Development of a National Fuel-type Map for Canada Using Fuzzy Logic

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ABSTRACT

The Canadian Forest Fire Danger Rating System (CFFDRS) is used by fire management agencies across Canada in evaluating daily forest fire danger. Fuel-type information is essential for the prediction of fire behavior with CFFDRS. To provide this information, a fuel-type map (FTM) for Canada with 1-km resolution was produced with inputs derived from remote sensing and forest inventory data. The relationships (rules) between inputs and fuel types were established by expert opinion and incorporated into a computer program through fuzzy set methodology. The new national FTM was compared with provincial and territorial FTMs produced and used by fire management agencies in the Yukon, Alberta, Saskatchewan, Ontario, and Quebec. A challenging aspect of comparing fuel types between the provincial and territorial FTMs and the national FTM was the interpretation of fuel-type categories not included in the CFFDRS that appeared in the provincial and territorial maps. Overall data point agreement between the provincial and territorial and the national FTMs was 60%. A map of possibility values was also produced. The low overall possibility value reflects the confidence of the fire scientists who produced the rules and the low number of inputs used to produce the national FTM. Given the heterogeneous nature of fuels across Canada, it is noteworthy that a small number of inputs produced a national FTM that had reasonable agreement with the provincial and territorial FTMs. The national FTM will be useful in fire behavior prediction in a national fire management information system.

RÉSUMÉ

Partout au Canada, des organismes de lutte contre les incendies de forêt se servent de la méthode canadienne d'évaluation des dangers d'incendie de forêt (MCEDIF) pour évaluer quotidiennement les risques de feu de forêt. Des données sur les types de combustibles sont essentielles à la prévision du comportement des feux au moyen de la MCEDIF. Pour fournir ces données, une carte des types de combustibles (CTC) au Canada à résolution de un kilomètre a été produite à partir de données de télédétection et d'inventaires forestiers. Les relations (règles) entre ces données et les types de combustibles ont été établies selon des opinions d'experts et intégrées dans un programme informatique par une méthode de logique floue. La nouvelle CTC nationale a été comparée aux CTC provinciales ou territoriales produites des organismes de lutte contre les incendies de forêt du Yukon, de l'Alberta, de la Saskatchewan, de l'Ontario et du Québec. L'interprétation des catégories de combustibles qui figurent sur les cartes provinciales et territoriales mais pas dans la MCEDIF a constitué un aspect difficile de ces comparaisons. Globalement, la concordance des points de données entre les CTC provinciales ou territoriales et la carte nationale s'est chiffrée à 60 %. Une carte des valeurs de possibilité a également été produite. La faible valeur de possibilité globale traduit la confiance des spécialistes des incendies qui ont produit les règles, ainsi que le petit nombre de données utilisés pour produire la CTC nationale. Étant donné

l'hétérogénéité des combustibles au Canada, il est remarquable qu'un petit nombre de données a permis de produire une CTC nationale qui concorde raisonnablement bien avec les CTC provinciales et territoriales. La CTC nationale sera utile pour prévoir le comportement des incendies dans le cadre d'un système national d'information pour la lutte contre les incendies.

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INTRODUCTION

The protection of natural resources and property from wildfires requires sound forest fire management practices. During decision making, fire managers need a system to reliably evaluate and integrate the multiple factors that influence fire danger. The Canadian Forest Service (CFS) has been developing models for fire-danger rating and forest fire management since the 1920s (Stocks et al. 1989; Lee et al. 2002). Development of the current Canadian Forest Fire Danger Rating System (CFFDRS) began in the mid-1960s (Stocks et al. 1989). Starting in 1992, CFS and Canadian fire management agencies began to use geographic information systems (GIS) to assist in constructing of spatial fire management information systems. The Canadian Wildland Fire Information System calculates and displays national fire danger maps on a daily basis, implementing both subsystems of the CFFDRS, the Canadian Forest Fire Weather Index System and the Canadian Forest Fire Behavior Prediction (FBP) System. To accurately map fire behavior potential, as calculated by the FBP system, these systems require a national fuel-type map (FTM). The objective of this project was to produce such a national FTM.

The Canadian Interagency Forest Fire Centre (2003) defines the term "fuel type" as "an identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behavior under defined burning conditions." Fuel type is interpreted qualitatively in terms of stand structure and composition, presence of surface and ladder fuels, and type of forest floor cover. Sixteen fuel-type classes were developed for the CFFDRS to predict fire behavior characteristics such as fuel consumption, rate of spread, and frontal fire intensity (Forestry Canada Fire Danger Group 1992) (Table 1).

The existing Canadian FTM (http://cwfis.cfs.nrcan.gc.ca/en/background/bi_Static_Maps_e.php?static_map=fbpft) was developed by CFS in 1993 from satellite imagery acquired by the Advanced Very High Resolution Radiometer (AVHRR) sensor on the National Oceanic and Atmospheric Administration (NOAA) satellite series. A drawback of this FTM is that only five FBP fuel types are represented.

