Chapter

Effects of Fire on Grassland Soils and Water: A Review

Daniel George Neary and Jackson McMichael Leonard

Abstract

Grasslands occur on all of the continents. They collectively constitute the largest ecosystem in the world, making up 40.5% of the terrestrial land area, excluding Greenland and Antarctica. Grasslands are not entirely natural because they have formed and developed under natural and anthropogenic pressures. Their importance now is to the variety of ecosystem services that they provide: livestock grazing areas, water catchments, biodiversity reserves, tourism sites, recreation areas, religious sites, wild food sources, and natural medicine sources. An important function of grasslands is their sequestration and storage of carbon (C). Mollisol soils of grasslands have deep organic matter horizons that make this vegetation type almost as important as forests for C fixation and storage. Fire has been and continues to be an important disturbance in grassland evolution and management. Natural wildfires have been a component of grasslands for over 300 million years and were important in creating and maintaining most of these ecosystems. Humans ignited fires over many millennia to improve habitat for animals and livestock. Prescribed fire practiced by humans is a component of modern grassland management. The incidence of wildfires in grasslands continues to grow as an issue as droughts persist in semi-arid regions. Knowledge of fire effects on grasslands has risen in importance to land managers because fire, as a disturbance process, is an integral part of the concept of ecosystem management and restoration ecology. Fire is an intrusive disturbance in both managed and wildland forests and grasslands. It initiates changes in ecosystems that affect the composition, structure, and patterns of vegetation on the landscape. It also affects the soil and water resources of ecosystems that are critical to overall ecosystem functions and processes.

Keywords: wildfire, prescribed fire, fire severity, watershed impacts, grasslands

1. Introduction

Fire is a dynamic ecosystem process, generally predictable but uncertain in its timing and occurrence on landscapes [1]. It is an integral component of most wildland forest ecosystems as well as wild and managed grasslands (**Figure 1**). It has been a factor in shaping plant communities for over 300 million years, as long as vegetation and lightning have existed on earth [2–5]. Both managed and wild grasslands are susceptible to localized and widespread fires if climate conditions (drought and wind) are conducive to fire spread [6, 7]. Wildland fire covers a spectrum from low severity, prescribed and grassland fires, to landscape-level

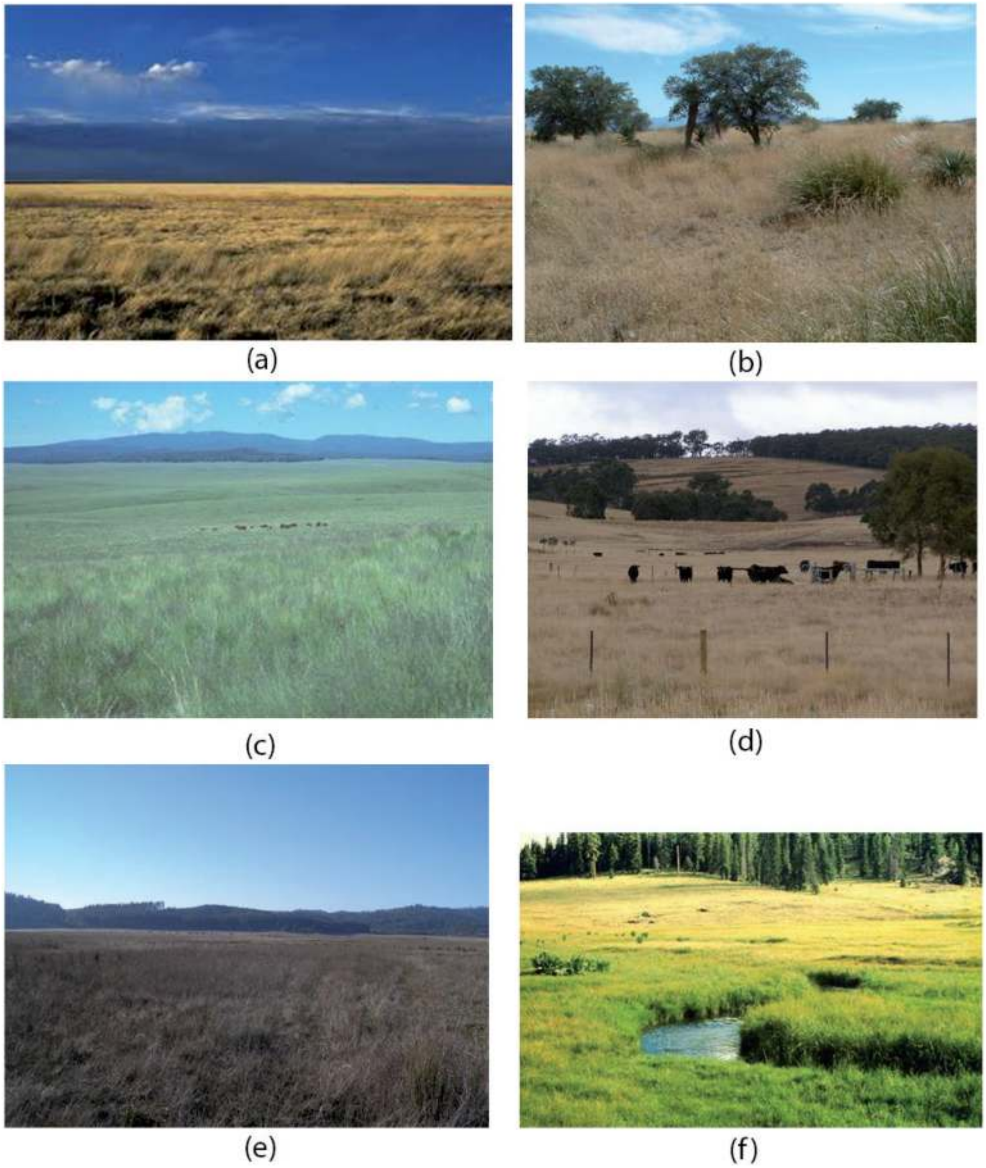

Figure 1.
Examples of grassland ecosystems: (a) Great Plains Comanche National Grasslands, Colorado (photo courtesy of the Pike and San Isabel National Forest), (b) Emory oak savanna, Coronado National Forest, Arizona, (photo by Daniel G. Neary, USDA Forest Service), (c) high altitude grassland, Apache-Sitgreaves National Forest, Arizona, (photo by Daniel G. Neary, USDA Forest Service), (d) Australia farm, Victoria (photo by Daniel G. Neary, USDA Forest Service), (e) Valparaiso, Chile, watershed (photo by Daniel G. Neary, USDA Forest Service), (f) riparian grassland, Arizona (photo by Daniel G. Neary, USDA Forest Service).

high severity wildfires that affect vegetation, soils, water, fauna, air, and cultural resources [8–12]. Knowledge of fire effects has risen in importance to land managers because fire, as a disturbance process, is an integral part of the concept of ecosystem management and restoration ecology. Fire is an intrusive disturbance in both managed and wildland forests and grasslands. It initiates changes in ecosystems that affect the composition, structure, and patterns of vegetation on the landscape. It also affects the soil and water resources of ecosystems that are critical to overall ecosystem functions and processes [1, 10].

Recycling of carbon (C) and nutrients depends on biological decomposition and fire. In regions where decay is constrained either by dry or cold climates or saturated conditions, fire plays a dominant role in recycling organic matter [1].

