Ignition probability of organic soils

William H. Frandsen

Abstract: Evaluating the effects of prescribed fire and wildland fire requires a greater understanding of the fire behavior of organic soils. Determining the ignition limit of organic soils over a wide geographical area is the subject of this study. Side ignitions were attempted with an electrically powered red-hot coil to simulate common ignition by lateral smoldering. Inorganic content was fixed by the sample's origin. Moisture content was altered to establish a moisture range that included the ignition limit. Recorded successes and failures of attempted ignitions were analyzed through logistic regression to give ignition probability based on the moisture and inorganic content and the organic bulk density. These probabilistic results lend themselves to lightning and person caused fire occurrence predictive systems required for wildfire management. A limited comparison of results with Frandsen (1987. Can. J. For. Res. 17: 1540-1544) shows encouraging similarities.

Wsumi : L'evaluationdes effets du brutlage dirige et des incendies forestiers requiert une meilleure comprehension du comporternent du feu dans les sols organiques. La determination des limites de l'ignition dans les sols organiques, A l'interieur d'une vaste region geographique, constitue l'objet de cette etude. Des allumages lat6raux ont ete tentes a l'aide d'une bobine electrique chauffee an rouge de facon a simuler les ignitions laterales communement observees lors des feux couvants. Le contenu inorganique a ete etabli par l'origine de 1'echantillon. Le contenu en humidite a ete altere pour obtenir un registre de teneur en humidite comprenant les limites de l'ignition. Les succes et les echecs des tentatives d'allurnage ont ete enregistres puis analyses par regression logistique de maniere a obtenir les probabilites d'ignition fondees sur la teneur en humidite et le contenu inorganique de meme que sur la densite apparente organique. Ces resultats probabilistes se pretent bien aux systemes de prediction des feux de foudre et de cause humaine, necessaires dans la gestion des incendies forestiers. Une comparaison restreinte des resultats de cette etude avec ceux de Frandsen (1987. Rev' can. rech. for. 17: 1540-1544) montre des ressemblances encourageantes.
[Traduit par la R6daction]

Introduction

Smoldering ground fires commonly occur in organic soil horizons following the passage of surface and crown fires including lightning and person-caused fires. Because of their intimate contact with the mineral soil, they have the potential for making a large heat impact on forest regeneration (Flinn and Wein 1977, 1988). Fire suppression in some wetlands has increased the development of organic soils, encouraging the invasion of vegetation into bodies of water. Burning during dry periods would decrease organic soil buildup, allowing these ecosystems to return to a more natural state. Knowing the ignition potential of the organic soils would allow managers to more accurately apply fire to meet their objectives and make more knowledgeable predictions of the probability of ground fires in a wildland fire situation.

Frandsen (1987) showed that the smoldering ignition limit of peat moss mixed with water and mineral soil depends on the mixture's moisture and inorganic content. The ignition limit can be approximated in two dimensions by a straight line extending from 110.0% on the moisture axis (ordinate) to 81.5% on the inorganic axis (abscissa) (Fig. 1). Both percentages are expressed on a dry weight basis. Successful ignitions are accomplished only within the triangle bounded by the axes and the ignition limit.

Frandsen (1987) limited his study to the addition of inorganic clay soil and fixed the organic bulk density at 110 kg· m^{-3}. Hartford (1989) extended the study to include changes in the inorganic material and organic bulk density. Increasing the organic bulk density decreased the probability of ignition, especially at low moisture levels.

Artsybashev (1974) described the smoldering ground fire as spreading downward and laterally forming a balloon-shaped cavity (Fig. 2). Downward spread eventually runs out of fuel or encounters conditions that do not support combustion, leaving only lateral spread. Lateral spread continues until the smoldering front encounters conditions that will no longer support combustion.

It is suggested that the limits of ignition can be used interchangeably with the limits of combustion. Forts (1946) viewed fire spread in surface fuels as a series of sequential ignitions of fuel particles. Smoldering fire spread is similar but is a more continuous process where conceptual volume elements ahead of the smoldering front are heated to ignition instead of particles. They are initially endothermic and finally become exothermic as the temperature of the volume element approaches the state of pyrolysis and becomes part of the combustion zone. The transition from an endothermic to exothermic process can be thought of as ignition. If the heat input is not sufficient to drive off the moisture and bring the dry bulk material (both organic and inorganic) up to ignition temperature, then the volume element will not ignite, i.e., it will not sustain smoldering combustion.