One condition for producing a new national FTM was the availability of new and relevant spatial data (inputs) from across Canada. Few consistent, up-to-date national spatial inputs are available because of the difficulty of mapping such a vast area on a regular basis. As a result, the new national FTM described here was produced with a computer program that used a rule-based approach to accommodate situations where information was incomplete (Morgan et al. 2001). One rule-based approach, the fuzzy logic approach (Nadeau et al. 2002; Nadeau and Englefield n.d.), seemed appropriate. Fuzzy logic was first applied to forestland management by Bare and Mendoza (1988) and to forest ecology by Roberts (1989, 1996a, 1996b). More recently, Sitelogix, a program that includes aspects of fuzzy logic and statistics, has been used for ecosite identification (Beckingham et al. 1999; Geographic Dynamics Corp. 1999. Ecological classification of the Drayton Valley Forest Management Agreement Area using Sitelogix. Prepared for Weyerhaeuser Canada Ltd., Edmonton, AB. 46 pp.). Other programs based on fuzzy logic for community classification have been published and described extensively (Nadeau et al. 2002, 2004; Nadeau and Englefield n.d.). Fuzzy logic has also been applied for assessment of land values or land suitability for scientific research reserves (e.g., Stoms et al. 2002; Tran et al. 2002), and for interpretation of imagery (Woodcock and Gopal 2000).

With the fuzzy logic approach, expert knowledge need not be well defined but can be "fuzzy"; thus, a degree of uncertainty is acceptable, on the understanding that uncertain data are better than no data at all. Other advantages of fuzzy logic include the ability to incorporate the knowledge of more than one expert in a computer program and automation of a large number of decisions. The results can then be easily compiled with GIS technology to produce a national FTM along with a possibility map.

Table 1. Fuel-type descriptions used by the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992)

FBP fuel type	Stand structure and composition
C-1 (Spruce–lichen woodland)	Open black spruce (*Picea mariana*) with dense clumps; associated species: jack pine (*Pinus banksiana*), white birch (*Betula papyrifera*); well-drained upland sites
C-2 (Boreal spruce)	Moderately well-stocked black spruce stands on both upland and lowland sites; *Sphagnum* spp. bogs excluded
C-3 (Mature jack or lodgepole pine)	Fully stocked jack pine or lodgepole pine (*Pinus contorta*) stands; mature
C-4 (Immature jack or lodgepole pine)	Dense jack or lodgepole pine stands; immature
C-5 (Red and white pine)	Moderately well-stocked red pine (*Pinus resinosa*) and white pine (*Pinus strobus*) stands; mature; associated species: white spruce (*Picea glauca*), white birch, and aspen (*Populus tremuloides*)
C-6 (Conifer plantation)	Fully stocked conifer plantations; complete crown closure regardless of mean stand height; mean stand crown base height controls rate of spread and crowning
C-7 (Ponderosa pine/Douglas-fir)	Open ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) stands; mature, uneven aged; associated species: tamarack (*Larix laricina*), lodgepole pine; understory conifer thickets
D-1 (Leafless aspen)	Moderately well-stocked trembling aspen stands; semimature; leafless (i.e., in spring or fall or diseased)
M-1, M-2 (Boreal mixedwood)[a]	Moderately well-stocked mixed stands of boreal conifers (e.g., black and white spruce, balsam fir [*Abies balsamea*] and subalpine fir [*Abies lasiocarpa*]) and deciduous species (e.g., trembling aspen, white birch); fuel types differentiated by season and percent conifer and deciduous species composition
M-3, M-4 (Dead balsam fir/ mixedwood)[a]	Moderately well-stocked mixed stands of spruce, pine, and birch with dead balsam fir, often as understory; fuel types differentiated by season and age since balsam fir death
S-1 (Jack or lodgepole pine slash)	Slash from clear-cut logging of mature jack or lodgepole pine stands
S-2 (Spruce/balsam slash)	Slash from clear-cut logging of mature or overmature white spruce, subalpine fir, or balsam fir stands
S-3 (Coastal cedar/hemlock/Douglas-fir slash)	Slash from clear-cut logging of mature to overmature cedar (*Thuja* spp.), hemlock (*Tsuga* spp.), or Douglas-fir stands
O-1 (Grassland)	Grassland; scattered trees, if present, do not appreciably affect fire behavior

[a]M-1 and M-3 occur in spring, before emergence of vegetation (leafless stage). M-2 and M-4 occur after vegetation has emerged (i.e., when deciduous trees have leafed out).

METHODS

Data Sources

Three data sources were used in the development of the national FTM:

1. a land-cover map, Land Cover 2000 (Natural Resources Canada 2004b), produced by the Canada Centre for Remote Sensing on the basis of Système pour l'Observation de la Terre (SPOT) — VEGETATION imagery (SPOT Image 2004);
2. ecozones and ecoregions, obtained in digitized map form from Environment Canada (2003); and
3. the 2001 Canadian Forest Inventory (CanFI) database (Natural Resources Canada 2004a), which was specifically used to identify the dominant forest species and its age, as well as the percent area covered by the dominant species in a pixel.

