential consequences of climate variability and change for the Midwestern United States. In: National Assessment Synthesis Team (U.S.), editors. Climate change impacts on the United States: the potential consequences of climate variability and change. Cambridge: Cambridge University Press; 2001.

104. Skaggs RH, Baker DG. Fluctuations in the length of the growing season in Minnesota. Clim Change. 1985;7:403–414. http://dx.doi.org/10.1007/BF00139055

105. Hatfield J, Swanston C, Janowiak M, Steele R, Hempel J, Bochicchio J, et al. Midwest and Northern Forests Regional Climate Hub: assessment of climate change vulnerability and adaptation and mitigation strategies [Internet]. Washington, DC: United States Department of Agriculture; 2015 [cited 2016 Jun 7]. Available from: http://climatehubs.oce.usda.gov/sites/default/files/pdf/Midwest%20Region%20Vulnerability%20Assessment%203_20_2015.pdf

106. Coffin DP, Laurenroth WK. Transient responses of North American grasslands to changes in climate. Clim Change. 1996;34:269–278. http://dx.doi.org/10.1007/BF00224638

107. Sousounis PJ, Bisanz JM. Preparing for a changing climate: the potential consequences of climate variability and change. Great Lakes overview. Ann Arbor, MI: Great Lakes Regional Assessment, University of Michigan, Atmospheric, Oceanic and Space Sciences Department; 2000.

108. Conner R, Seidl A, VanTassell L, Wilkins N. United States grasslands and related resources: an economic and biological trends assessment [Internet]. College Station, TX: Institute of Renewable Resources, Texas A&M University; 2001 [cited 2016 Jun 7]. Available from: http://irnr.tamu.edu/media/252770/us_grasslands.pdf

109. Shafer M, Ojima D, Antle JM, Kluck D, McPherson RA, Petersen S, et al. Great Plains. In: Melillo JM, Richmond TC, Yohe GW, editors. Climate change impacts in the United States. Washington, DC: U.S. Government Printing Office; 2014. p. 441–461. http://dx.doi.org/10.7930/J0D798BC

110. Omernik JM. Ecoregions of the conterminous United States. Ann Assoc Am Geogr. 1987;77:118–125. http://dx.doi.org/10.1111/j.1467-8306.1987.tb00149.x

111. Stevens RL, Coffey CR. Grasses of the Great Plains: a pictorial guide. Ardmore, OK: Samuel Roberts Noble Foundation, Inc.; 2012.

112. Trimble DE. The geologic story of the Great Plains. Washington, DC: United States Department of Interior; 1980. (Geological Survey Bulletin; vol 1493).

113. Karl TR, Melillo JM, Peterson TC. Global climate change impacts in the United States. Cambridge: Cambridge University Press; 2009.

114. Hatfield J, Takle G, Grotjahn R, Holden P, Izaurralde RC, Mader T, et al. Agriculture. In: Melillo JM, Richmond TC, Yohe GW, editors. Climate change impacts in the United States. Washington, DC: U.S. Government Printing Office; 2014. p. 150–174. http://dx.doi.org/10.7930/J02Z13FR

115. Ojima DS, Lackett JM, the Central Great Plains Steering Committee and Assessment Team. Preparing for a changing climate: the potential consequences of climate variability and change – Central Great Plains. Fort Collins, CO: Colorado State University; 2002.

116. Hu Q, Weiss A, Feng A, Baenziger PS. Earlier winter wheat heading dates and warmer spring in the US Great Plains. Agric For Meteorol. 2005;135:284–290. http://dx.doi.org/10.1016/j.agrformet.2006.01.001

117. Hatfield J, Boote K, Fay P, Hahn L, Izaurralde C, Kimball BA, et al. Agriculture. In: Backlund P, Janetos A, Schimel D, Hatfield J, Boote K, Fay P, et al., editors. The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, DC: U.S. Department of Agriculture; 2008. (Synthesis and Assessment Product; vol 4.3).

118. Loehman, R. Understanding the science of climate change: talking points – impacts to prairie potholes and grasslands. Fort Collins, CO: National Park Service; 2009. (Natural Resource Report NPS/NRPC/NRR; vol 2009/138).