To provide reliable results the laboratory ignition test must

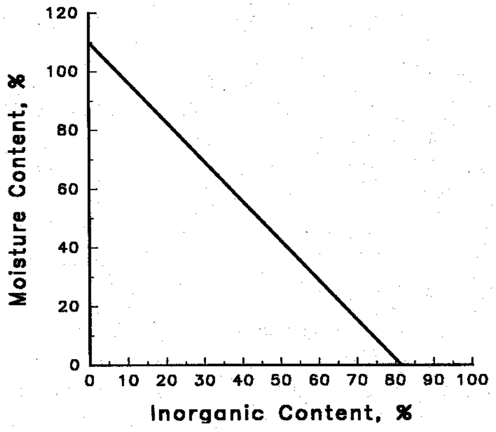
---

Received October 15, 1996. Accepted May 29, 1997.

W.R. Frandsen Intermountain Fire Sciences Laboratory, Intermountain Research Station, P.O. Box 8089, Missoula, MT 59807, U.S.A.

Present address: 2509 Valley View Drive, Missoula, MT 59803, U.S.A. e-mail: wfranzen@aal.com

Fig. 1. Ignition limit from Frandsen (1987). The line is the ignition limit for a mixture of peat moss, moisture, and inorganic mineral soil at an organic bulk density of 110 kg· m^{-3}. Successful ignitions are accomplished only by moisture and inorganic contents that lie within the triangle bounded by the axes and the ignition limit.



simulate the conditions of the lateral spreading fire. The method of ignition must produce sufficient heat flux for a limited time to bring one side of the sample to ignition and provide a lateral smoldering front. Once a front is established, sustained ignition results if a combustion zone can be established in the sample that can produce sufficient heat to continue smoldering spread in the sample. The term sustained is associated with the sample's ability to repeatedly ignite the unburned fuel ahead of the moving combustion zone.

Previous work of Frandsen (1987) and Hartford (1989) is limited to one fuel type, commercial peat moss. This study carries those investigations to a broader geographical range and includes a modification to the method of ignition and the method of analysis tailored to field samples. Ignition was attempted over a range of moisture contents covering the ignition limit for each sample group.

Methods

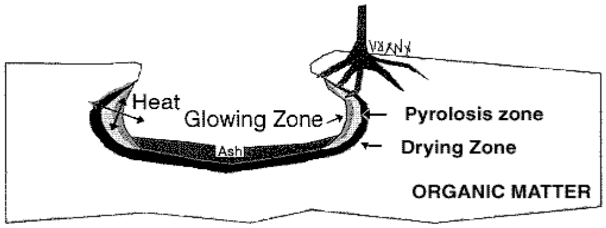
Sample collection

Samples were collected from 17 locations covering Alaska, Montana, Minnesota, and Michigan in the northern United States and North Carolina, Georgia, and Florida in the southeastern United States. The Alaska study area was located 10 miles (16 km) east of Tok Junction near the Tetlin National Wildlife Refuge (TNWR) that had similar vegetation. Sample locations in the northern part of the United States were Seney National Wildlife Refuge (SNWR) in the upper peninsula of Michigan, Agassiz National Wildlife Refuge (ANWR) in northwestern Minnesota, Glacier National Park (GNP) in northwestern Montana, and Seeley Lake in western Montana. Sample locations in the southeastern portion of the United States were St. Marks National Wildlife Refuge (SMNWR) in Florida, Okefenokee National Wildlife Refuge (ONWR) on the Georgia-Florida border, Alligator River National Wildlife Refuge (ARNWR) and Pocosin Lakes National Wildlife Refuge (PNWR) of North Carolina, and a pine flatwoods forest in North Carolina. Detailed locations and descriptions are given in Table 1.

Sample extraction technique

Ignition probability cannot be obtained from a single sample. In general from 25 to 30 cubical samples (10 x 10 x 5 cm) were tested to ensure that the transition region from "burn" to "no burn" was covered while traversing a moisture content range. Field samples have the natural variability of inorganic content and organic bulk density (Table 2). Consequently, for the ignition probability to have some specificity, sampling should be confined to a small area that appears homogeneous.

Fig. 2. Smoldering ground fire spreading in a downward and lateral direction (Hungerford et al. 1995).



Although this general concept was followed, no specific technique was developed until after samples were collected in Alaska. The technique was to grid a small area (40 x 100 cm) and cut adjacent samples from the grid (Fig. 3). Sample volume size ensured a maximum of 40 samples and certainly 30. Enough samples are needed to locate the transition region from successful to unsuccessful ignitions and sufficient remaining samples to cluster in that region. Grid samples were obtained at both surface and subsurface levels.

Pocosin, swamp forest, and flatwoods samples had no structure and could not be removed as cubical blocks as above. Instead, these organic soils were friable and removed as loose material. Average inorganic contents obtained from three random samples within each soil type were 2.5, 50.6, and 80.2%. Sample variation was minimal (Table 2).