Rule Definition

Rules are made out of inputs, variables, and outputs. The basic fuzzy logic rules incorporated into the program related land-cover classes (Natural Resources 2004b) to fuel types. These rules were derived from the opinions of CFS fire behavior experts. Land-cover data, relevant variables for these data, and the resulting most probable outputs of the fuzzy logic program are shown in Table 2. This table represents less than 10% of all the rule component combinations used in the program and does not indicate the certainty attached to each rule component combination by the fire experts.

Ecozones and ecoregions were used for the geographic classification of fuel types. Pertinent rules were taken mainly from a previous publication (Rowe 1972), which helped in defining where different fuel types might exist. Rules pertaining to CanFI data (i.e., dominant tree species, area covered by the dominant tree species, and age) were established by CFS fire behavior experts. The scale for the CanFI data was coarser (10-km pixel) than that for the land-cover data (approximately 1-km pixel), and the following rules were developed to compensate for this difference: if a species covered more than 50% of the total area of a 10-km pixel, then the species was considered dominant in that pixel; if less than 50% of the area was covered by a single species, then rules pertaining to land cover, ecozones, and ecoregions determined the fuel type.

Table 2. Land Cover 2000 (Natural Resources Canada 2004b) inputs and relevant variables used in rules of the fuzzy logic program and the resulting most probable outputs identified from expert opinion surveys

Land Cover 2000 input	Forest canopy	Possible FBP fuel-type outputs[a]
Broad-leaved deciduous forest	Closed	D-1
Needle-leaved evergreen forest	Closed	C-2, C-3, C-4, C-5
Needle-leaved evergreen forest	Open	C-1, C-7
Mixed forest	Closed or open	M-1, M-2
Deciduous shrubland	Closed	D-1, O-1
Evergreen shrubland	Closed	C-2, C-3, C-4, C-5
Evergreen shrubland	Open	C-1, C-7
Mixed dwarf shrubland	Open	O-1, nonfuel
Grassland	NA[b]	O-1
Polar grassland	NA	Tundra, alpine
Cropland	NA	Cropland
Evergreen forest, lichen understory	Open	C-1
Wetlands	NA	Nonfuel, O-1, C-1
Unconsolidated or consolidated material with sparse vegetation, urban, burnt, snow, or ice	NA	Nonfuel
Water	NA	Open water

[a]As used in the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992).
[b]NA = not applicable.

Program Structure

A fuzzy logic program was designed to classify fuel types for Canada; the program used the FuzzyTECH software package (version 5.52a, Professional Edition; Inform Software Corporation, Chicago, Illinois, 2001). Program inputs were organized as 10 land-cover inputs (from Land Cover 2000), 1 ecozone input, 5 ecoregion inputs based on specific ecoregions, and 3 CanFI 2001 inputs (Table 3). Outputs were fuel types, expressed as a specific FBP System fuel type (Table 1), a grouped FBP System fuel type incorporating immature and mature lodgepole pine (*Pinus contorta* Dougl. ex Loud.) or jack pine (*Pinus banksiana* Lamb.) (i.e., a combined C-3 and C-4 fuel type), or grouped FBP System fuel types incorporating seasonal changes (i.e., M-1 and M-2 or M-3 and M-4). Unclassified fuel categories that normally do not present a fire concern included open water, tundra–alpine, cropland, and nonfuel categories.

In a fuzzy logic program, input and output values are translated into words or linguistic variables, referred to here simply as variables (Table 3). Relationships between inputs and variables and between outputs and variables are established by creating functions, referred to as membership functions. The advantage of membership functions is that they are more flexible than an absolute value or a range of values that are given the same importance. For example, for the "percent area covered by dominant species" input in the program used here, three membership functions were created, one for each of the variables "low," "medium," and "high." A 50% area coverage by the dominant species resulted in a higher membership value from the "medium" membership function than an area with 75% coverage, whereas the opposite was true for the "high" membership function. The linguistic variables were based on rule complexity.

Linguistic rules are then used to join inputs to outputs. The following is an example of such a rule, which is composed of inputs, input variables, outputs, and output variables: if the land cover consists of a conifer forest (input) that is dense (variable of conifer forest input) and occurs in the Western Alberta Upland (ecoregion variable of the Boreal Plains input) of the Boreal Plains (ecozone variable of the ecozone input), and if the area (input) covered by the dominant species is high (input variable), and if the dominant species (input) is white spruce (*Picea glauca* (Moench) Voss) (input variable), then the site has a very high possibility (output variable) of representing the C-2 (Boreal Spruce) fuel type (output) of the FBP System. The resulting output is then translated into a numeric value, referred to as the possibility value (see Von Altrock [1997] for more details).

Map Production

Initially, the Land Cover 2000 and CanFI grids were converted to polygon maps. These polygon maps and the ecozones and ecoregions map were combined by means of ArcView's (Version 3.3, ESRI, Redlands, California, 2003) union function, so that each unique combination of polygons resulted in one polygon on the output map containing the attributes of all of the input maps. Polygons were used instead of grids because the resulting data sets were substantially smaller than data sets generated from grids.

The attribute table of the output map was processed by the fuzzy logic program, which generated possibility values for each fuel type contained in each polygon. The fuel type with the highest possibility value was determined and assigned to the polygon. This process resulted in generation of a national FTM, as well as a map of the possibility occurrence of each fuel type.