119. Knapp AK, Fay PA, Blair JM, Collins SL, Smith MD, Carlisle JD, et al. Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland. Science. 2002;298:2202–2205. http://dx.doi.org/10.1126/science.1076347

120. Morgan JA, Mosier AR, Milchunas DG, LeCain DR, Nelson JA, Parton WJ. CO_2 enhances productivity of the shortgrass steppe, alters species composition, and reduces forage digestibility. Ecol Appl. 2004;14:208–219. http://dx.doi.org/10.1890/02-5213

121. Parton WJ, Morgan JA, Wang G, Del Grosso S. Projected ecosystem impact of the prairie heating and CO_2 enrichment experiment. New Phytol. 2007;174:823–834. http://dx.doi.org/10.1111/j.1469-8137.2007.02052.x

122. von Fischer JC, Tieszen LL, Schimel DS. Climate controls on C_3 vs. C_4 productivity in North American grasslands from carbon isotope composition of soil organic matter. Glob Chang Biol. 2008;14:1141–1155. http://dx.doi.org/10.1111/j.1365-2486.2008.01552.x

123. Campbell BD, McKeon GM, Gifford RM, Clark H, Stafford Smith MS, Newton PCD, et al. Impacts of atmospheric composition and climate change on temperate and tropical pastoral agriculture. In: Bouma WJ, Pearman GI, Manning MR, editors. Greenhouse: coping with climate change. Melbourne: CSIRO; 1996. p. 171–189.

124. White TA, Campbell BD, Kemp PD. Invasion of temperate grassland by a subtropical annual grass across an experimental matrix of water stress and disturbance. J Veg Sci. 2009;8:847–854. http://dx.doi.org/10.2307/3237029

125. White TA, Campbell BD, Kemp PD, Hunt CL. Sensitivity of three grassland communities to simulated extreme temperature and rainfall events. Glob Chang Biol. 2000;6:671–684. http://dx.doi.org/10.1046/j.1365-2486.2000.00344.x

126. Notaro M. Response of the mean global vegetation distribution to interannual climate variability. Clim Dyn. 2008;30:845–854. http://dx.doi.org/10.1007/s00382-007-0329-7

127. Horton R, Yohe G, Easterling W, Kates R, Ruth M, Sussman E, et al. Northeast. In: Melillo JM, Richmond TC, Yohe GW, editors. Climate change impacts in the United States. Washington, DC: U.S. Government Printing Office; 2014. p. 371–395. http://dx.doi.org/10.7930/J0SF2T3P

128. Hannaway, DB, Fribourg, HA, editors. Country pasture/forage resource profiles: United States of America [Internet]. 2011 [cited 2016 Jun 7]. Available from: http://www.fao.org/ag/agp/agpc/doc/counprof/PDF%20files/USA.pdf

129. Fribourg HA, Hannaway, DB, West CP. Tall fescue for the twenty-first century. Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America; 2009. (Agronomy; vol 53).

130. Huntington, TG, Richardson AD, McGuire, KJ, Hayhoe, K. Climate and hydrological

changes in the Northeastern United States: recent trends and implications for forested and aquatic ecosystems. Can J For Res. 2009;39:199–212. http://dx.doi.org/10.1139/X08-116

