

A Soil Burn Severity Index for Understanding Soil-fire Relations in Tropical Forests

Methods for evaluating the impact of fires within tropical forests are needed as fires become more frequent and human populations and demands on forests increase. Short- and long-term fire effects on soils are determined by the prefire, fire, and postfire environments. We placed these components within a fire-disturbance continuum to guide our literature synthesis and develop an integrated soil burn severity index. The soil burn severity index provides a set of indicators that reflect the range of conditions present after a fire. The index consists of seven levels, an unburned level and six other levels that describe a range of postfire soil conditions. We view this index as a tool for understanding the effects of fires on the forest floor, with the realization that as new information is gained, the index may be modified as warranted.

INTRODUCTION

Tropical forests vary considerably in the rates of fuel accumulation, the amount of biomass available for burning, the frequency and intensity of fires, and fire effects. Throughout these forests, structure and composition vary widely in response to the wide disparity of climates (e.g., temperature and precipitation), rates of evapotranspiration, and physical settings (e.g., topography, geology, elevation). Within dry tropical forests, fire frequency and diversity of fire types occur because of the variety of biophysical environments and seasonal fluctuations between wet and dry cycles in many areas (1). Although conditions are generally too damp and fuel is limited to sustain fires in moist and wet tropical forests, canopy openings created by disturbances (e.g., fires, land clearing) give surface fuels an opportunity to dry, thus creating conditions that favor future fires (2). Additionally, in both dry and moist tropical forests, postdisturbance vegetation often consists of an abundance of vines, lianas, grasses, and forbs, which add to fuel loads and thus increase the potential for a forest to burn with high intensity and be more susceptible to damaging fires (3, 4). Given that fire is a component of tropical forests, fire-related changes to the forest floor and its contribution to soil organic matter have strong influences on the composition and structure of postfire forest communities (5, 6).

The impacts of fires on soil range from lightly scorching the organics to their total consumption to heating mineral soil to a degree that water repellency occurs. When temperatures and durations are extreme, even soil particles can be fused. Several studies have described these conditions for boreal and temperate forests, and results have been widely used in understanding fire as a disturbance (7, 8). In the Rocky Mountains of the US, knowledge gained by understanding the relation between prefire forest characteristics and soil burn severity has led to the development of fuel treatments and techniques (e.g., prescribed burning, harvesting methods, activity slash treatments) designed to alter fire behavior and soil burn severity outcomes (9, 10, 11).

Although many soil burn severity studies have been conducted throughout the world, classes used to describe fire effects on soil are inconsistent, making it difficult to synthesize

information. To partially address this deficiency, Jain and Graham (12) used a soil burn severity index for the cold, moist, and dry temperate forests of the Rocky Mountains of western North America, placing available literature within the context of a fire-disturbance continuum presented by Jain et al. (13) (Fig. 1). Rather than attempting to redefine severity, Jain and Graham (12) synthesized current applications of severity into one integrated index that is applicable for a variety of fires and objectives and that is useful at a variety of spatial and temporal scales. A full range of possible severity outcomes was included, allowing users to select, combine, or identify severity outcomes appropriate for their needs or application. We used this approach to develop a working hypothesis of a soil burn severity index for fires in tropical forests that scientists can apply and test for validity and provide ways to improve it. In addition, managers can use identified relations between the index and values at risk to develop fire-management strategies for dry and moist tropical forests.

METHODS

Physical, chemical, and biological responses of soils are influenced by the prefire, fire, and postfire environments (13) (Fig. 1). The prefire environment refers to conditions that can influence a fire's outcome, such as land cover or physical setting. The fire environment includes fire-behavior character-