Comparisons of Fuel Types and Areas

For validation, the national FTM was compared with the provincial and territorial FTMs used by fire management agencies in the Yukon, Alberta, Saskatchewan, Ontario, and Quebec (Fig. 1). These provincial and territorial FTMs are based on various combinations of aerial surveys, satellite imagery, forest inventory data, and sampling plots. They are used for operational fire danger monitoring and resource allocation and were the only fuel-type data available for validating the new national FTM. The accuracy of these maps is unknown. The pixel size varied between 25 and 100 m depending on the data sources and methods used by the particular province or territory.

All maps were scaled (by means of a majority filter) to a standard 1-km pixel size, and the provincial and territorial maps were then compared with the national maps in three ways. In the first method, the percent area covered by each fuel type for each province or territory was calculated and compared to percent coverage on the national FTM. The second comparison introduced a spatial aspect. As expected, few boundaries of the various fuel types overlapped perfectly. This imperfect correspondence resulted from a combination of problems associated with determining boundaries, which are often not discrete but represent gradual transition areas, and from scaling problems associated with landscape ecology (Wu and Qi 2000). In addition, it was not possible to go back to the original data used to produce the provincial and territorial FTMs or to the original data used to produce the spatial inputs used for the national FTM. To take care of this problem, a buffer area 1 km on either side of fuel-type boundaries was eliminated from the analysis, and only the data in the "center" of each area of a given fuel type was used in the comparisons. This process allowed for a clearer comparison and a better understanding of regional differences in fuel-type interpretations. Although this method took care of some errors due to the transitional nature of the boundaries and scaling, it prevented comparison of areas with a width less than 3 km. Therefore, trends and patterns for the human-caused fuel types C-6 (Conifer Plantation), S-1, S-2, and S-3 (slash fuel types), and the national fuel type C-5 (Red and White Pine) were not obtained by this method, as they tend to occur only in small areas. In the third method, point data were compared between the national and the provincial and territorial FTMs. The points were chosen at random on the national FTM, and fuel types observed were compared with those found at the same location on the provincial and territorial maps. This allowed for use of fuzzy logic outputs in a detailed assessment of the certainty of matches and the seriousness of mismatches.

Accuracy Assessment

Traditionally, the accuracy of a thematic map is determined by comparing the map with ground data, and the results are tabulated in the form of a confusion matrix. The number of sites along the main diagonal of the matrix represents the number of correct matches, and the remaining number of sites represent the errors. In addition, the producer's and the user's accuracies can be calculated to yield omission and commission errors, respectively. The correct number of entries in one class is divided by the column total (producer's accuracy) or the row total (user's accuracy). The Kappa statistic is sometimes used as measure of agreement between the map and the ground data; this statistic takes chance occurrence into account (Congalton 1991).

For a thematic map produced with fuzzy logic, each polygon has not only the most possible fuel-type class associated with it but also all the other classes that were not chosen along with their corresponding possibility values. Accuracy assessment using possibility values quantifies the seriousness of mismatches, which provide a means of tolerating some degree of disagreement between the map classifications. If the fuel type selected by the program is wrong, but its associated possibility is not much higher than that of the correct fuel type, the implication is that experts rated the two fuel types similarly for a given set of inputs, which means that the difference may not be that serious in practice. This is an alternative to the standard Boolean approach generally used in validation. In a related method, published by Gopal and Woodcock (1994) and used by Muller et al. (1998) and Laba et al. (2002), a map is produced by methods other than fuzzy logic, and fuzzy logic is applied during field validation, at which point experts assign a possibility value to their site classification.

For comparison with the national FTM, 45 random points from each of the Yukon, Alberta, Saskatchewan, and Quebec and 90 points from Ontario were used. The resulting total of 270 points was large enough to determine the magnitude of matches and mismatches. The certainty of matches was determined by subtracting the second-highest possibility value from the highest possibility value, that of the mapped fuel type. The difference ranged from 0 to 1. For mismatches, the difference between the possibility value of the mismatched fuel type and the possibility value of the mapped fuel type was calculated, and it ranged from 0 to −1. For example, if the possibility values for fuel types A, B, and C were 0.70, 0.25, and 0.05, respectively, and A was the fuel type observed in the field, the magnitude of the match was 0.45 (0.70–0.25). However, if the fuel type actually observed was C, the magnitude of the mismatch was −0.65 (0.05–0.70).

Table 3. Inputs and variables used in the fuzzy logic program.