In warmer, moist climates, decay plays the dominant role in organic matter recycling, except in soils that are predominantly saturated. However, fires do cause hydrologic and physical changes in these soils [13]. Fire in grasslands affects mainly the aboveground components of vegetation and normally does little damage to the large underground reservoir of organic matter in Mollisols typically found in grassland ecosystems (**Figure 2**, [14]). These soils have typically 80–90% of their carbon pool below ground, away from most of the damaging effects of grassland fires.

Soil is the earth's layer of mineral and organic matter, unconsolidated at the interface between atmosphere and geosphere. It results from physico-chemical and biological processes operating simultaneously and over a long period of time on original geological material [15]. Soil is formed by continual interaction between the soil system and the biotic (faunal and floral), climatic (atmospheric and hydrologic), and topographic components of the environment [1]. Grassland soils are unique because of the herbaceous fine root turnover that contributes to the development of deep, organic matter rich, "A" horizons (**Figure 3**).

Soil is variously integrated to other ecosystem components. It provides plants with air, water, nutrients and also mechanical support for subsistence [10]. It also receives and filters rainfall. In this way, it somewhat defines the portion that evaporates on the surface and the portion that is stored belowground to be slowly drained from upstream slopes to the channels, as well as the portion retained and used for soil processes (e.g., sweating, leaching, etc.). As soon as the infiltration capacity of soil precipitation increases, organic and inorganic surface particles are eroded and end up as sediments, nutrients and pollutants in watercourses that affect water quality. An uninterrupted active movement of gas also occur within the soil and it atmosphere. Soil also provides a repository for many cultural artifacts, which can remain in the soil for thousands of years without undergoing appreciable change [16].

Fire can produce a wide range of changes in landscape appearance but the degree of change and duration in grasslands is usually much less than in forested ecosystems [1]. Grass recovery is usually so rapid that the occurrence of fire is masked within 1 year by rapid regrowth. The fire-induced changes coupled with burn intensities generate varied responses in the water, soil, flowers and fauna of burned ecosystems due to the co-variation between fire severity and ecosystem resonance. There are instantaneous and sustainable reactions to wildfires. Immediate effects result from the combustion of biomass and the release of chemicals in the ash created by fire. The response of biological elements (soil microorganisms and ecosystem vegetation) to these disruptions is both drastic and accelerated.

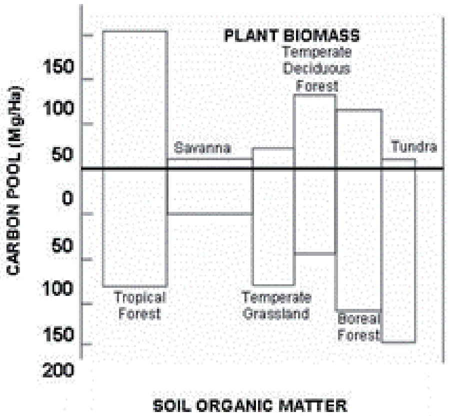

Figure 2.
Distribution of C and soil organic matter (including litter) in major ecosystem types of the world [49].

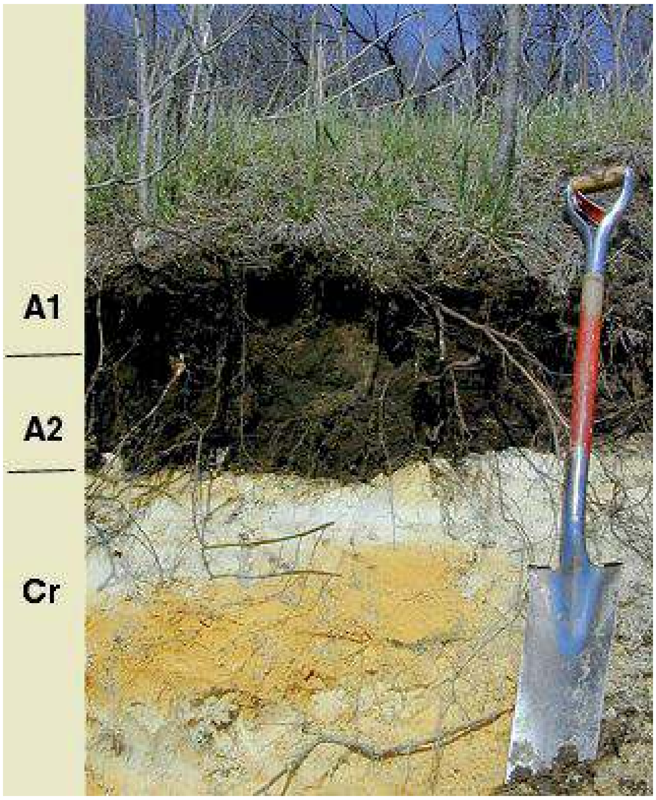

Figure 3.
Mollisol soil typical of grasslands throughout the world. The notable feature is the organic-rich dark A1 and A2 horizons in the upper 10 to 30 cm formed by grass fine root decomposition and organic matter accumulation in weathered limestone. The deeper white and gold-colored horizon (Cr) is the weathered sedimentary parent material. (photo courtesy of the USDA Natural Resources Conservation Service).

Figure 4.
Wallow fire, Arizona, 2011 (photo courtesy of the USDA Forest Service, Apache-Sitgreaves National Forest).

Fire also releases gas, particles and air pollutants through the combustion of biomass and soil organic matter (**Figure 4**). It thus affects air quality in large airsheds [9, 17]. The long-term fire effects on soils and water are usually subtle, can persist for years following the fire, or can be permanent [10]. Other long-term fire effects arise from the relationships between fire, soils, hydrology, nutrient cycling, and site productivity [18].

Therefore, the objective of this chapter is to examine the effects of fire on natural and managed grassland ecosystems. Fire has been and continues to be an important disturbance in grassland evolution and management. Natural wildfires have been a component of grasslands for millions of years and were important in creating many of these grass and herbaceous ecosystems. Humans ignited fires over many millennia to improve habitat for animals and livestock. Prescribed fire is a component of modern grassland management. The incidence of wildfires in grasslands continues to grow as droughts persist in semi-arid regions of the world [19].

2. Grassland ecosystems

Grasslands collectively constitute the largest ecosystem in the world [20]. They make up 40.5% of the terrestrial land area, excluding Greenland and Antarctica. The areas of grass in the latter two ice-dominated land masses are minor in the global context. Grasslands are divided into woody savannahs and savannahs (13.8%), open and closed shrublands (12.7%), non woody grasslands (8.3%) and tundra (5.7%). The UNESCO definition of grasslands is “lands covered with herbaceous plants that are covered with <10% trees and shrubs”. Wooded grasslands typically have 10 to 40% tree and shrub cover [21].

Grasslands are not entirely natural because they have formed and developed under natural (e.g. fire, wild herbivore grazing) and anthropogenic pressures (e.g. prescribed and wildfire, livestock grazing, woody vegetation clearing, over-sowing with pasture grass, etc.) [20]. Grasslands are not considered to be natural if they have been subject to plowing and grass seeding. Their importance now is to the variety of ecosystem services that they provide: livestock grazing areas, water catchments, biodiversity reserves, tourism sites, recreation areas, religious sites, wild food sources, and natural medicine sources. An important function of grasslands is their sequestration and storage of C [22]. Grasslands are characterized by Mollisols, soils with deep organic matter horizons (**Figure 3**) [14]. This vegetation type is almost as important as forests for C fixation and storage. Grassland soils are organic matter sinks on the same order of magnitude as tree biomass.