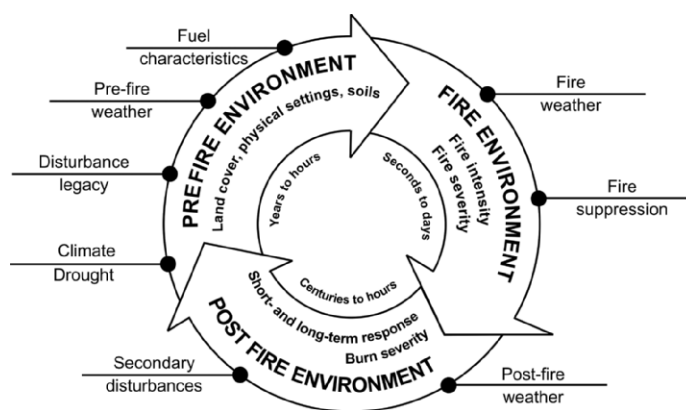


Figure 1. The fire disturbance continuum is a cycle that contains three components that describe different environments influencing fires (13). The first component, the prefire environment, includes forest vegetation and state of the environment (moisture levels, amount of biomass, and species composition) the year the fire occurs and immediately prior to the fire. However, factors such as disturbance legacy and climate affect the fuel characteristics. The second component, the fire environment, includes the characteristics during combustion. This would include weather, fire behavior, and suppression tactics. Fire intensity (indicator used to describe fire behavior) and fire severity (direct fire effects) concentrate on describing the fire process. The third component, referred to as the postfire environment, includes burn severity that describes what is left after the fire is out and the ecological, social, and economic responses. These responses can occur immediately after the fire to several centuries later. In addition, other disturbances (e.g., storms or agriculture development) play a role in the postfire environment. The postfire environment characteristics are dependent upon the prefire environment and fire environment. For soils, the ecological response includes the physical, chemical, and biological properties of the soil after the fire and is used to provide a rationale for classifying burn severity.

Table 1. Integrated soil burn severity contains seven levels, including an unburned state, through the full range of postfire conditions. Indicator characteristics 1 and 2 will always be present. Indicator characteristic 3 may or may not be present.

Indicator characteristic 1	Indicator characteristic 2	Indicator characteristic 3	Levels of soil burn severity
Unburned	No evidence of recent fire	—	0
>40% litter cover and/or root mat	Both charred litter and unburned litter could be present	Mineral soil has a combination of unburned and black char; litterfall since fire	1
2% through 39% litter cover and/or root mat	A plurality of black char influences the mineral soil appearance	Lines of gray char from logs; litterfall since fire	2
	A plurality of gray and/or white char influences the mineral soil appearance	Lines of orange under logs; litterfall since fire	3
≤1% litter cover or root mat	A plurality of black char influences the mineral soil appearance	Gray char and orange-colored soils occur under logs; litterfall since fire	4
	A plurality of gray and/or white char influences the mineral soil appearance	Orange-colored soils occur under logs; litter fall since fire	5
	A plurality of orange char influences the mineral soil appearance	Black ash line present 1 through 2 cm below soil surface	6

istics associated with the fire, such as rate of spread, flame length, and energy produced (referred to as fire intensity in the literature) (14, 15). Fire severity, which occurs during the fire event, describes the direct effects from the fire-combustion process (8). Measures of soil fire severity concentrate on factors specifically caused by a fire such as litter consumption or changes to the soils. The postfire environment is best described as “what is left behind” or the appearance of the forest floor (soil) after combustion is finished, which we call soil burn severity. The intent behind burn severity characterizations is not to measure consumption but to describe the environment created by the fire within the context of the prefire and fire environments. Descriptors include the forest floor conditions using metrics such as amount of new (postfire) and old (prefire) litter cover, amount of mineral soil exposed, and mineral soil color (12).

Using the fire-disturbance continuum as a guide, we synthesized relevant literature describing fire effects in the tropics, temperate, and boreal forests and modified the soil burn severity index developed for temperate forests (12). Keywords used in the literature search included: *i*) tropical, fire, soils, fire severity, fire intensity, *ii*) litter present, absent, consumed, partially consumed, char color, and *iii*) mineral soil exposed and its state or color (unburned, black, gray, white, orange). We then assembled severity definitions, with emphasis on tropical studies, and identified the minimum number of levels that would characterize the full range of severity outcomes available from the current fire literature. Using this literature base and the fire-disturbance continuum as a framework, we identified levels of soil burn severity and logical breaks between the levels applicable for tropical forest soils. We placed the soil burn severity index within the continuum to determine if the levels complemented characteristics related to the prefire, fire, and postfire environments.