Source of inputs	Inputs	Variables[a]
Land Cover 2000 (Natural Resources Canada 2004b)	Treed wetland	Very tall shrub, mixedwood, conifer
	Treed broadleaf	Sparse, medium, dense
	Treed mixedwood	Sparse, medium, dense
	Treed conifer	Sparse, medium, dense
	Dryland herb to shrub	Bryoid, herb, low shrub, tall shrub
	Wetland herb to shrub	Bryoid, herb, low shrub, tall shrub
	Water	None, maybe, present
	Tundra	None, tundra
	Cropland	None, cropland
	Nonfuel	Snow, ice, exposed land
Ecozone (Environment Canada 2003)	Ecozone	Arctic Cordillera, Northern Arctic, Southern Arctic, Taiga Plains, Taiga Shield, Boreal Shield, Atlantic Maritimes, Mixedwood Plains, Boreal Plains, Prairies, Taiga Cordillera, Boreal Cordillera, Pacific Maritimes, Montane Cordillera, Hudson Plains
Ecoregion (Environment Canada 2003)	Pacific Maritime	Mount Logan, Northern Coastal Mountains, Nass Basin, Queen Charlotte Ranges, Queen Charlotte Lowland, Nass Ranges, Coastal Gap, Pacific Ranges, Western Vancouver Island, Eastern Vancouver Island, Georgia-Puget Basin, Lower Mainland, Cascade Ranges
	Montane Cordillera	Skeena Mountains, Omineca Mountains, Central Canadian Rocky Mountains, Bulkley Ranges, Fraser Plateau, Fraser Basin, Chilcotin Ranges, Columbia Mountains and Highlands, Western Continental Ranges, Eastern Continental Ranges, Interior Transition Ranges, Thompson-Okanagan Plateau, Okanagan Range, Okanagan Highland, Selkirk-Bitterroot Foothills, Southern Rocky Mountain Trench, Northern Continental Divide
	Boreal Plains	Slave River Lowland, Clear Hills Upland, Peace Lowland, Mid-Boreal Uplands, Wabasca Lowland, Western Boreal, Western Alberta Upland, Mid-Boreal Lowland, Boreal Transition, Interlake Plain
	Boreal Shield	Athabasca Plain, Churchill River Upland, Hayes River Upland, Lac Seul Upland, Lake of the Woods, Rainy River, Thunder Bay-Quetico, Lake Nipigon, Big Trout Lake, Abitibi Plains, Lake Temiscaming Lowland, Algonquin-Lake Nipissing, Southern Laurentians, Rivière Rupert Plateau, Central Laurentians, Anticosti Island, Mecatina Plateau, Paradise River, Lake Melville, Strait of Belle Isle, Northern Peninsula, Long Range Mountains, Southwestern Newfoundland, Central Newfoundland, Northeastern Newfoundland, Maritime Barrens, Avalon Forest, South Avalon-Burin Oceanic Barrens

Table 3. Concluded.

Source of inputs	Inputs	Variables[a]
Ecoregion (Environment Canada 2003)	Atlantic Maritime	Appalachians, Northern New Brunswick Uplands, New Brunswick Highlands, Saint John River Valley, Southern New Brunswick Uplands, Maritime Lowlands, Fundy Coast, Southwest Nova Scotia Uplands, Atlantic Coast, Annapolis-Minas Lowlands, South-central Nova Scotia Uplands, Nova Scotia Highlands, Cape Breton Highlands, Prince Edward Island, Îles-de-la-Madeleine
CanFI 2001[b] (Natural Resources Canada 2004a)	Dominant species	Uncertain, black spruce/larch, white spruce, lodgepole/jack pine, red/white pine, ponderosa pine/Douglas-fir, hemlock (*Tsuga* spp.), red cedar (*Thuja plicata*), cypress (*Chamaecyparis* spp.), deciduous trees, not able to burn
	Dominant species age	Low (≤50 years old), high (>50 years old)
	% area covered by dominant species	Low (0%–50%), medium (50%–75%), high (75%–100%)

[a]Membership functions.
[b]CanFI = Canadian Forest Inventory.

