DEVELOPING PLANT FUNCTIONAL GROUP PARAMETERS FOR ECO-HYDROLOGIC ASSESSMENT IN THE WESTERN UNITED STATES

A Thesis

by

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ABSTRACT

The Western United States (WUS), also known as the American West and the Far West, is the largest region in the country, taking up almost half of the contiguous United States' total land area. The vast region has various physical features, such as glaciers, mountain ranges, deserts, and temperate rainforests. The complex interplay of temperature, disturbance, and varying vegetation across spatial landscape patterns influence ecosystem dynamics.

The region's entire area is approximately 1200 million acres. In 2012, the primary land uses were grassland pasture and range lands with an area of 655 million acres (29 percent of the US total), forest land use with an area of 632 million acres (28 percent), and cropland with an area of 392 million acres (15 percent); totaling slightly more than 35 percent of the US land area or 798 million acres (Bigelow et al., 2006).

The Missouri River, a tributary of the Mississippi River, and the Colorado River (CR) are the only significant rivers in the area. The CR originates in the Rocky Mountains and empties into the Gulf of California after passing through parts of seven Western US and Mexico (Christensen et al., 2004). Between seven Western States (Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming) and northern Mexico, the Colorado River Basin (CRB) spans an area of around 640,000 km^2.

Salinity in the CR has increased two-fold due to anthropogenic activity in the basin. CR transports estimated salt loads of 7 to 9 million tons annually. Irrigation consumes 70% of the river's flow and contributes to salinity. However, most salts run naturally off soils and rocks (Mancos Shale).

The overall goal of this study is to use an integrated and enhanced APEX modeling tool to understand processes governing the transport of sediment and salt from upland areas to streams in the CRB, identify critical source areas, and assess the efficiency of suggested management scenarios. Plant functional groups (FGs) parameters, a crucial input data set for modeling the various CRB vegetation types, must be developed before the APEX model can be used. Plant FGs parameters were developed by adapting the minimum basic plant parameters to fit a given FG representative plant species using three approaches: i) modifying parameters of plant species out of three models: Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC), Environmental Policy Integrated Climate (EPIC)/APEX, and Soil & Water Assessment Tool (SWAT); ii) data from the literature, United States Department of Agriculture (USDA) Natural Resources Conservation Services (NRCS) Plants Database; and iii) expert judgments. Remotely sensed satellite data for ET and LAI were collected for 19 sites across CRB. In addition, plant height data was collected from the Landscape Monitoring Framework (LMF) dataset using the NRCS-NRI methodology. APEX models were built for chosen locations. Developed FGs parameters were used to simulate and test the integrated APEX model and Bureau of Land Management (BLM) field and remote sensing data to evaluate ET, LAI, and plant height outputs. A total of 18,876 distinct plant species were assigned to 55 FGs throughout the WUS. Sensitivity analysis was conducted for each output to determine the parameters most sensitive to outputs. Soil water limit (PARM 15), DLAI, and HMX were observed to be the most sensitive parameters for ET, LAI, and plant height. Results demonstrated the viability of using FG to parameterize, simulate, and perform sensitivity analyses on biophysical models to simulate alternative land management strategies. This technique can address various eco-hydrological issues, including water quality and quantity, salinity, sediment transport, pesticide and fertilizer fate, movement, soil carbon sequestration, N and P nutrient cycles and losses, and land management practices across the CRB.

DEDICATION

To my parents, Rajesh Singh and Savita Singh, my family members, friends, and teachers who have helped me in this journey.

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NOMENCLATURE

ALMANAC	Agricultural Land Management Alternative with Numerical Assessment Criteria
APEX	Agricultural Policy Environmental eXtender
BCM	Billion Cubic Meters
BLM	Bureau of Land Management
BMPs	Best Management Practices
CEAP	Conservation Effects Assessment Project
CN	Curve Number
CONUS	Contiguous United States
CR	Colorado River
CRB	Colorado River Basin
DLAI	Fraction of growing season when leaf area declines
DLAP1	First point on optimal leaf area development curve
DLAP2	Second point on optimal leaf area development curve
DMLA	Maximum potential leaf area index
EPIC	Environmental Policy Integrated Climate
FG	Functional Groups
HI	Harvest Index
HMX	Maximum Crop Height
LAI	Leaf Area Index
MAF	Million Acre-Feet
NRCS	Natural Resources Conservation Services

NRI	National Resources Inventory
NVCN	Non-Varying CN-CN2 Used
SA	Sensitivity Analysis
SW	Soil Water
SWAT	Soil & Water Assessment Tool
TDS	Total Dissolved Solids
USDA	United States Department of Agriculture
WUS	Western United States

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1. INTRODUCTION

The Western United States (WUS) comprises Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming. However, for this study, the state of Washington was excluded from the study area. The WUS is the country's largest region, covering nearly half of the contiguous United States land area. This area is also the most geographically diverse, with numerous distinct sub-regions and topographic features, including the Great Plains, deserts (like the Mojave and Great Basin), high mountain ranges (like the Sierra Nevada, the Cascade Range, and the Rocky Mountains), and temperate rain forests of Oregon. The western part includes arid and semi-arid plateaus and plains (predominantly in the Southwest states of Arizona, California, and New Mexico), forested mountains, the extensive Pacific Coast of America's coastline, and the rain forests of the Pacific Northwest. The region has a total area of 1198.99 million acres. In 2012, the primary land uses were grassland pasture and range lands with an area of 655 million acres (29 percent of the US total); forest land use with an area of 632 million acres (28 percent); and cropland with an area of 392 million acres (15 percent), totaling just over 35 percent of the US land area or 798 million acres (Bigelow et al., 2006).

The climate of the WUS is volatile, with arid portions receiving as little as 130 mm annually of precipitation, while other parts of the region receive excessive snow or rain. The West Coast Ranges experience warm summers and moderate winters with little to no snow; however, the seasonal temperatures vary widely depending on the area. The deserts have extreme summers and mild winters, whereas the mountains generally receive high amounts of precipitation from snow. Rainfall is high in the Pacific Northwest Coastal Ranges and tapers down towards the eastern side of the region.

1.1. Colorado River Basin

Significant rivers, such as the Missouri River, a tributary of the Mississippi River, and the CR, flow through the WUS. The CR originates in the Rocky Mountains and flows through portions of seven Western United States and Mexico before emptying into the Gulf of California. The CRB consists of seven Western states (Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming) and northern Mexico. It encompasses approximately 246,000 square miles. The CRB is mainly dry, with an average native stream flow of roughly 40 mm annually. Snowfall at high elevations is responsible for almost 70% of the annual runoff in the Rocky Mountains. Most of the basin's seasonal runoff pattern is mainly influenced by winter snowfall and spring melt. On average, 90% of the annual stream flow is generated in the Upper Basin (above Lees Ferry, AZ). The naturalized flow of the CR also exhibits significant temporal fluctuation. The minimum annual flow was 6.5 BCM (5.3 MAF) from 1906 to 2000, the greatest was 29.6 BCM (24.0 MAF), and the average was 18.6 BCM (15.1 MAF) (Christensen et al., 2004).

The CR transports 7 to 9 million tons of salt annually to the Gulf of California, depending on climatic conditions and salt mitigation practices within the basin. High salinity in the CR system in the WUS causes approximately $300 million in economic damages annually (Bureau of Reclamation, 2013). Salt concentration in the CR has increased two-fold due to anthropogenic activity in the basin. Geology and human activity are some of the critical factors in river (or stream) chemistry, especially salinity in the WUS (Peterson et al., 1995). Most of the salts in the region run naturally off soils and rocks (Mancos Shale). Salinity in soils, groundwaters, and surface waters threatens food production, soil health, ecosystem biodiversity, and the widespread use of water resources in many regions of the world, thus becoming a global water quality challenge (Thorslund and van Vliet, 2020).

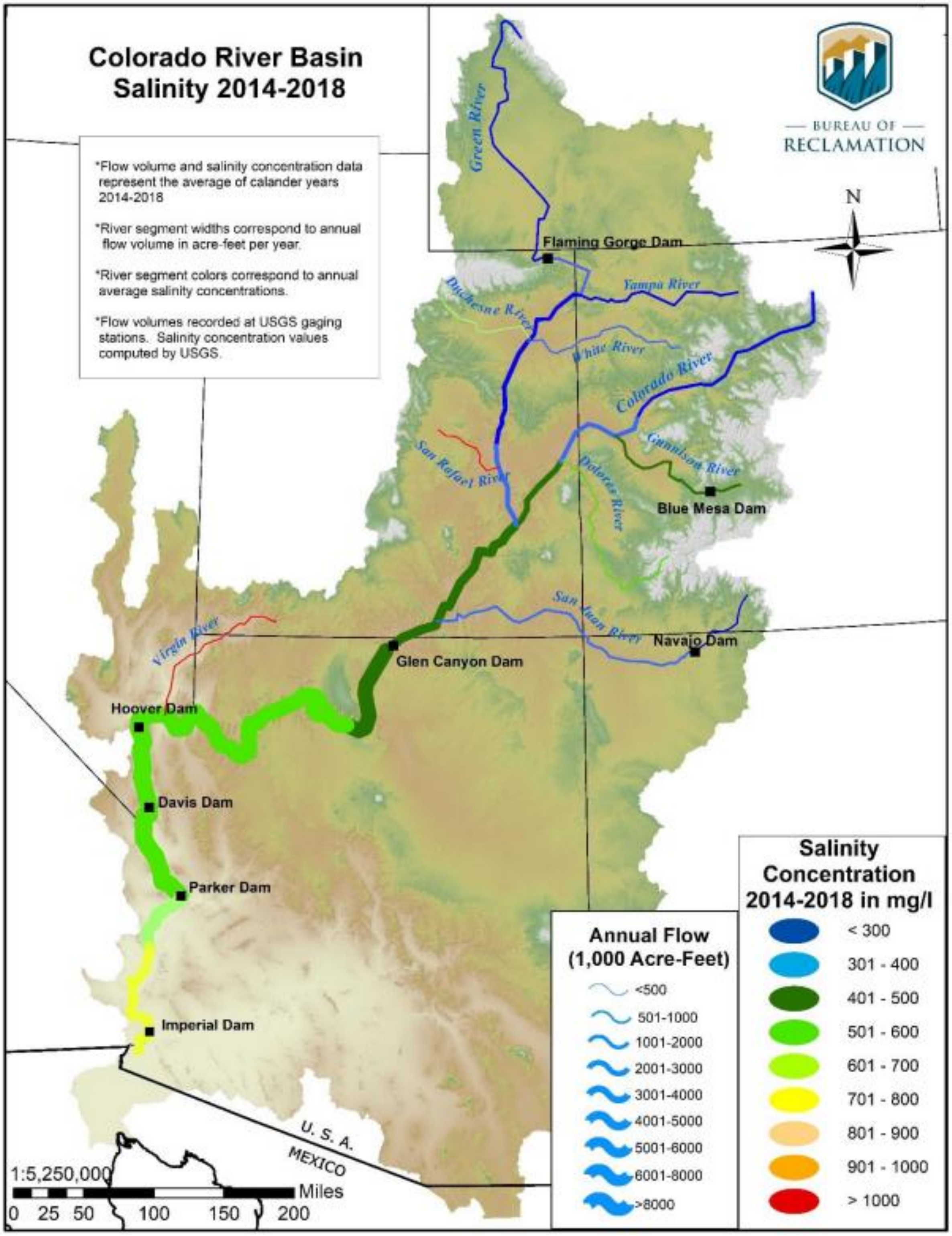


Fig. 1. Salinity in the CR increases downstream primarily due to agricultural waste use. Source: Morford, Scott. "Salinity in the CRB." Bureau of Reclamation. Phoenix, AZ (2014)

Along with salinity, a significant decrease in the CR flow has long been a primary concern (Brownell et al., 1975). Salinity also called total dissolved solids (TDS), is defined as the mass of dried ionic constituents that pass a 2 μm filter and is quantified in-river as either a concentration (mass/volume) or as a load (mass/time). Under the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500), salinity numerical standards/thresholds were established throughout the basin and are monitored at large reservoirs. Because no large sink for salinity exists within the basin (except for the Salton Sea), the numerical threshold standards increase downstream (Morford, 2014).

The water quality challenges in the CR and its tributaries are diverse and location dependent. Industrial, mining, agricultural, and municipal activities contribute to local and regional water quality impairment (Spahr et al., 2000) for human use and ecological services. The increased salt load threatens wildlife (e.g., selenium) and imposes a substantial economic cost on the public and private sectors (Morford, 2014). Regular monitoring and evaluation of the state of natural resources and management effects are necessary for effective range land management (Williams et al., 2007). Keeping track of changes in resource status is essential for adapting management strategies and furthering the achievement of management goals. Handbooks, technical references, and websites guide the rangeland monitoring and assessment (e.g., Elzinga et al., 2001; Herrick et al., 2005; Pellant et al., 2005). In the western United States, range lands are managed by public land management organizations like the Bureau of Land Management (BLM) for various purposes, including cattle grazing and preserving sensitive species and their habitats (Veblen et al., 2014). Despite taking several steps to mitigate the issue of erosion and degrading soil water quality, the problem remains at large.

1.2. Knowledge Gap

Regional or large-scale assessments with a process-based model like APEX need realistic plant parameters to evaluate the impacts of land management practices. The growth of different vegetation types and their effect on environmental changes are central issues in conservation practices, management strategies, and plant ecology. A challenge to understanding development and input from local to global scales is that numerous critical metabolic processes vary among species. Recognizing that species can be grouped into FGs based on metabolic similarity and that these FGs can then be examined in process-based models that simulate ecosystem function is an innovation in addressing this challenge (Zhang et al., 2021). As such, a realistic simulation of plant development is necessary for effective simulation. A functional group is a term based on similarities in plant type and parameter values (Kiniry, 2014). Shared features allow plant species to be simulated as generalized FGs and have been helpful in this context while simulating community rather than individual species (Meki et al., 2021). In addition, plant FG has been used to characterize plant communities and productivity (Domingues et al., 2007).

1.3. Research Objective

This study aims to develop plant FG for the vegetation types present in the WUS. Developed FG will be applied to the APEX model to simulate eco-hydrological resource concerns like salinity and eco-hydrological parameters like ET, runoff, nutrients, and sediments in the CRB.

2. REVIEW OF LITERATURE

An ecological site plant community is not a precise representation of species for which the distribution keeps varying from place to place and year to year. In all plant communities, variability in productivity or occurrence of individual species is apparent. However, spatial boundaries in the communities can be identified by unique traits like species composition, occurrence, and structure of the community. A robust and complex parameterization of plant growth characteristics is needed for the modeled location, which accurately represents the biotic influences of the actual site. It is used to run simulation models on rangelands, grazing lands, croplands, forested lands, or agricultural lands to successfully determine the net effects of conservation practices (NRCS National Rangeland Pasture Handbook (NRPH), 1997).

All modeling methods accurately represent the ecological site's attributes, suggesting the necessity for standardized plant (FG) parameters that connect the modeled and natural worlds. Understanding the physical characteristics of the land that distinguish ecological sites from other lands in terms of the kinds and amounts of vegetation they can produce, as well as how they react to disturbances, are used, and are managed, is essential. These physical characteristics include topography, soil type, geology, and water availability. Ecological sites do not just represent the plant communities that grow there. Grouping plants according to their physical and chemical growth features and function—the niche they compete for on a site—produces a stable and practical model framework and a description of the plant community that accurately represents how plant communities act on an ecological site. A site's species must be classified so that the full spectrum is covered, from the lower to the higher end of the precipitation zone, the transition of species from one type to another in between ecological sites, land resources, and physical characteristics for these sites. Areas with higher species variability will have more variation in the contribution of the individual species. Plant community on an ecological site varies naturally from one place to another, season to season, year to year. This variability in the real world poses a challenge in the modeled world, thus creating a need to develop FG (Metz et al., 2019).

While establishing plant FG, species are primarily grouped based on their tendency to compete for resources like soil moisture and sunlight. Second, the grouping is based on species' methods to form new plants and occupy available space. The distribution of water, nutrients and energy flow in the modeled community is unaffected by the existence of these species. This development compensates for species' geographical and temporal variation within the same FG. The Conservation Effects Assessment Project was established in 2003 through a partnership between the Natural Resources Conservation Services (NRCS) of the United States Department of Agriculture (USDA) and other federal agencies (CEAP) to quantify environmental effects. Most rangelands and croplands demonstrate significant spatial and temporal variability, which provides biophysical models driven by daily and climatic variables to assess natural resources management alternatives across time and large areas (watershed, regional, and national scale) (Meki et al., 2021).

In some situations, simulation of FG or communities may be beneficial rather than individual species. For regional assessments using process-based models like Agricultural Policy/Environmental eXtender, realistic estimations of plant parameters for the main plant FG in the area are required (APEX). Plants grouped in FG are of the same type and have similar plant characteristics (Kiniry et al., 2014).

FG has been applied in several ways and using multiple grouping schemes. Plant communities and productivity have been described using them (Gitay et al., 1996; Hooper et al., 2004; Domingues et al., 2007). FG has been employed when evaluating how plants respond to disturbance and grazing (Noble et al., 1980; Nobel et al., 1996). These organizations have been utilized to evaluate community resistance to plant invasion (Pokorny et al., 2005). Managing unusual plants (Franks et al., 2009) and examining the drivers of soil biodata are two more uses for them (Eisenhauer et al., 2011).

Additionally, FG has been applied to simulation models and model platforms. Utilizing the LAMOS landscape modeling framework, plant FG was used to mimic plant succession and grazing disturbance (Cousins et al. 2003). Additionally, researchers in Northern Spain used FG to simulate how a non-native grass invasion may alter fire regimes (Grigulis et al., 2005). Using the ARENA model, Boer et al., 2003 employed plant FG to simulate water and nitrogen competition on Australian rangelands.

In fire-prone ecosystems (Pausas et al., 2002), plant functional classes were used to simulate the dynamics of grasslands using the grid-cell raster-based stochastic model MELCHA. Plant species can be mimicked as a generalized FG rather than as separate species because of shared traits (Kiniry et al., 2013). To simulate biomass, response to water stress, competition for soil water, and regrowth of herbaceous perennials on grazing fields, FG is employed for plant parameterization, calibration, and validation (Zilverberg et al., 2017). Furthermore, due to the highly different ecosystems represented by a broad regional approach centered on Land Resource Region (LRR H), FG is used to assess the environmental consequences of conservation strategies on grazing lands in the CONUS (Meki et al., 2021).

Wetlands offer a wide range of ecological services, such as flood water storage, groundwater recharge, biodiversity refugia, and water quality improvement. A suitable simulation of each site’s hydrology and an accurate simulation of the upland and wetland plant growth cycles are necessary for a realistic evaluation of the ecosystem service benefits connected to wetlands. To enable process-based modeling, functional groups in this study were based on these variables and plant growth types (Williams et al., 2017). Exotic warm-season perennial grasses (FG) that are simple to grow have been and are still being purposefully introduced outside their native areas. Such introductions frequently have positive and negative effects: they may boost soil stabilization and carrying capacity while decreasing biodiversity and altering the nutrient and water cycles. The project's fundamental concept was that growth characteristics created in well-managed stands of representative species within a functional group could predict the future growth of other species within the same functional group (Kiniry et al., 2013).

3. OBJECTIVES AND HYPOTHESES

The central focus of the study is the need for land management scenarios and conservation practices that private landowners can adopt, government-owned lands, or any CRB - affiliated stakeholders to mitigate soil and water quality issues and assess the eco-hydrological parameters in the WUS. Specific objectives of the study were to:

1. develop plant FGs for various vegetation types in the WUS.

2. build apex model sites that reflect real-world scenarios for selected 19 locations across CRB by collecting data related to ET, LAI, and plant height from remotely sensed satellite data and LMF dataset using NRCS-NRI methodology for these locations.

3. incorporate these FGs into APEX to simulate a range of variables like ET, LAI, and plant height across the selected sites.

4. simulate, calibrate, and validate the APEX model against the developed FGs for ET, LAI, and plant height for sites chosen across CRB.

5. conduct SA to evaluate which parameters are most sensitive to the simulated variables.

Hypothesis:

The FGs show plant species characteristics in the APEX model during simulation.

This hypothesis was tested on developed plant FGs in the WUS. Results showed that the model correctly simulated ET, LAI, and plant heights for locations chosen across CRB to within 5% of the observed data from the satellite and database. Therefore, FGs were found to be showing individual plant species characteristics in the APEX model during simulation.

4. MATERIALS AND METHODS

4.1. Study Area

The study locations include the states of Arizona, California, Colorado, Idaho, Montana, Oregon, New Mexico, Nevada, Utah, and Wyoming, which are in the WUS (Fig. 2) and cover approximately 290 M ha.

Fig. 2. States which comprise the WUS and in focus for this study, except Washington

4.2. Major Vegetation Types and Soil Orders in WUS

Variations in available soil types, temperature, and precipitation results in an extensive range of growing plants that can be found even within short distances within a state. Because of the wide variety of growing conditions, specified FGs are required to describe plant communities in an ecological area adequately. Table 1 depicts several soil orders, their descriptions, percentages of covering, and applicability in various land management scenarios.

Table 1 Description of the various dominant Soil Orders present in the WUS

Soil Orders	Percent	Description	Use
Mollisols	24.6	Present in areas with low to moderate rainfall. Dark-colored texture. It has a high base A horizon	Croplands and rangelands
Inceptisols	18.2	Young soil with B horizon, no illuviation	Croplands, forested areas, and rangelands
Alfisols	13.4	Present in cool, moist climates, light-colored soil texture. Slightly to moderately acidic with an illuvial layer. Common to northcentral mountain states	Croplands, forested areas, and rangelands
Aridiols	11.5	They have a high base indicating they are alkaline. They are common in WUS with salted horizons	Rangelands and irrigated farming
Ultisols	12.1	Highly weathered soils. They are present in areas with a warm climate. They are acidic in nature with low fertility. Common in the southeast United States	Forests and croplands

Entisols	7.9	Very young soils where alluvial deposition or erosion limits profile development (slopes)	Rangelands, croplands, and forested lands
Spodosols	5.1	Found in cool, humid regions, often coniferous forests. Light-colored texture. Most common in the northeast United States. They are infertile	Forests
Andisols	<1	The origin of these soils is volcanic materials. Dark and fertile. Standard in the Pacific Northwest region of the USA.	Croplands and forests

Similarly, elevation and precipitation data for the research region are presented in Table 2. There does not appear to be a direct correlation between elevation and precipitation. However, moisture-laden winds from the Pacific Ocean ensure that the states of Oregon and California receive maximum rainfall of 27.4 and 22.2 inches, respectively, among all the states considered in this study. In contrast, Utah gets the lowest amount of precipitation, as it lies on the leeward side of the mountain ranges, which acts as a barrier for the prevailing winds carrying moisture from the Pacific Ocean. The distributions of elevation and precipitation for states in the WUS are shown in Fig. 3 and Fig. 4, respectively.

Table 2 Information about the elevation and precipitation for states in WUS

S. No.	State	Elevation (ft)	Precipitation (inches)
1.	Arizona	4100	13.6

2.	California	2900	22.2
3.	Colorado	6800	15.9
4.	Idaho	5000	18.9
5	Montana	3400	15.3
6.	Nevada	5500	9.5
7.	New Mexico	5700	14.6
8.	Oregon	3300	27.4
9.	Utah	6100	12.2
10.	Wyoming	6700	12.9

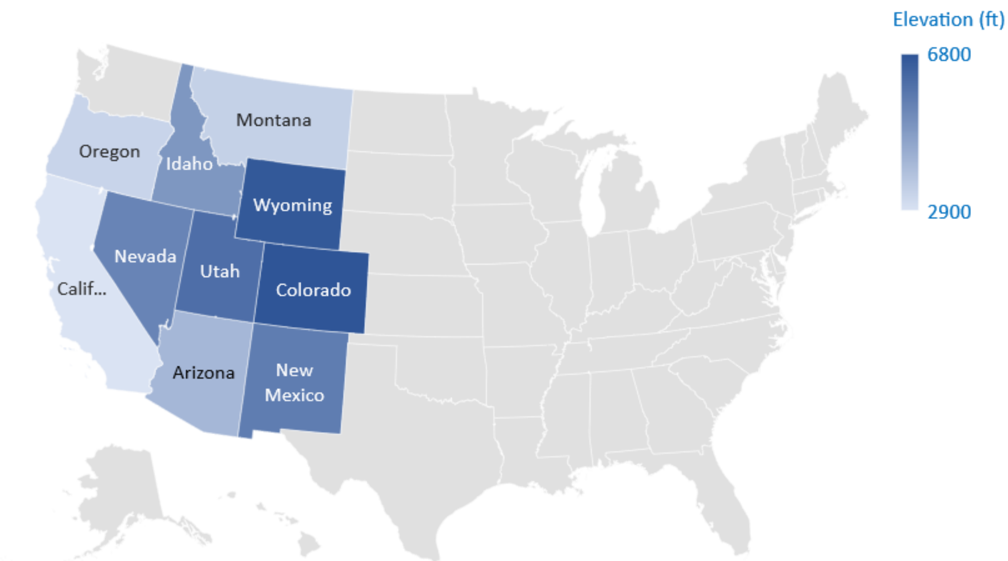


Fig. 3. Mean elevation of different states in WUS

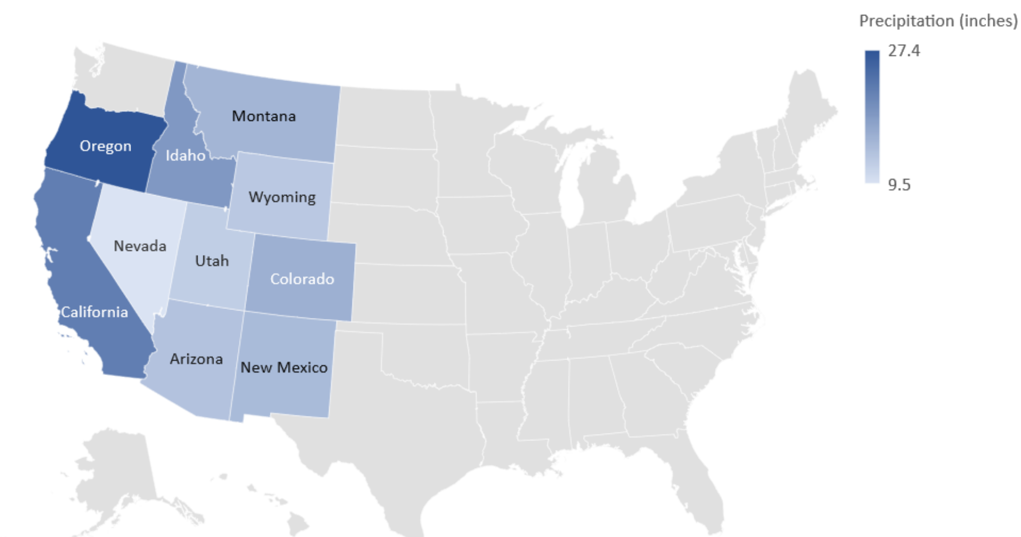


Fig. 4. Annual average precipitation in WUS as provided by NOAA, National Climatic Data Center

4.2.1. Arizona

The daily difference between the highest and lowest temperatures can sometimes reach 50 to 60 degrees Fahrenheit. Elevation and the time of year significantly impact Arizona's precipitation. Arizona is classed semi-arid, and extended intervals without significant rainfall are anticipated. The soil orders Aridisols, Alfisols, Entisols, and Mollisols dominate the state. Due to semi-arid conditions and Aridisols soil order, the state supports desert shrub and woodland vegetation. Higher elevation provides suitable conditions for pinyon-juniper woodland and sagebrush with a mix of Galleta grass, Indian rice grass, and needle grass at lower elevations. As we move south, we see the landscape inhabited by forests, grassland vegetation, and savanna due to higher precipitation values and different soil order. Evergreen forest savannas occur at moderate heights, whereas pine-oak woodlands are found at higher elevations. The predominant species are Arizona white oaks, one-seed junipers, jojoba, Mexican blue oaks, and turbinella oaks. On the drier soils at lower altitudes, whitethorn, soap tree yucca, four-wing saltbush, mesquite, and ocotillo flourish. Distribution of diverse types of vegetation found throughout the state, as shown in Fig. 5.