RESULTS

Soil Burn Severity Index

We identified seven burn severity levels, including an unburned level, within the postfire environment using two indicator variables (litter abundance and mineral soil color) (Table 1). Due to the common use of an unburned category in several studies for unburned sites within tropical forests, we added a level 0 to the index for sites with no sign of recent burning (Table 1). These were sites identified either prior to the fire (5, 16, 17), outside the fire perimeter (6, 18), or patches within the fire perimeter (19). Ellingson et al. (20) conducted soil sampling prior to an initial fire as well as in reference sites adjacent to burned sites. For characterizing burned sites, we selected litter (e.g., dead, partially decomposed material such as grass, leaves,

or needles) (indicator characteristic 1) because it has the potential to be present across all places that support vegetation. Next, we partitioned percent litter cover into three classes. Mineral soil color (characteristic 2) can serve as an indicator of the postfire state of physical, biological, and chemical soil components (21). Therefore, we partitioned the broad litter-cover classes (levels 2 through 6) according to the abundance of black-, gray-, or orange-colored char, resulting in six soil burn severity levels. We added a third indicator characteristic, which may not always be present, because outside of tropical forests, these attributes have been associated with mineral soil char (e.g., lines of differing mineral soil char) (22).

Organic matter, on the surface and in the soil, influences physical, biological, and chemical responses and is an important component to include in a soil burn severity index (23, 24). Because we did not find any studies conducted in the tropics that identified litter cover thresholds related to an ecological response, we used thresholds identified in literature outside of the tropics that relate to postfire erosion potential. These thresholds include 30% litter cover (25), 40% litter cover (26), 45% litter cover (27), and 50% litter cover (28). Based on this literature, we selected a threshold of 40% litter cover to partition level 1 from levels 2 and 3. Level 1 consists of litter cover from 40% through 100%, and levels 2 and 3 have litter cover from 2% through 39%. We further partitioned levels 2 and 3 by mineral soil color, with level 2 containing a plurality of black char and level 3 a plurality of gray or white char.

In some tropical forest studies, the absence of litter and the state of the mineral soil were used as an indicator of severity. Perez (19) characterized the postfire environment as containing no litter, root mat, nor woody debris as one indication of severity, and Chacón and Dezzio (24) observed litter decomposition in litterbags in forests where charcoal was in and on soils. We designed levels 4 through 6 to reflect these postfire characteristics (Table 1). These levels have either a trace (≤1%) or no litter remaining and were partitioned by the color of the mineral soil. Level 4 mineral soils contain a plurality of black char, and level 5 contains a plurality of gray or white char. A unique set of circumstances is required to create orange-colored mineral soils, such as slowly smoldering deep humus layers or wood. Because this level may be important under slash piles associated with land-clearing activities, we added level 6 (plurality of orange-colored soil) for tropical forests.

Placing the Soil Burn Severity Index within the Context of the Fire Continuum

Prefire Environment. Examples of the prefire environment include land cover, physical setting, and soils (Fig. 1). Characteristics of these are influenced by factors such as climate

and drought, disturbance legacy, prefire weather, and fuel characteristics. Land cover (vegetation) reflects the type, distribution, and flammability of the fuel (29, 30). For example, vegetation differences between tropical dry and moist forests can alter how a fire burns. In general, dry forests tend to contain deciduous vegetation with some evergreen, while moist forests are primarily evergreen. Plant biomass is lower and growth patterns are more variable in the dry compared to the moist forests. Dry forests tend to have high spatial diversity (intermingled grass, forest, and agriculture lands) compared to moist forests. Because diversity of fuel alters how a fire burns through a forest and what a fire leaves behind, this may result in more of a variety of soil burn severity levels in dry compared to moist forests, where a fire may burn more homogeneously across the landscape. Dry forests also have a wide range of understory vegetation that can serve as surface fuels, while the high canopy structure of moist forests inhibits understory vegetation development. Thus, in moist forests, surface or ground fires, depending on the litter depth, may favor smoldering fires (31), which tend to favor soil burn severity levels 5 and 6.

Physical setting describes where a site is located within a landscape. This can influence burn severity by altering fire intensity and affecting postfire responses, such as erosion and regrowth of vegetation. The location of a burned area within a landscape can be an important risk value, especially with reference to human settlements, roads, and agricultural practices. Thus, the application of fuel treatments to favor soil burn severity levels 1, 2, or 3 could be developed to mitigate postfire effects such as erosion potential, as noted in studies outside of the tropics (25–28). In the US, concerted efforts to mitigate erosion after fire using a variety of fire-rehabilitation treatments and decisions have been based on landscape position and exposed mineral soil (32).