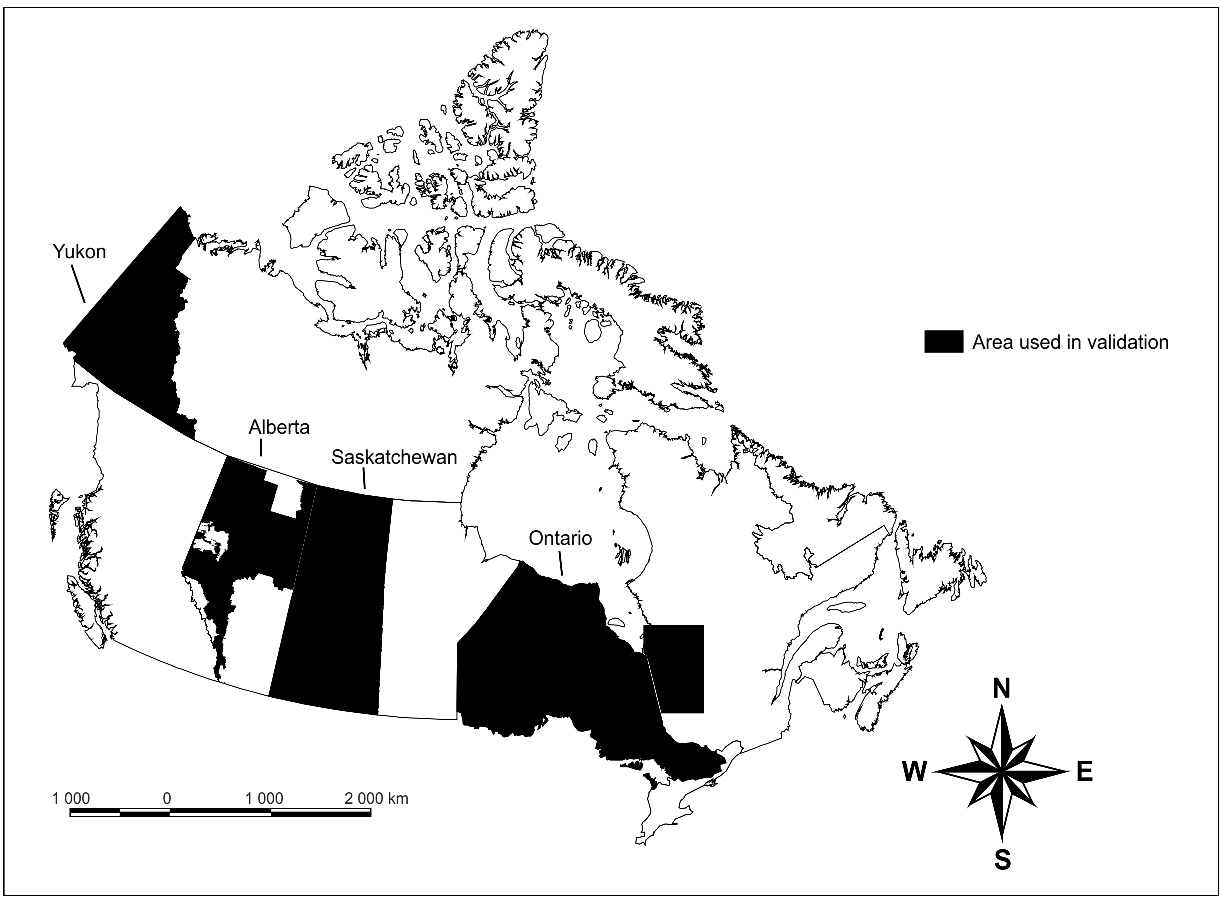

Figure 1. Areas of Canada used in validation of the new national fuel-type map.

RESULTS AND DISCUSSION

All fuel types except M-3 and M-4 (Dead Balsam Fir/Mixedwood) and S-1, S-2, and S-3 (slash fuel types) were represented in the new national FTM (Fig. 2). The most common fuel type was C-2 at 13%, followed by D-1 (Leafless Aspen) at 8%. The terrestrial nonclassified category tundra–alpine was the most abundant of all classes or categories, covering 18% of the country. Fuel type C-6 was the least abundant, at less than 1%, and was identified only in British Columbia. Fuel type C-5 was also uncommon (less than 1%) because of past intense harvesting of red pine (*Pinus resinosa* Ait.) and eastern white pine (*Pinus strobus* L.); it was found only in central Ontario. Fuel type C-7 (Ponderosa Pine/Douglas-fir) was limited to British Columbia and Alberta (1%). All other fuel types were distributed across Canada. The possibility of mapped fuel-type occurrence varied between 0.3 and 1.0 (Fig. 3). The lowest value was for fuel type C-2 in northern Canada, whereas the highest values occurred for the nonclassified categories of water, nonfuel, and tundra–alpine.

Slash fuel types (S-1, S-2, S-3) were not found on the national FTM, because the data from the different layers used to produce the national map were insufficient for isolating these fuel types. At present, additional inputs such as year of cut would not have been helpful for the coarse 1-km resolution of the national FTM since the slash fuel types tend to occur over small areas. Similarly, the fuel type M-3 and M-4 could not be mapped because of insufficient information from the available inputs as to where dead balsam fir (*Abies balsamea* (L.) Mill.) occurs.

The combined fuel type C-3 and C-4 represented areas where the age of jack or lodgepole pine was not available. On the provincial and territorial FTMs, this combined class would be represented by the C-3 (Mature Jack or Lodgepole Pine) or C-4 (Immature Jack or Lodgepole Pine) fuel types. In Canada, volume of wood in combination with tree species and location is a good substitute for age in determining fuel type, and these data come from the same source as age (i.e., CanFi 2001; Natural Resources Canada 2004a).