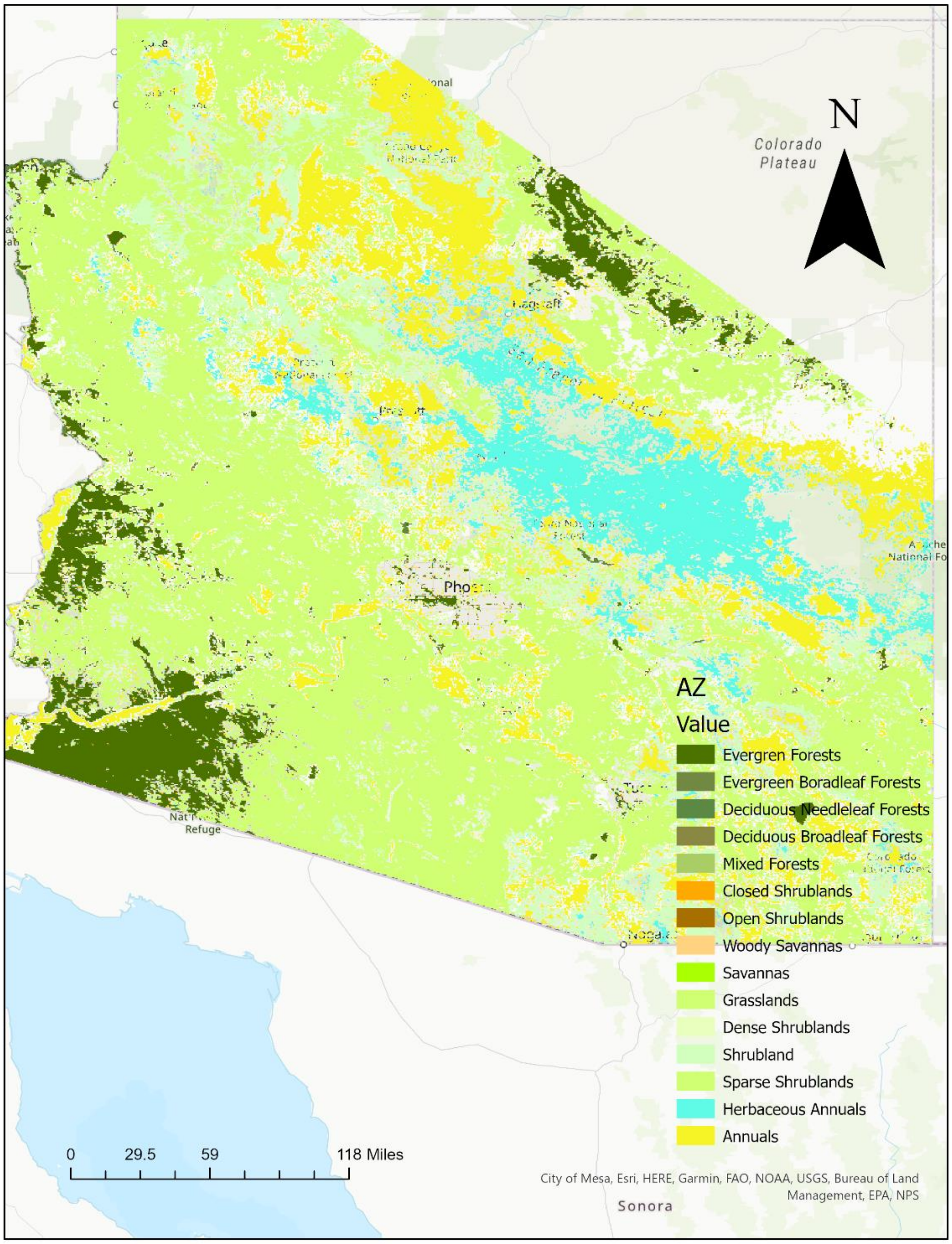


Fig. 5. Land Cover of dominant vegetation species in Arizona

4.2.2. California

The easternmost mountain chains, which operate as a barrier, protect California from the Great Basin's freezing winter air. The western mountain ranges protect the interior from the powerful airflow of the Pacific Ocean. Precipitation is, therefore, heavier on the coastal or western side of the Coast Range and Sierra Nevada and less so on the eastern slopes. Rainfall is also marginally decreased at the highest elevations of the Sierra Nevada because the range extends above the most significant transmission of the moisture-laden winds from the Pacific. Alfisols, Aridisols, Entisols, Mollisols, and Vertisols soil order constitute the soil of California.

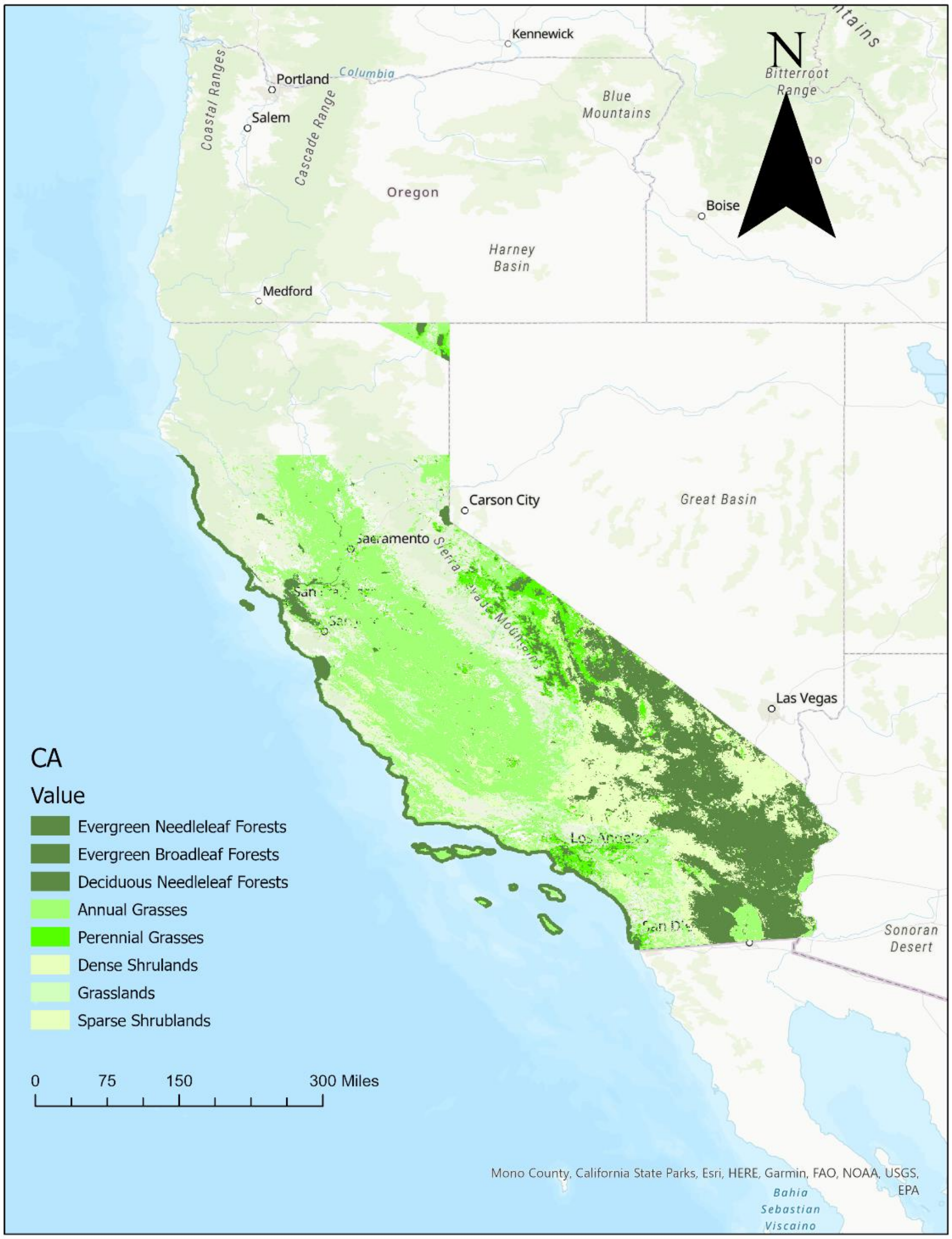


Fig. 6. Land Cover of dominant vegetation species in California

The coast of California, along with the Sierra Nevada mountains, is dominated by forest and grass vegetation species like Redwood, Douglas-fir, Grand fir, Red Alder, Bishop pine, Western

Red Cedar, California bay laurel, and California black oak. Wild oats, soft chess, burclover, fescues, bluegrass, blue wildrye, and mountain brome are some of the dominant perennial and annual grassland species in the Central California Coastal Valley. Salt weed, tules, cattails, and saltgrass are marshy vegetation species dominating the Central California delta region. Sacramento and San Joaquin Valley vegetation types are characterized by annuals and scattered trees like wild barley, wild oats, foxtail fescue, and burclover, as shown in Fig. 6.

4.2.3. Colorado

Eastern Plains and Western Colorado are the two topographic divisions of Colorado. The weather on the plains changes depending on where you are. Its defining features are low relative humidity, a wide range of daily temperatures, ample sunshine, little rain, and moderate to intense winds. Because of the region's challenging topography, few generalizations about climate apply to the entire area in western Colorado. The dominant soil order is Alfisols, Mollisols, Entisols, and Inceptisols. Potential vegetation species in this region are grasses, shrubs, and sage brushes in lower elevations, coniferous trees, forests at mid-elevations, and alpine tundra at high peaks. Some typical plants are mountain big sagebrush, western wheatgrass, Douglas-fir, white fir, Arizona fescue, mountain muhly, common snowberry, Parry's oat grass, mountain brome, blue grama, and buffalo grass. The eastern part of the state supports prairie grasses like June grass, Galleta, and cottonwood. As we move South, desert shrub-grassland vegetation dominates the landscape. The common plants are greasewood, rabbitbrush, four-wing saltbush, salt grass, alkali sacaton, western wheatgrass, sedges, and rushes, as shown in Fig. 7.

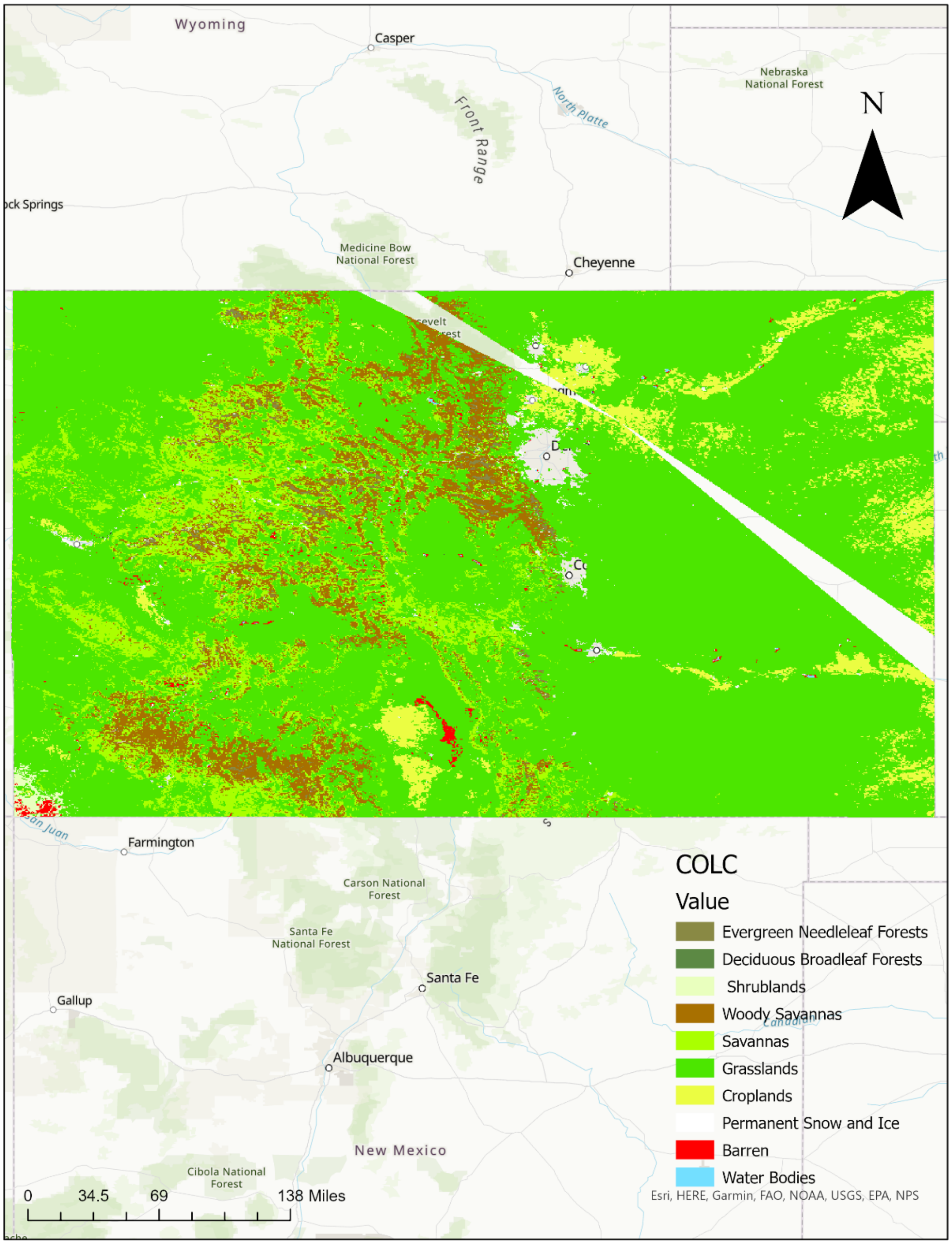


Fig. 7. Land Cover of dominant vegetation species in Colorado

Agriculture uses approximately 80% of the water in the Colorado River to irrigate 15% of the nation's farms and produce 90% of its winter crops. Rationing of supplies to manage water stress and the crops, such as alfalfa and hay, used by farmers to feed cattle, are likely to put a particular strain on wheat, corn, berries, and fresh produce. Along with this, cattle, dairy, cotton, and vegetables are also essential commodities in the region. Concerns regarding water quality are rising, with sediment deposition, nutrients, pesticides, and salinity being identified as the significant non-point sources of surface and sub-surface water pollution (Meki et al.,2021).

4.2.4. Idaho

It lies west of the Continental Divide, sharing a boundary with Yellowstone National Park. The northern part of the state averages lower than the much larger central and southern portions.

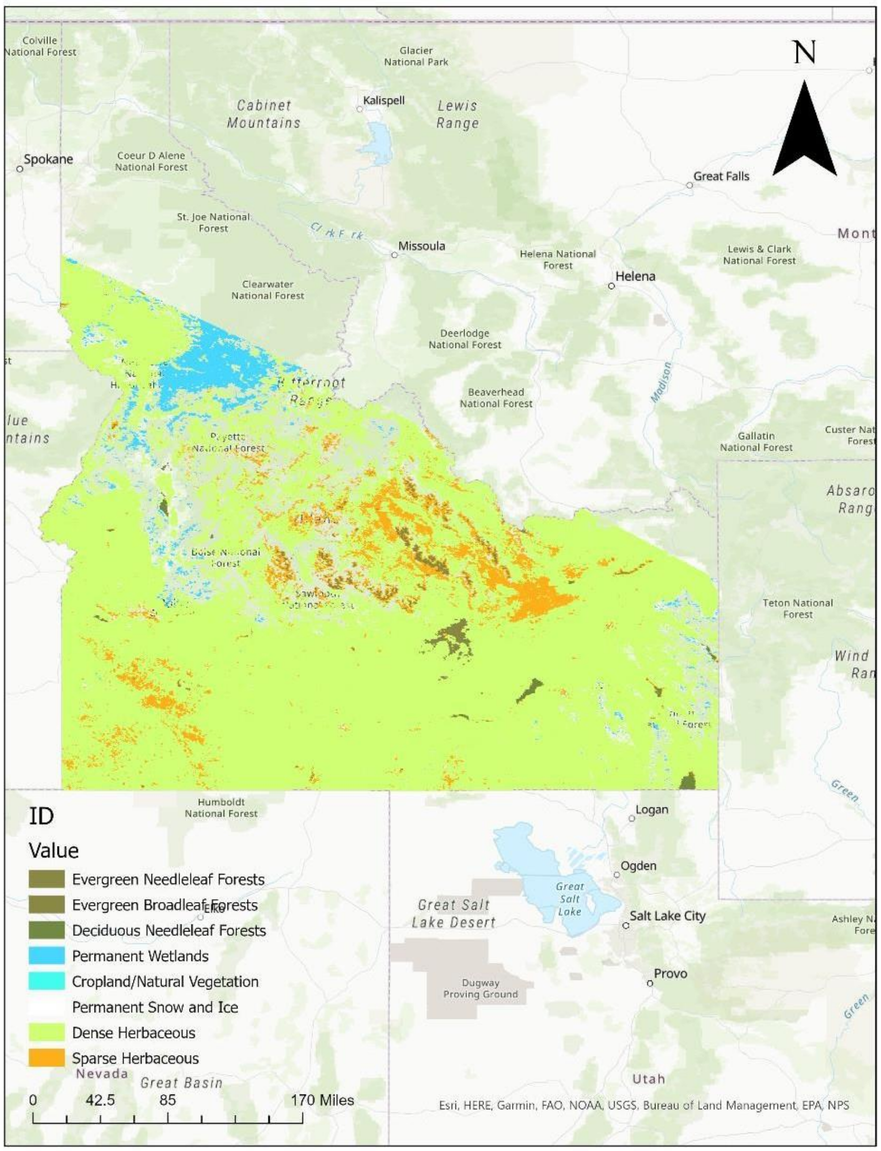


Fig. 8. Land Cover of dominant vegetation species in Idaho

Latitude and longitude affect the pattern of mean annual temperatures of the state. The temperatures can range from -60 ^{o}F to 118 ^{o}F. The state's moisture source is the Pacific Ocean, with the Gulf of Mexico and the Caribbean region also contributing from the South. Aridisols and Mollisols are the significant soil order in the state supporting dominantly forbs, shrubs, and grass-associated vegetation types. Snowberry and big sagebrush are some of the dominant shrub species in the region, whereas Idaho Fescue and blue bunch wheatgrass are the dominant grasses in the state. Antelope bitterbrush grows on moist sites. Western juniper is associated with rock outcrop and rubbly areas. Western Juniper has dramatically expanded its extent in Oregon due to the suppression of wildfires. However, rose cow parsnip, black hawthorn, and arrow leaf balsamroot also are essential. Forestland, ponderosa pine, and Douglas fir are some of the major tree species. The northeastern part of the state supports desert shrubs, shrub grass, and forest vegetation like Indian ricegrass, needle thread, and shad scale. Prairie June grass, onion grass, Indian paintbrush, lupine, sedge, big and low sagebrush, and rabbitbrush grow on low mountain slopes. We can see how temperature and precipitation affect vegetation species across Idaho, with desert shrubs being the dominant species and shrub grass in the Western part of the state, indicating lower temperatures and higher precipitation as we go from East to West, as shown in Fig.8.

4.2.5. Montana

The Continental Divide traverses the state's western half in a north-south direction. Barrier summers are cooler, precipitation is more evenly distributed throughout the year, barrier winters are milder, and winds are lighter on the mountain's western side than on the eastern side. There is more cloudiness in the west in all seasons, humidity runs higher, and the growing season is shorter than in the east of plains areas. Areas adjacent to mountain ranges generally are the wettest, although there are a few exceptions where the "rain shadow" effect appears. Nearly half the annual long-term average total falls from May through July. It is the main reason Montana is consistently one of the largest producers of dryland grain crops. The state supports coniferous forests due to high altitude and low temperatures and grassland vegetation, prairies, and inland areas.

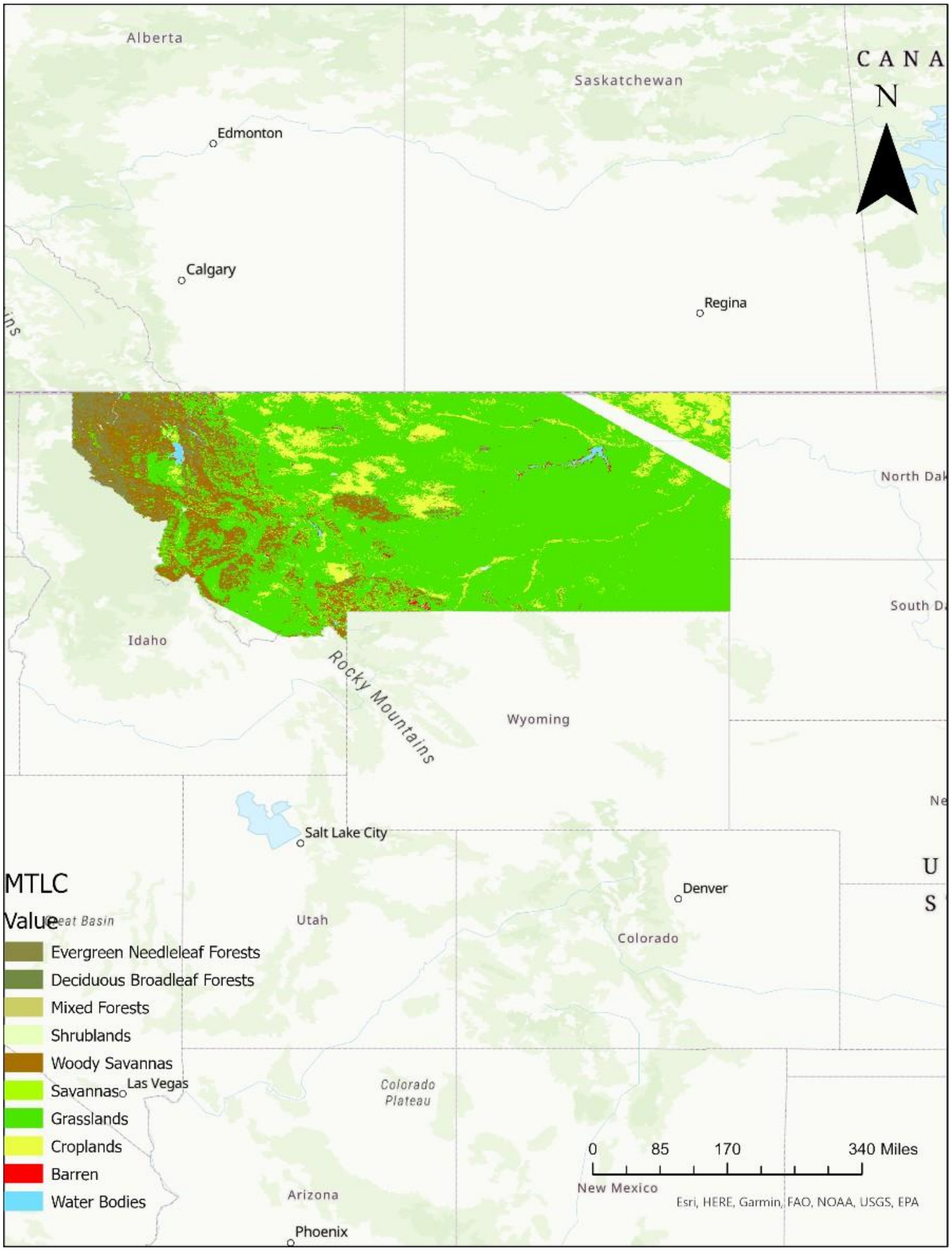


Fig. 9. Land Cover of dominant vegetation species in Montana

As shown in Fig. 9, the most common plants in the area are grand fir, Douglas-fir, western red cedar, western hemlock, western larch, subalpine fir, whitebark pine, and western white pine. Blue bunch wheatgrass, rough fescue, bearded wheatgrass, green needlegrass, and blue grama dominate the valleys and foothills.