Important soil characteristics relevant to burn severity include soil texture, structure, moisture, amount of clay minerals, amount of organic matter (on the surface and in the soil), and the amount of exchangeable ions. All these factors influence the soil's physical, chemical, and biological characteristics when a fire occurs (21). For instance, on the mineral soil surface, soil structure is influenced by the combination of mineral soil particles and organic matter. With increasing depth, clay minerals begin to play a more important role in influencing soil structure, and the aggregation of individual mineral particles enhances porosity (8). Fire can influence clay minerals and organic components; therefore, the abundance of these components in the soil prior to a fire can influence a burn severity outcome. Outside of the tropics, fire-induced changes in these components are typically identified by changes in mineral soil color and have been related to changes to the biological (e.g., microbial biomass), chemical (e.g., organic matter quantity and quality), and physical (e.g., water repellency and bulk density) conditions (8, 21, 33–35). Coupling these prefire attributes with the burn severity index (mineral soil color and abundance of organic matter) can lead to an improved understanding of prefire and postfire relations common in many tropical studies (Table 2).

Elements associated with climate and weather, such as periods of drought, affect fuel moisture, annual biomass, and seasonal fluctuations in precipitation. For example, in the tropics, a fire may occur in a particular year during a distinctive dry or wet season, depending on El Niño–Southern Oscillation occurrence, or after an extended drought in disturbed and undisturbed forests (36–38). The time of the year a fire burns gives rise to expected fuel moistures, which in turn affects fire behavior and soil temperature and duration of the fire event. Lower fuel moisture will contribute to higher soil temperatures

during a fire. Castaño-Meneses and Palacios-Vargas (39) used drying period (which affects moisture content) of slash to understand diversity and population of 16 ant species in response to slash-and-burn treatments (Table 2). A study such as this could compare ant population responses and activities to soil burn severity levels 0 through 3 to levels 4 through 6. In another study related to fuel moisture, Kauffman et al. (40) used drying period of prefire biomass to evaluate changes in soil nutrients (Table 2). These changes could be quantified in relation to soil burn severity levels 0 through 4, where the greatest change in nutrient dynamics occurs during a fire. The time of the year or particular year a fire burns can determine vegetative response as shown by Sampaio et al. (41), who used drying period to explain coppice regeneration (Table 2). The extent of each level within the soil burn severity index will vary depending on the climate and weather in any given year a fire occurs.

Disturbance legacy (e.g., type and timing of the last disturbance) is a factor that influences the prefire environment and is especially important with the prevalence of slash-and-burn agriculture occurring in places such as the neotropics. Prefire disturbances (or lack of disturbances) can determine the configuration, amount, and moisture content of surface fuels in tropical forests. Canopy openings created by disturbances can cause these fuels to dry (2), as well as create more fuels from growth of secondary forest vegetation. Disturbance legacy includes frequency of past fires (2) or other disturbances such as slashing (39) or landslides (5). Several studies contain disturbance legacy as a source of variation to understand the role of fires in tropical forests (24, 42–45) (Table 2).

Interactions among all the aforementioned factors influence fuel characteristics. Many of the fire effects described in the literature were attributed to the amount of fuel and fuel moisture prior to the burning (40, 41) (Table 2). Fuels consist of live and dead organic materials, and their density and moisture contents change over time and space. Vertical and horizontal arrangement of fuels can also be important. For example, burning coarse woody debris (material >8 cm in diameter) in contact with or in close proximity to the soil surface can transfer large amounts of heat to the mineral soil for long periods, thus altering its physical, chemical, and biological properties (46–48). Under slash piles commonly associated with land-clearing activities, the presence of orange-colored soil (soil burn severity level 6) indicates that woody debris may have been present, favoring long fire duration and creating high soil temperatures.