A question that often arises in grassland management is: Are livestock grazing and burning compatible? Studies in Africa grasslands have demonstrated that fire (natural and prescribed) is often essential in grasslands for maintaining livestock forage in a state critical for herbivores [23]. The negative side of the combined practices is that the amounts of C sequestered in these ecosystems can be reduced.

Fire is typically used as a tool to kill undesirable brush, prevent invasions of poor native species or exotics, and increase forage production [24]. Prescribed burning is used especially on tall-grass prairies of the USA central Great Plains, but timing is important [25]. Cool season grass production can be decreased by spring burns. These early burns can increase summer forage in some species but reduce autumn productivity [26]. Late winter burns have been shown to initiate spring growth 2–3 weeks earlier [27]. Although wildfires have always been a constant part of the prairie fire regimes [6], wildfire numbers and area burned have surged in the 21st Century [28]. Wildfire numbers in the Great Plains of North America increased from 33.4 year^{-1} in 1985 to 116.8 year^{-1} in 2014. The total burned area grew by 400% over the same time period.

In grasslands of the Russian steppe, fire has been used as a tool for millennia to augment natural wildfire starts [29]. Some research has indicated that the treeless steppe is predominantly a result of fire, not soil conditions or climate [3]. Burning is done to remove dead vegetation from the previous year and dry the soil out quicker in the spring. Regrowth after spring fires in the Russian steppes has shown to be richer in nutrient content but lower in yield and cover with decreased soil moisture content [20].

3. Fire characteristics

3.1 Fire regime

The overall fire behavior in a particular type of cover or ecosystem during long successions is defined as the fire mode. This mode describes the typical severity of a fire. But it is recognized that on occasion, relatively severe fires also occur in one type of cover. For example, a stand renewal crown fire is common in forests with large fire-return intervals. The fire regime concept is useful for comparing the relative role of fire between ecosystems and for describing the degree of departure from historical conditions [30, 31]. The fire regime classification used here contains a discussion of the development of fire regime classifications based on fire characteristics and effects [32], combinations of factors including fire frequency, periodicity, intensity, size, pattern, season, and depth of burn, severity, and fire periodicity [10].

The fire modes presented in **Table 1** are described below [10]:

- Understory Fire: These fires are globally not lethal to the dominant canopy and do not significantly change the physiognomy of the predominant vegetation. At least 80% of the dominant vegetation prevails over fires. This mode applies to some types of fire-resistant forests and wooded formations, but also describes the fire regime for true savanna ecosystems (**Figure 5**).

- Stand Replacement Fire: These fires are lethal to most trees, shrub, and grass stems. Greater than 80% of the aboveground dominant vegetation is either incinerated or dies as a result of fire, substantially changing the aboveground vegetative structure. This mode applies to fire-susceptible forests and woodlands, shrublands, and grasslands. In the case of the latter, recovery is very swift within 1 year as grasses sprout from prolific root systems.

- Mixed Fire: The severity of fires varies between nonlethal understory and lethal stand replacement fires. The variation occurs in space or time. First, spatial variability occurs when fire severity varies, producing a spectrum from understory burning to stand replacement within an individual fire. The ultimate result is a fine pattern of vegetation patches. This type of fire regime commonly occurs in some ecosystems because of fluctuations in the fire environment [1, 33]. Complex landscapes facilitate alternating fire severity due to the moisture of the fuel and wind that varies spatially. Temporal change in fire severity results from alternation of individual low intensity, non-repetitive surface fires and long interval stand replacement fires. The result is a variable

Fire Regime Group	Frequency (years)	Severity	Severity and Effects	Fire Regime
I	0-35	Low	Understory Fire	1
II	0-35	Stand Replacement	Stand Replacement	2
III	35-100	Mixed	Mixed	3
IV	35-100+	Stand Replacement	Stand Replacement	2
V	>200	Stand Replacement	Stand Replacement	2
			Non Fire	4

Table 1.
Comparison of fire regime classifications [17, 30, 34].

fire regime [33, 34]. Temporal variability also occurs when cool-moist climate cycles are followed by warm dry ones, leading to multiple decade changes in the role of fire [35].

- Non-fire: In this regime, fire is not likely to occur. However, in rare instances fires do burn in these vegetation types. Although frequently very wet, swamps such as the Everglades in Florida, the Okefenokee Swamp in Georgia, and wet savannas in Brazil have "grassland" areas and have carried wildfires during droughts in the past [36].

3.2 Fire severity

The effects of a specific fire can be described at the stand and community level [1, 33, 37]. The concept describing the ecological and physical effects of a type of fire is the severity. This term indicates the degree of modification and, by extension, the degree of change in ecosystem components. Fire affects both overhead and underground ecosystems components. Most of the effects are above ground level. This is particularly true in grassland fires (**Figure 6**). The degree of fire severity is also related to the vegetation type. For example, in grasslands the differences between prescribed fire and wildfire are normally small due to the lower fuel loads and short duration of burning. In forested environments, the magnitude of the

Figure 5.
Post-fire results in an Emory oak savanna in Southwest New Mexico, 2008. (photo courtesy of A. Kauffman, University of Arizona).

Figure 6.
Wildfire in the Kiowa National Grassland, Cibola National Forest, New Mexico. (photo courtesy of the USDA Forest Service).

effects of fire on water is much lower after a prescribed fire than after a wildfire because of the larger amount of fuel consumed in a wildfire and the heat generated [10]. Canopy-consuming wildfires would be expected to be of the most concern to land managers because of the loss of canopy coupled with the destruction of soil properties. These losses present the worst-case scenario in terms of watershed function impacts.

There is confusion in both the literature and media reports between the terms fire intensity and fire severity. Fire professionals trained in the United States and Canada in fire behavior prediction systems use the term fire intensity in a strict thermodynamic sense to describe the rate of energy released per unit length of fire line [38, 39]. Fire intensity is concerned mainly with the rate of aboveground fuel consumption and energy release rate [37]. The faster a given quantity of fuel burns, the greater the intensity and the shorter the duration [10]. Because the rate at which energy can be transmitted through the soil is limited by the soil's thermal properties, the duration of burning is critically important to the effects on soils [40]. Fire intensity is not necessarily related to the total amount of energy produced during the burning process. Most energy released by flaming combustion of aboveground fuels is not transmitted downward. Only about 5% of the heat from a surface fire is transmitted to the soil [40]. Thus, fire intensity is not always an indicator for measuring the energy transmitted to the soil, nor the physico-chemical and biological changes of the latter. Thus, it is likely that a high intensity, high velocity grass fire would consume little surface litter due to the low energy that is dissipated to the ground during fuel combustion and discharged onto the litter [33]. Only about 5% of the heat released by a surface fire is transmitted into the ground [40]. Therefore, fire intensity is not necessarily a good measure of the amount of energy transmitted downward into the soil, or the associated changes that occur in physical, chemical, and biological properties of the soil. For example, it is possible that a high intensity and fast moving crown fire will consume little of the surface litter because only a small amount of the energy released during the combustion of fuels is transferred downward to the litter surface [33]. In this situation, the resulting surface litter is blackened (charred), but not consumed. Wind driven grassland wildfires will do the same for different reasons.