4.2.6. Nevada

Rapid heating and sudden cooling of land during day and night result in wide daily ranges in temperature. Nevada lies on the eastern lee side of the Sierra Nevada Range, a massive mountain barrier that markedly influences the state’s climate. As a result of this mountain range, the lowlands of Nevada are large deserts. Aridisols, Mollisols, Entisols, and Inceptisols are the dominant soil order in Nevada. Most dominant vegetation types belong to forbs, shrub grass, desert shrubs, and woodland vegetation. Prevalent species in the state are big sagebrush, low sagebrush, needlegrass, saltbush, saltgrass, squirrel tail, blue bunch wheatgrass, western wheatgrass, milkvetch, Indian rice-grass, shade scale, cactus, Creosote bush, white bursage, and Mormon tea.

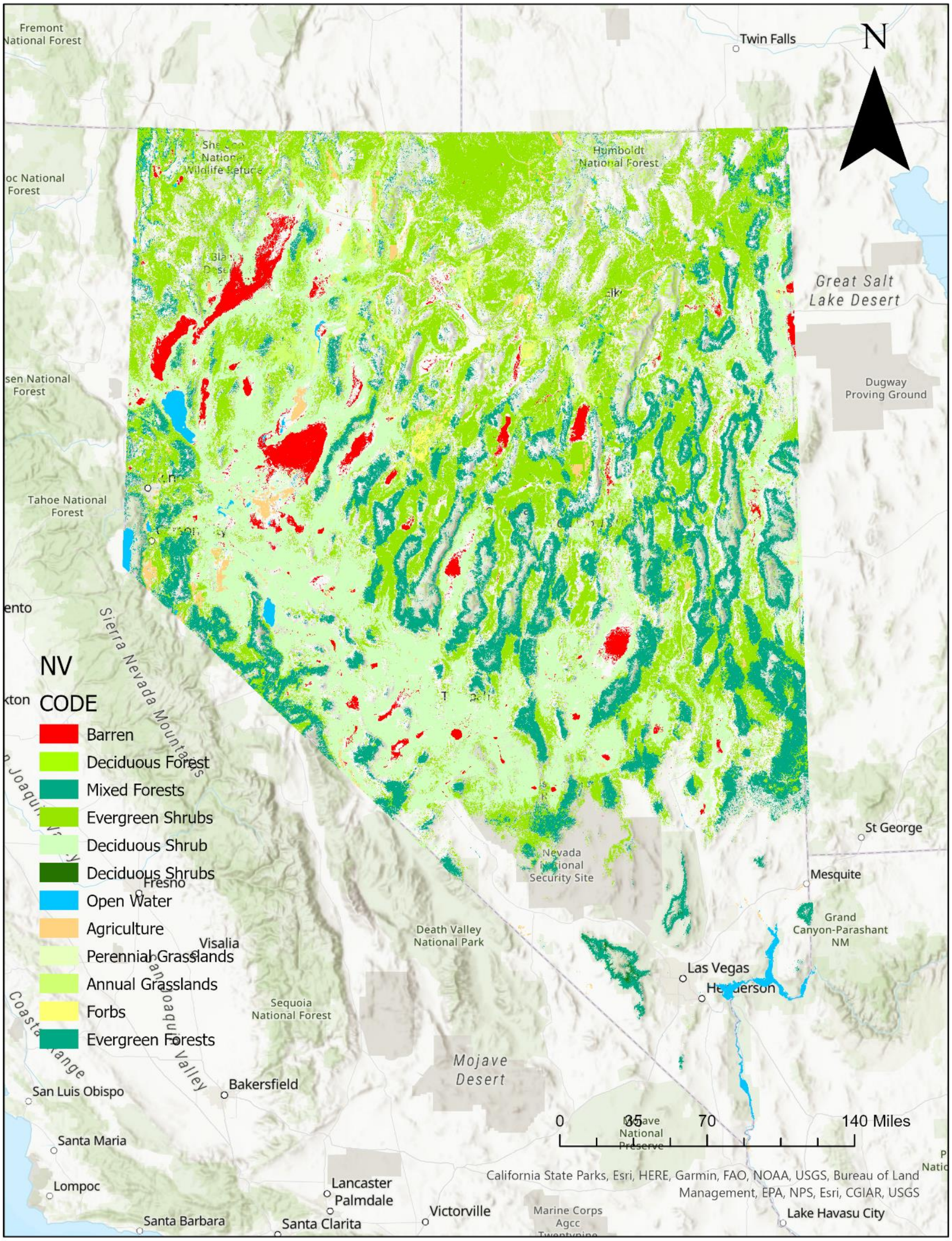


Fig. 10. Land Cover of dominant vegetation species in Nevada

4.2.7. New Mexico

A warm, arid, or semi-arid continental climate prevails in New Mexico, distinguished by a sizable annual and diurnal temperature range, abundant sunshine, low relative humidity, and little to no precipitation. In the extreme southeast, the yearly average temperature is 64° F, while in the high mountains and valleys of the north, it is 40° F or lower. On average, the southern desert and the Rio Grande and San Juan Valleys receive less than 10 inches of yearly precipitation, whereas higher elevations receive more than 20 inches. Alfisols, Aridisols, Entisols, and Mollisols are the most significant soil order which supports desert shrub or arid vegetation types. Sand sagebrush and yuccas thrive in scattered patches on the sandier soils. Creosote bush, tar bush, and cat claw grow on calcareous, gravelly soils on foot slopes. Giant sacaton, vine-mesquite, desert willow, and Brickell bush flourish in drainage channels and depressions. Fig. 10 depicts the land cover for various vegetation species across the state.

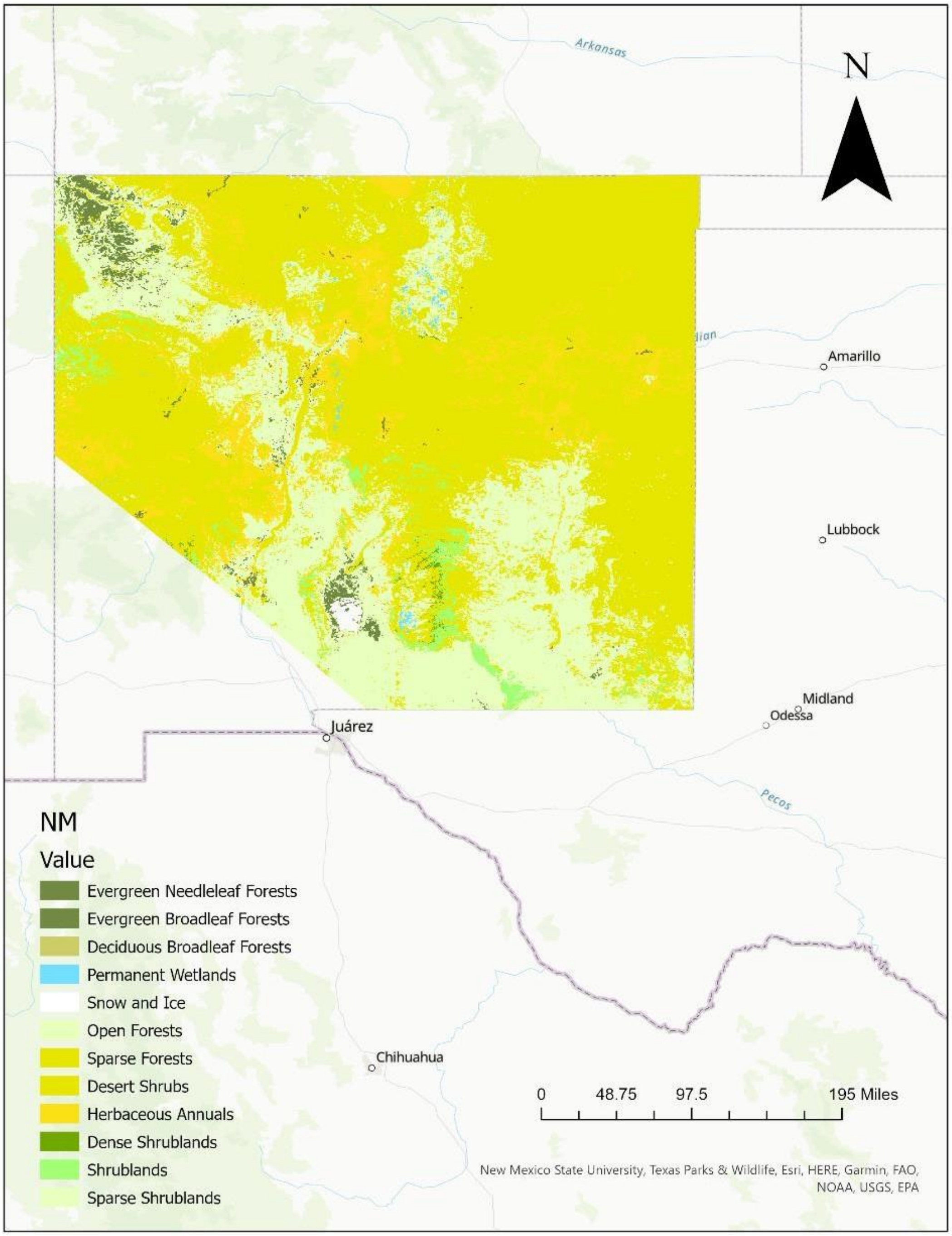


Fig. 11. Land Cover of dominant vegetation species in New Mexico

4.2.8. Oregon

It is one of the coldest states in the United States. It experiences high-temperature variability ranging from a low of 54 ^{o}F below zero to a high of 119 ^{o}F. In contrast, annual average precipitation ranges from about eight inches in the Plateau region to two hundred inches in the

Upper West slopes of the Coastal Range. Rainfall decreases as we move inward.

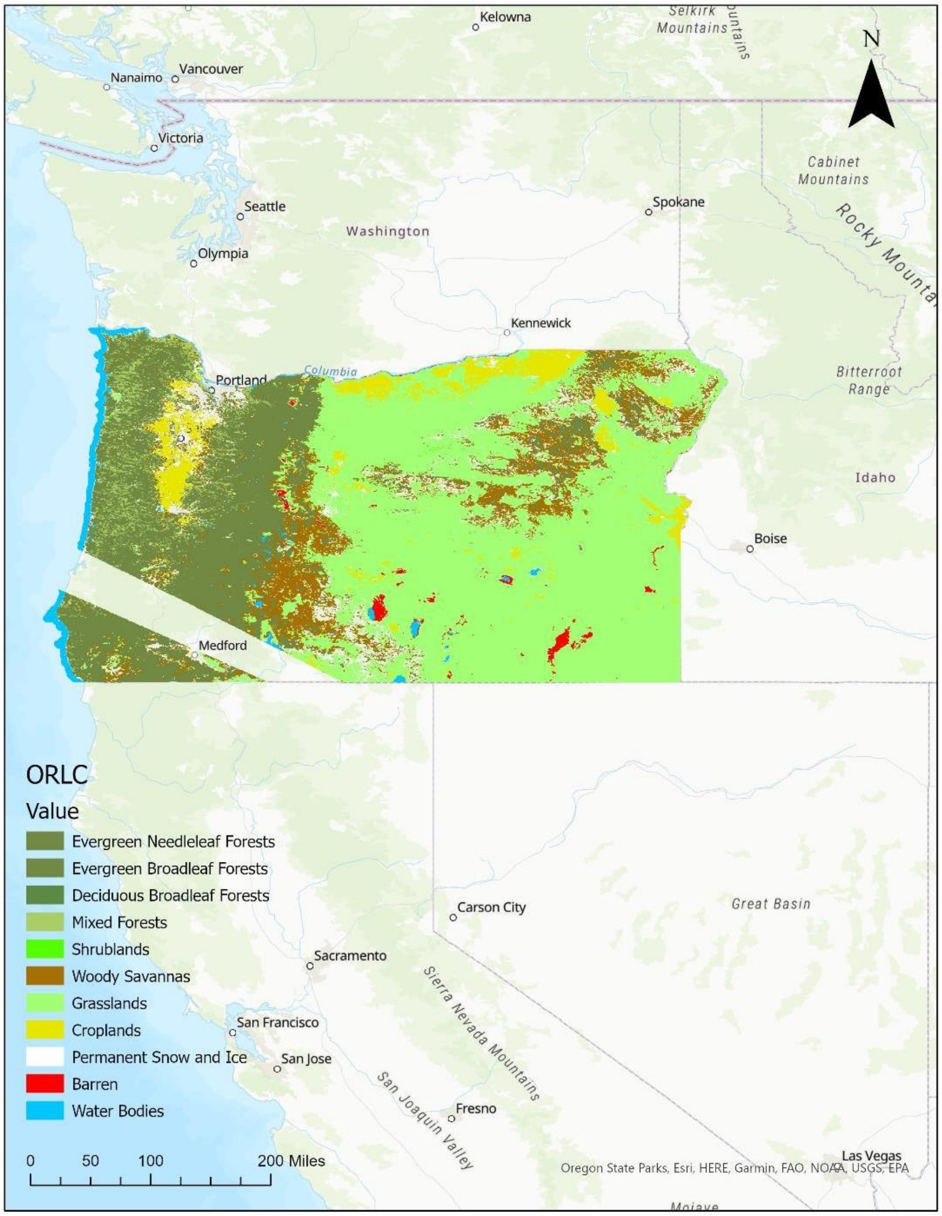


Fig. 12. Land Cover of dominant vegetation species in Oregon

The soil orders found in the state are Alfisols, Andisols, Inceptisols, Mollisols, Spodosols, and Ultisols. Entisols are present dominantly along the coastline throughout Oregon and Washington. The soil order primarily supports dense forest stands, prairie, and savannah vegetation. High altitude and frigid zones make it optimal for keeping conifers like Douglas-fir, Western Hemlock, Red Alder, Grand fir, Pacific Silver fir, White fir, Sitka Spruce, and Oregon White Oak in the Northern, Western, and Central parts of the state. As we move towards the east, i.e., plains, deserts, and rangelands, a significant change in the vegetation type can be observed from coniferous trees to shrubs and grasses. Basin big sagebrush, Pine grass, blue bunch wheatgrass, and Wyoming big sagebrush are some of the region's most dominant species of shrubs and grass. Stiff sagebrush, Low sagebrush, and Sandberg bluegrass are some of the dominant grasses in the drier sites, as shown in Fig. 12.

4.2.9. Utah

Utah experiences relatively strong insolation during the day and rapid nocturnal cooling, resulting in wide daily ranges in temperature. Even after the hottest days, nights are usually cool over the state. The average annual precipitation in the leading agricultural areas is between 10 to 15 inches. Northwestern Utah, over and along the mountains, receives appreciably more rainfall in a year than at similar elevations over the rest of the state, primarily due to terrain and the direction of typical storm tracks. Alfisols, Aridisols, Entisols, and Mollisols are the dominant soil orders in the state. Desert-salt, desert zone, and foothill zones in the upland areas support desert shrubs, woodland vegetation, and forbs. Given the prevalent landscape, Castle Valley saltbush, Gardner's saltbush, mat bush, greasewood, and salina wildrye. Upland foothill zones are dominated by Utah juniper and pinyon pine forests. Precipitation lies in (305-405) mm, along with black sagebrush, prairie June grass, mutton grass, Utah serviceberry, and mountain mahogany growing at higher elevations. Moreover, the state's southern region is covered with desert shrubs and woodland vegetation species like blue grama, black grama, and western wheatgrass, which can be observed in Fig. 13.

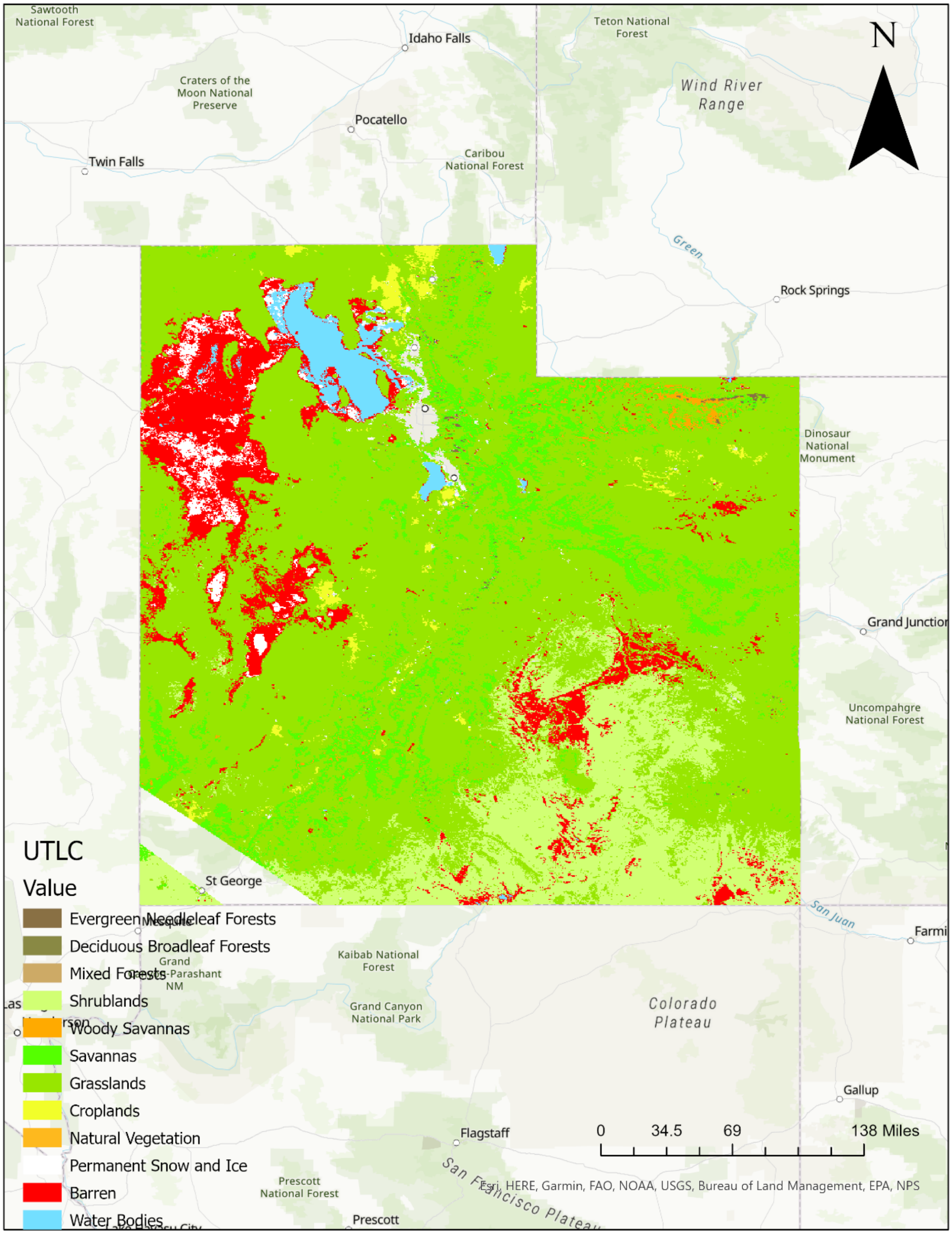


Fig. 13. Land Cover of dominant vegetation species in Utah

4.2.10. Wyoming

Because of the high altitude, the climate is relatively cool. The mountain ranges block the flow of moisture-laden air from the east and west. Aridiols and Entisols form the dominant soil order in the state.

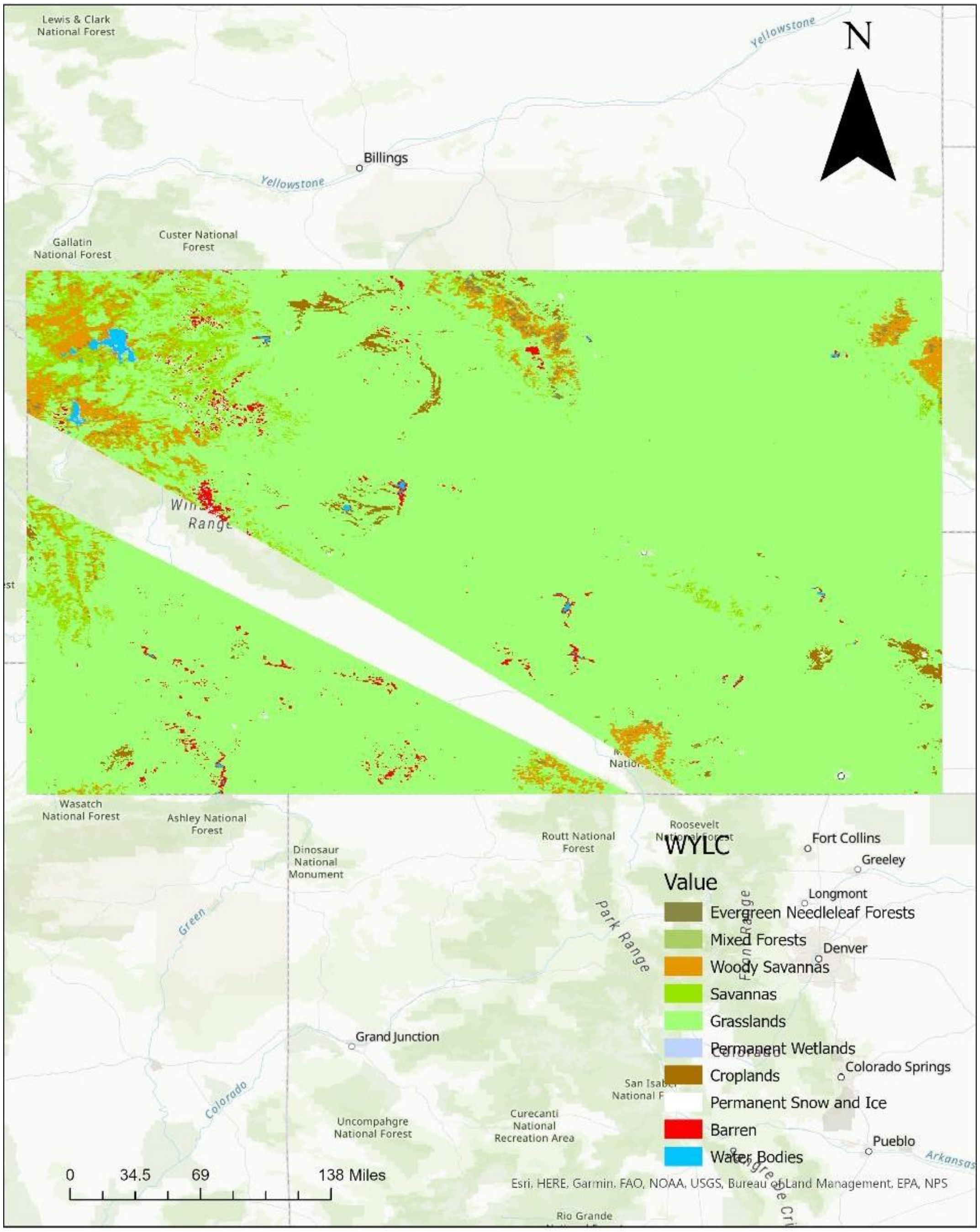


Fig. 14. Land Cover of dominant vegetation species in Wyoming

In northern mountain desert basins, a lack of such soil and appropriate precipitation hinders the natural vegetation's ability to maintain shrub-grass, cool and warm seasoned grassland vegetation species such as large sagebrush, Gardner's saltbush, rhizomatous wheatgrass, and Indian ricegrass. In contrast, the southern and southwestern Cool Central Desertic Basins and Plateaus support riparian zones. These areas support cool and warm season grasses like blue bunch mutton grass, big sagebrush, rhizomatous wheatgrass, Indian rice grass, basic wildrye, and green needlegrass, as depicted in Fig. 14.

4.3. Developing Plant Functional Group Parameters

Many plant characteristics were used to model croplands from measurements collected from custom-designed field plots. However, because of the wide variation in the plant species present throughout the research area, similar strategies are not recommended for simulating range lands. The study region of WUS has approximately 18,876 distinct species. Adopting earlier practices will increase the time needed to collect data and require a large workforce. In contrast, the APEX model's current plant growth database contains information about 170 plants and crop species. Each species defined in the model has been characterized by seventy distinct parameters, out of which a minimum set of 25 parameters are considered "critical" for the calibration and validation of the model and are implemented in the APEX-CUTE Auto-Calibration Tool (Wang et al., 2014). However, for this study, the auto-calibration approach was not adopted. Instead, manual calibration was chosen to adjust the parameters for a good fit. The minimum set of parameters is the one that differentiates between individual plant species within a region. The development and identification of these parameters were carried out in previous research studies conducted by (Wang et al., 2006; Yin et al., 2009), literature values, and APEX developers' and users' suggestions cited and documented by (Wang et al., 2012).