Sample preparation and evaluation

Pocosin samples could not be re-moisturized after normal room drying. Therefore, samples were prepared by freeze-drying. They could then be re-moisturized for the ignition test (Hungerford et al. 1995). Samples were smaller in size (4 cm in diameter and 2 cm wide) than the cubical samples. Sample volume expansion was noted when adding water and was accounted for in the organic bulk density.

Individual swamp forest and flatwoods samples were constructed to standard volume size in the ignition box (see Ignition test below). Organic bulk densities similar to densities in their natural state were achieved through selection of sample mass. Constructed organic bulk densities were 200 kg· m^{-3} for swamp forest and 120 kg· m^{-3} for flatwoods.

The volume of cubical samples was evaluated just prior to ignition by measuring the samples' dimensions. Two measurements from each dimension were obtained, and the volume variability was calculated by examining all combinations of those dimensions. Coefficients of variation for individual, volumes range from 1 to 10%.

Inorganic contents of cubical samples were obtained from sub samples of each sample tested. After assessing the moisture content, the remaining sub sample was ashed and evaluated. The range of inorganic contents and organic bulk densities (Table 2) was fixed by the location from which the samples were obtained (Table 1).

Sample moisture content was varied in the laboratory. To identify the region of moisture contents associated with the ignition limit, a hunt was conducted that homed in on the region as more information was gathered from the ignition tests. Important data for the probability distribution are contained in the transition region from burn to no burn. Tests were clustered in that region. Initially, moisture contents were prepared over a broad range and subsequent moisture contents were projected on a dynamic basis as indicated above. Sub samples taken from individual samples were oven-dried to obtain the initial moisture content. The final sample was weighed and sealed in

Table 1. Sample collection locations and descriptions.

Sample identification (latitude, longitude)	Site	Sample area description
Sphagnum, feather, reindeer/feather (63°18′, 142°40′)	TNWR	Open black spruce (*Picea mariana* (Mill.) BSP) forest (Viereck et al. 1992), sphagnum moss, feather moss, feather moss with a covering of reindeer lichen
Sedge meadow (63°18′, 142°40′)	TNWR	Subarctic lowland sedge–bog meadow (Viereck et al. 1992)
White spruce duff (63°18′, 142°40′)	TNWR	Beneath the crown of a white spruce (*Picea glauca* (Moench) Voss) tree near open black spruce forest but at a slightly higher elevation
Peat (48°16′30″, 96°02′30″)	ANWR	Collection between an upper dense zone of fine fibrous roots and a lower zone of coarse aspen roots, near aspen stand, surface grass and forbs, land undisturbed
Peat muck (48°16′30″, 96°02′30″)	ANWR	Fine graminoid roots at sampling depth, surface grass and forbs, land previously farmed
Sedge meadow (Seney) (46°10′45″, 86°02′30″)	SNWR	Seasonly flooded, coarse roots above and organic soil muck below sampling depth, soil muck still fibrous and darker in color, total peat depth from 70 to 130 cm
Pine duff (Seney) (46°10′45″, 86°02′30″)	SNWR	Collection from humus and fermentation organic soil horizons, overstory was red pine (*Pinus resinosa* Ait.) with surface layer dominated with pine litter and small patches of feather moss
Spruce/pine duff (49°43′, 114°10′)	GNP	Collection from humus and fermentation organic soil horizons, overstory was ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), western larch (*Larix occidentalis* Nutt.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and Engelmann spruce (*Picea engelmannii* Parry), understory was thimbleberry (*Rubus parviflorus* Nutt.), snowberry (*Symphoricarpos albus* (L.) Blake), and the perennial grass species timothy (*Phleum pratense* L.), fescue (*Festuca* spp.), and brome (*Bromus* spp.)
Grass/sedge marsh (47°12′4″, 113°32′25″)	Seeley Lake, Mont.	Seasonally flooded, surface covering was bluejoint (*Calamagrostis canadensis* (Michx.) Beauv.), bulrush (*Scirpus* spp.), and *Carex*
Southern pine duff (30°07′, 84°05′)	SMNWR	Collection from humus and fermentation organic soil horizons, seasonally flooded, poorly drained, overstory was slash pine (*Pinus elliottii* Engelm.) with midstory of scattered cabbage palm (*Sabal palmetto* (Walt.) Lodd. ex J.A. & J.H. Schultes), understory contained medium to heavy palmetto (*Serenoa repens* (Bartr.) Small)/gallberry (*Ilex glabra* (L.) Gray), area characterized as low flatlands, 2% or less slope
Hardwood swamp (30°43′, 82°08′)	ONWR	Collection from humus and fermentation organic soil horizons, overstory was scattered mature loblolly pine (*Pinus taeda* L.) and slash pine, midstory was numerous red maple (*Acer rubrum* L.), black gum (*Nyssa sylvatica* var. *biflora* Marsh.), and loblolly bay (*Gordonia lasianthus* (L.) Ellis), no understory grew in the middle of the depression where samples collected, scattered hurrah-bush (*Lyonia lucida* (Lam.) K. Koch) and gallberry with scattered palmetto were on the edge of the sample plot, duff/litter layer was 2.5–15.0 cm of organic material over a coarse, sandy soil
Pocosin (34°50′30″, 75°43′30″)	ARNWR	Elevated swamp (not alluvial) (Shafale and Weakley 1990), overstory vegetation varies from widely scattered, stunted pond pine (*Pinus serotina* Michx.) with red bay (*Persea palustris* (Raf.) Sarg.), loblolly bay, and white bay (*Magnolia virginiana* L.), understory was typically dominated by evergreen and deciduous sclerophyllous shrubs, highly decomposed unstructured organic muck
Swamp forest (35°37′30″, 76°33′00″)	PNWR	Nonriverine swamp forest (Shafale and Weakley 1990), overstory was closed canopy of loblolly pine, red maple, black gum, and pond cypress (*Taxodium ascendens* Brongn.), understory was open with some invading hardwoods, unstructured organic soil
Flatwoods (35°51′30″, 76°39′30″)	Plymouth, N.C.	Mesic pine flatwoods forest (Shafale and Weakley 1990), overstory was closed canopy dominated by loblolly pine, red maple, tulip tree (*Liriodendron tulipifera* L.), and black gum, understory was sparse with some white bay, red bay, and green brier (*Smilax laurifolia* L.), unstructured organic soil