Because the actual energy released in a fire is not easily measured, the term fire intensity has limited practical application when evaluating ecosystem responses to fire. Fire severity is used more appropriately to indicate the effects of fire on the different ecosystem components [10, 32, 33]. Fire severity has been used describe the magnitude of negative fire impacts on natural ecosystems [41]. It can be seen in a post-fire environment in contrast to intensity which can only be estimated indirectly (**Figure** 7). A further extension of the concept to cover all fire phenomena has been suggested [1, 10]. In this case, severity is a measure of the disruption or damage extent to resources caused by a fire and does not always mean that the phenomenon has negative connotations. Thus, a less severe fire can restore and maintain a range of ecological characteristics that are generally perceived as positive, such as a burning in a pasture. In contrast, a high severity fire in a forest may be a dominant disturbance. In a non-fire adapted ecosystem, it becomes an abnormal, destructive event with long-term consequences.

3.3 Depth of burn

The relationship of fire intensity to fire severity remains largely undefined because of difficulties encountered in relating resource responses to the burning process [33]. While quantitative relationships have been developed to describe changes in the thermal conductivity of soil, and changes in soil temperature and

Figure 7.
Fire severity indicated by color differences (orange spots high severity and black or gray spots moderate severity) and consumption of vegetation, Brins Fire, Arizona. (photo by Daniel G. Neary, Rocky Mountain Research Station, USDA Forest Service).

water content beneath surface and ground fires, these relationships have not been thoroughly extrapolated to field conditions [40, 42]. It is not always possible to estimate the effects of fire on soil, vegetation, and air when these effects are judged by only fire intensity measurements because other factors overwhelm fire behavior. For instance, grassland fires are often high intensity, but their residence time at any one point is extremely short (<15 seconds). The effects on soils are minimal but they are often fatal to animals and humans [43].

The range of fire effects on soil resources can be expected to vary directly with the depth of burn as reflected in the amount of surface litter, organic soil horizons, and woody fuel consumed [10, 33]. Thus, for example, the depth of lethal heat (approximately 60°C) penetration into the soil can be expected to increase with the increasing depth of surface organic material that is burned. In grassland soils this depth is usually very minimal.

The depth of burn into the organic soil horizons, visual observation of charring, and combustion of plant materials defines fire severity for interpreting the effects of fire on soils, plants, and early succession [1, 10, 37] Depth of burn is directly related to the length of time of burning and fuel load in woody fuels [44] and litter [45]. Burn depth can be classified on the basis of visual observation of the degree of fuel consumption and charring on residual plant and soil surfaces [33, 46].

A 1985 summary on the relationships between depth of burn and the charring of plant materials has been updated into a table to reflect subsequent literature [1, 37]. **Table 2** can be used as a guide to classifying depth of burn. The characteristic classes are provided for clarification of subsequent discussion of fire effects:

- Unburned: Plant parts are green and unaltered, there is no direct effect from heat.

- Scorched: Fire did not burn the area, but radiated or convected heat from adjacent burned areas caused visible damage. Soil heating is negligible. Scorched areas occur to varying degrees along the edges of more severely burned areas.

- Light: This class is mostly applicable grasslands but can be found in shrubland and forest types. Plants are charred or consumed, but herbaceous plant bases are not deeply burned, and are still identifiable. Charring of the mineral soil is negligible. Light depth of burn is associated with short duration fires either

Burn class	Category	Description
Unburned	**Surface**	Fire did not burn on the surface.
	Fuels	Some vegetation injury may occur from radiated or convected heat resulting in an increase in dead fuel mass.
	Occurrence	A wide range exists in the percent unburned in natural fuels. Under marginal surface fire conditions the area may be >50%. Under severe burning conditions <5% is unburned. 10 to 20% of the area in slash burns is unburned.
Light	**Surface**	Leaf litter is charred or consumed but some plant parts are discernable. Herbaceous stubble extends above the soil surface. Some plant parts may still be standing, bases not deeply burned, and still recognizable. Surface is black after fire. Charring is limited to <0.2 cm into the soil.
	Fuels	Typically, 50 to 90% of herbaceous fuels are consumed and much of the remaining fuel is charred.
	Occurrence	Burns are spotty to uniform, depending on grass continuity. Light depth of burn occurs in grasslands when soil moisture is high, fuels are sparse, or fires burn under high wind. This is the dominant type of grassland burning.
Moderate	**Surface**	In upland grasslands litter is consumed. Charring extends to <0.5 cm into mineral soil, otherwise soil not altered. Gray or white ash quickly disappears. In grasslands, sedge meadows and prairies growing on organic soils, moderate fires partially burn the root-mat.
	Fuels	Herbaceous plants are consumed to the ground-line.
	Occurrence	Moderate depth of burn tends to occur when soil moisture is low and fuels are continuous. Then burns tend to be uniform. In discontinuous fuels, high winds are required for high coverage in moderate depth of burn.
Deep	**Surface**	In grasslands growing on mineral soil the litter is completely consumed leaving a fluffy white ash surface that soon disappears. Charring to depth of 1 cm in mineral soil. Soil structure slightly altered. In grasslands growing on deep organic soils, fires burn the root-mat and the underlying peat or muck to varying depths.
	Fuels	All above ground fuel is consumed to charcoal and ash.
	Occurrence	In uplands, deep depth of burn is limited to areas beneath the occasional log or anthropogenic features (e.g., fences, corrals). In wetland grasslands, deep burns can occur over large areas when the water table is drawn down.

Table 2.
Depth of burn classes for grasslands [10].

because of light fuel loads, high winds and fire spread, wet fuels, or a combination of these three factors.

- Moderate: This class is mostly applicable to forests but can occur in grasslands or shrublands that are savannas. In grasslands, plants are consumed, and herbaceous plant bases are deeply burned and unidentifiable. In shrublands or woodlands with grass components, average char-depth of the mineral soil is on the order of less than 1 cm, but soil texture and structure are not noticeably altered. Charring may extend up to 3.0 cm beneath shrubs with deep leaf litter in savanna grasslands (**Figure 5**).

- Deep: This class of depth of burn is limited to forests since fuel loads and fire residence times in grasslands are insufficient to produce deep burns. The only exception would be wet savanna grasslands and swamps.

Surface litter and organic soil horizon consumption is a complex process [45]. Depth, bulk density, fire load, mineral filler, moisture rate and wind velocity all affect the heat emission and understory heating. Since these factors are not easily accessed after a fire, it is not possible to define the post-fire criteria potential for discriminating the class. Although analyzing soil calcination is not sufficient to classify the burning severity, the actual depth can be inferred from the preponderance of findings, including the re-composition of the pre-fire plant stratum. Analyses of soil properties, combustion and charring depth of residual vegetation are potential tools to classify the burning extent from the traits presented in **Table 2**.

4. Soil effects

4.1 Soil heating

The energy generated during the ignition and burning of fuels is the driving force behind the physico-chemical and biological alterations in a soil under warming [10]. The soil thermal transmission phenomena include radiation, conduction, convection, mass transport, vaporization and condensation.

- Radiation is defined as the transfer of heat from one body to another, not in contact with it, by electromagnetic wave motion. Radiated energy flows outward in all directions from the emitting substance until it encounters a material capable of absorbing it [1, 10].

- Conduction is the transfer of heat by molecular activity from one part of a substance to another part, or between substances in contact, without appreciable movement or displacement of the substance as a whole [1, 10].

- Convection is a process whereby heat is transferred from one point to another by the mixing of one portion of a fluid with another fluid. Heat transfer by convection plays an important role the rate of fire spread through aboveground fuels.

- Vaporization and condensation are important coupled heat transfer mechanisms that facilitate the rapid transfer of heat through dry soils. Vaporization is the process of heating water until it changes phase from a liquid to a gas. Condensation occurs when a gas is changed into a liquid with heat being released during this process.