Due to the high heterogeneity of plant species in the study locations, one of the main objectives was to ascertain whether it was possible to calibrate and validate the APEX model using a less representative selection of plant species. Consequently, plant modeling parameters for the areas were developed based on plant FG. As was already mentioned, plant FG is composed of plant species that exhibit similar reactions to the environment and impacts on ecosystem function. As a result, plant modeling parameters for the WUS based on plant FG were developed. By classifying plants according to their form and function, or the on-site niche they compete for, we may create a stable and practical framework and a description of the plant community that reflects their diversity and how it functions on a given site. For this study, distinct plant species distributed across ten states within the WUS were assigned FG considering a wide range of parameters, including:

a) grouping plants by their duration of growth (annual/perennial)

b) grouping plants based on their primary growing season (spring/summer/winter)

c) grouping plants by their origin (native/introduced)

d) grouping plant's type of growth form (shrub/forb/grasses/trees)

e) grouping plants by their ability to keep leaves (deciduous/evergreen)

Each unique species was assigned an FG and FG season that was developed and is used in the Conservation Effects Assessment Project (CEAP)-Grazing Land program. BLM provided data regarding the vegetation species in the WUS. The extensive database provided by BLM recorded major dominant vegetation species in these states. The species were assigned to FG using three techniques:

- Plant species were assigned to a given FG representative plant species based on the same or similar plant species in the ALMANAC Crop Parameter Database (Kiniry et al., 1992), EPIC/APEX (Williams et al., 2000; Gassman et al., 2010) and SWAT (Arnold et al., 2012) models. An example of the database for different parameters of Indian Grass is shown in Fig. 15.

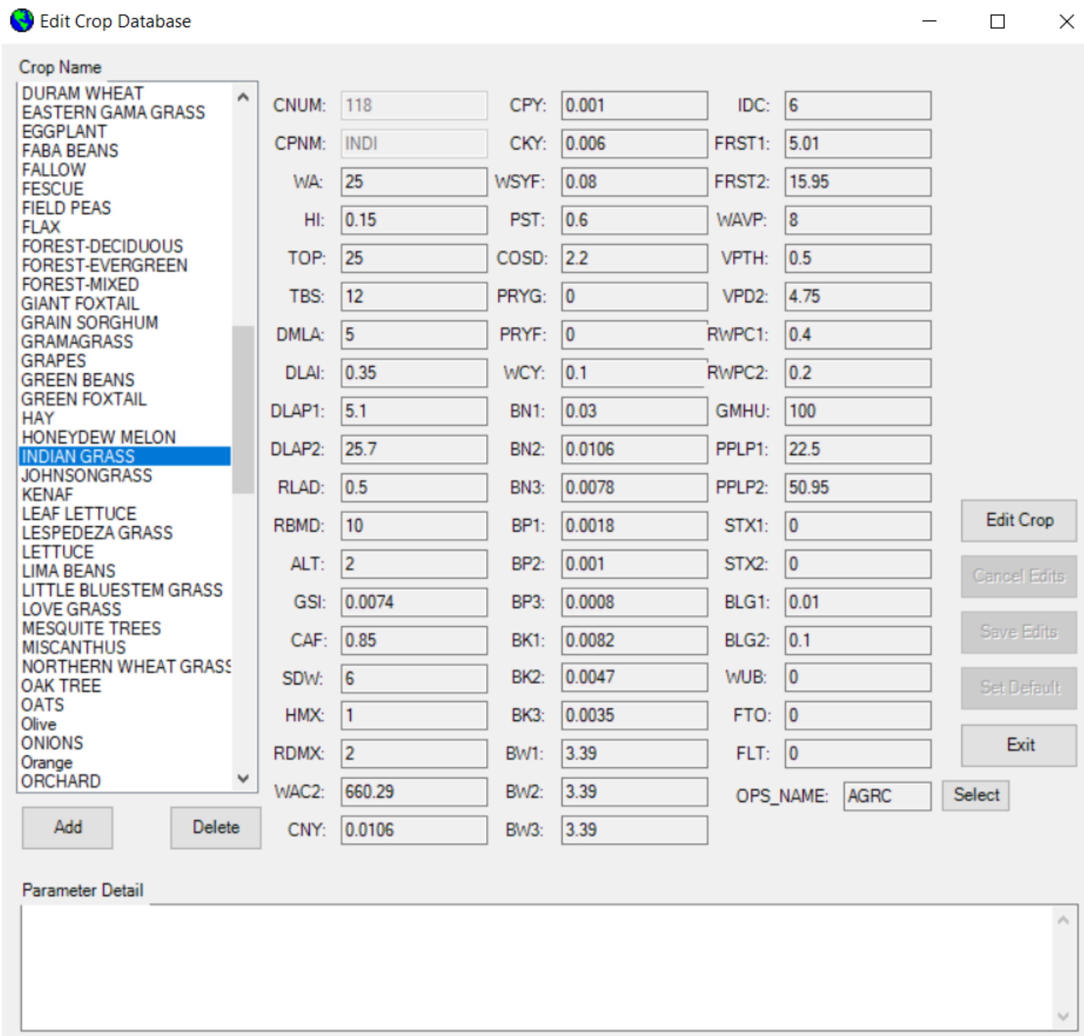


Fig. 15. ALMANAC Database illustrating various parameters associated with Indian Grass

- Data sources such as the United States Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS) Plants Database give crucial information such as the family and growth type of vegetative species (see Fig. 16). It includes plant symbols, growth habits, growth types, crop information, nativeness of species (native, introduced species, or both), distribution of species across the USA, and essential references. Similar information about various species was obtained from websites like Lady Bird Johnson Wildflower Center (https://www.wildflower.org/) and iNaturalist (https://www.inaturalist.org/), shown in Fig. 16 and Fig. 17.

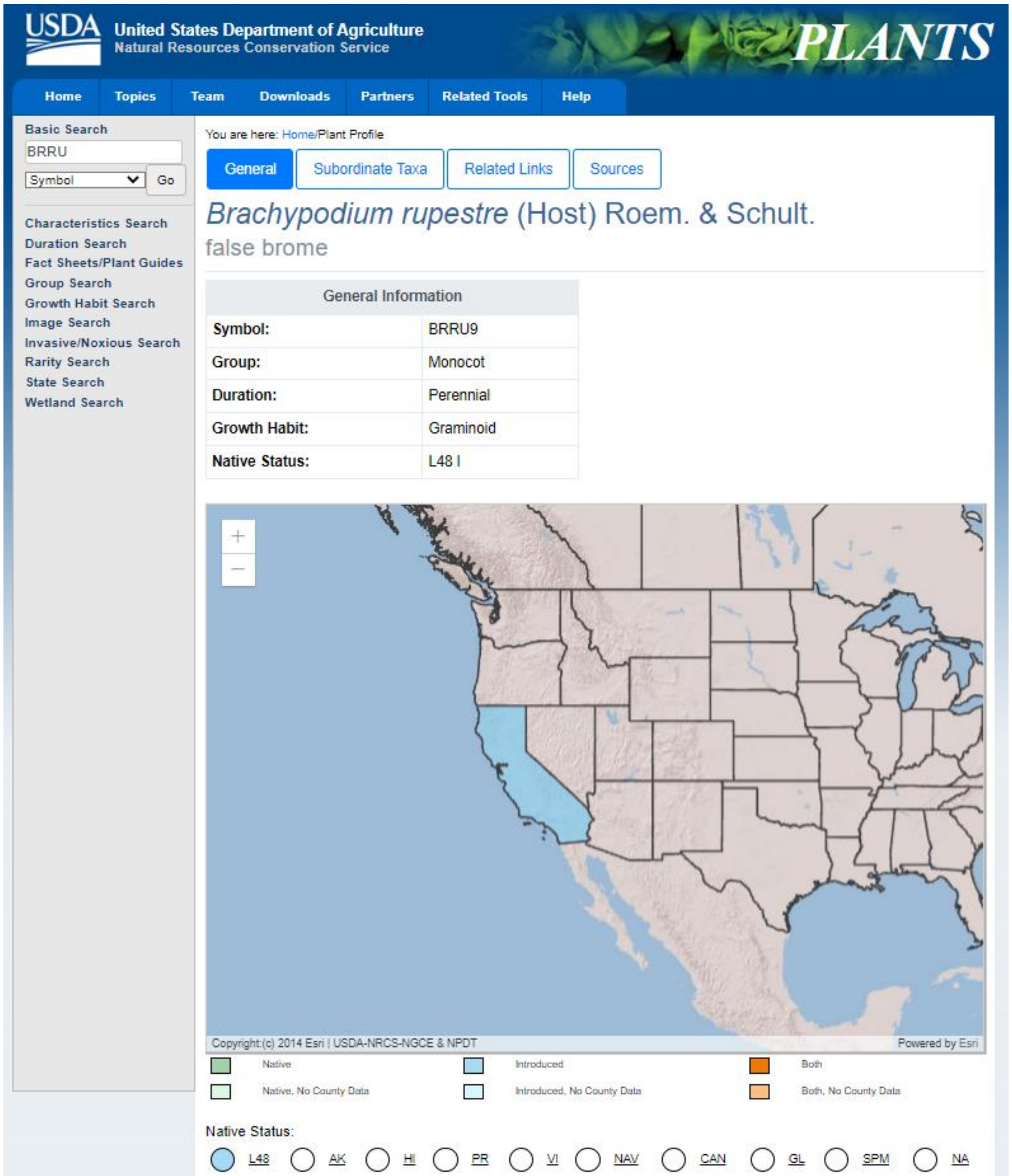


Fig. 16. USDA Plants Database illustrating details about species' common name, growth habits, and native status

Classification	
Kingdom	*Plantae* - Plants
Subkingdom	*Tracheobionta* - Vascular plants
Superdivision	*Spermatophyta* - Seed plants
Division	*Magnoliophyta* - Flowering plants
Class	*Liliopsida* - Monocotyledons
Subclass	*Commelinidae*
Order	*Cyperales*
Family	*Poaceae* Barnhart - Grass family
Genus	*Brachypodium* P. Beauv. - false brome
Species	*Brachypodium rupestre* (Host) Roem. & Schult. - false brome

Fig. 17. Information about the classification of plant species-genus and family name obtained from the USDA Plants Database

Hordeum pusillum

Hordeum pusillum Nutt.

Little Barley

Poaceae (Grass Family)

Synonym(s): *Critesion pusillum*, *Hordeum pusillum* var. *pubens*

USDA Symbol: HOPU

USDA Native Status: L48 (N), CAN (N)

Strickland, Sam C.

An annual grass with each stem bearing an unbranched, erect, flattened, bristly spike of narrow, crowded, greenish-brown spikelet.

Although now widespread in the United States, this relative of the cultivated Barley (*H. vulgare*) was probably originally native only in the southern states. In some areas it is extremely abundant, becoming especially conspicuous when the plants mature, which they do quickly, and turn brown; at that stage the spikes break up into short sections.

Figure 18. Information about the classification of plant species like common name, family name, symbol, and native status obtained from Lady Johnson Wildflower Center

- Expert opinion was used when data about the vegetation type could not be gathered from other sources.

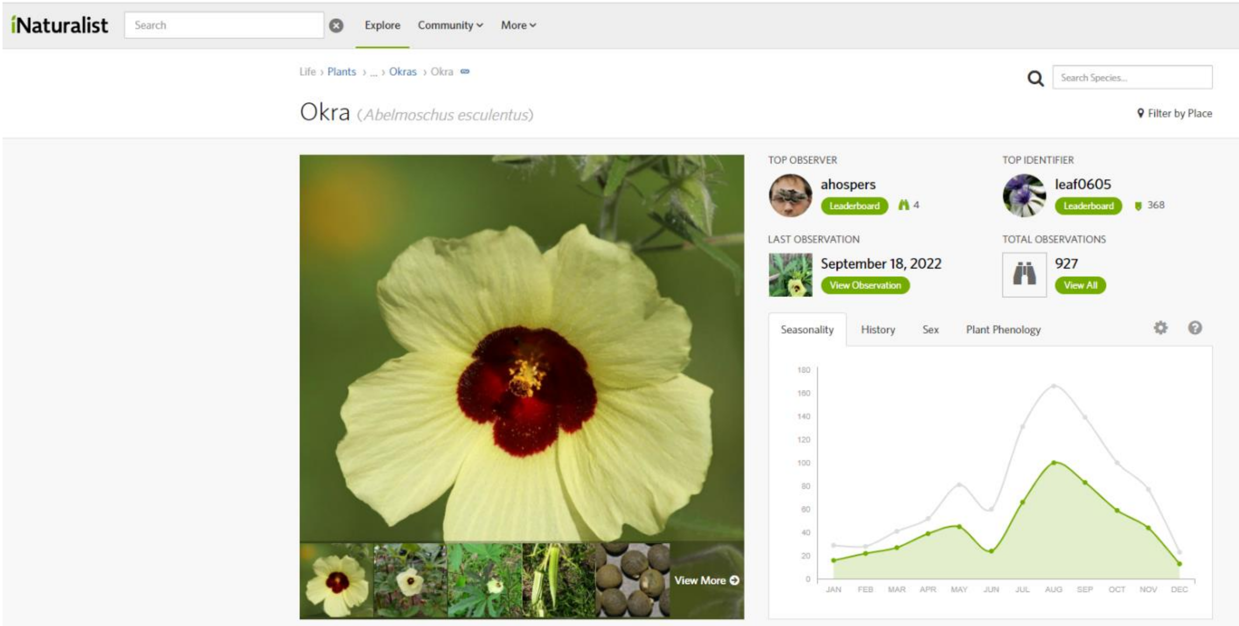


Fig. 19. Information about the seasonality of a species obtained from the iNaturalist database, which helped assign the FG season for a species

Additionally, choosing a crop/plant parameter template from the ALMANAC, EPIC/APEX, and SWAT databases required figuring out the optimum fit for a species based on the matching set of parameter values chosen using the crop category number (IDC) (in the APEX User's Manual). IDC assisted in assigning the type of crop/plant, FG, FG number, and FG season, among other parameter values that already exist in the database. A brief description of which IDC number corresponds to which FG for different plant species is shown in Table 3.

Table 3 IDC values corresponding to each FG

IDC	FG
1	Warm season annual legume
2	Cold season annual legume
3	Perennial legume
4	Warm season annual
5	Cold season annual
6	Perennial
7	Evergreen Tree Crop
8	Deciduous Tree Crop
9	Cotton
10	Leguminous Tree Crop

4.4. Model Setup

4.4.1. APEX

The Blacklands Research and Extension Centre developed the model in Temple, Texas. APEX is a daily time-step process-based model developed to evaluate the effects of various best land management practices (BMPs) considering sustainability, erosion (wind, sheet, and channel), soil and water quality, plant growth, weather parameters, routing of pesticides, and sediments. In addition, it can also estimate the impacts on a broad range of environmental indicators and natural resource concerns such as carbon sequestration, nitrogen (N) and phosphorus (P) nutrient cycling, water quantity and quality, and soil erosion. It can also perform long-term continuous simulations for modeling the effects of nutrients, weather, irrigation, land management practices, tillage operations, soil characteristics, and cropping patterns on surface runoff, nutrients, and other pollutants. Besides these, the latest enhancements in the APEX model now allow for simulating and estimating salt movement (Bailey et al., 2022). A detailed description of the broad application of the model is provided by (Gassman et al., 2009), whereas details of the enhancements are described by (Zilverberg et al., 2017). APEX can simulate the growth of several plant species as they compete for water, nutrients, and light. LAI and plant height both affect competition for light. It is highly flexible and dynamic. As mentioned previously, one of the study's primary objectives was to determine if the developed FG for the plant species throughout the WUS resembled the characteristics of the plant species in the APEX model during simulation against ET, LAI, and plant height data for locations selected all over CRB. APEX provides a standalone version of APEXeditor, a spreadsheet-based tool for altering APEX models' input and output files (Osorio, 2019).

4.4.2. APEX CUTE

Another goal of the study was to calibrate and validate the model using data on ET, LAI, and plant height observed at various points and locations within the WUS. The model includes a calibration and validation tool with a graphical user interface (GUI), making it easy to do parameter uncertainty analysis, auto-calibration, and sensitivity analysis (Wang et al., 2014). The program also includes a Dynamically Dimensioned Search (DDS) algorithm that can choose between using the same or different unbiased random ensembles for simulation during auto-calibration and validation (Tolson and Shoemaker, 2007). The most recent APEX-CUTE version, v7.1, has all the above-described functionality.

4.5. Creating Input Files for APEX

To correctly simulate the developed FGs, the input files must replicate the natural world ecosystem at the chosen locations as accurately as possible. The ability of the model to correctly simulate the developed FGs depends on how well the input files are created and how closely they reflect the on-site conditions in terms of soil properties, climatic conditions, and vegetation species growing at those locations.

Various locations in the states of Arizona (2), California (3), Colorado (3), New Mexico (2), Nevada (5), Utah (1), and Wyoming (3) were used for the APEX simulation, calibration, and validation. These areas were chosen to simulate the plant species growing within the region and their corresponding FGs. Other important model parameterization input data include soil, dryland management, and daily and monthly weather data. The coordinates of locations chosen for simulating the developed FG are provided in Table 4.

Table 4 Table showing coordinates of points/locations chosen for simulation within CRB in APEX

Locations	Latitude	Longitude
AZ2109	34.276	-112.148
AZ9309	34.860	-113.682
CA3157	41.711	-120.002
CA3710	36.101	-117.870
CA4374	41.282	-120.476
CO3016	37.290	-108.250
CO3359	39.592	-106.779
CO6832	40.075	-108.687
NM2837	36.532	-106.770
NM8535	32.262	-106.597
NV0507	39.523	-117.093

NV2189	41.173	-115.163
NV4527	41.711	-118.672
NV4950	39.517	-114.817
NV7123	40.313	-115.682
UT2696	40.274	-112.221
WY0540	44.712	-107.976
WY1165	44.512	-106.701
WY6595	42.417	-107.690

4.5.1. Daily and Monthly Weather Files

From 1960 to 2005, the input weather data set was compiled for each of the selected simulation locations. The model applied daily and monthly weather datasets from the nearest weather stations to the chosen sampling location for simulation, calibration, and validation purposes. After feeding the values of year, month, day, solar radiation, maximum temperature, minimum temperature, precipitation, wind speed, and relative humidity into the APEXeditor, .DLY files for each site were created, as shown in Fig. 20.a. A listing included all the .DLY files were compiled and were available for creating runs. This listing contains daily weather stations and the corresponding latitude, longitude, and weather station location, as shown in Fig. 21. The model references this file to determine which weather station (.DLY) will be used for daily weather.

Similarly, APEX Monthly Weather Data List is a listing of all monthly weather station files which were created for all selected locations.

AZ2109 - Notepad

File Edit Format View Help

```
1960   1   1  13.0  2.78 -6.67  0.00  0.56  2.23
1960   1   2  13.0  3.89 -8.89  0.00  0.30  4.84
1960   1   3  13.0  6.67 -7.78  0.00  0.46  4.26
1960   1   4  13.0  5.56 -6.67  0.00  0.52  4.21
1960   1   5  13.0  6.67 -6.67  0.00  0.46  3.70
1960   1   6  13.0 10.00 -4.44  0.00  0.51  4.10
1960   1   7  13.0 13.89 -3.33  0.00  0.48  4.74
1960   1   8  13.0 16.11 -1.11  0.00  0.51  3.30
1960   1   9  13.0 15.00 -1.67  0.00  0.56  4.91
1960   1  10  13.0 10.00  1.11  0.00  0.37  4.40
1960   1  11   4.0 10.00  3.33  3.05  0.98  1.71
1960   1  12   4.0  7.78  3.33 15.24  1.00  3.04
1960   1  13   5.0  5.56 -1.11 23.62  0.99  2.14
1960   1  14  14.0  2.22-10.00  0.00  0.43  3.79
1960   1  15   8.0  3.89 -6.11  3.30  0.95  3.73
1960   1  16  13.0  4.44 -2.22  0.00  0.31  2.98
1960   1  17  13.0  1.67 -8.33  0.00  0.64  4.60
1960   1  18  13.0  7.22 -8.33  0.00  0.52  3.29
1960   1  19  14.0 10.00 -6.67  0.00  0.64  3.52
1960   1  20  14.0 12.78 -3.89  0.00  0.38  1.21
1960   1  21  14.0 13.33 -2.22  0.00  0.37  5.14
1960   1  22  15.0 15.56 -1.67  0.00  0.33  4.87
1960   1  23  15.0 18.33  1.67  0.00  0.60  4.59
1960   1  24  15.0 18.33  2.22  0.00  0.46  2.85
1960   1  25  15.0 16.11  0.56  0.00  0.21  3.29
1960   1  26  15.0 14.44  2.22  0.00  0.26  2.27
```

(a) Sample Daily (.DLY) Weather file

AZ2109 - Notepad

File Edit Format View Help

```
AZ2109

 14.31 15.94 18.21 22.58 27.76  33.4  35.5 34.07 31.02 25.41  18.8  14.4
  0.27  1.34  2.72  5.33  9.34 14.09 18.63 18.04 14.72  9.23  3.73  0.42
  4.74  4.86  5.06  5.02  4.41  4.08  2.97  3.13  3.63  4.99  4.98  4.92
   3.6  3.56  3.44  3.55  3.58  3.76  2.64  2.58   3.3  3.77  3.65  3.56
 37.96 42.81 38.15  14.9  9.57  5.53  42.8 60.83 47.02 27.34 30.03 36.55
 10.14 11.82  8.96  7.13   4.9   5.0  9.12 11.64 14.33 10.92 14.11 11.92
  1.87  2.13  2.36  2.05  1.44  1.33  1.76   2.9  2.94  2.26  2.77  3.04
  0.09  0.09  0.09  0.05  0.04  0.03  0.15  0.17   0.1  0.06  0.07  0.08
  0.42  0.41  0.48  0.32  0.27  0.21  0.28  0.33  0.32  0.39  0.35  0.43
  4.02  3.84  4.61   2.2  1.61  1.07   5.2  6.18  3.91  2.68   2.7   3.8

 12.22 16.74 21.76 26.36 29.92 30.79 27.45 25.56 23.39 18.45 14.02 11.38
  0.54  0.53  0.51  0.47  0.43  0.38   0.9   0.9   0.9  0.43  0.46  0.53
  3.28  3.79   4.4  4.61  4.68  4.67  3.76  3.47  3.76  3.58  3.33  3.24
```

(b) Sample Monthly (.WP1) Weather file

Figure 20. Sample Daily (.DLY) and Monthly (.WP1) Weather file

File Edit Format View Help

```
   1 AZ2109.DLY      34.27 -112.14
   2 AZ9309.DLY      34.86 -113.68
   3 CA3157.DLY      41.71    -120
   4 CA3710.DLY       36.1 -117.86
   5 CA4374.DLY      41.28 -120.47
   6 CO3016.DLY      37.29 -108.25
   7 CO3359.DLY      39.59 -106.77
   8 CO6832.DLY      40.07 -108.68
   9 NM2837.DLY      36.53 -106.77
  10 NM8535.DLY      32.26 -106.59
  11 NV0507.DLY      39.52 -117.09
  12 NV2189.DLY      41.17 -115.16
  13 NV4527.DLY      41.71 -118.67
  14 NV4950.DLY      39.51 -114.81
  15 NV7123.DLY      40.31 -115.68
  16 UT2696.DLY      40.27 -112.22
  17 WY0540.DLY      44.71 -107.97
  18 WY1165.DLY      44.51  -106.7
  19 WY6595.DLY      42.41 -107.69
```

File Edit Format View Help

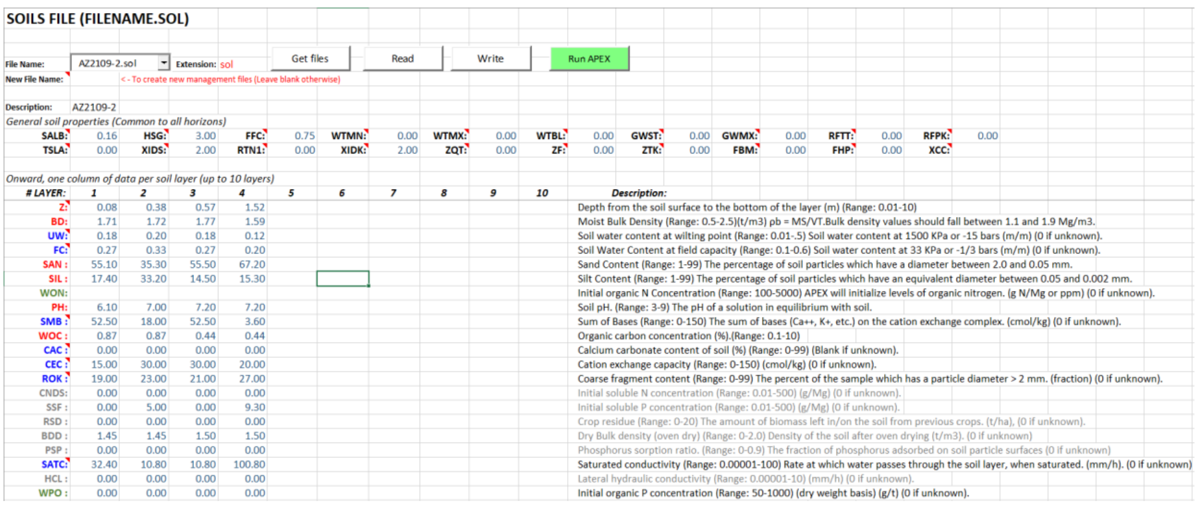
```
   1 AZ2109.WP1      34.27 -112.14     AZ
   2 AZ9309.WP1      24.86 -113.68     AZ
   3 CA3157.WP1      41.71    -120     CA
   4 CA3710.WP1       36.1 -117.86     CA
   5 CA4374.WP1      41.28 -120.47     CA
   6 CO3016.WP1      37.29 -108.25     CO
   7 CO3359.WP1      39.59 -106.77     CO
   8 CO6832.WP1      40.07 -108.68     CO
   9 NM2837.WP1      36.53 -106.77     NM
  10 NM8535.WP1      32.26 -106.59     NM
  11 NV0507.WP1      39.52 -117.09     NV
  12 NV2189.WP1      41.17 -115.16     NV
  13 NV4527.WP1      41.71 -118.67     NV
  14 NV4950.WP1      39.51 -114.81     NV
  15 NV7123.WP1      40.31 -115.68     NV
  16 UT2696.WP1      40.27 -112.22     UT
  17 WY0540.WP1      44.71 -107.97     WY
  18 WY1165.WP1      44.51  -106.7     WY
  19 WY6595.WP1      42.41 -107.69     WY
```

Fig. 21. List of weather stations in the WDLSTCOM.DAT file and WPM1US.DAT files for all locations

4.5.2. Soil Files

Data for soil properties at each site was kept in a file, *filename.sol*, as shown in Fig. 23 a. Properties of soil layers were retrieved from STATSGO for three locations in Colorado, namely

(CO3016, CO3359, and CO6832). In contrast, the rest were retrieved from gSSURGO to create the individual soil files for every chosen location. The final soil attribute tables supply the most relevant information for process-based modeling. The attributes include information about soil albedo, soil hydrologic group selected for a site, and soil bulk density. The APEX Soil list file lists all the soil files previously created for every location and are available for creating runs. It is made in a free FORMAT and must be identified correctly in the APEXFILE.DAT file. An image showing the various attributes considered while creating a .SOL file is shown in Fig. 22.