---

Note: TNWR, Tetlin National Wildlife Refuge; ANWR, Agassiz National Wildlife Refuge; SNWF, Seney National Wildlife Refuge; GNP, Glacier National Park; SMNATR, St. Marks National Wildlife Refuge; ONWR, Okefenokee National Wildlife Refuge; ARNWR, Alligator River National Wildlife Refuge; PNWR, Pocosin Lakes National Wildlife Refuge.

Table 2. Sampling groups described in terms of their average inorganic content, average organic bulk density, and the coefficient of variation (CV), along with the sampling depth for each group.

Sample identification	Average inorganic content, %	CV, %	Average organic bulk density, kg·m^{-3}	CV, %	Depth, c
Sphagnum (upper)	12.40	20	21.8	24	0–5
Sphagnum (lower)	56.70	22	119.0	16	10–25
Feather	18.10	30	42.7	23	0–25
Reindeer/feather	26.10	30	56.3	33	0–5
Sedge meadow (upper)	23.30	23	69.4	28	5–15
Sedge meadow (lower)	44.90	21	91.5	22	15–25
White spruce duff	35.90	31	122.0	20	0–5
Peat	9.40	7.1	222.0	6.8	17–25
Peat muck	34.90	15	203.0	13	12–20
Sedge meadow (Seney)	35.40	7.6	183.0	13	17–25
Pine duff (Seney)	36.50	16	190.0	19	0–5
Spruce/pine duff	30.70	43	116.0	27	0–5
Grass/sedge marsh	35.20	12	120.0	12	0–5
Southern pine duff	68.00	29	112.0	39	0–5
Hardwood swamp	18.20	88	138.0	28	0–5
Pocosin	2.50	5.2	210.0	2.5	10–30
Swamp forest	50.60	0.7	200.0	—	0–15
Flatwoods	80.20	0.02	120.0	—	0–15

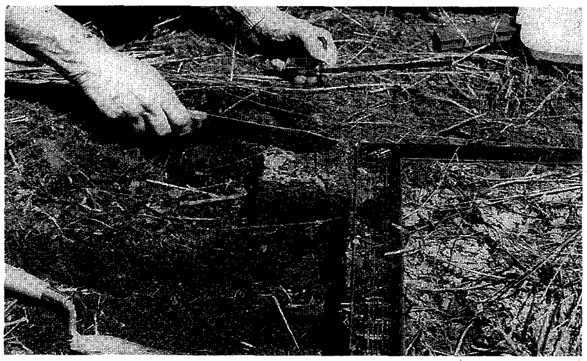


Fig. 3. Field sampling grid. Adjacent samples are cut from a 40 X 100 cm grid to a 5 cm depth. About 30 samples are taken.