Fire and Postfire Environment. Fire severity concentrates on soil heating, which includes temperature and duration, as well as depth of heat penetration and amount of material consumed by the fire (7, 49). The relation between fire intensity and fire severity is not one-to-one. A smoldering fire (low intensity) may favor high soil heating. In contrast, a fast-moving, high-intensity fire may lead to low soil heating (8). Rather, the amount and type of fuels, as well as other factors mentioned previously, greatly influence heat pulse into the soil and the resultant temperature. There is typically considerable variation in temperatures produced within a fire, both horizontally and vertically. However, there are ranges of soil temperatures and heat duration that have to occur to create a particular burn severity outcome. An understanding of the role of temperature and heat duration, combined with burn severity indicators, can provide ways to predict the physical, chemical, and biological effects of fire. In cases where consumption, a measure of fire severity, is of interest, the inverse of the index would be appropriate, provided prefire characteristics of litter cover and soil color are noted.

In a review of literature on the effects of fire on forest soil properties, Certini (21) suggested that physical soil character-

Table 2. Tropical forest research studies where investigators identified or discussed ecological outcomes (postfire response) after a fire. Many studies manipulated the prefire conditions and used this to relate to postfire response. An "x" under measurement time indicates if investigators obtained measurements prefire and postfire. Postfire soil characteristics column shows the description used to characterize burn severity. Several investigators did not use postfire characteristics in their studies.

Prefire manipulations or source of variability	Postfire responses	Measurement time		Postfire soil characteristics	Literature source
		Prefire	Postfire		
Fuel moisture	Nutrients	x	x	None given	6
Fuel moisture	Ants	x	x	None given	39
Fuel moisture	Coppice regeneration	x	x	None given	41
Fuel moisture	Biomass & nutrients	x	x	None given	40
Fuel loading	Regeneration	x	x	None given	56
Fuel loading & moisture	Nutrients	x	x	Biomass consumption	20
Fuel loading & moisture	Nutrients	x	x	None given	17
Fuel loading & moisture	Nutrients	x	x	None given	16
Disturbance legacy	Vegetation	x	x	None given	2
None given	Plant mortality	x	x	Forest floor	19
Disturbance legacy	Vegetation	—	x	Regeneration strategy	43
Fuel loading	Vegetation	—	x	None given	48
Fuel loading	Plant mortality	—	x	Soil color	47
Fuel loading	Phosphorus	x	x	Soil color	46
Pre- & postfire	Mineralogy	x	x	None given	5
Fuel loading	Soil fertility	x	x	None given	34
Disturbance legacy	Nutrients	—	x	Fuel biomass	42
Disturbance legacy	Nutrients	—	x	Biomass	44
Disturbance legacy	Vegetation	—	x	Biomass distribution	45
Disturbance legacy	Litter decomposition	—	x	Forest floor	24
Agriculture land	Soil chemistry	—	x	Residual litter	23
Agriculture land	Soil chemistry	—	x	Litter & soil char	35

istics when combined with fire could influence water repellency, structure stability, bulk density, particle-size distribution, mineralogical assemblages, and color. DeBano (50) found that water repellency intensifies when soils experience temperatures between 200°C and 260°C for longer than 15 min. Soil burn severity levels 3 and 4 (particularly level 4) would tend to indicate conditions that could favor water repellency. If not much litter is present ($\leq 1\%$), and there is a plurality of gray- or orange-colored soil, temperatures could have exceeded 290°C, indicating water repellency is destroyed (8) (levels 5 and 6). However, the type of soils, their physical setting, and other soil erosion indicators must also be satisfied in order to evaluate erosion potential (51). As mentioned previously, we selected 40% litter cover as the threshold between soil burn severity levels 1 and 2, based on postfire erosion potential. In addition, Lewis et al. (25) found that gray-colored char on mineral soil coupled with less than 30% litter cover could be indicators of potential water repellency. Certini (21) noted that mineralogy would change because of fire, but only at temperatures exceeding 500°C. Ketterings et al. (47) verified this when they found that severe burning ($>500^\circ\text{C}$) changed soil mineralogy under slash piles, where orange-colored soil occurred (level 6). Although changes in mineralogy only occur at high temperatures, the soil burn severity index could be used in similar studies to gain a better understanding of soil appearance and its relation to soil physical properties.