SOILS FILE (FILENAME.SOL)

File Name: AZ2109-2.sol Extension: sol | Get files | Read | Write | Run APEX

New File Name: < - To create new management files (Leave blank otherwise)

Description: AZ2109-2

General soil properties (Common to all horizons)

SALB:	0.16	HSG:	3.00	FFC:	0.75	WTMN:	0.00	WTMX:	0.00	WTBL:	0.00	GWST:	0.00	GWMX:	0.00	RFTT:	0.00
TSLA:	0.00	XIDS:	2.00	RTN1:	0.00	XIDK:	2.00	ZQT:	0.00	ZF:	0.00	ZTK:	0.00	FBM:	0.00	FHP:	0.00

RFPK:	0.00
XCC:	

Onward, one column of data per soil layer (up to 10 layers)

# LAYER:	1	2	3	4	5	6	7	8	9	10	Description:
Z:	0.08	0.38	0.57	1.52							Depth from the soil surface to the bottom of the layer (m) (Range: 0.01-10)
BD:	1.71	1.72	1.77	1.59							Moist Bulk Density (Range: 0.5-2.5)(t/m3) ρb = MS/VT.Bulk density values should fall between 1.1 and 1.9 Mg/m3.
UW:	0.18	0.20	0.18	0.12							Soil water content at wilting point (Range: 0.01-.5) Soil water content at 1500 KPa or -15 bars (m/m) (0 if unknown).
FC:	0.27	0.33	0.27	0.20							Soil Water Content at field capacity (Range: 0.1-0.6) Soil water content at 33 KPa or -1/3 bars (m/m) (0 if unknown).
SAN :	55.10	35.30	55.50	67.20							Sand Content (Range: 1-99) The percentage of soil particles which have a diameter between 2.0 and 0.05 mm.
SIL :	17.40	33.20	14.50	15.30							Silt Content (Range: 1-99) The percentage of soil particles which have an equivalent diameter between 0.05 and 0.002 mm.
WON:											Initial organic N Concentration (Range: 100-5000) APEX will initialize levels of organic nitrogen. (g N/Mg or ppm) (0 if unknown).
PH:	6.10	7.00	7.20	7.20							Soil pH. (Range: 3-9) The pH of a solution in equilibrium with soil.
SMB :	52.50	18.00	52.50	3.60							Sum of Bases (Range: 0-150) The sum of bases (Ca++, K+, etc.) on the cation exchange complex. (cmol/kg) (0 if unknown).
WOC :	0.87	0.87	0.44	0.44							Organic carbon concentration (%).(Range: 0.1-10)
CAC :	0.00	0.00	0.00	0.00							Calcium carbonate content of soil (%) (Range: 0-99) (Blank if unknown).
CEC :	15.00	30.00	30.00	20.00							Cation exchange capacity (Range: 0-150) (cmol/kg) (0 if unknown).
ROK :	19.00	23.00	21.00	27.00							Coarse fragment content (Range: 0-99) The percent of the sample which has a particle diameter > 2 mm. (fraction) (0 if unknown).
CNDS:	0.00	0.00	0.00	0.00							Initial soluble N concentration (Range: 0.01-500) (g/Mg) (0 if unknown).
SSF :	0.00	5.00	0.00	9.30							Initial soluble P concentration (Range: 0.01-500) (g/Mg) (0 if unknown).
RSD :	0.00	0.00	0.00	0.00							Crop residue (Range: 0-20) The amount of biomass left in/on the soil from previous crops. (t/ha), (0 if unknown).
BDD :	1.45	1.45	1.50	1.50							Dry Bulk density (oven dry) (Range: 0-2.0) Density of the soil after oven drying (t/m3). (0 if unknown)
PSP :	0.00	0.00	0.00	0.00							Phosphorus sorption ratio. (Range: 0-0.9) The fraction of phosphorus adsorbed on soil particle surfaces (0 if unknown)
SATC:	32.40	10.80	10.80	100.80							Saturated conductivity (Range: 0.00001-100) Rate at which water passes through the soil layer, when saturated. (mm/h). (0 if unknown)
HCL :	0.00	0.00	0.00	0.00							Lateral hydraulic conductivity (Range: 0.00001-10) (mm/h) (0 if unknown).
WPO :	0.00	0.00	0.00	0.00							Initial organic P concentration (Range: 50-1000) (dry weight basis) (g/t) (0 if unknown).

Fig. 22. Image from APEXeditor USER Interface used to create .sol files for a site (AZ2109)

The .SOL file for a location and list of all .SOL files complied to create runs for simulations are shown in Fig. 23. and 23. b.

```
AZ2109 - Notepad
File  Edit  Format  View  Help
AZ2109
    0.16       C    0.75    0.00    0.00    0.00    0.00    0.00    0.00    0.00
    0.00    2.00    0.00    2.00    0.00    0.00    0.00    0.00    0.00
    0.08    0.38    0.57    1.52
    1.71    1.72    1.77    1.59
    0.18    0.20    0.18    0.12
    0.27    0.33    0.27    0.20
   55.10   35.30   55.50   67.20
   17.40   33.20   14.50   15.30

    6.10    7.00    7.20    7.20
   52.50   18.00   52.50    3.60
    0.87    0.87    0.44    0.44
    0.00    0.00    0.00    0.00
   15.00   30.00   30.00   20.00
   19.00   23.00   21.00   27.00
    0.00    0.00    0.00    0.00
    0.00    5.00    0.00    9.30
    0.00    0.00    0.00    0.00
    1.45    1.45    1.50    1.50
    0.00    0.00    0.00    0.00
   32.40   10.80   10.80  100.80
    0.00    0.00    0.00    0.00
    0.00    0.00    0.00    0.00
```

(a) Sample Soil (.SOL) file screen for AZ2109

```
 1 AZ2109.SOL
 2 AZ2109.SOL
 3 AZ9309.SOL
 4 CA3710.SOL
 5 CA4374.SOL
 6 CO3016.SOL
 7 CO3359.SOL
 8 CO6832.SOL
 9 NM2837.SOL
10 NM8535.SOL
11 NV0507.SOL
12 NV2189.SOL
13 NV4527.SOL
14 NV4950.SOL
15 NV7123.SOL
16 UT2696.SOL
17 WY0540.SOL
18 WY1165.SOL
19 WY6595.SOL
```

(b) SOILCOM.DAT file

Fig. 23. Image shows .SOL file for a site (AZ2109) and SOILCOM.DAT files for all locations within the CRB

4.5.3. Land Management Files

The timing of rangeland’s seasonal life cycle is essential for setting up efficient land management plans and conservation strategies and for the ecosystem’s productivity. Through APEX simulations of plant growth, LAI, and ET during the growing season at locations chosen across the WUS, the developed FG plant parameters were modified and improved to reflect the representative plant species’ growth accurately. A specific FG was selected to reflect the predominant vegetation at each location accurately. The operations schedule file was created to keep track of all land management operations at each site concerning the chosen FG, as shown in Fig. 10(a). For this study, a simple land management operation was adopted for all locations, which involved:

(i) Seeding/Planting

(ii) Killing the crop if it is an annual species

The APEX Operation Schedule list, as shown in Fig. 10(b), lists all operation schedule files that were previously created. The Operation Schedule list consists of a numbered listing of all operation schedule files, which can be referenced by number in the APEX Subarea file.

```
 13 Greesewood/saltgrass
21
1  4  1  146    0   31    0 1550.00    0.00    0.00    0.00    0.00  500.00    0.00   Seeding/Sowing (IHC = 5)
1  3  1  146    0   19    0 1550.00    0.00    0.00    0.00    0.00  500.00    0.00   Seeding/Sowing (IHC = 5)
1  3  1  146    0    6    0 1400.00    0.00    0.00    0.00    0.00  500.00    0.00   Seeding/Sowing (IHC = 5)
1  4  1  146    0    3    0 1400.00    0.00    0.00    0.00    0.00  500.00    0.00   Seeding/Sowing (IHC = 5)
```

(a) Sample Operations (.OPS) file screen for AZ2109

```
1    RNGB.OPC
```

(b) Sample OPSCCOM.DAT file for AZ2109

Fig. 24. Images illustrating .OPC and .OPSCCOM.DAT file for AZ2109

4.5.4. Crop File

The already created FG was integrated into the APEXeditor to create the Crop File (CROPCOM.DAT), which lists the species associated with each FG in the study region. Each species is described by fifty-six factors listed on a single line and designated as crucial or essential for simulating or modeling plant growth. The CROPCOM.DAT file for the species discovered in the research region is shown in Figures 25 and 26.

Crop		1	2	3	4	5	6	7	8
#	NAME	WA	HI	TOP	TBS	DMLA	DLAI	DLAP1	DLAP2
1	ABA3	8.452	0.05	31.352	11.793	1.5	0.99	15.7	13.99
2	ABAB	15	0.05	30	0	0.6	0.99	5.05	40.6
3	ABAL	16.228	0.1	18.249	8.279	1.557	0.85	5.01	55.95
4	ABAM	8.452	0.05	31.352	11.793	1.5	0.99	15.7	13.99
5	ABAN	7.548	0.05	20.578	5.356	1.23	0.75	5.05	30.95
6	ABAR	9.869	0.05	23.868	7.195	1.23	0.75	5.05	42.95

Fig. 25. CROPCOM.DAT file

48	49	50	51	52	53	54	55	56	57	
PPLP1	PPLP2	STX1	STX2	BLG1	BLG2	WUB	FTO	FLT	EXTC	
500.9	20.1	0.05	1	0.01	0.1	0	0.01	0	0.65	JUNIPER
500.9	100.1	0.05	1	0.01	0.1	0	0.1	0	0.65	BROOM_SNAKEWEED
42.1	91.9	0.05	7.7	0.01	0.1	0	0	0	0.65	CUMAN_RAGWEED
500.9	20.1	0.05	1	0.01	0.1	0	0.01	0	0.65	JUNIPER
43.1	91.9	0.05	1	0.01	0.1	0	0	0	0.7	WOOLLY_PLANTAIN
47.1	92.9	0.05	1	0.01	0.1	0	0	0	0.7	SCARLET_GLOBEMALLOW
45.1	92.9	0.05	1	0.01	0.1	0	0	0	0.65	RUSSIAN_THISTLE
500.9	100.1	0.05	1	0.01	0.1	0	0.1	0	0.65	SWEET PELOTAZO

Fig. 26. CROPCOM.DAT file

4.6. Performing APEX Simulations

The already created input files and the developed FG were incorporated into the APEX model to perform simulations for each location chosen across the CRB. Five methods are provided in APEX for estimating potential ET. They are Penman-Monteith (Monteith, 1965), Penman (Penman, 1948), Priestley – Taylor (Priestley and Taylor, 1972), Hargreaves (Hargreaves and Samani, 1985) and Baier – Robertson (Baier and Robertson, 1965) methods. The “Penman” method (IET = 1) was used in this study.

The APEX model’s crop/plant growth module is based on the EPIC model (Williams et al., 1989). About 100 crop growth-related parameters have been included in the model. The APEX model can simulate annual growth and perennial plant species. Annual plants grow from planting to harvest or until the accumulated heat units of crops equal their potential heat units. Perennial plants maintain their root systems throughout the year, even though they become dormant after frost. They start to regrow when the mean daily temperature exceeds their minimum needed temperature.

The first step was to examine the APEX hydrology model outputs for modification. Before sensitivity analysis, some default methods and input parameters might need to change for improved simulation. Accordingly, the default values of some parameters from the APEX control, parameter, and subarea files were modified. APEX has various methods for linking CN and SW. This study used a variable that estimates daily non-linear CN, NVCN = 0, as it can perform well in multiple situations (Wang et al., 2008; Kumar et al., 2011). APEX offers a variety of methods for calculating the field's capacity or wilting point. For farmland modeling, the Behrman-Norfleet-Williams method is a dynamic approach (Wang et al., 2012). The Field Capacity/Wilting Point, ISW = 6 Behrman-Norfleet-Williams method was used to conduct this study. Carbon dioxide concentration was set at 450 ppm; and the wind erosion adjustment factor was set at 0 to account for no wind erosion.

APEX was run from 1991 to 2006. The first five years were considered the model warm-up period. Parameters were adjusted by iteratively running APEX until an acceptable goodness-of-fit match of the growth curve for each FG was achieved. Wherever possible, simulated plant growth curves were compared to plant phenology reports and information in the literature, particularly at (https://www.inaturalist.org/) and (https://plants.usda.gov/home).

For any sample point, simulated data of ET, LAI, and plant height were collected from the output file created by the model to represent each plant species in the FG at a time.

4.7. Sensitivity Analysis, Model Calibration, and Validation

Model sensitivity analysis is a method of finding key parameters that affect model performance and are essential for model parametrization. Numerous hydrological, sediment, nutrient, agricultural, and other environmental parameters are accounted for by the APEX model's many parameters (like CN2, PARM 92, and PARM 12). Sensitivity analysis is the first step for hydrological models, which helps diagnose and narrow down the large sets of parameters for calibration. After performing initial simulations for each location across the WUS, the results obtained were deemed acceptable. Later, upon expert review, it was decided that the model was performing satisfactorily; hence, there was no need to calibrate and validate the model.

It was not felt that the model needed to be calibrated or validated because the simulated outcomes from running the model were satisfactory and accurately reflected real-world scenarios.

4.8. Model Performance Evaluation Statistics

APEX performance in predicting the system's hydrology and plant growth characteristics was evaluated using two statistical measures: i) square of Pearson's product-moment correlation coefficient (R^2) (Legates and McCabe Jr, 1999) and Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970). NSE (equation 1) is a normalized statistical measure proposed by (Clausen et al., 1996). The R^2 indicates the proportion of total variance of the observed data that the simulation result can explain. The R^2 ranges from 0 to 1, with higher values representing better model performance. The NSE denotes how well the plot of observed versus simulated results matches with the 1:1 line. The NSE ranges from -∞ to 1, and the value of NSE closer to 1 indicates better model performance.

$$NSE = 1 - \left\{ \frac{\left[\sum_{i=1}^{n} (Y_{obs} - Y_{si})^2\right]}{\left[\sum_{i=1}^{n} (Y_{obs} - Y_{avg})^2\right]} \right\}$$

Y_{obs} and Y_{si} are the ith observed and simulated values for the parameters being evaluated, respectively; Yavg is the mean observed data for the parameter being estimated, and n is the total number of observations.

ET, LAI, and plant height were the main parameters to estimate the model performance. After evaluating the model performance, the predicted ET, LAI, and plant height were compared against the observed/measured ET, LAI, and plant height to determine the R^2 and NSE coefficient values.

5. RESULTS

5.1. Plant Parameterization

Forty-six thousand four hundred ninety-two (46,492) species[1] were classified as FG throughout the WUS, as shown in Fig. 27. Also, California has the highest number of species discovered across all states. However, only 18,876 "distinct" species were divided into 55 different FGs, with the FG season (spring or summer active growth season) being developed from plant species that naturally occur in the WUS. These species included forbs, grasses, sedges, vines, shrubs, subshrubs, cacti, trees, and mosses. Fig. 27 details the overall number of species detected in each WUS state. Through APEX simulation of plant height, LAI, and ET as influenced by numerous site-specific ecological factors, such as soil type and climate, the obtained FGs parameters were enhanced and evaluated for their ability to depict the growth of the plant species appropriately.

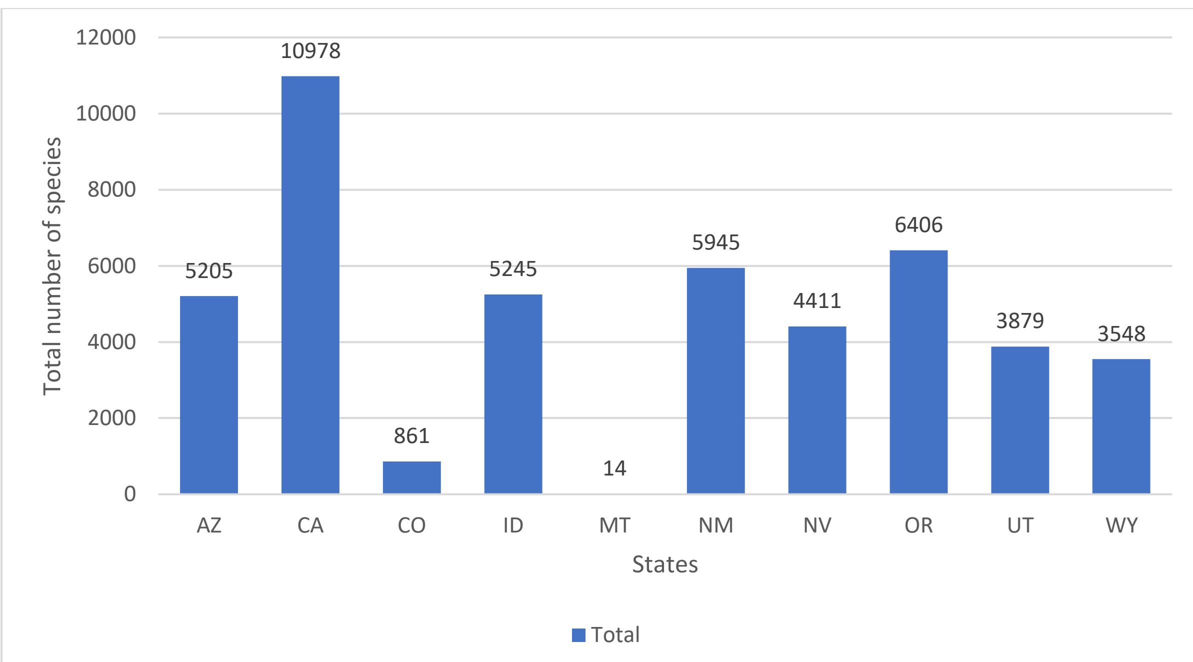


Fig. 27. Statewise distribution of the total number of species in WUS

[1] Bureau of Land Management Database

As a result of the region's arid and semi-arid climate, warm-season vegetation predominates in Arizona, as seen in Fig. 28. However, when temperatures are significantly lower, trees and subshrubs predominate. As we proceed southward, the terrain becomes dominated by grasses, shrubs, and rangeland vegetation because of increased precipitation and altered soil structure. At lower elevations and in arid locations, yucca, mosses, and mesquites thrive. Fig. 28 depicts a graphical representation of the distribution of several species within the state.

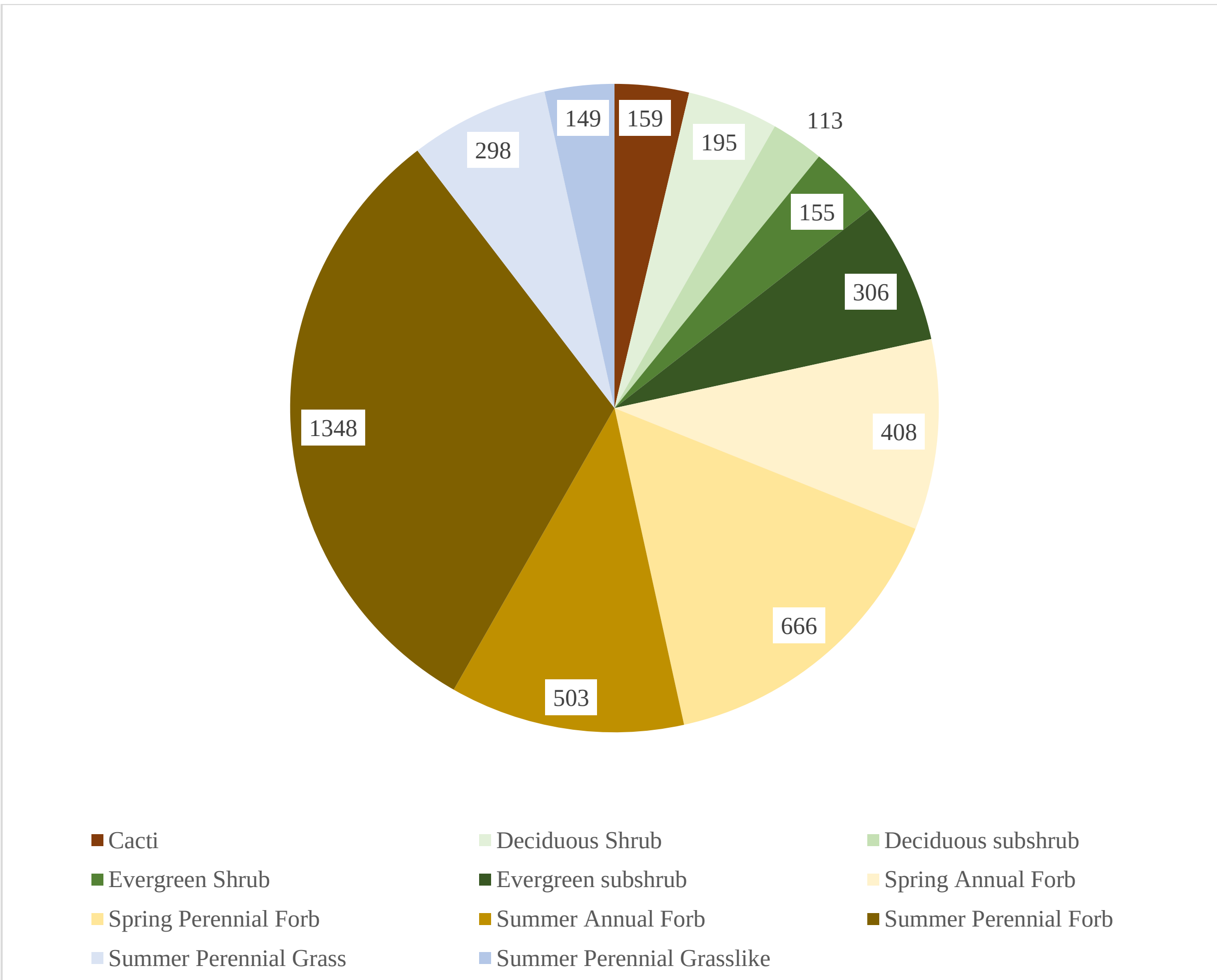


Fig. 28. Count of dominant FGs in Arizona

Due to the region's high precipitation, permanent and annual grassland species predominate along the coast of California. As we approach Central California or the Sacramento region, we observe a transition in the dominant plant species, with annual and perennial forbs dominating the area. Fig. 29 depicts the total number of species within the state of California. Close to 6900 species, more than 50% of the entire species found in the state of California, are perennial or annual forbs due to the soil order, higher temperatures in California during summers, and drought-resistant vegetation.

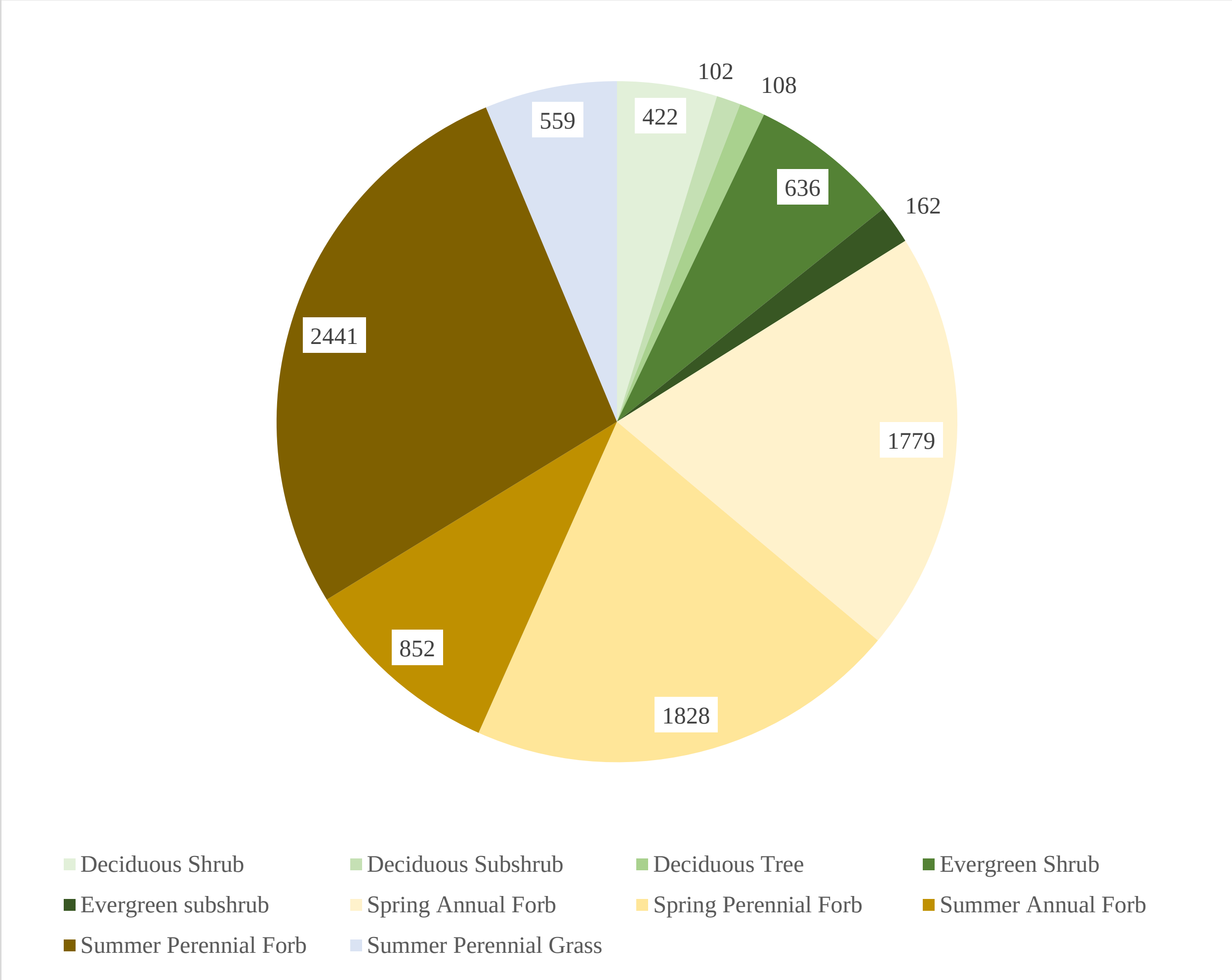


Fig. 29. Count of dominant FGs in California

Forbs and grasses form most of the vegetation species growing within Colorado, as seen in Fig. 30. The southern part of Colorado supports cacti or desert-shrub vegetation, whereas prairie grasses dominate the eastern region.