131. Rustad L, Campbell J, Dukes JS, Huntington T, Fallon Lambert K, Mohan J, et al. Changing climate, changing forests: the impacts of climate change on forests of the Northeastern United States and Eastern Canada. Newtown Square, PA: U.S. Forest Service; 2012. (General Technical Report NRS; vol 99).
132. Gowik U, Westhoff P. The path from C_3 to C_4 photosynthesis. Plant Physiol. 2011;155:56–63. http://dx.doi.org/10.1104/pp.110.165308
133. Asseng S. Agriculture and climate change in the Southeast USA. Chapter 7. In: Ingram KT, Dow K, Carter L, Anderson J, editors. Climate of the Southeast United States: variability, change, impacts, and vulnerability. Washington, DC: Island Press; 2013. p. 128–164. (National Climate Assessment Regional Technical Input Report Series). http://dx.doi.org/10.5822/978-1-61091-509-0_7
134. Weigl PD, Knowles TW. Temperate mountain grasslands: a climate–herbivore hypothesis for origins and persistence. Biol Rev Camb Philos Soc. 2014;89:466–476. http://dx.doi.org/10.1111/brv.12063
135. Ball, DM, Hoveland CS, Lacefield GD. Southern forages: modern concepts for forage crop management. 5th ed. Atlanta, GA: International Plant Nutrition Institute; 2015.
136. Carter LM, Jones JW, Berry L, Burkett V, Murley JF, Obeysekera J, et al. Southeast and the Caribbean. In: Melillo JM, Richmond TC, Yohe GW, editors. Climate change impacts in the United States. Washington, DC: U.S. Government Printing Office; 2014. p. 396–417. http://dx.doi.org/10.7930/J0NP22CB
137. Butler PR, Iverson LR, Thompson III FR, Brandt LA, Handler SD, Janowiak MK, et al. Central Appalachians forest ecosystem vulnerability assessment and synthesis: a report from the Central Appalachians Climate Change Response Framework Project [Internet]. Newton Square, PA: USDA Forest Service; 2015 [cited 2016 Jun 7]. (General Technical Report NRS; vol 146). Available from: http://www.fs.fed.us/nrs/pubs/gtr/gtr_nrs146.pdf
138. McCulley RL, Bush LP, Carlisle AE, Ji H, Nelson JA. Warming reduces tall fescue abundance but stimulates toxic alkaloid concentrations in transition zone pastures of the U.S. Front Chem. 2014;2:88.
139. SCRIPPS Institution of Oceanography [Internet]. The Keeling curve. San Diego, CA: University of California; 2016 [cited 2016 Jun 7]. Available from: https://scripps.ucsd.edu/programs/keelingcurve/
140. Worster D. Dust Bowl: the Southern Plains in the 1930s. New York, NY: Oxford University Press; 2004.
141. Riebsame WE. Sustainability of the Great Plains in an uncertain climate. Great Plains Research . 1991;1:133–151.
142. Campbell BD, Stafford Smith DM, GCTE Pastures and Rangelands Network Members. A synthesis of recent global change research on pasture and rangeland production: reduced uncertainties and their management implications. Agric Ecosyst Environ. 2000;82:39–55. http://dx.doi.org/10.1016/S0167-8809(00)00215-2
143. FAO. Climate change and food security: a framework document [Internet]. Rome: Food and Agriculture Organization of the United Nations; 2008 [cited 2016 Jun 7]. Available from: http://www.fao.org/forestry/15538-079b31d45081fe9c3dbc6ff34de4807e4.pdf
144. Weather Source LLC [Internet]. Salem, NH. 2016 [cited 2016 Apr 8]. Available from: http://weather-warehouse.com/WeatherHistoryListing/monthlyWeatherDataStart.html

Zbiorowiska łąkowe w USA i spodziewane kierunki ich przekształceń związane ze zmianami klimatycznymi

Streszczenie

Trwałe użytki zielone, w tym pastwiska, należą do ekosystemów trawiastych i zajmują duże obszary w strefach klimatycznych, gdzie niemożliwy jest rozwój formacji drzewiastych. Pastwiska na ogół zajmują regiony marginalne pod względem klimatycznym i glebowym, co dodatkowo przyczynia się do pogarszania ich podstawowej wydajności w stosunku do zasobów systemowych, w tym czynników antropogenicznych. Dynamika klimatu, jak wynika z danych kopalnych, jest trwałą cechą zmian zachodzących na naszej planecie. Notowane obecnie wzorce temperatury i opadów różnią się od danych wieloletnich, co wiąże się z działalnością człowieka i wzrostem emisji gazów cieplarnianych, w szczególności CO_2. Trwałe użytki zielone, z ich

różnorodnym składem florystycznym i oddziaływaniem i/lub uzależnieniem od roślinożerców, mają szczególną zdolność do przetrwania i utrzymywania produktywności przy zmieniających się zasobach siedliska. Ta odporność i elastyczność na zmiany długoterminowe oraz niepewne warunki pogodowe, sprawia że trwałe użytki zielone są istotnym elementem dla ochrony i zapewnienia bezpieczeństwa żywnościowego.
W prezentowanej pracy dokonano przeglądu trwałych użytków zielonych w poszczególnych regionach USA oraz oceniano ich produkcyjność i funkcjonowanie w odniesieniu do zmian klimatycznych. Niezbędne są badania w celu identyfikacji zasobów roślinnych i opracowanie technologii produkcji opartych o rozpoznanie fizjologicznych i anatomicznych cech roślinności. Technologie te umożliwiają, w powiązaniu z różnymi warunkami uprawy, wykorzystanie potencjalnych możliwości zbiorowisk trawiastych.