The soil burn severity index was designed to identify indicators that relate to the postfire state of nutrients as a result of the fire. Litter begins to char at $\sim 175^\circ\text{C}$, but it is not consumed (level 1) (52). Therefore, the presence of litter, although charred, indicates little change in nitrogen. Black char (remaining litter after combustion) tends to occur from $\sim 175^\circ\text{C}$ to 300°C (level 2) (52). Gray char (levels 3 and 5) begins to occur from $\sim 300^\circ\text{C}$ to 500°C , which may lead to both nitrogen volatilization and mineralization (53, 54). Orange soils (level 6) occur anywhere from $\sim 400^\circ\text{C}$ to $>500^\circ\text{C}$, indicating a major loss of nitrogen (46). In addition, these chemical changes occur relatively rapidly and in relatively cool temperatures ($\sim 175^\circ\text{C}$ to 400°C) (levels 1 through 4). In contrast, as the organics are volatilized, other nutrients, such as sulfur, sodium, potassium,

magnesium, and phosphorus concentrations, can increase with increasing temperatures (47, 55) (levels 5 and 6). The abundance of litter (level 1) and presence of black char (levels 2 and 4), gray char (levels 3 and 5), and orange char (level 6) should provide an indication of nutrient abundance after a fire.

Vegetation response is strongly dependent on what plant components are still alive or viable after a fire (41, 56). Trees are the vegetation most often studied after a fire. However, understory vegetation, such as perennial forbs, grasses, and shrubs, can influence the postfire environment. Germination of seeds is dependent on their presence. Seeds tend to occur in the surface organic layers or surface mineral soil (56). Soil burn severity at level 0 or level 1 can indicate the presence of seeds. Depending on their size, most seeds can withstand temperatures ranging from $\sim 70^\circ\text{C}$ to 140°C and a typical duration of 0.5 to 1.5 hr (49). Because charring of litter tends to begin at $\sim 175^\circ\text{C}$, any material that is not charred indicates that some seed in the material is most likely viable. Survival of perennial forbs is strongly dependent on reproduction method and the soil depth of stolons, caudex, rhizomes, and/or bulbs. Therefore, factors such as mineral soil exposed (levels 3 through 6), char color (identified in levels 2 through 6), and depth of char in relation to bud location could be useful burn severity indicators for postfire vegetation response (Table 1).

Arthropods, molluscs, worms, fungi, bacteria, and other organisms living within surface and mineral soil layers play important ecological roles, ranging from soil creation to nutrient cycling. The influence of soil organisms on soil structure and processes is due, in large part, to the high diversity and abundance of soil microbes and fauna (57). Soil microarthropods, for example, can reach densities of thousands to millions of individuals per square meter, even in dry soils with low organic matter (e.g., coastal sand dunes) (58). Fire begins to affect soil organisms at temperatures from $\sim 60^\circ\text{C}$ to 100°C (49) (level 1). In a laboratory experiment, Guerrero et al. (55) found that 91% of the microbial carbon was lost when soil temperatures reached 300°C (levels 2 through 4). Thus, relatively low burn severities can influence microbial communities (59).

DISCUSSION

Our objective was to develop a simple soil burn severity index applicable to tropical systems and useful for assessing fire effects by integrating and synthesizing information related to soil burn severity from many places. The levels of soil burn severity describe a continuum that includes a full range of fire outcomes, which may or may not be detrimental, depending on values and management objectives. For example, some may consider a severe fire (level 6) as beneficial because the species that occur after a fire may be more resilient to disease and other disturbances (60). Therefore, rather than place an absolute value (e.g., low, moderate, or high) on our soil burn severity index levels, results from scientific investigation and management issues, which are dependent on the objective, should dictate a particular value.

The applicability of the soil burn severity index is dependent on its acceptance as a hypothesis that can be tested and evaluated. As researchers add information concerning fire in tropical systems, the index may change to reflect lessons learned from new information. Our intention for the index is to develop a standardized index that permits a hierarchical evaluation. Scientists may choose not to use all seven levels. Rather, we believe through our literature synthesis that researchers will group, select, or in some cases split levels into finer groups. For example, a soil scientist interested in soil fauna may concentrate an investigation on comparing level 0 to level 1, and then split level 1 into sublevels to validate the litter cover threshold of 40%. However, for ease in communication among different forums and to provide context, using the index to state that the work was concentrated on soil burn severity level 1 allows for a common dialog to occur and the applicability of results may be broadened. As a result, the pursuit of knowledge concerning fire in tropical forests will be integrated and adaptable to a variety of uses.