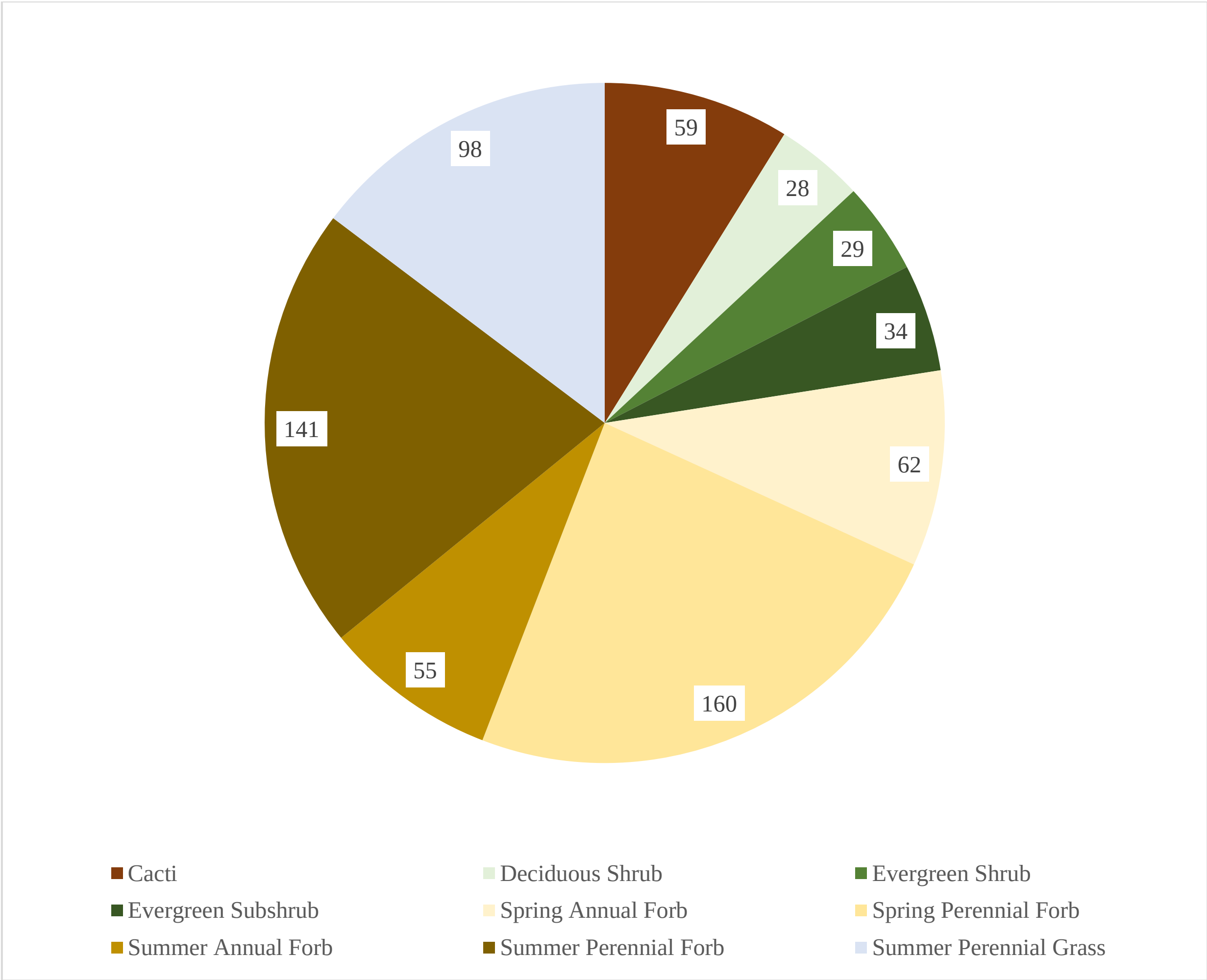


Fig. 30. Count of dominant FGs in Colorado

The southern region of the state is arid, with precipitation less than 12 inches annually, resulting in yucca, mesquite, and desert-shrubs kind of vegetation. Short annual and perennial grass dominate the region as we move north towards the state's central region and high plains. Similarly, the northern part is predominated by shrubs and rangeland grasses for forage. The distribution of vegetation found within the state is shown in Fig. 31.

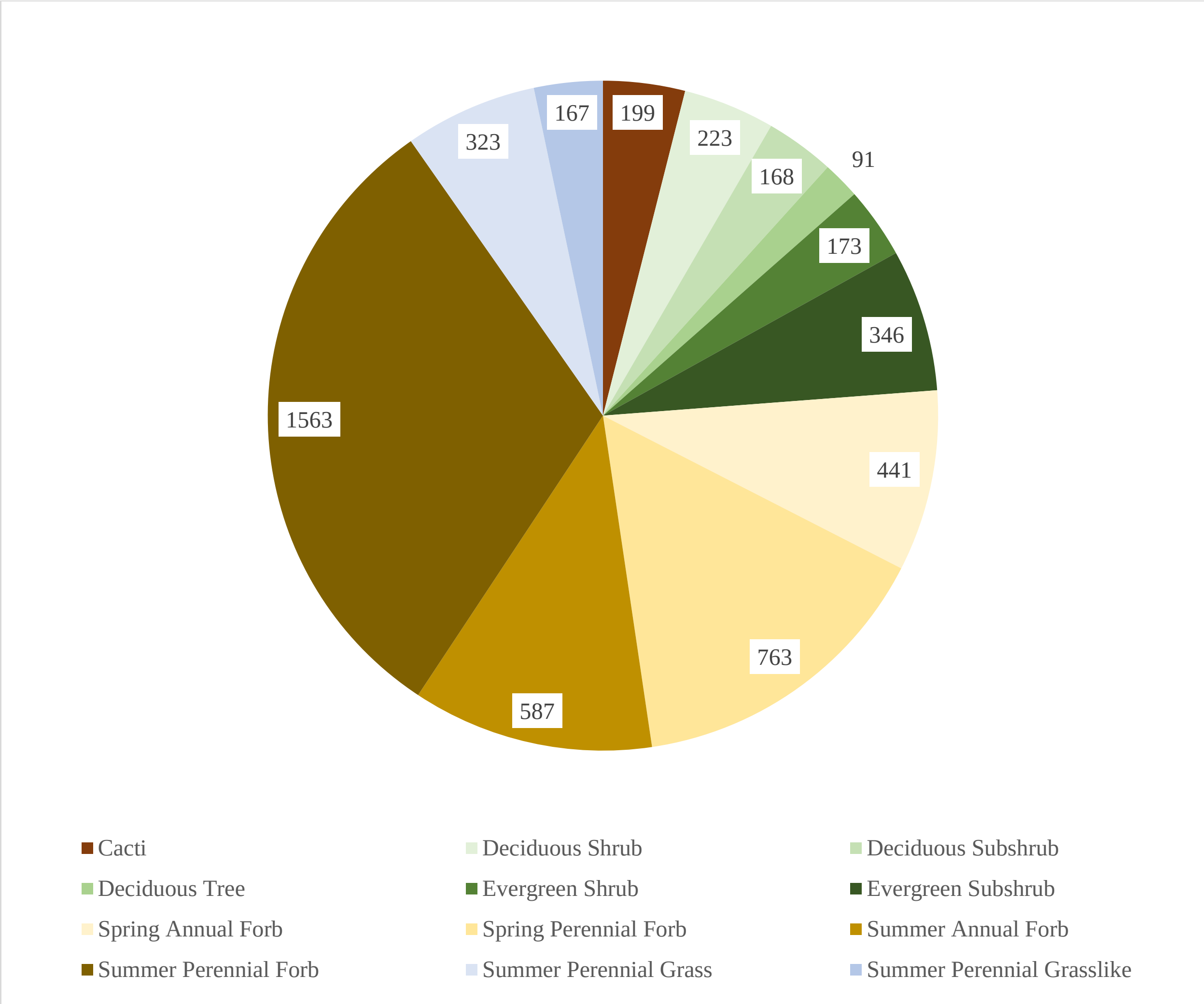


Fig. 31. Count of dominant FGs in New Mexico

Despite rugged terrain and scanty rainfall, Nevada has a variety of vegetation throughout the state. At higher elevations of The Great Basin, deciduous trees are dominant. Since the state lies on the leeward side of the Sierra Mountains ranges, desert shrubs, woody vegetation, grasses, and warm-season forbs are the most found species in the lower elevation. The distribution of various FGs throughout the state is shown in Fig. 32

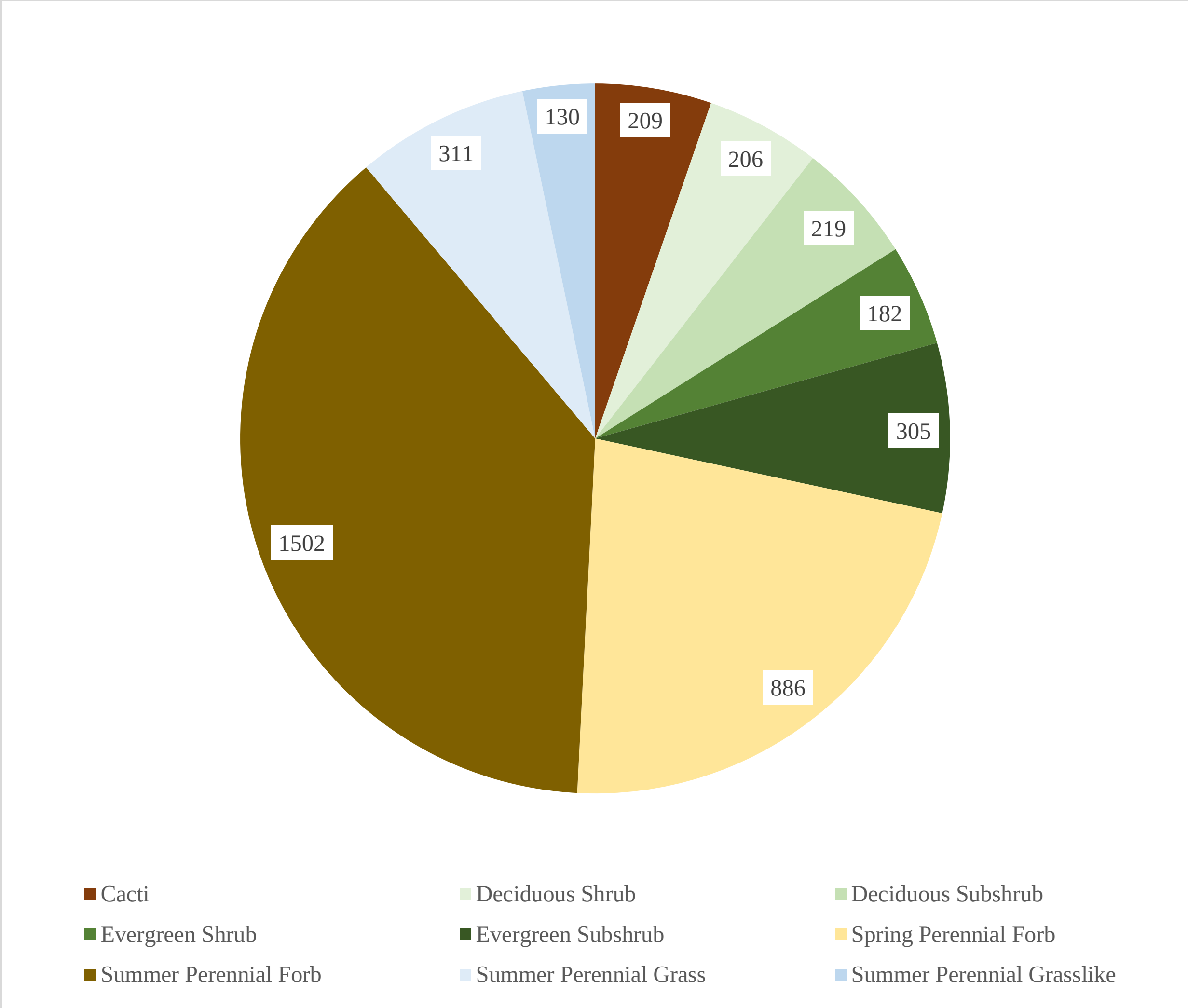


Fig. 32. Count of dominant FGs in Nevada

Shrubs and woody plant species dominate the foothill vegetation throughout the entire state. As we approach the Northern Desert region, the scenery changes significantly, with deciduous desert shrubs, warm-season grasses, and forbs becoming more prominent and widespread. Fig. 33 depicts the total number of dominant species assigned to FGs in Utah.

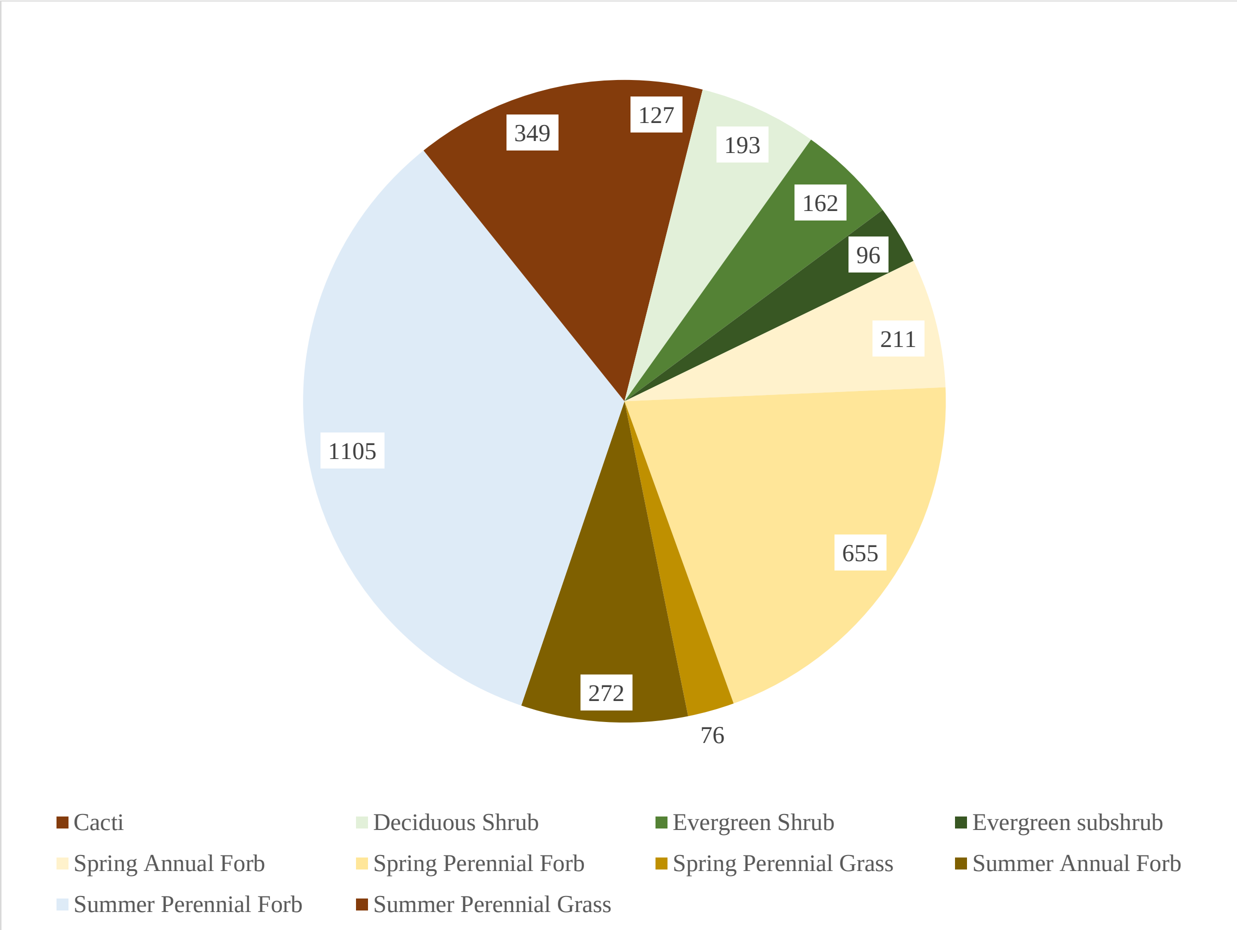


Fig. 33. Count of dominant FGs in Utah

Warm-season perennial grasses and forbs constitute most of the vegetation species throughout the state. However, southern, and southwestern central plateaus support cool-season grasses. Fig. 34 shows the distribution of most species among various FGs throughout the state.

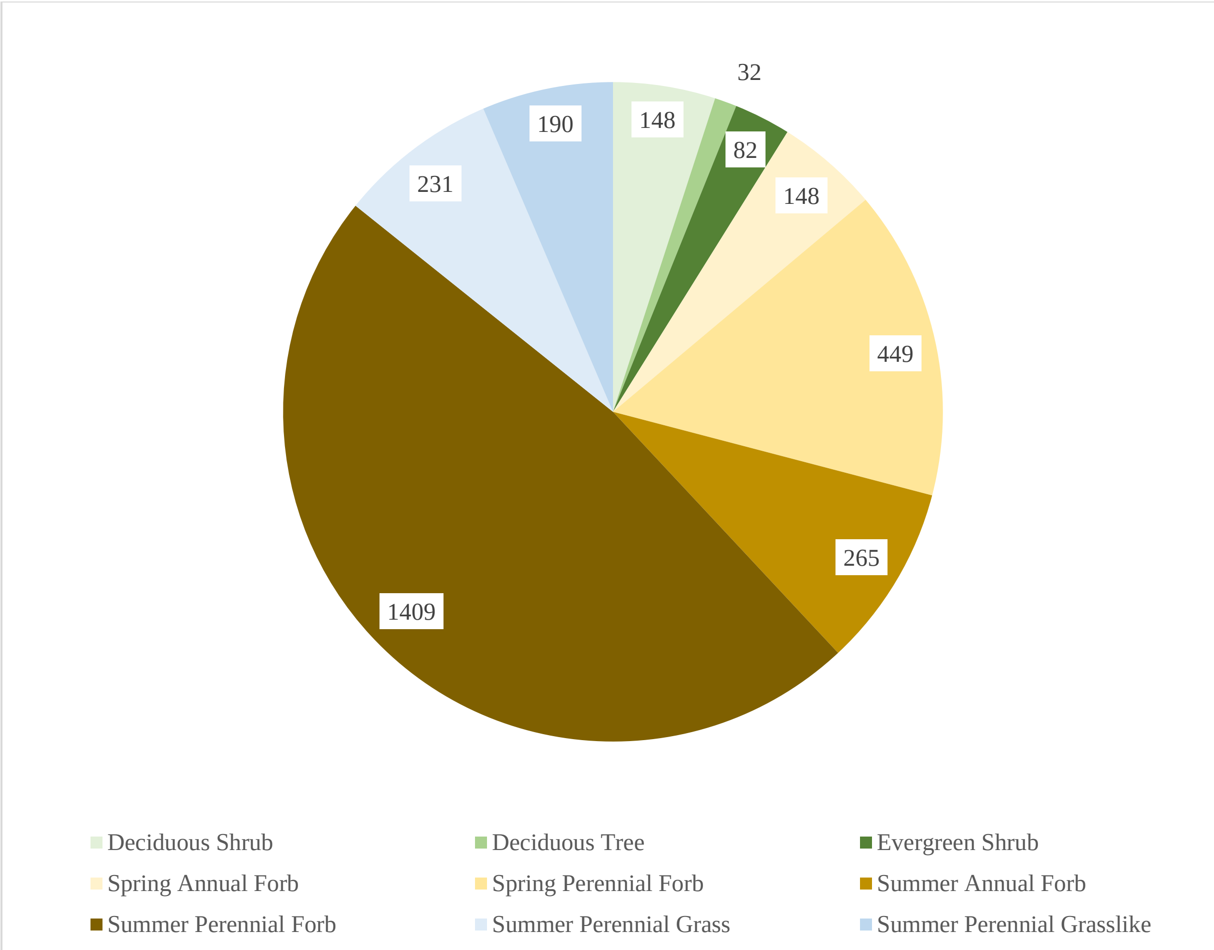


Fig. 34. Count of dominant FGs in Wyoming

For coniferous plants, higher altitudes are optimum. As depicted in Fig. 35, the plant habitat changes dramatically from evergreen coniferous trees to shrubs and grazing-friendly grassland grasses. Since winter temperatures are below freezing, most plant life is observed during the warm season, when temperatures are optimal. Annual and perennial forbs and grasses form most of the state's vegetation species.

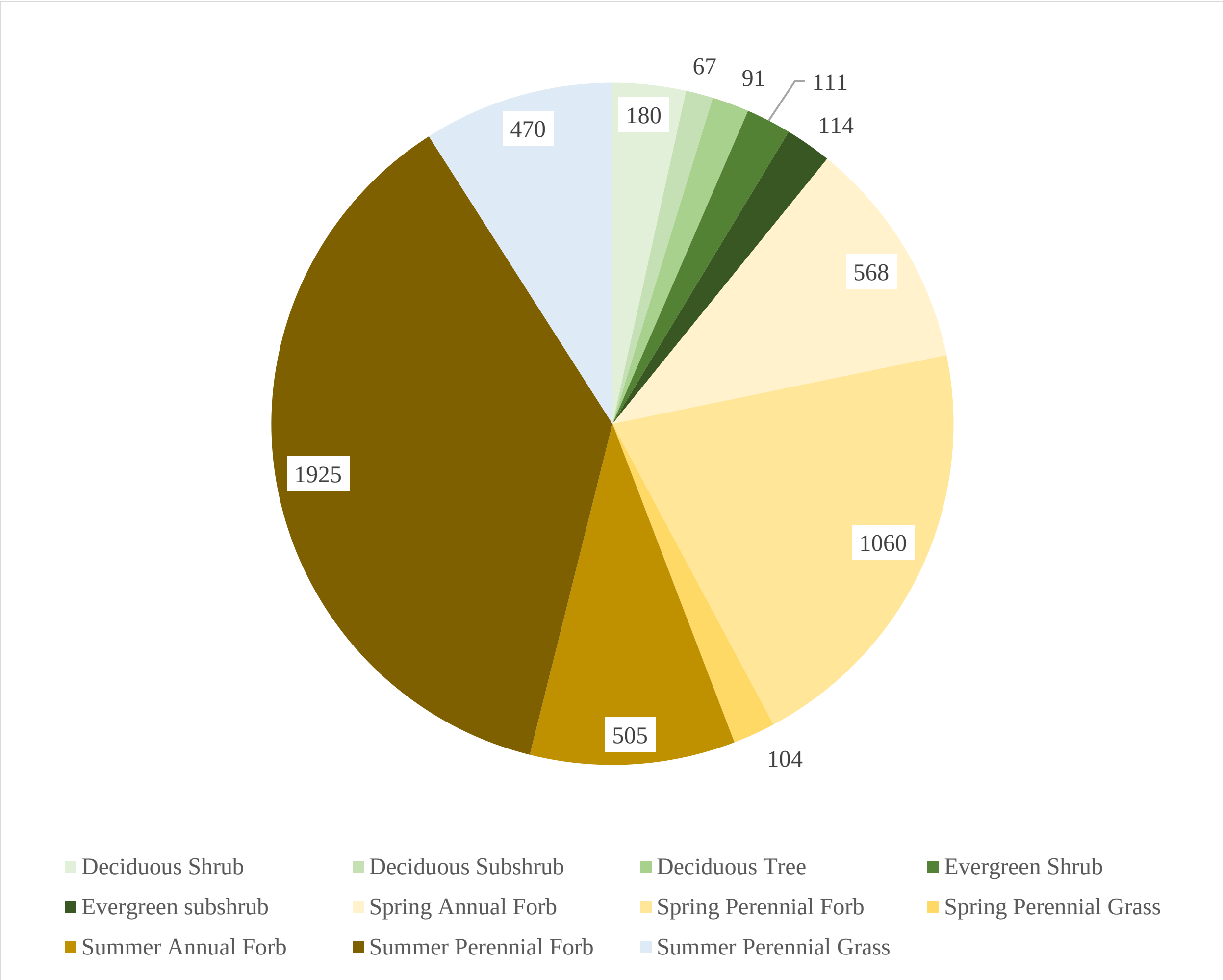


Fig. 35. Count of dominant FGs in Oregon

Prairie grasses, perennial forbs, and forest vegetation dominate the low mountain slopes. Most of the species discovered grow during the warm season, as can be observed in Fig. 36. As we move towards the west, with receding precipitation and rising temperature, the state supports desert shrubs.