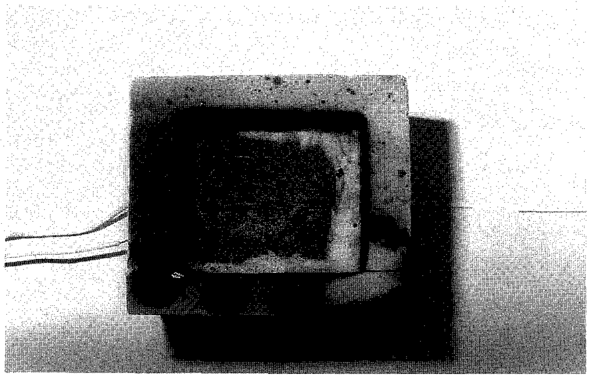


Fig. 4. Ignition box. Samples are held within an insulated box with inside dimensions of 10 x10 cm. Ignition takes place on the left side in dry peat moss with an electrically heated coil. The smoldering combustion front then passes to the right into the sample. Ignition is successful if the sample is consumed.

a plastic bag. Targeted moisture contents were achieved by adding moisture to the sample or drying the sample by opening the bag to the air. The amount of water to be added or removed was calculated from the initial sample weight and moisture content and the targeted moisture content. After adding or removing water the sealed sample was placed in a warming oven at 50°C for at least 3 days. Warming the sealed sample aided in reaching moisture equilibrium. Following the warming oven the sample remained at room temperature (20°C) for 1 to several days until it was tested for ignition. Final moisture contents were calculated from the initial weight and moisture content and the final sample weight change, since the change is due only to a gain or loss of water.

Sample source variability was expressed through the coefficient of variation (CV) as a percentage (Table 2). The CV for inorganic content of friable samples ranged from 0.02 to 5.2%. Values of CV were obtained from three random samples from each soil type: pocosin, swamp forest, and flatwoods. Pocosin had a very low CV, 2.5%, for organic bulk density. The other two soil types had no CV because the sample volume was fixed. CV values for cubical samples ranged from 7 to 88% for the inorganic content, with most lying within the range 20-30%. CV values for the organic bulk density ranged from 7 to 39%.

Ignition test

An ignition box was constructed to accommodate the moisture-treated cubical samples collected in the field. Inside dimensions were 10 x 10 x 5 cm. In contrast with surface ignition (Frandsen 1987), samples were ignited on the 5 x 10 cm side to simulate lateral smoldering spread. The top opening was 10 x 10 cm with more than sufficient room to accommodate the 5 cm depth of the sample (Fig. 4). A

Table 3. Parameters of the probability equation listed for each sample group.

Sample identification	*B*0	*B*1	*B*2	B3
Sphagnum (upper)	–8.8306	–0.0608	0.8095	0.2735
Sphagnum (lower)	327.3347	–3.7655	–8.7849	2.6684
Feather	9.0970	–0.1040	0.1165	–0.0646
Reindeer/feather	8.0359	–0.0393	–0.0591	–0.0340
Sedge meadow (upper)	39.8477	–0.1800	–0.3727	–0.1874
Sedge meadow (lower)	29.0818	–0.2059	–0.2319	–0.0420
White spruce duff	332.5604	–1.2220	–2.1024	–1.2619
Peat	–19.8198	–0.1169	1.0414	0.0782
Peat muck	37.2276	–0.1876	–0.2833	–0.0951
Sedge meadow (Seney)	7.1813	–0.1413	–0.1253	0.0390
Pine duff (Seney)	45.1778	–0.3227	–0.3644	–0.0362
Spruce/pine duff	58.6921	–0.2737	–0.5413	–0.1246
Grass/sedge marsh	236.2934	–0.8423	–2.5097	–0.4902
Southern pine duff	32.8921	–0.1676	–0.3211	–0.0409
Hardwood swamp	33.6907	–0.2946	–0.3002	–0.0404
Pocosin	–18.4047	–0.0044	—	0.0908
Swamp forest	13.4691	–0.2273	—	—
Flatwoods	—	—	—	—

1 cm slice from the sample's side was replaced with dry peat moss. A separating sleeve was inserted into the box when constructing the sample from friable swamp forest and flatwoods organic soil. The separator was removed after filling the 1 cm void with dry peat moss. The source of ignition was an electrically powered ignition coil located inside the box, midway between the top and bottom of the sample. The coil was surrounded on one side by dry peat moss that replaced the 1 cm slice. The dry peat moss readily ignited within the specified 3 min of exposure to the red-hot coil. The moss in turn acted as a robust ignition source for the sample as recommended in the Introduction. Finally, if ignition occurs, it will spread laterally, simulating lateral spread in the field.

A successful ignition is followed by sustained smoldering combustion that consumes the sample. Sustained smoldering suggests that there is sufficient heat to satisfy the heat requirement lost to moisture and inorganic material along with enough residual heat to continue the smoldering process, i.e., the ongoing repetition of ignition of unburned fuel.