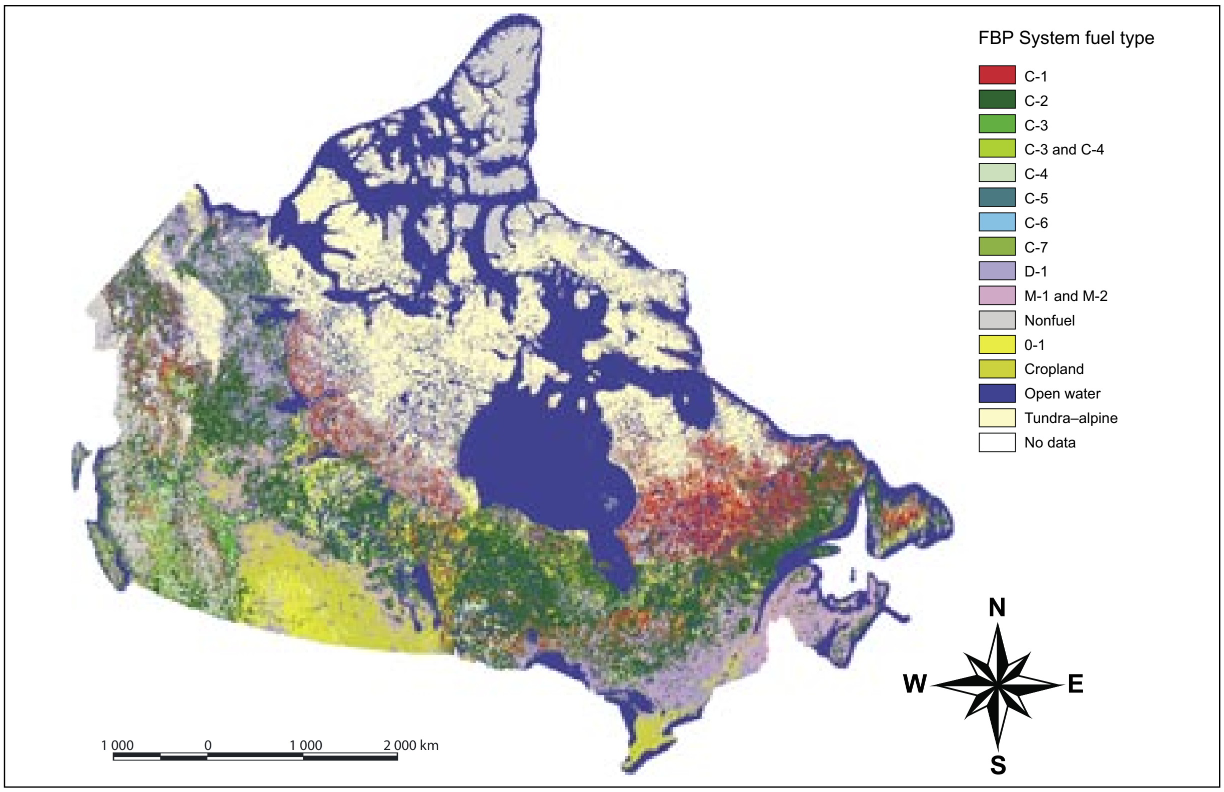

Figure 2. New Canadian fuel-type map, based on Land Cover 2000 (Natural Resources Canada 2004b), ecozones and ecoregions of Canada (Environment Canada 2003), and Canadian Forest Inventory 2001 (Natural Resources Canada 2004a). FBP = Forest Fire Behavior Prediction. C-1 (Spruce–Lichen Woodland), C-2 (Boreal Spruce), C-3 (Mature Jack or Lodgepole Pine), C-4 (Immature Jack or Lodgepole Pine), C-5 (Red and White Pine), C-6 (Conifer Plantation), C-7 (Ponderosa Pine/Douglas-fir), D-1 (Leafless Aspen), M-1, M-2 (Boreal Mixedwood), M-3, M-4 (Dead Balsam Fir/Mixedwood), S1 (Jack or Lodgepole Pine Slash), S-2 (Spruce/Balsam Slash), S-3 (Coastal Cedar/Hemlock/Douglas-fir Slash), and O-1 (Grassland).