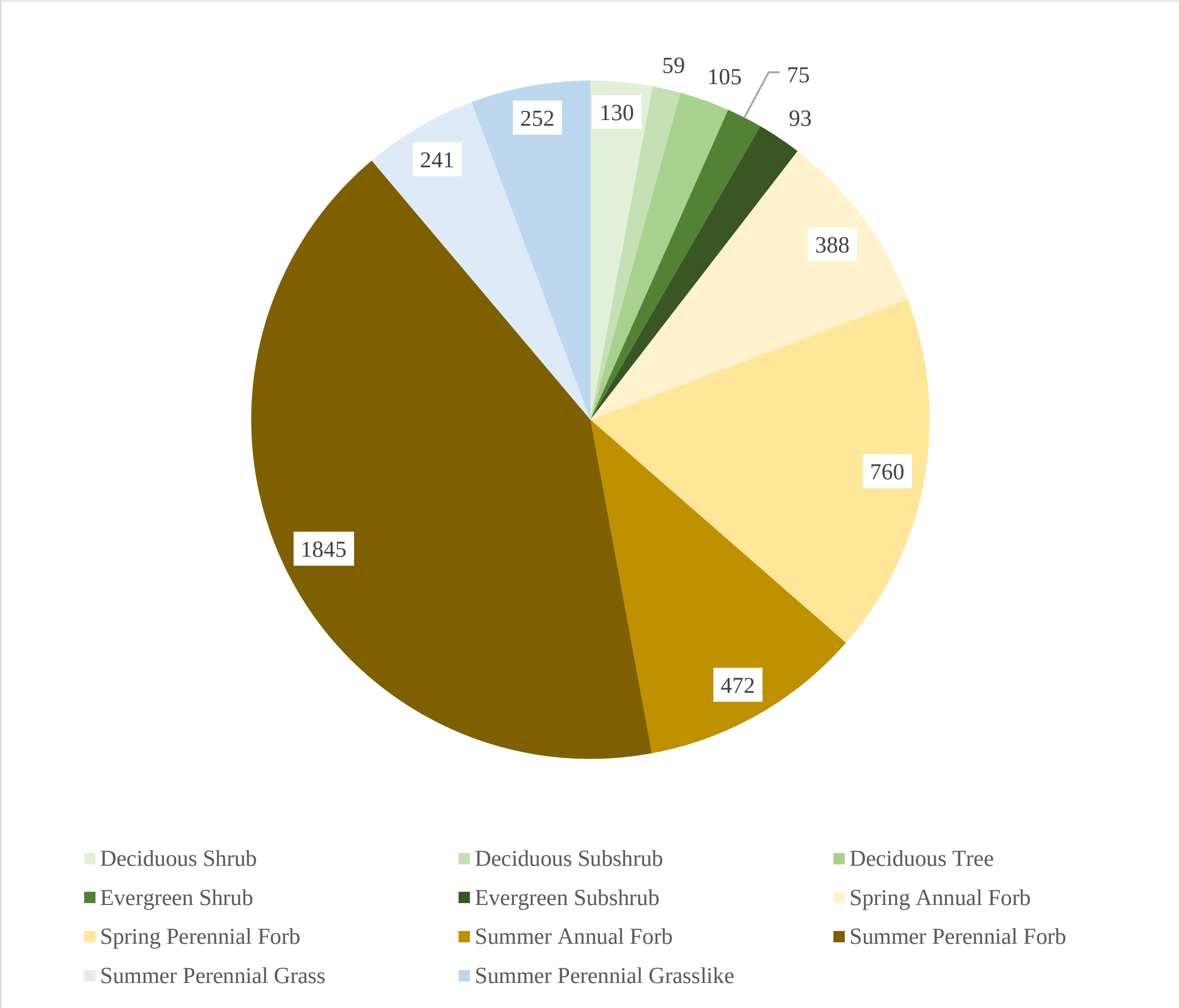


Fig. 36. Count of dominant FGs in Idaho

5.2.Simulated versus Observed ET across all sites

Evapotranspiration is the sum of all processes through which water moves from the land surface to the atmosphere via evaporation and transpiration. Simulated results show that catchment/local site characteristics such as vegetation cover, soil type, and climate seasonality dominate ET variability along with precipitation following the study conducted by (Feng et al., 2020). Management conditions also play an important role in affecting ET. Sites in Arizona, California, Nevada, and New Mexico have critically low to medium ET generally due to arid to semi-arid climatic conditions, which support desert shrubs and warm season forb vegetation type. Lack of proper vegetation to increase transpiration rate and the dominance of cold and warm season annual vegetation types with low LAI contribute to the smaller ET values throughout the region. In contrast, Colorado, Wyoming, and Utah have significantly higher ET values than the westernmost states due to higher precipitation, resulting in higher ET and perennial vegetation types (like grasses), which grow throughout the year, thus contributing significantly to ET. The simulated and observed average annual ET values and the related model performance indicators were compared, as shown in Fig. 37.

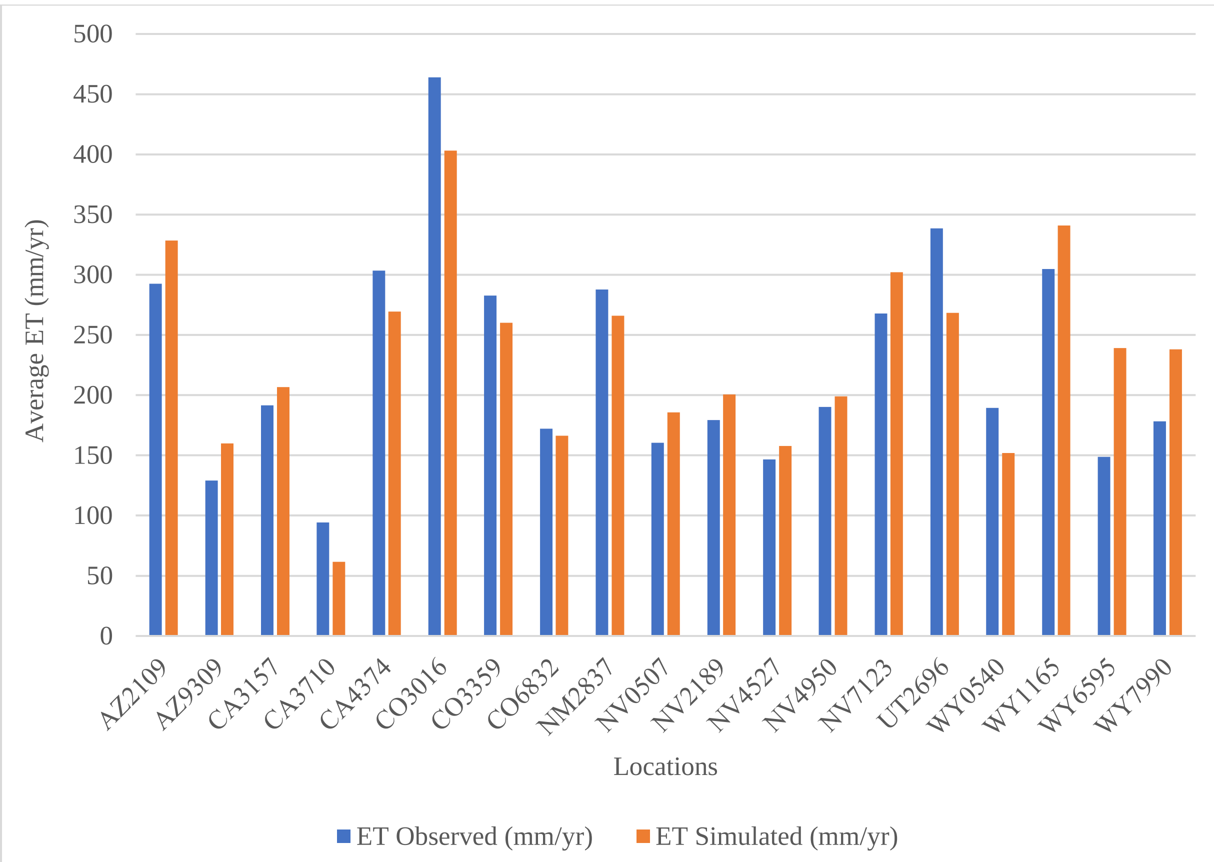


Fig. 37. Comparison between observed and simulated annual average ET values for sites chosen across CRB

Fig. 38 shows the variations in observed ET values as we move from East to West across the US and the North-South variation. One interesting finding illustrated in the map shows that in regions such as the High Plains and Central Valley of California, ET exceeds the amount of precipitation because water is imported from other regions. The arid Southwest has ET rates that usually exceed 80 percent of precipitation. It is observed that ET in the Western and Southwestern states is generally lower due to vegetation types that support arid climates and soil types. In contrast, Eastern states have slightly higher ET due to better and healthier vegetation throughout the region.

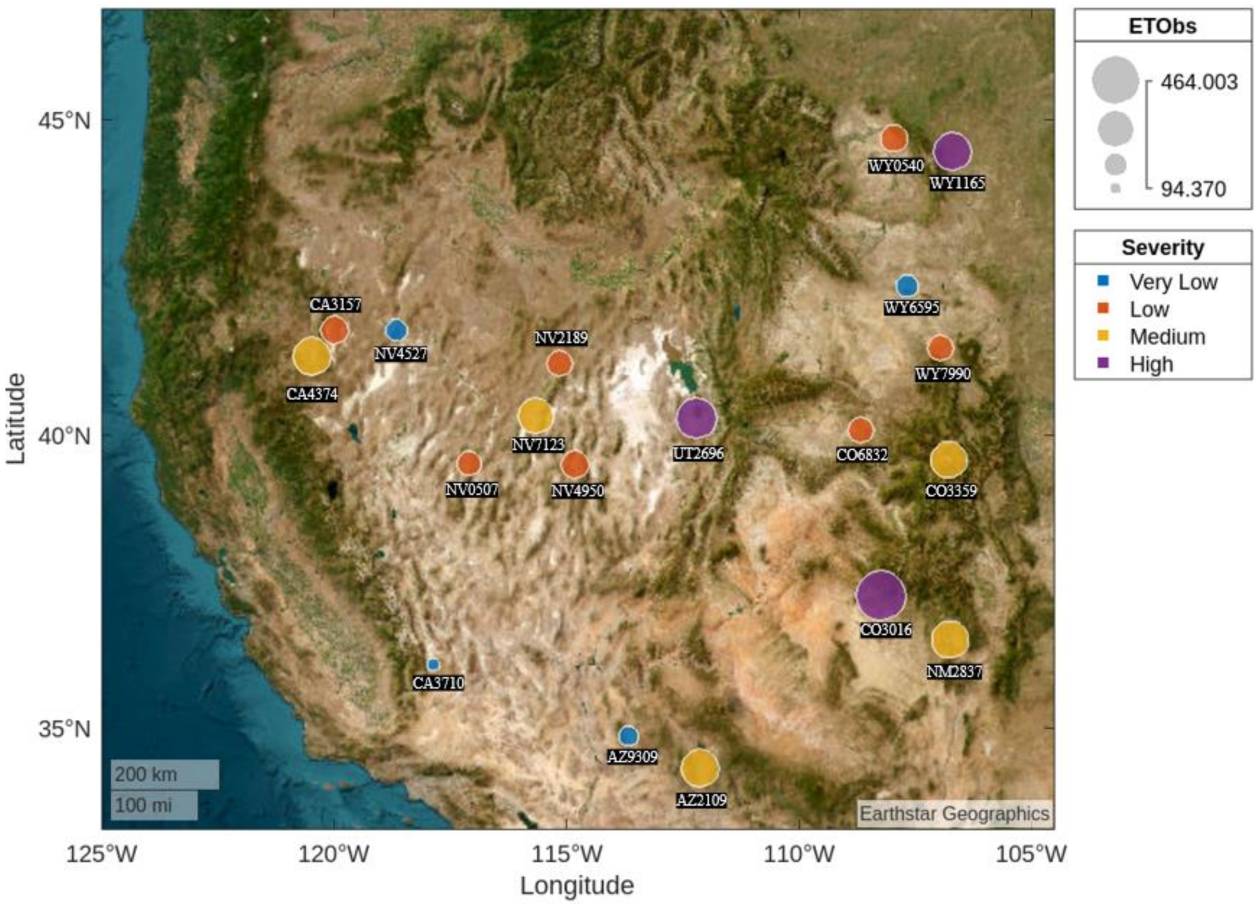


Fig. 38. ET Variations across WUS

The simulation's average ET values were accurate and within 5% of the measured ET values. As demonstrated in Fig. 39, the model could account for 97% (R^2) of the variance in the observed ET values in the simulation. R^2 levels were generally regarded as satisfactory when they exceeded 0.5 (Santhi et al., 2001). Additionally, if NSE > 0.5, model simulation can be deemed suitable (Moriasi et al., 2007). For this study, ET simulations resulted in an NSE value of 0.79. The overall performance indicators point to APEX's simulation of ET utilizing FG parameters in CRB performing satisfactorily.

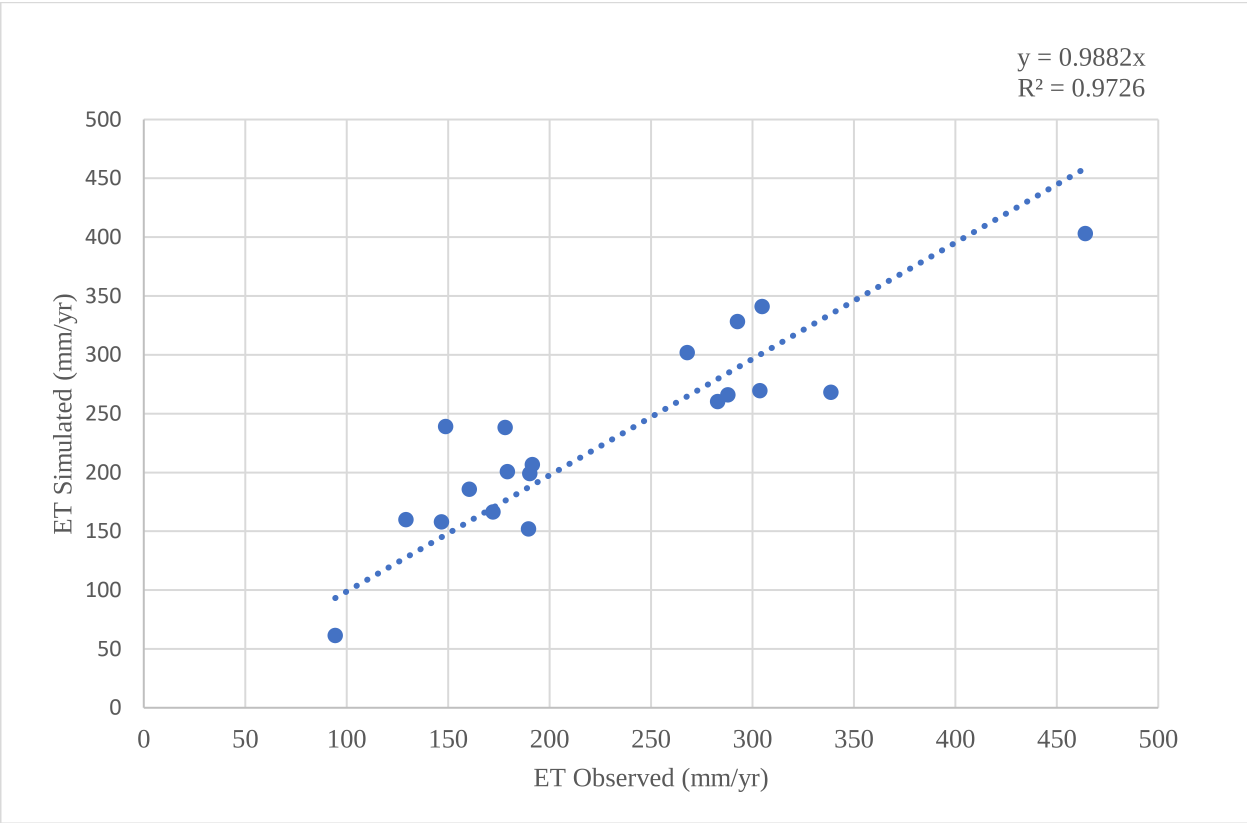


Fig. 39. R^2 value between Simulated and Observed annual average ET values

5.3.Simulated versus Observed LAI across all sites and chosen FGs

The model accurately approximated the FG's LAI. Fig. 40-44 depict the average monthly LAI variations for different FGs chosen for simulation at one of the CRB's sites (CA4374). For cool-season forbs and grasses, leaf maturity begins about the middle of March and continues through the end of summer, possibly July, before diminishing as the plant sheds its leaves, as seen in Fig. 40 and 41. The optimal soil temperatures for spring perennial forbs and grasses are (5-8) ^{o}C.

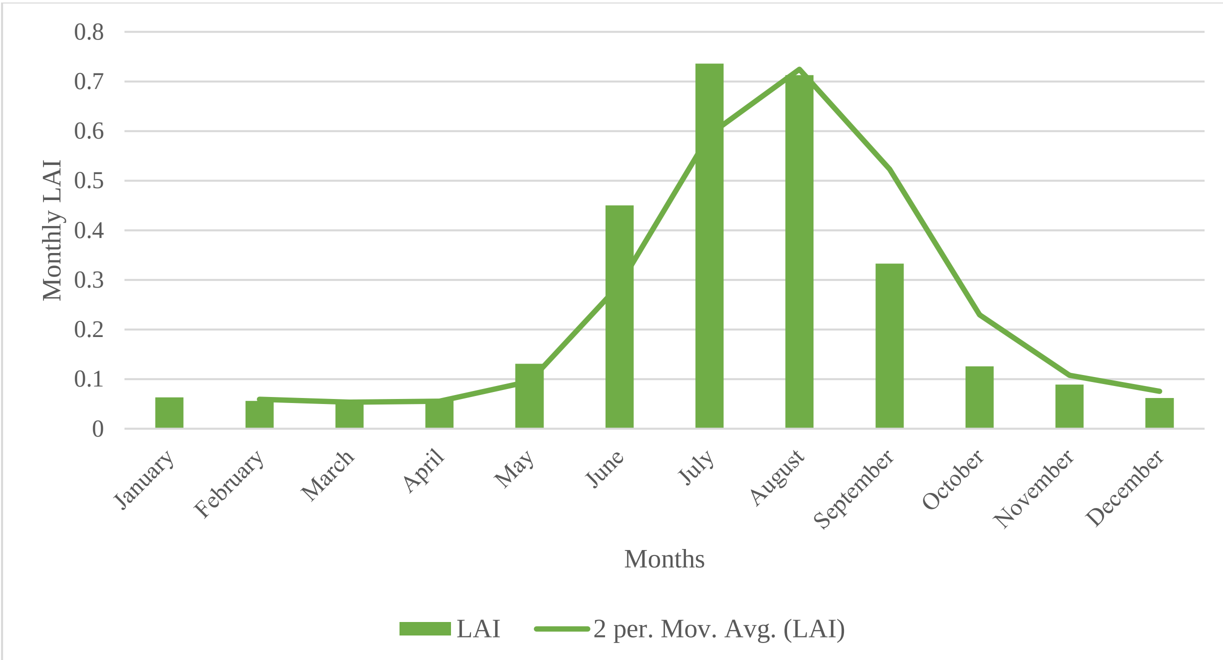


Fig. 40. Monthly variations in LAI as simulated by APEX for "Spring Perennial Forb"

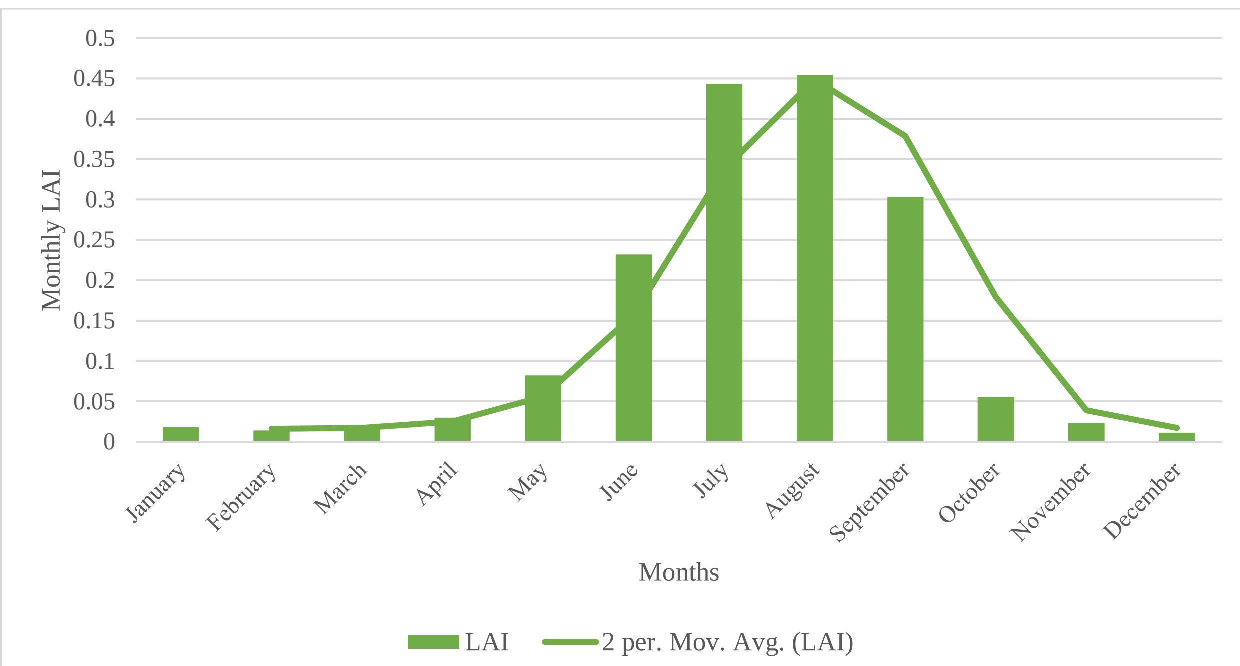


Fig. 41. Monthly variations in LAI as simulated by APEX for "Spring Perennial Grass"

Fig. 42 and 43 demonstrate that the maturity and germination periods for warm-season forbs and grasses are delayed when the optimal temperature reaches between 15 and 20 degrees Celsius in April, continuing until late September before decreasing.

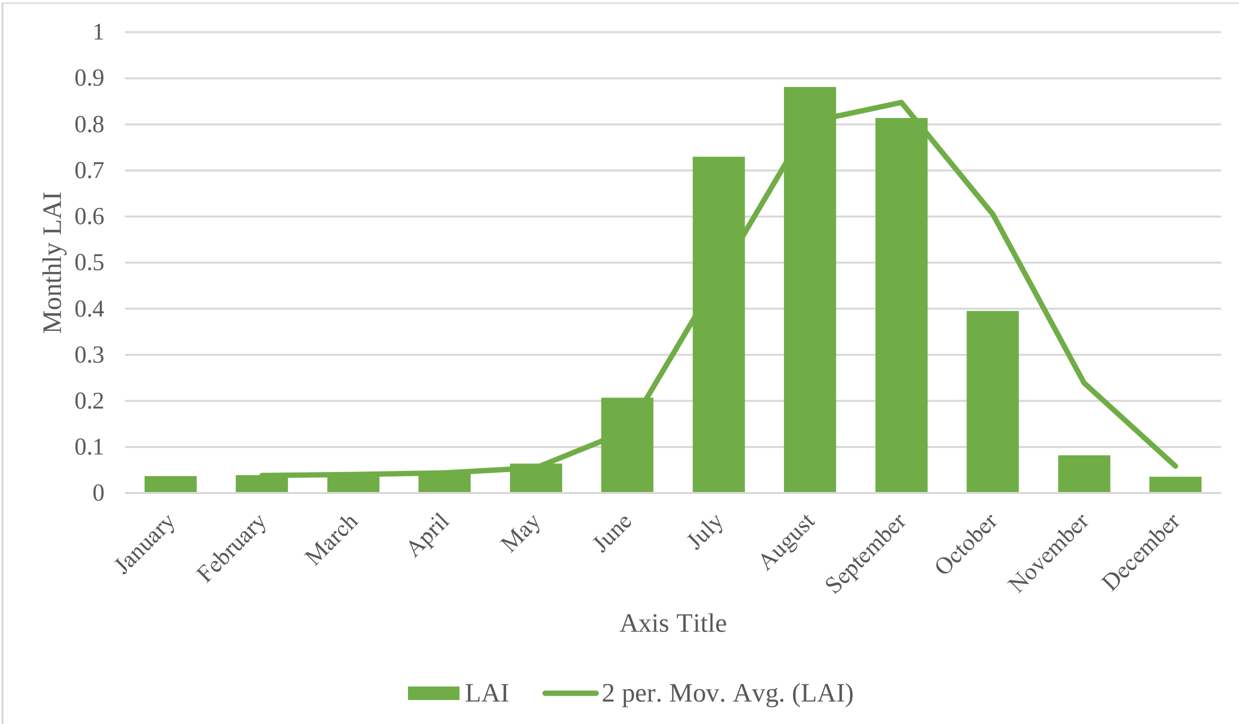


Fig. 42. Monthly variations in LAI as simulated by APEX for "Summer Perennial Forb"

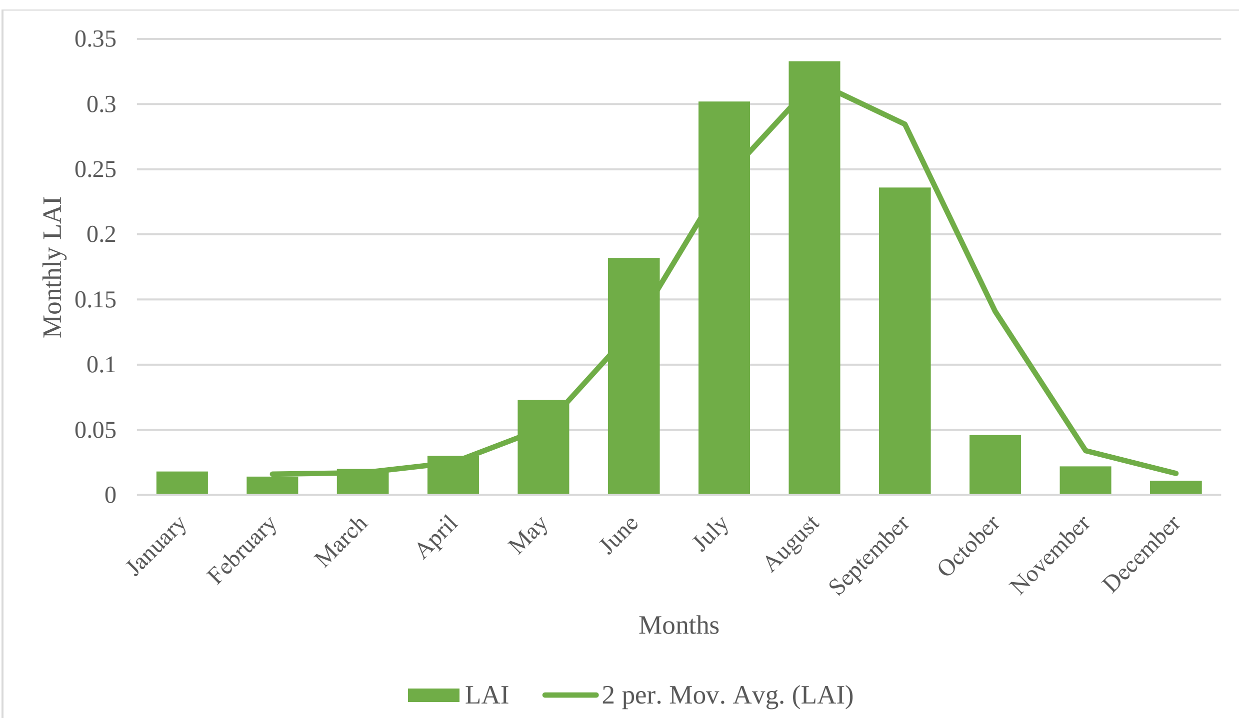


Fig. 43. Monthly variations in LAI as simulated by APEX for "Summer Perennial Grass"

Overall, the model replicated the site' LAI parameter correctly, as shown in Fig. 44, with all the FG contending for nutrients and displaying good values following the information in the literature and plant phenology reports, particularly at: https://www.inaturalist.org/ and https://plants.usda.gov/home.