Current knowledge on the correlation between soil heating and fire type [10] states the following:

- Crown fires are usually large scale, fast-moving, wind-driven, large, and usually uncontrollable by direct attack. They often have a deep flame front. Generally there is little soil heating when a fire front passes rapidly through the tree crowns. However, if there is sufficient fuel from the forest floor to the crowns, fire will consume all the fuel and produce significant soil heating. These fires are typically occurring in forest canopies and dense shrublands.

- Surface fires which spread slowly, are small-scale, sporadic and controllable, and often having a thick flame front. These fires are capable of igniting and combusting a large part of the forest biomass, bushes and grasslands and can substantially heat the mineral soil.

- Wind-driven grass fires spread very quickly, being sometimes large and marked by a restricted flame front. This is the typical fire of pastoral and wildland ecosystems. The fuel biomass of pastures is less abundant than that of brush and forests and, as a result, soil heating is limited to the passage of surface fires.

- Smoldering fires are flame-free, slow moving and unimpressive, but frequently have long burnout times. These fires are not common in grasslands but can occur, particularly in savannas, where woody roots have extended into grass areas.

4.2 Soil physical properties

The general effects of fire on soil physical properties range from very minor to serious [1, 10]. Since grassland fires are often rapidly-moving with the wind, and have much less fuel than that in brush and forest ecosystems, soil heating is significantly lower, and therefore physical damage much less than what occurs during crown, surface, or smoldering fires. Physical effects include alterations in soil physical properties, development of water repellency, and erosion [47, 48]. Comparisons of wildfire and prescribed fire in grassland ecosystems show little differences in soil impacts due to the low fire severities characteristics of both types of fire.

The amount of aboveground and belowground organic matter varies widely between different vegetation types depending upon on the temperature and moisture conditions prevailing in a particular area. In almost all ecosystems throughout the world, greater quantities of C (a measure of organic matter production) are found belowground than aboveground (**Figure 2**). In grasslands, savannas, and tundra-covered areas, much greater quantities of organic C are found in the underground plant parts of herbaceous vegetation ecosystems (90%) than in aboveground components (<10% of the total C) [49]. Because of the large belowground pools of C in grasslands, fires do not significantly affect the role or importance of C in soil physical properties.

Plant litter is a key factor in determining watershed condition. In grassland ecosystems, easily identifiable layers (Oi, Oe, and Oa layers) may not be present and will be different from forests with thin Oi and Oe horizons and a very deep Oa. The Oi layer consists of freshly fallen plant litter. The Oe layer is made up of partially decomposed litter, and the Oa layer consists of well-decomposed organic matter [50]. Mesic grasslands have a complete herbaceous plant cover and well-developed organic soil horizons (60 cm or more), but in semi-arid environments, the soil is sometimes devoid of cover between the plants. Surface organic matter absorbs precipitation, allowing water to infiltrate deep down instead. Reduction of organic material by high severity fire could result in adverse changes in hydrologic conditions in some instances.

Undisturbed forests have the highest saturated hydraulic conductivities (Ksat) because of their deep soils and high porosities [50]. Grassland soils are similar but not quite as porous as woodlands due to the lack of root-caused macroporosity. Woodlands have the lowest since they are less productive ecosystems and their soils are often lithic, shallow, poorly structured, less permeated by roots and soil organisms that develop macroporosity. Thus the relationships of (Ksat) in these wildland soils is forests > grasslands > woodlands. The importance of surface organic horizons in determining the levels of (Ksat) in forest, woodland, and grassland soils cannot be overstated.

The (Ksat) rates for most undisturbed forests range from 143 to 1000 mm hr^1 [50]. The rates for grasslands reported by in the same paper are 8–612 mm hr^{-1}. Heavily grazed grasslands can have significantly lower rates due to compaction

Location	Reference	Burned condition		Soil depth (cm)
		Saturated hydraulic conductivity K_{sat} (mm hr^{-1})		
		Unburned	Burned (Rx/Wf)	
Australia	[51]	16	34	0–40
Slovakia	[52]	612	972	0–05

Table 3.
Effects of fire in grasslands on soil saturated hydraulic conductivity (K_{sat}). Adapted from [50].

from animal traffic. The highest Ksat rates are usually associated with thick Oe or Oa horizons. A number of recent studies reported changes in Ksat that demonstrate clear reductions in conductivity after fires. Fire severity plays a key role in some of these reductions, but other investigators have demonstrated a surprising lack of correlation with severity and even a reverse trend (**Table 3**; [51, 52]).

An interesting trend emerging out of some of the recent Australian research on the impacts of wildfires on soil hydrologic properties is that the soil surface Ksat values can be similar regardless of severity and that natural water repellency may produce Ksat values less than those measured in burned soils [53]. Seasonal effects are occur when summer natural water repellency disintegrates and the Ksat coefficient reinforces the correlation between control and burnt soils during winter. As a result, fire's gravity—water repellency—hydraulic conductivity ratios are obviously more complex.

4.3 Nutrients

Investigations about the impacts of fire frequency on grazing lands and shrubs have had less desirable outcomes. For example, the annual burning of tall grass prairies in the Great Plains of the Central United States resulted in a significant decrease in soil organic nitrogen (N), microbial biomass, N availability and higher C/N ratios in soil organic matter [54]. Similarly, the increase in available N could harm some nutrient-deficient shrub ecosystems, as previously reported in South Africa. On lowland fynbos, a double increase in soil nutrient content through fire threatens the survival of native species developed on these impoverished ecotopes [55].

4.4 Soil Fauna

The influence of soil heating on earthworms is still little known. The indirect effects of a fire are probably more pronounced than the direct heating of earthworm populations in tallgrass pastures and prairies [56]. Thus, fire intensified the activity of earthworms due to differences in productivity between plants before and after the occurrence of fire. In general, grassland soils are full of roots and rhizomes, which, combined with soil moisture, provide an ideal microclimate for earthworms in the upper 10–20 cm of soil depth. Deep soil protects earthworms from the direct consequences of soil heating during fuel burning, except in the case of severe, long-lasting fires under slash and log piles or in smoldering roots and litter. Grassland fires increase exotic earthworm species at the expense of endemic ones [57].

4.5 Roots and reproductive structures

Many plant roots, regeneration structures and seeds are just above the ground or spread deep down. These plant parts include taproots, surface roots, rhizomes, stolons, root crowns and bulbs. Many roots are in the superficial plant litter layers (L, F and H horizons) and are directly affected when these layers are heated or consumed by fire [10]. Roots of grass plants are less susceptible to damage since they are distributed mainly in the mineral soil and at depths where heating is minimal (**Figure 2**).

Plant roots are sensitive to both duration of heating and the magnitude of the temperature reached. Temperatures of 60°C for 1 minute are sufficient to coagulate protein [58]. Lethal temperatures can occur before proteins began to coagulate. The plant material lethal temperature is very dependent on its moisture content. Wetter plants are prone to destruction at very low temperatures and during shorter warming [59]. Plant roots of grassland soils are well insulated by the soil and have a lower risk of being subjected to lethal temperatures during a fire [1]. The two most important factors that insulate roots against soil heating are their depth in the soil and the soil water content. Generally, the deeper the plant roots are located in the soil, the greater will be the survival rate [60]. Grassland soils have deep "A" horizons formed by fine root turnover and thus are less at risk from low severity, high intensity, and short duration herbaceous fuel fires [14]. Low-severity fire destroys only the surface plant litter aboveground plant structures. In contrast, high-severity fires can consume all the surface organic matter and easily heat the mineral soil above the lethal temperature for roots [1, 10]. This situation typically occurs where woody trees and shrubs have invaded grasslands in the absence of fire. It contributes to the mortality of the woody species and survival of herbaceous plants.