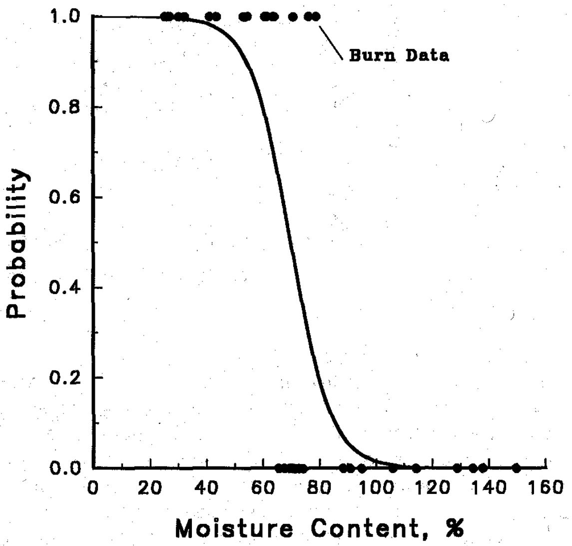
Although not enclosed in an insulating box, the freeze-dried 4 x 2 cm pocosin samples were surrounded by insulating ash when ignited. Ignition was attempted by holding a propane torch to a flammable patch of ground carbon briquette material placed on top of the sample. After ignition of the carbon briquette material, an insulating layer of ash was sprinkled over the top of the sample. Pocosin samples did not lend themselves to lateral spread. Insulating with the layer of ash was an attempt to accommodate to the insulating effect of lateral smoldering below the organic surface.

Analysis

Hartford (1989) modified the analysis method of Frandsen (1987) by applying probability analysis. Logistic regression was used to analyze the results of ignition success or failure for a given fuel condition in response to changing moisture content.

Each set of raw data was analyzed by logistic regression. Burn response (1 = burn, 0 = no burn) was the dependent variable and moisture content, inorganic content, and organic bulk density were the independent variables, except for friable samples from organic soil types (pocosin, swamp forest, flatwoods) where inorganic content was evaluated from the bulk sample container and not from each individual sample. Organic bulk density and moisture content were recorded as independent variables for each pocosin sample. However, organic bulk density was constructed in the ignition box to a fixed value for swamp forest and flatwoods samples, leaving only moisture content as the independent variable for these two sample types.

Fig. 5. Example probability distribution of ignition versus moisture content (sedge meadow (upper)) from logistic regression analysis of burn/no burn data. Individual burn success data are plotted for comparison. Successes are plotted at a probability of 1 against the moisture content of the sample point, and failures are plotted at a probability of 0. Circles identify both successes and failures. Data are from the sedge meadow (Seney) sample group.



Logistic regression allows the experimenter to use the variables at hand. Only the moisture content is modified to examine the transition through the ignition limit. The inorganic content and the organic bulk density are in situ properties of the sample. Their effect on the ignition potential is handled through the logistic regression model. Here, the experimenter can express the transition from ignition success to ignition failure as a probability. This becomes especially useful when the moisture content of successful ignitions overlaps that of failures. As the range of overlap increases, the moisture content covering the transition broadens, as expressed by the probability curve, i.e., there is more uncertainty in the potential for ignition. Uncertainty is likely to be the result of sample variations in the inorganic content and the organic bulk density. The probability of ignition is expressed in terms of the independent variables:

[1] $$P = 1/\{1 + \exp[-(B0 + B1 \cdot \mathrm{MC} + B2 \cdot \mathrm{ash} + B3 \cdot \mathrm{rho})]\}$$

where P is probability, MC is percent moisture content, ash is percent inorganic content, rho is organic bulk density (kilograms per cubic metre), and B's are constants of the probability expression. The B values are determined through logistic regression analysis.

Results

Results are expressed in tabular form as B coefficients for the probability equation for each sample group (Table 3). There is no simple way to express ignition probability in terms of the testing variable, moisture content. However, ignition probability can be expressed against moisture content (Fig. 5) for each sample group through its set of B coefficients (Table 3)