While developing the soil burn severity index, some questions arose concerning its applicability. For example, considering that fuel treatments are designed to favor fire suppression, is it possible for fuel treatments to influence burn severity outcomes? Current studies are considering the role of the prefire environment (fuels) and its influence on soil burn severity (11) for specific use in developing fuel treatments and their implementation. When scientific information is related to a soil burn severity index such as the one we present, results can be used to guide management activities.

Another question relates to the indicator characteristics used to identify soil burn severity levels (Table 1). What if these characteristics occur in more than one soil burn severity level? Although this may often occur, the objective is to quantify the most abundant characteristic. Thus, we chose a plurality of the char class rather than dominant or majority. Moreover, litter cover is the distinct and first indicator that clearly separates the levels. Another application would be to quantify in detail the actual cover of the litter and different char classes and then postclassify the data into the soil burn severity index. This method may be very appropriate when testing the effectiveness of the index when quantifying and communicating soil effects.

Other questions concern spatial and temporal aspects. For example, what is the minimum spatial extent in order to have a positive or negative effect on erosion or changes in invertebrate communities? For another example, what is the time frame required for microbes to recover after a fire as a function of soil burn severity? There are no clear answers to these questions, and answers are rare in the literature. Our hope is that by testing and implementing the soil burn severity index, a variety of studies can then be synthesized to begin to address such questions. Another question concerns appropriate plot size to

quantify soil burn severity. There are a variety of sampling procedures used in the literature, and plot size varies depending on the scientific or management objective. The soil burn severity index is designed to quantify postfire characteristics, no matter the plot size or study design.

CONCLUSION

Methods for assessing the effects of fire and predicting ecosystem responses to wildfire are ongoing needs in natural resource management. These needs will only increase with human pressure on land for agricultural, residential, commercial, and recreational uses, in addition to ecosystem services related to air, water, and biodiversity maintenance. These needs are increasing in the tropics, especially in areas where population pressures are high. The lessons learned in developing and using consistent assessment methods can be useful to predict ecosystem responses to different types of fires, thus increasing our understanding of soil-fire relations across regions and disciplines. Information from these applications of soil burn severity may result in developing prescribed fire programs and adjusting prefire conditions to favor desired outcomes and response. The soil burn severity index is one method that can add to our ecological understanding of the role of fire in tropical forests. Cochrane and Schulze (2) state that the "extreme heterogeneity within burned forests must be explicitly addressed in any effort to model regional fire dynamics or to estimate the consequences of fire to forest well-being." We believe the soil burn severity index is a step toward addressing this issue.

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Theresa B. Jain is a research forester with the US Department of Agriculture (USDA). Her address: USDA Forest Service, Rocky Mountain Research Station, 1221 S. Main, Moscow, ID 83843, USA.

E-mail: tjain@fs.fed.us

William Gould is a research ecologist with the USDA Forest Service. His address: USDA Forest Service, International Institute of Tropical Forestry, Río Piedras, 00926-1115, Puerto Rico.

E-mail: wgould@fs.fed.us

Russell T. Graham is a research forester with the USDA Forest Service. His address: USDA Forest Service, Rocky Mountain Research Station, 1221 S. Main, Moscow, ID 83843, USA.

E-mail: rtgraham@fs.fed.us

David S. Pilliod is a research ecologist with the US Geological Survey. His address: US Geological Survey, Forest and Rangeland Ecosystem Science Center, Snake River Field Station, 970 Lusk St., Boise, ID 83706, USA.

E-mail: dpilliod@usgs.gov

Leigh B. Lentile is an assistant professor with The University of the South. Her address: The University of the South, 735 University Avenue, Seawanee, TN 37375, USA.

E-mail: lbentile@sewanee.edu

Grizelle González is a research ecologist with the USDA Forest Service. Her address: USDA Forest Service, International Institute of Tropical Forestry, Río Piedras, 00926-1115, Puerto Rico.

E-mail: ggonzalez@fs.fed.us