Most seeds are stored in the litter and under the foliage. Medium and intensive fires heat the surface deposits enough to eliminate the seeds deposited there. The deadly seed temperature is about 70°C in wet soils and 90°C in dry soils [61]. Fire can destroy seeds, but it also can enhance reproduction by destroying allelopathic substances that inhibit seed production [62]. Or, fire can provide a mineral seedbed required for new grass germination and growth. The heating associated with fires may also stimulate the germination of seeds that lie dormant in the soil for years because of impermeable seed coats. Regeneration of grass ecosystems after burning is mostly dependent on sprouting from deep and undamaged root systems than seed sprouting.

Soil heating, heat transport and the lethality consequences on seeds and roots are more complex in moist than dry soils [10]. Dry soil is a poor thermal vector and, as a result, heat does not reach deeper into the ground, especially whether the flame front is of short duration. This is the situation with grassland fires. They are incredibly hot, but move rapidly over any one point of ground. The surface of dry soil can easily exceed the lethal temperature of living tissue of roots, while ambient daily soil temperatures can prevail in just 2 cm downward in the soil, with little damage occurring to the roots. Therefore, when the roots of grassland plants are in dry soil, they are not likely to be damaged by wildfire unless the residence time of the flaming front is long.

5. Watershed responses

5.1 General effects

The magnitude of the effects of fire on water quantity and quality are primarily driven by fire severity, and ancillary factors such as post-fire cover, slope, water repellency, and rain fall amount and intensity [1, 10]. Fire intensity is rarely a factor. Fire severity is related to the amount of fuel consumed and resource damage, while fire intensity is only a measure of the rate of heat release. The more severe the fire, the greater the amount of fuel consumed, heat released, soil properties affected, and hydrologic condition altered.

High severity fires increase the amount of nutrients mobilized and alter the hydrologic response of catchments. These combinations of factors make sites more susceptible to erosion of soil and release of nutrients into stream and lakes where they could potentially affect water quality. Wildfires usually are more severe than prescribed fires because of controls over burning conditions and fuel loads in the latter case. As a result, they are more likely to produce significant impacts on watershed resources.

As mentioned earlier, the degree of fire severity is related to the vegetation type. For example, in grasslands the differences between prescribed fire and wildfire are usually small. In forested environments, the magnitude of the effects of fire on water yield and water quality are much lower after a prescribed fire than after a wildfire because of the larger amount of fuel consumed in a wildfire, the greater heat release, and the generally higher severity. Canopy-consuming wildfires are the greatest concern to watershed managers because of the loss of canopy coupled with soil property damage and alterations to hydrologic conditions. The differences between wildfire and prescribed fire in shrublands are intermediate between those seen in grass and forest environments.

In grassland ecosystems, high-severity fires have been shown to increase the amount of nutrients mobilized and alter the hydrologic response of catchments [63]. The combination of these factors makes sites more susceptible to erosion of soil and the release of nutrients into stream and lakes where they could potentially affect water quality. Typically, prescribed fires are less severe than wildfires because of controls over burning conditions and fuel loads. Prescribed fire at Konza Prairie Biological Station, one of the last remaining areas of unplowed, tall-grass prairie in the Midwestern United States, released Dissolved Black Carbon (DBC) into nearby grassland stream systems [64]. The study concluded that there was not a direct relationship between water quality and DBC generated by prescribed burning. They suggest one reason for this is that the export of DBC through stable grassland systems can be on the scale of decades to centuries.

5.2 Scale

Another important factor in the impact on wildfire on watershed function is the size of the fire. Wildfire spread in grasslands is a function of fuel type, fuel moisture, air temperatures, and wind speeds. Influenced by the spotting of embers out ahead of the main fire front, wind-driven fire events in grasslands can move rapidly. Fire spread was modeled in Australian grasslands based on a critical wind speed based on a critical wind speed of 5 km hr^{-1} [65]. A linear relationship was used for rates of spread below wind speeds of 5 km hr^{-1}. Above that speed a power function with an exponent of less than 1 was needed for the model to match field data. Data from 21 grassland fires with wind speeds ranging from 27 to 78 km hr^{-1} produced spread rates of 4 to over 23 km hr^{-1}.

After months of drought, low-humidity and above average temperatures in 2011 a series of wind-driven grassland fires in the state of Texas, U.S.A. consumed nearly 1,618,750 ha during a single fire season, nearly double the previous record [66]. Multiple individual fires were in excess of 50,000 ha in size. Due to their size, fires of this magnitude compound the impacts of large scale erosion events [63]. This sort of situation has the potential to result in large scale degradation of grassland soil nutrients and hydrologic function and lead to desertification on the scale seen in the Great Plains of North America in the 1930s.

A prescribed fire in a Texas grassland resulted in a large increase (1150%) in streamflow in comparison to an unburned watershed in the first year after burning [68]. The increased post-fire streamflow was short lived, however, with flows returning to pre-fire levels shortly after the burning. By contrast, post-fire streamflow increases in forests and shrublands remained elevated for significant number of years because of the delay in revegetation. Grassland vegetation growth after fire is usually quite rapid (a few months to a year).

Another important determinant of the magnitude of the effects of fire on water is slope. Steepness of the slope has a significant influence on movement of soil and nutrients into stream channels where they can affect water quality. A study of the impacts of slope on grassland fires demonstrated that as slope increased in a prescribed fire, erosion from slopes accelerated [67, 68].

Annual streamflow totals (annual water yields) generally increase as precipitation inputs to a watershed increase [10]. Streamflows originating on forest watersheds, therefore, are generally greater than those originating on grassland watersheds, and those from grasslands are greater than flows originating on desert watersheds. Furthermore, annual streamflow totals frequently increase when mature forests are harvested or otherwise cut, attacked by insects, or burned [68, 69]. The observed increases in streamflow following disturbances often diminish with decreasing precipitation inputs to a watershed. This decrease can occur within a year or take many years, depending on the disturbance and vegetation type.

6. Summary and conclusions

Grasslands collectively are the largest ecosystem in the world, making up 40.5% of the land mass excluding Greenland and Antarctica. They are not entirely natural because they have formed and developed under the influence of natural and anthropogenic disturbances fire, (e.g. prescribed fire, wildfire, livestock grazing, woody vegetation clearing, over-sowing with pasture grass, etc.). Their importance now is in the variety of ecosystem services that they provide. A critical function of grasslands in global C circulation is their subsoil sequestration and storage of organic matter. Grasslands soils are classified as Mollisols, soils with deep, organic matter horizons. This characteristic makes grasslands almost as important as forests for C fixation and storage. Grassland soils are organic matter sinks on the same order of magnitude as tree biomass.

Although wildfires have always been a constant part of prairie fire regimes, wildfire numbers and area burned have surged in the 21st Century due to drought. The number of wildfires in the Great Plains of North America increased from 33.4 year^{-1} in 1985 to 116.8 year^{-1} in 2014. The total burned area grew by 400% over the same time period. Measured wind speeds ranging from 27 to 78 km hr^{-1} have produced spread rates of 4 to over 23 km hr^{-1}.