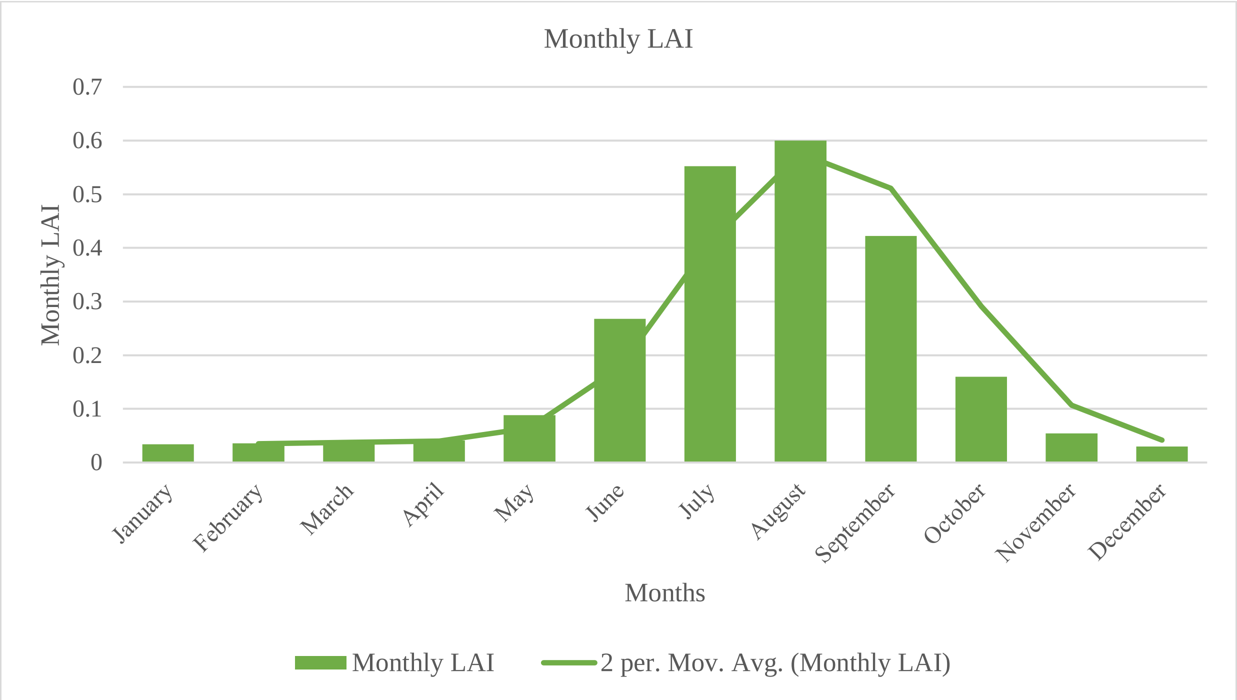


Fig. 44. Monthly simulated LAI variation for a site (CA-4374) with all the FG

Fig. 45 depicts observed and simulated LAI values for each specified FG at many sites. LAI is the expected leaf area (m^2/m^2) across a unit of land. When constructing the Operation Management (.OPC file) file at each location, the measured or observed LAI accounted for all species or FG present at the site, as all species fight for nutrients, sunshine, and water.

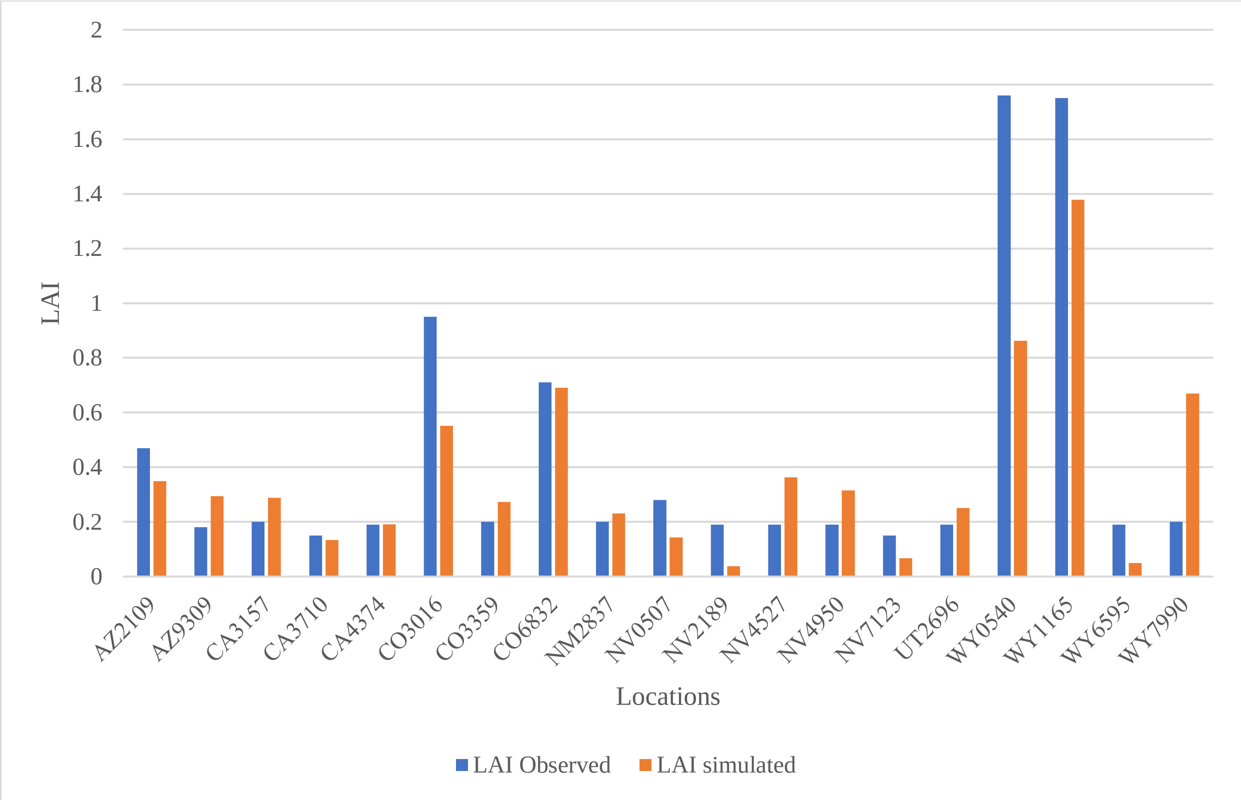


Fig. 45. Comparison between average observed and simulated LAI values for different FGs at various locations across the WUS

Like the average simulated ET values, the average simulated LAI values were within 5% of the observed LAI values throughout the simulation. As depicted in Fig. 46, after conducting the LAI simulation, the modeled LAI displayed a strong correlation with observations, with R^2 values greater than 0.80. In addition, it generated an NSE value of 0.68 for LAI simulations.

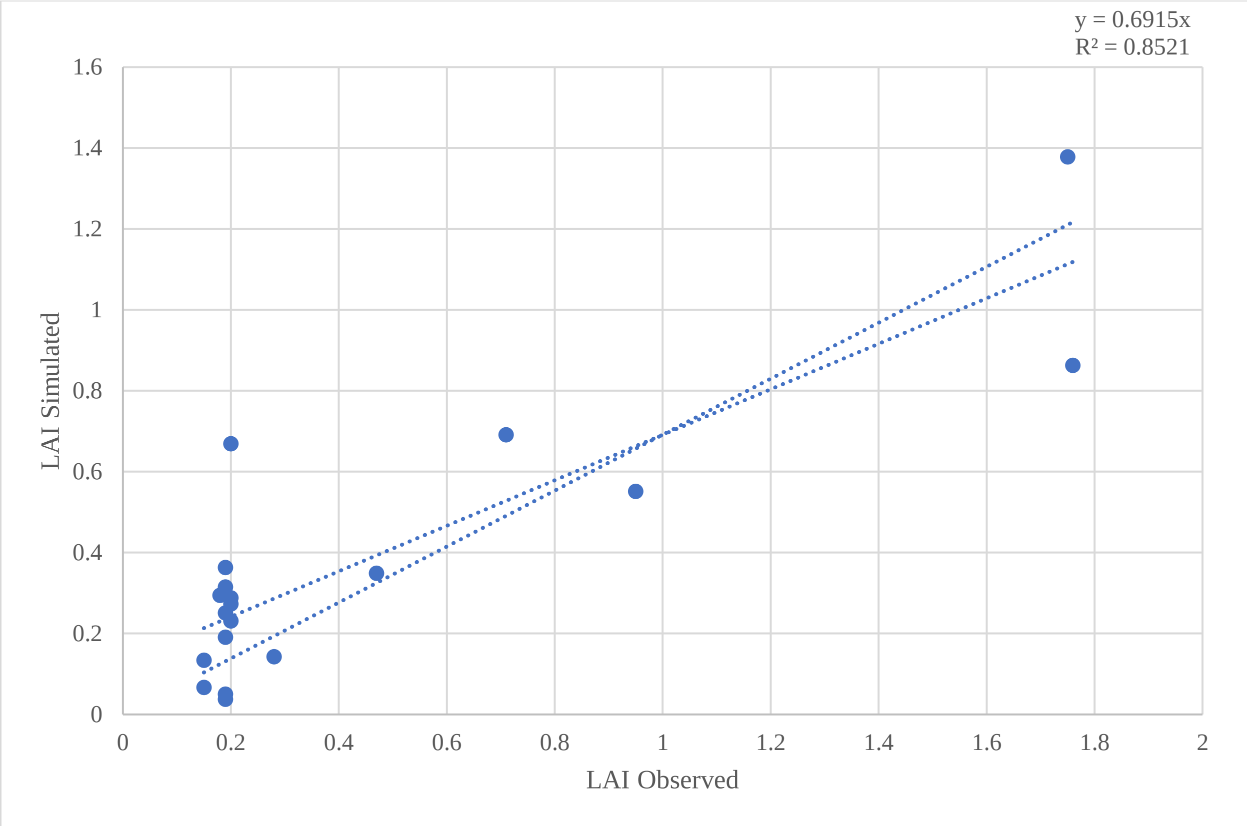


Fig. 46. Comparison between average observed and simulated LAI values for different FGs at various locations across the WUS

5.4.Simulated versus Observed Plant Heights for chosen FG across all sites

The species representing the FG at each site were simulated to compare the actual and simulated plant heights at these locations. A total of 32 species, including forbs, grasses, shrubs, and subshrubs, were chosen for 19 distinct areas depending on their dominance in terms of growth at any site in the CRB, representing varied FG. As indicated in Fig. 47, the simulated plant height was compared to the actual plant height for each species. As depicted in Fig. 48, the model performed well by explaining 99 percent (R^2) of the variance in the observed plant height values during simulation. The NSE value greater than 0.99 demonstrates the excellent correlation between the simulated and observed data.

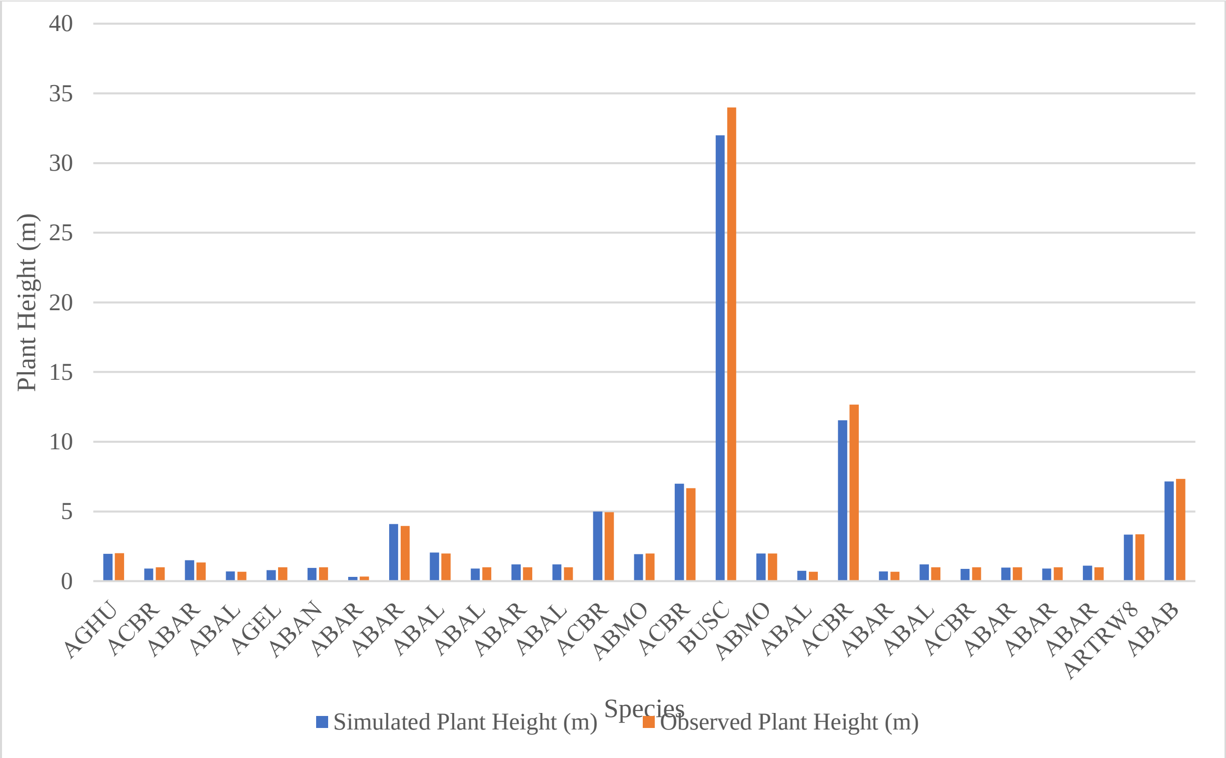


Fig. 47. Comparison between simulated and observed plant heights for various species across CRB; each site is different, with different species chosen for simulation

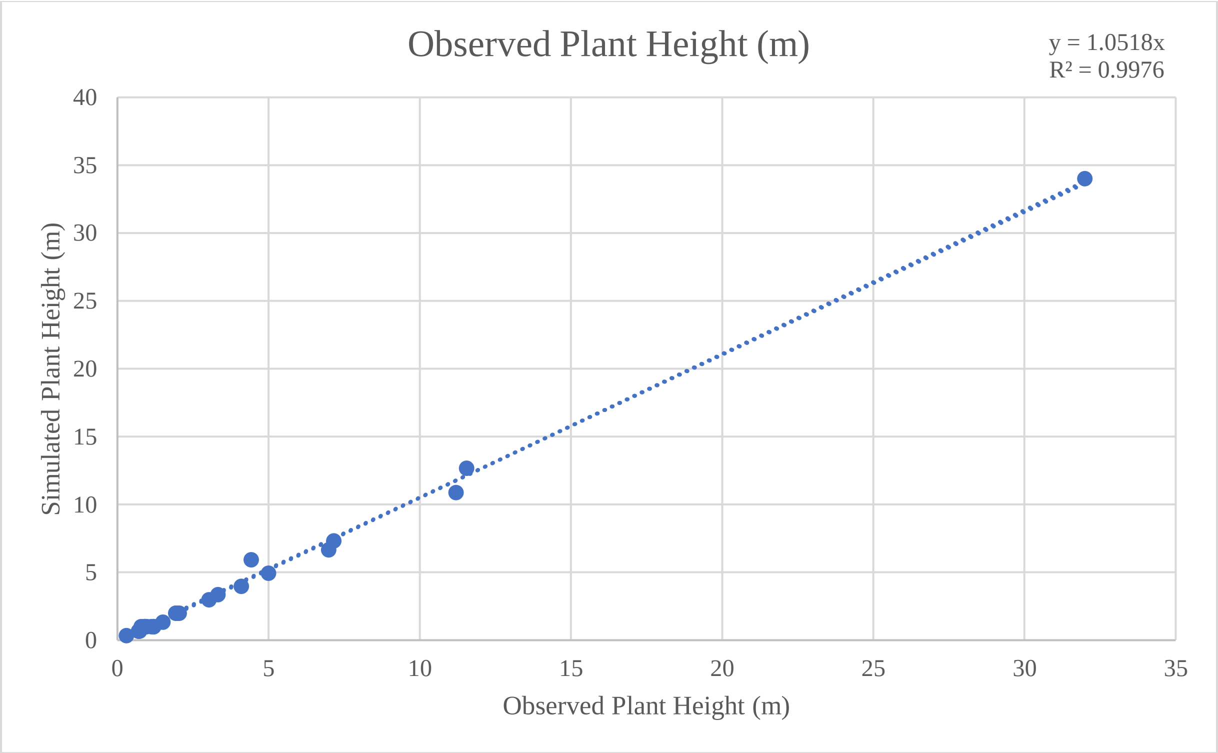


Fig. 48. Comparison between observed and simulated plant heights for species at different locations across CRB; each site is different

5.5.APEX model Sensitivity Analysis for ET, LAI, and Plant Height

The sensitivity analysis (SA) covered all pertinent parameters for APEX evapotranspiration components based on expert opinion and the APEX-CUTE v4.6 User Manual. The results of sensitivity analysis for AZ 2109, one of the sites selected for sensitivity analysis, indicated that ET was sensitive to the following parameters: soil water limit (PARM5), soil evaporation coefficient (PARM 12), and soil evaporation – plant cover factor (PARM 17) (Tadesse et al., 2018) in decreasing order of influence. Soil and crop characteristics were shown to be the most sensitive criteria, given that the local growth conditions of a species have a significant impact on ET. The state of any site's vegetation throughout its growth will be substantial since it will directly influence the amount of water lost through transpiration by plant leaves, which will affect ET.

Soil water limit (PARM 5) parameter was ranked first. The availability of soil water directly affects the amount of water available to the plants for E.T. Hence, it is the most sensitive parameter. Soil evaporation plant cover factor (PARM 17) was ranked second. Soil evaporation is related to LAI, and root growth soil strength is related to soil mechanical resistance to root growth, which also affects the LAI. As soil strength increases, root growth decreases which impacts ET Additionally, parameters such as HMX, WA, and HI were sensitive to ET. Their sensitivity index, however, was significantly insufficient to be taken into consideration to impact ET.

Table 5 Sensitive parameters for ET at daily time step

Parameter	Ranking Influence	Daily SI
PARM5	1	1.66
PARM17	2	0.27
PARM12	3	0.04

Table 6 Sensitive Parameters for ET at monthly time step

Parameter	Ranking Influence	Monthly SI
PARM5	1	1.66
PARM17	2	0.27
PARM12	3	0.037

Table 7 Sensitive Parameters for ET at yearly time step

Parameter	Ranking Influence	Yearly SI
PARM5	1	1.56
PARM17	2	0.19
PARM12	3	0.033

Similarly, LAI was found to be sensitive to DLAI, DLAP2, and DMLA, primarily in descending magnitude order. DLAI is the point in the growing season when leaf area begins to decrease due to leaf senescence. Hence, it plays a pivotal role in quantifying LAI for FGs. In contrast, DLAP2 is the most sensitive parameter (Table 10) at the yearly time step compared to DLAI at the daily time step (Table 8).

Table 8 Sensitive Parameters for LAI at daily time step

Parameter	Ranking Influence	Daily SI
DLAI	1	1.08
DLAP2	2	0.31
DMLA	3	0.08
DLAP1	4	0.013

Table 9 Sensitive Parameters for LAI at monthly time step

Parameter	Ranking Influence	Monthly SI
DLAI	1	1.07
DLAP2	2	0.318
DMLA	3	0.08
DLAP1	4	0.013

Table 10 Sensitive Parameters for LAI at yearly time step

Parameter	Ranking Influence	Yearly SI
DLAP2	1	0.700

DLAI	2	0.557
DMLA	3	0.371
DLAP1	4	0.011

Maximum plant height (HMX) was the most sensitive parameter to crop height characteristics compared to other parameters, DLAP2 and DLAP1.

Table 11 Sensitive Parameters for Plant Height at daily time step

Parameter	Ranking Influence	Daily SI
HMX	1	1.02
DLAP2	2	0.005

Table 12 Sensitive Parameters for Plant Height at monthly time step

Parameter	Ranking Influence	Monthly SI
HMX	1	0.812
DLAP2	2	0.008

Table 13 Sensitive Parameters for Plant Height at yearly time step

Parameter	Ranking Influence	Yearly SI
HMX	1	0.893
DLAP2	2	0.02

6. DISCUSSIONS

Due to the considerable plant species variety observed in rangelands, croplands, and agricultural lands, the effects and benefits of land management strategies would be far more successful if the rangeland plants were simulated as FG rather than individual plant species. A collection of FG was created to represent the various plant species found in the WUS. The APEX model was subsequently updated to include the generated FG, which gave a decent approximation of the growth dynamics of the FG plant species. Overall, the model’s simulation performance against ET, LAI, and plant height was acceptable.

With a sensitivity analysis tool and a graphical user interface streamlining the model’s parameter sensitivity, APEX is a highly adaptable and dynamic model. Additionally, the application includes a built-in parameter selection tool that enables users to choose one or more parameters for each variable (ET, LAI, and plant height) in an enhanced APEX-CUTE v7.1. Results demonstrated the viability of using FG to parameterize, simulate, and perform sensitivity analyses on biophysical models to simulate alternative land management strategies. This technique can be used to address various eco-hydrological issues, including water quality and quantity, salinity, sediment transport, pesticide and fertilizer fate, movement, soil carbon sequestration, N and P nutrient cycles and losses, and land management practices across the CRB and by extension to other regions throughout the WUS.

7. CONCLUSIONS

The APEX model has proven to be a versatile and useful tool for evaluating complex landscape and management scenarios. The multi-subarea capabilities of the model greatly expand the simulation strengths inherent in the predecessor EPIC and provide a platform for performing a much wider array of hydrologic and environmental impact scenarios than previously possible.

At various locations throughout the CRB, the established FG parameters for plant species discovered in the WUS were assessed and incorporated into the enhanced APEX model. The model had acceptable performance using satellite measurements (ET and LAI) and the reviewed literature. Since many rangelands exhibit significant geographical and temporal variability, none of the models that are currently in use can accurately represent the diverse resource issues and ecosystem services that rangelands provide (Ma et al., 2019). The outcomes shown here serve as an example of the potential application of FG and the use of APEX to simulate various plant species under different climatic circumstances. In addition, the sensitivity analysis results from this study here further underscore the strength of APEX and indicate that the model can provide an accurate accounting of different scenario impacts, especially when used to generate relative comparisons of different plant types and management system impacts.

However, ongoing testing for process-based models like APEX is needed to improve its ability and accuracy to evaluate natural resource management alternatives across broad areas when properly parameterized, calibrated, and thoroughly validated. Furthermore, the simulation of FG could assist land stakeholders in assessing the potential adaptability, water use, and soil erosion of different FG under various soil and climatic circumstances (Kiniry et al., 2013).

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