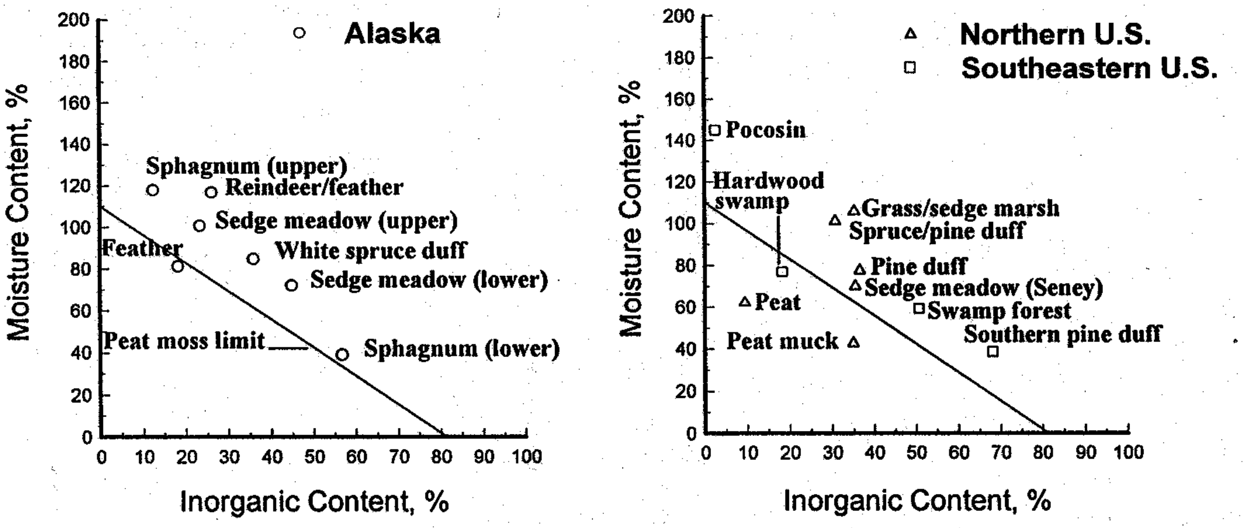


Fig. 6. Moisture content at 50% probability of ignition plotted against the average inorganic content of the sample group. Data illustrated represent samples obtained from Alaska (circles), the southeastern United States (squares), and the northern United States (triangles). The line representing the combustion limit for peat moss (Frandsen 1987) is shown for comparison.

by fixing the inorganic content and organic bulk density at their average values for that sample group (Table 2). There are 17 probability distributions, one for each sample group, except for flatwoods because this sample group did not burn even at oven-dry moisture content. All distributions were dependent on moisture and inorganic content and organic bulk density, except for pocosin and swamp forest sample groups.

All sample groups exhibited a reverse sigmoid curve moving from high probability at low moisture contents to low probability at high moisture contents, except for pocosin. The rest were initially at 100% probability at zero moisture content (66% for pocosin), Pocosin ignition data exhibited reasonable behavior from 104 to 219% moisture content, having sustained burning from 104 to 129%. An overlapping range of uncertainty extended from 130 to 154% followed by unsustained burning from 160 to 219%. However, this order was confounded with another overlapping range of uncertainty from 224 to 300% beyond the range of unsustained burning already mentioned. Ignoring data above the 219% moisture content level, the sample group's logistic regression analysis resulted in 100% ignition probability at zero moisture followed by the commonly observed reverse sigmoid curve observed for all other sample groups.

Discussion

The high inorganic content of the flatwoods sample group, 80.2%, may be the contributing factor for its lack of ignition. An inorganic content of 81.5% is the limit found by Frandsen (1987) for peat moss ignition at oven-dry conditions (Fig. 1). An interesting coincidence is that this value is near the inorganic content that marks the transition from organic soil to mineral soil agreed upon by soil scientists.

Taking the 50% probability level as a common measure of each sample group's ignitability, these data can be brought together into one graphical expression and compared with the peat moss ignition limit of Frandsen (1987). The moisture content at 50% probability is a measure of the moisture ignition limit. The average inorganic content of the sample group is a measure of the corresponding inorganic ignition limit. Each sample group is plotted according to its average inorganic content (abscissa) and moisture content at 50% probability (ordinate) (Fig. 6). All but four sample groups lie above the peat moss limit, suggesting that these field samples will burn at higher moisture and inorganic contents than peat moss. An argument can be made that the difference lies in the method of ignition. Side ignition primarily below the surface has less heat loss than surface ignition (Frandsen 1987), which is exposed to surface cooling. As a result, more heat is available in side ignition for driving off additional moisture and heating inorganic material, thus causing the ignition limit to occur at a higher moisture content.

Sedge meadow and sphagnum have a very interesting relationship to the slope of the peat moss limit. Both increase in inorganic content with depth (Table 2) and as a result display a moisture content ignition limit that decreases with increasing inorganic content similar to peat moss. However, feather moss taken from depths of 0-5 and 10-25 cm was similar in both inorganic content and density and was combined into one larger sample group, feather. Note that sedge meadow (upper) and sedge meadow (lower) lie about the same distance from the peat moss limit. However, sphagnum (lower) is closer to the peat moss limit than sphagnum (upper). The average organic bulk density for sedge meadow (upper) and sedge meadow (lower) is very similar. However, the organic bulk density for sphagnum (lower) is six times the density for sphagnum, (upper). This may account for its closer position to the peat moss limit, suggesting that it does not burn at a higher moisture limit as do the rest of the sample groups above the peat moss limit. Hartford (1989) found that increasing organic bulk density decreased the probability of ignition. Although this argument might seem convincing for sphagnum, it does not explain why feather is located below the peat moss limit, since it has an organic bulk density less than half that of peat moss.