The general effects of fire on soil physical properties range from very minor to serious. Since grassland fires are often rapidly-moving with the wind, and have much less fuel than that in brush and forest ecosystems, soil heating is significantly lower, and therefore physical damage is much less than what occurs during crown, surface, or smoldering fires in forests and woodlands. Physical effects of fire include alterations in soil physical properties, development of water repellency, and erosion. Comparisons of wildfire and prescribed fire in grassland ecosystems show little differences in physical impacts due to the low fire severities characteristics of both types of fire, the narrow flame fronts, and rapid spread rates.

In grasslands, savannas, and tundras, much greater quantities of organic C are found in the underground (90%) than in aboveground components (<10% of the total C). Because of these large belowground pools of C in grasslands, fires do not significantly affect the role or importance of organic C in maintaining the physical and hydrological properties of Mollisol soils.

Acknowledgements

The Authors would like to thank the Rocky Mountain Research Station, Air-Water-Aquatic Environments Research Program, and the Program Manager, Frank McCormick, for support of this effort.

Conflict of interest

There are no "Conflicts of Interest" associated with this paper. It was produced by U.S. Forest Service employees during normal work hours and on appropriated funding.

Author details

Daniel George Neary* and Jackson McMichael Leonard
USDA Forest Service, Rocky Mountain Research Station, Air, Water, Aquatic Environments Program, Flagstaff, Arizona, USA

*Address all correspondence to: dan.neary@usda.gov

IntechOpen

References

[1] DeBano LF, Neary DG, Ffolliott PF. Fire's Effects on Ecosystems. New York: John Wiley & Sons, Inc.; 1998. p. 333

[2] Pyne SJ. Fire in America: A Cultural History of Wildland and Rural Fire. Seattle: University of Washington Press; 1982. p. 654

[3] Pyne SJ, Andrews PL, Laven RD. Introduction to Wildland Fire. New York: John Wiley & Sons; 1996. p. 769

[4] Scott AC. The pre-quaternary history of fire. Paleogeography, Paleoclimatology, Paleoecology. 2000;**164**:281-329

[5] Smith JK, Zouhar K, Sutherland S, Brooks ML. Chapter 1: Fire and nonnative invasive plants – Introduction. Pp. 1-31. In: Zouhar K, Smith JK, Sutherland S, Brooks ML, editors. Wildland Fire in Ecosystems: Fire and Nonnative Invasive Plants. General Technical Report RMRS-GTR-42 Volume 6. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2008. p. 355

[6] Jackson AS. Wildfires in the Great Plains grasslands. In: Komarek EV, editor. Proceedings of the 4th Tall Timbers Fire Ecology Conference. 1965. pp. 241-259

[7] Noble JC. Behaviour of a very fast grassland wildfire on the riverine plain of southeastern Australia. International Journal of Wildland Fire. 2008;**1**:189-196

[8] Smith JK, editor. Wildland Fire in Ecosystems: Effects of Fire on Fauna. General Technical Report RMRS-GTR-42 Volume 1. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2000. p. 83

[9] Sandberg DV, Ottmar RD, Peterson JL. Wildland Fire in Ecosystems: Effects of Fire on Air. General Technical Report RMRS-GTR-42 Volume 5. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2002. p. 79

[10] Neary DG, Ryan KC, DeBano LF, editors. Wildland Fire in Ecosystems: Effects of Fire on Soil and Water. General Technical Report RMRS-GTR-42 Volume 4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2005. p. 250

[11] Zouhar K, Smith JK, Sutherland S, Brooks ML, editors. Wildland Fire in Ecosystems: Fire and Nonnative Invasive Plants. General Technical Report RMRS-GTR-42 Volume 6. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2008. p. 355

[12] Bento-Gonçalves A, Vieira A, Úbeda X, Martin D. Fire and soils: Key concepts and recent advances. Geoderma. 2012;**191**:3-13

[13] Watts AC, Schmidt CA, McLaughlin DL, Kaplan DA. Hydrologic implications of smoldering fires in wetland landscapes. Freshwater Science. 2015;**34**:1394-1405

[14] Fenton TE. Chapter 4: Mollisols. In: Developments in Soil Science, Part B. Vol. 11. Amsterdam, Netherlands: Elsevier; 1983. pp. 125-163

[15] Singer MJ, Munns DN. Soils: An Introduction. 3rd ed. Upper Saddle River, NJ: Prentice Hall; 1996. p. 480

[16] Ryan KC, Jones AT, Koerner CL, Lee KM. (Editors) Wildland Fire in Ecosystems: Effects of Fire on Cultural Resources and Archeology.

General Technical Report RMRS-GTR-42 Volume 3. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Ogden, UT; 2012. p. 224

[17] Hardy CC, Menakis JP, Long DG, Brown JK. Mapping historic fire regimes for the Western United States: Integrating remote sensing and biophysical data. In: Greer JD, editor. Proceedings of the 7th Forest Service Remote Sensing Applications Conference; 1998 April 6-10; Nassau Bay, TX. Bethesda, MD: American Society for Photogrammetry and Remote Sensing; 1998. pp. 288-300

[18] Neary DG, Klopatek CC, DeBano LF, Ffolliott PF. Effects of fire on belowground sustainability: A review and synthesis. Forest Ecology and Management. 1999;**122**:51-71

[19] Brown KJ, Clark JS, Grimm EC, Donovan JJ, Mueller PG, Hansen BCS, et al. Fire cycles in north American interior grasslands and their relation to prairie drought. Proceedings of the National Academy of Sciences. 2005;**102**:8865-8870

[20] Suttie JM, Reynolds SG, Batelio C, editors. Grasslands of the World. Food and Agriculture Organization of the United Nations, Plant Production and Protection Series, No. 342005. p. 514

[21] White F. The Vegetation of Africa: A Descriptive Memoir to Accompany the UNESCO/AETFAT/UNSO Vegetation Map of Africa. Natural Resources Research Series XX. UNESCO: Paris, France; 1983. p. 356

[22] Minahi K, Goudriaan J, Lantinga EA, Kimura T. Significance of grasslands in emission and absorption of greenhouse gases. In: Barker MG, editor. Grasslands for our World. Wellington, New Zealand: SIR Publishing; 1993

[23] Dublin HT. Vegetation dynamics in the Serengeti-Mara ecosystem: The role of elephants, fire, and other factors. In: Sinclair ARE, Arcese P, editors. Serengeti II: Dynamics, Management, and Conservation of an Ecosystem. Chicago, Illinois: University of Chicago Press; 1995. pp. 71-90

[24] Wright HA, Bailey AW. Fire Ecology United States and Southern Canada. New York: John Wiley & Sons; 1982. p. 501

[25] Wright HA. Range burning. Journal of Range Management. 1974;**27**:5-11

[26] Vallentine FF. Range Development and Improvements. 3rd ed. New York: Academic Press; 1989. p. 524

[27] Ehrenreich JH, Aikman JM. An ecological study of certain management practices on native plants in Iowa. Ecological Monographs. 1963;**33**:113-130

[28] Donovan VM, Wonkka C, Twidwell D. Surging wildfire activity in a grassland biome. Geophysical Research Letters. 2017;**44**:5986-5993

[29] Boonman JG, Mikhalev SS. Chapter 10. The Russian steppe. Pp. 381-416. In: Suttie JM, Reynolds SG, Batelio C, editors. Grasslands of the World. Food and Agriculture Organization of the United Nations, Plant Production and Protection Series, No. 34. 2005. p. 514

[30] Hardy CC, Schmidt KM, Menakis JP, Sampson RN. Spatial data for national fire planning and fuel management. International Journal of Wildland Fire. 2001;**10**:353-372