Pocosin appears to lie very high above the peat moss limit. However, it is not unusual in a relative sense if the trend of the 50% ignition limit of the other field data is extrapolated to low inorganic content. It is unusual that although it shows a reasonable trend towards unsustained burning as the moisture content is increased, it again has occurrences of sustained burning as the moisture content is further increased. This anomalous property does not appear to be the result of sample preparation. Sample ignition, although consistent, may hold some explanation for this anomalous behavior. Ignition was at the top of the sample; however, ash was sprinkled on the ignited sample to insulate it during smoldering to reduce heat loss similar to side ignition.

Conclusions

Studies of the smoldering ignition limit with modified peat moss as a simulated fuel (Frandsen 1987; Hartford 1989) have been extended to ignition tests on organic soil samples brought from the field. Results are now in the form of ignition probabilities covering organic soils from Alaska and the northern and southeastern United States. Knowledge of the inorganic and moisture content of organic soils allows the land manager to determine the probability of smoldering ignition. Knowing the probability of ignition, the manager can then determine when prescribed fires are within prescription and where suppression should be applied under wildfire conditions when ground fire does not meet management goals.

Systems analysts who deal with probabilities of the occurrence of lightning and person-caused fires will find these probability expressions useful for arriving at overall predictions of the probability of ground fire.

Acknowledgments

This research is supported, in part, by the U.S. Department of the Interior, Interior Fire Coordinating Committee, and is administered by the U.S. Fish and Wildlife Service. I would like to thank Mr. Bill Leenhouts for his support and interest in wetland fires. I would also like to thank many Fish and Wildlife Service employees, particularly Larry Vanderlinden and Steve Fowler, for showing interest and for providing information, resources, and field sites. Thanks are also extended to Ronald Phemetton, Howard McCullough, and John Fort for collecting field samples. Thanks also to Jim Reardon, Dr. Kevin Ryan, and Roger Hungerford for sample collection, site selection, and site identification. Finally, special appreciation to Michael Schneller for sample preparation and testing.

References

Artsybashev, E.S. 1974. Forest fires and their control. [Russian translation (1983) for the U.S. Department of Agriculture and the National Science Foundation, Washington D.C., by Amerind Publishing Co. Pvt. Ltd., New Delhi]. Lesnye Pozhary i Bor'ba s Nimi. Lesnaya Promyshlermost' Publishers, Moscow, Russia.

Flinn, M.A., and Wein, R.W. 1977. Depth of underground plant organs and theoretical survival during fire. Can. J. Bot. 55: 2550-2554.

Flinn, M.A., and Wein, R.W. 1988. Regrowth of forest understory following seasonal burning. Can. J. Bot. 66: 150-155.

Fons, W.L. 1946. Analysis of fire spread in light forest fuels. J. Agric. Res. 72: 93-121.

Frandsen, W.H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. Can. J. For. Res. 17:1540-1544.

Hartford, R.A. 1989. Smoldering combustion limits in peat as influenced by moisture, mineral content, and organic bulk density. In Proceedings of the 10th Conference on Fire and Forest Meteorology, April 1989, Ottawa, Ont. *Edited by* D.C. MacIver, H. Auld, and R. Whitewood. Forestry Canada, Petawawa National Forestry Institute, Chalk River, Ont. pp. 282-286.

Hungerford, R.D., Frandsen, W.H., and Ryan, K.C. 1995. Ignition and burning characteristics of organic soils. In Proceedings of the Tall Timbers Fire Ecology Conference: Fire in Wetlands, a Management Perspective, Tallahassee, Fla. *Edited by S.I.* Cerulean and R.T. Engstrom. No. 19, Tall Timbers Research Station, Tallahassee, Fla. pp. 78-91.

Shafale, M.P., and Weakley, A.S. 1990. Classification of the natural communities of North Carolina. North Carolina Natural Heritage Program, Division of Parks and Recreation, Department of Environment, Health, and Natural Resources, P.O. Box 27687, Raleigh, NC 27611.

Viereck, L.A., Dymess, C.T., Batten, A.R., and Wenzlick, K.J. 1992. The Alaska vegetation classification. USDA For. Serv. Gen. Tech Rep. PNW-GTR-286.