[31] Schmidt KM, Menakis JP, Hardy CC, Hann WJ, Bunnell DL. Development of Coarse-Scale Spatial Data for Wildland Fire and Fuel Management. General Technical Report RMRS-87. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO; 2002. p. 41

[32] Agee JK. Fire Ecology of Pacific Northwest Forests. Washington, DC: Island Press; 1993. p. 493

[33] Ryan KC. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fennica. 2002;**36**:13-39

[34] Brown JK, Smith JK, editors. Wildland Fire in Ecosystems: Effects of Fire on Flora. General Technical Report RMRS-GTR-42 Volume 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2000. p. 257

[35] Kauffman JB, Steele MD, Cummings D, Jaramillo VJ. Biomass dynamics associated with deforestation, fire, and conversion to cattle pasture in a Mexican tropical dry forest. Forest Ecology and Management. 2003;**176**:1-12

[36] Schmidt IB, Fidelis A, Miranda HS, Ticktin T. How do the wets burn? Fire behavior and intensity in wet grasslands in the Brazilian savanna. Brazilian Journal of Botany. 2017;**40**:167-175

[37] Feller MC. The influence of fire severity, not fire intensity, on understory vegetation biomass in British Columbia. In: Proceedings, 13th conference on fire and Forest meteorology; 1996 October 27-31; Lorne, Australia. International Journal of Wildland Fire. 1998;**7**:335-348

[38] Stocks BJ, Lynham TJ, Lawson BD, Alexander ME, Van Wagner CE, McAlpine RS, et al. The Canadian forest fire danger rating system: An overview. The Forestry Chronicle. 1989;**65**:250-257

[39] Alexander ME. Calculating and interpreting forest fire intensities. Canadian Journal of Botany. 1982;**60**:349-357

[40] Campbell GS, Jungbauer JD Jr, Bristow KL, Hungerford RD. Soil temperature and water content beneath a surface fire. Soil Science. 1995;**159**:363-374

[41] Simard AJ. Fire severity, changing scales, and how things hang together. International Journal of Wildland Fire. 1991;**1**:23-34

[42] Campbell GS, Jungbauer JD, Bidlake WR, Hungerford RD. Predicting the effect of temperature on soil thermal conductivity. Soil Science. 1994;**158**:307-313

[43] De Ronde C. Wildland fire-related fatalities in South Africa – A 1994 case study and looking back at the year 2002. P. 158. In: Viegas DX, editor. Forest Fire Research & Wildland Fire Safety. Rotterdam, Netherlands: Millpress; 2002. p. 228

[44] Albini FA, Reinhardt ED. Modeling ignition and burning rate of large woody natural fuels. International Journal of Wildland Fire. 1995;**5**:81-91

[45] Johnson EA, Miyanishi K, editors. Forest Fires, Behavior and Ecological Effects. San Francisco, California: Academic Press; 2001. p. 594

[46] Ryan KC, Noste NV. Evaluating prescribed fires. In: Lotan JE, Kilgore BM, Fischer WC, Mutch RW, editors. Proceedings—Symposium and Workshop on Wilderness Fire. General Technical Report INT-182. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1985. pp. 230-238

[47] DeBano LF. The role of fire and soil heating on water repellency in wildland environments: A review. Journal of Hydrology. 2000;**231-232**:195-206

[48] Doerr SH, Shakesby RA, Walsh RPD. Soil water repellency: Its causes, characteristics and hydro-geomorphological significance. Earth Science Reviews. 2000;**51**:33-65

[49] Anderson JM. The effects of climate change on decomposition processes in grassland and coniferous forest. Ecological Applications. 1991;**1**:326-347

[50] Neary DG. Impacts of wildfire severity on hydraulic conductivity in forest, woodland, and grassland soils. Pp. 123-142. In: Elango L, editor. Hydraulic Conductivity – Issues, Determination, and Applications. Rijeka, Croatia: INTECH; 2011. p. 424

[51] Valzano FP, Greens RSB, Murphy BW. Direct effects of stubble burning on soil hydraulic and physical properties in a direct drill tillage system. Soil& Tillage Research. 1997;**42**:209-219

[52] Novák V, Lichner L, Zhang B, Kňava K. The impact of heating on the hydraulic properties of soils sampled under different plant cover. Biologia. 2009;**64**:483-486

[53] Sheridan G, Lane PNJ, Noske PJ. Quantification of hillslope runoff and erosion processes before and after wildfire in a wet eucalyptus forest. Journal of Hydrology. 2007;**343**:12-28

[54] Ojima DS, Schimel DS, Parton WJ, Owensby CE. Long and short-term effects of fire on nitrogen cycling in tallgrass prairie. Biogeochemistry. 1994;**24**:67-84

[55] Musil CF, Midgley GF. The relative impact of invasive Australian acacias, fire and season on the soil chemical status of a sand plain lowland fynbos community. South African Journal of Botany. 1990;**56**:419-427

[56] James SW. Effects of fire and soil type on earthworm populations in a tallgrass prairie. Pedobiologia. 1982;**24**:140-147

[57] Callaham MA Jr, Hendrix PF, Phillips RJ. Occurrence of an exotic earthworm (Amynthas agrestis) in undisturbed soils of the southern Appalachian Mountains, USA. Pedobiologia. 2003;**47**:466-470

[58] Precht J, Chrisphersen J, Hensel H, Larcher W. Temperature and Life. New York: Springer-Verlag; 1973. p. 779

[59] Zwolinski MJ. Fire effects on vegetation and succession. In: Krammes MJ, editor. Proceedings of a Symposium Effects of Fire Management of Southwestern Natural Resources. General Technical Report RM-191. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1990. pp. 18-24

[60] Flinn MA, Wein RW. Depth of underground plant organs and theoretical survival during fire. Canadian Journal of Botany. 1977;**55**:2550-2554

[61] Martin RE, Miller RL, Cushwa CT. Germination response of legume seeds subjected to moist and dry heat. Ecology. 1975;**56**:1441-1445

[62] Miller M. Chapter 2: Fire autecology. Pp 9-34. In: Brown JK, Smith JK, editors. Wildland Fire in Ecosystems: Effects of Fire on Flora. General Technical Report RMRS-GTR-42 Volume 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 2000. p. 257

[63] Ravi S, D'Odorico P, Zobeck TM, Over TM. The effect of fire-induced soil hydrophobicity on wind erosion in a semiarid grassland: Experimental observations and theoretical framework. Geomorphology. 2009;**105**:80-86

[64] Ding Y, Yamashita Y, Dodds WK, Jaffé R. Dissolved black carbon in grassland streams: Is there an effect of recent fire history? Chemosphere. 2013;**90**:2557-2562

[65] Cheney NP, Gould JS, Catchpole WR. Prediction of fire spread in grasslands. International Journal of Wildland Fire. 1998;**8**:1-13

[66] Texas Forest Service; 2011. Available from: https://ticc.tamu.edu/Documents/Home/tx_sitrep.pdf [Accessed: 24 March 2019]

[67] Wright HA, Churchill FM, Stevens WC. Effect of prescribed burning on sediment, water yield, and water quality from juniper lands in Central Texas. Journal of Range Management. 1976;**29**:294-298

[68] Bosch JM, Hewlett JD. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology. 1982;**55**:3-23

[69] Hornbeck JW, Adams MB, Corbett ES, Verry ES, Lynch JA. Long-term impacts of forest treatments on water yields: A summary for northeastern USA. Journal of Hydrology. 1993;**150**:323-344