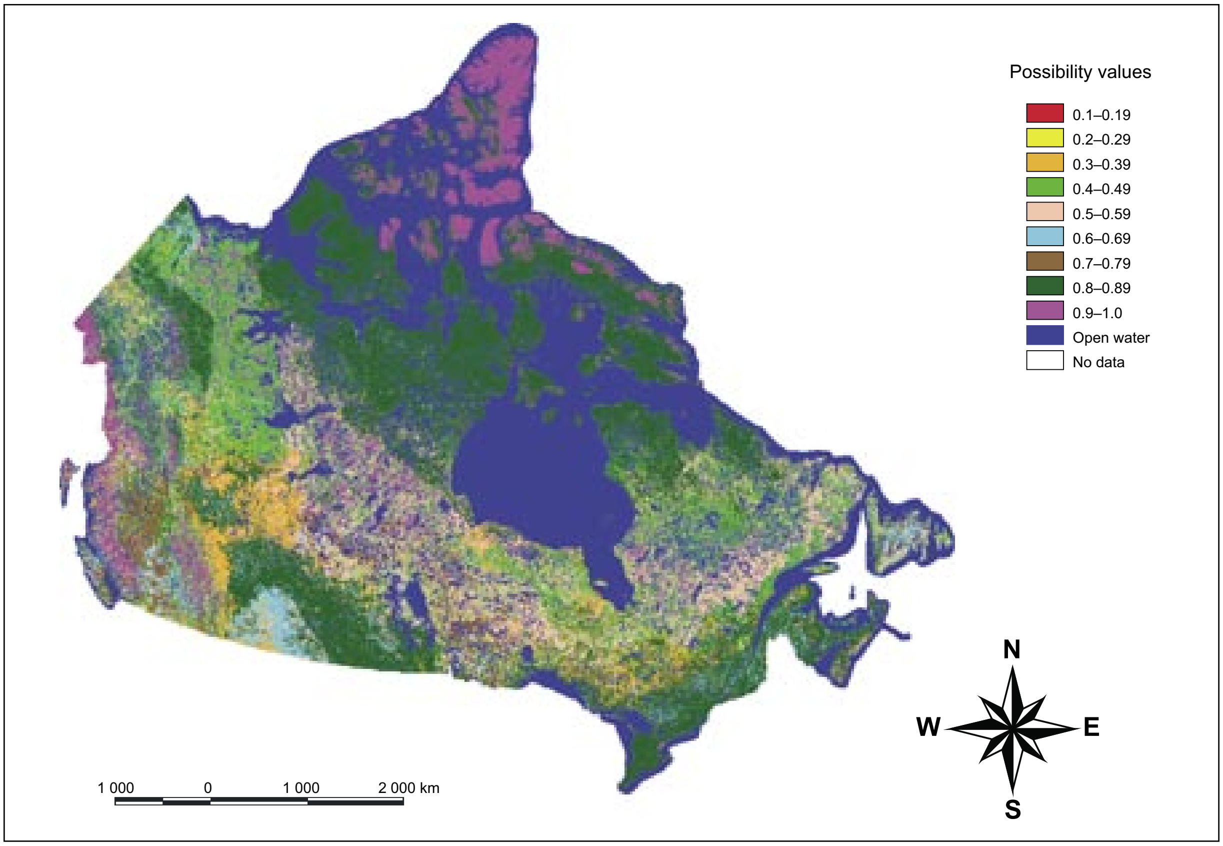

Figure 3. Distribution of possibility values for the fuel types in the new national fuel-type map (see Table 6).

Comparisons of Fuel Types and Areas

One challenging aspect of fuel-type comparisons between the national and the provincial and territorial FTMs is interpretation of unclassified categories, which are found on all maps, along with the FBP System fuel types. In some cases, selected fuel types and categories from provincial and territorial FTMs were combined for comparison purposes (Table 4). In the Yukon, wetland and water categories were both classified as water (wetlands made up only 2% of the combined wetland and water areas). In Ontario, the provincial categories of M-1 and M-2 and M-3 and M-4 with 25%–75% conifer content were retained in the mixedwood fuel types for the national FTM. However, the categories of M-1 and M-2 and M-3 and M-4 with less than 25% conifer content were combined and designated as the D-1 fuel type; and the categories of M-1 and M-2 and M-3 and M-4 with more than 75% conifer content were combined and designated as the C-2 fuel type. In Quebec, the bare dryland and humid land categories overlapped with all fuel types on the national FTM, and thus comparisons are presented both without them (Tables 4, 5, and 6) and with them (Table 7). For the national FTM, all cropland was considered O-1 (Grassland) for purposes of the comparisons.

After elimination of buffer areas along fuel-type boundaries, areas available for comparison represented 8%, 8%, 30%, 5%, and 0.7% of the total areas of the provincial and territorial FTMs of Yukon, Alberta, Saskatchewan, Ontario, and Quebec, respectively (Table 7). The Saskatchewan map had larger polygons than any of the other FTMs, which left more map area for comparison after removal of the buffer zones. Matches between the provincial and territorial FTMs and the national FTM varied from 24% for Quebec to 90% for Saskatchewan. However, when the bare dryland and humid land categories were removed from the Quebec data, the match increased to 64% for that province (Table 7).

Again, a consistent problem was the provincial and territorial interpretation of mixedwood fuel types and the differentiation of these fuel types

Table 4. Coverage of land area in each province or territory covered by each fuel type (%)

FBP[a] fuel type	Yukon		Alberta		Saskatchewan		Ontario		Quebec section[e]	
	TFTM[b]	NFTM[c]	PFTM[d]	NFTM	PFTM	NFTM	PFTM	NFTM	PFTM	NFTM
C-1	0.03	7.81	2.88	1.82	0.91	2.26	24.85	23.75	0.00	15.11
C-2	11.92 (45.07)[f]	20.20	28.62	38.87	7.56	20.41	22.16 (23.52)[f]	30.67	50.26	43.15
C-3	1.15	0.31	7.66	8.55	9.03	0.53	4.39	0.09	11.05	–[g]
C-4	0.06	1.08	2.70	5.26	2.70	3.79	3.68	4.63	–	–
C-3 and C-4	–	1.38	–	1.89	–	0.90	–	0.11	–	0.66
C-5	–	–	0.09	–	–	–	–	<0.01	<0.01	–
C-6	–	–	–	–	–	–	0.04	–	1.37	–
C-7	0.07	–	0.10	0.14	–	–	–	<0.01	–	–
D-1	23.13 (36.07)[h]	28.03	20.37	14.42	11.17	4.00	2.67 (7.32)[h]	10.52	6.13	8.25
M-1 and M-2	47.21 (0.21)[i]	0.26	14.62	15.09	3.03	3.90	9.51	7.62	13.21	14.46
M-3 and M-4	–	–	–	–	–	–	2.61	–	–	–
S-1	–	–	0.02	–	0.45	–	0.04	–	–	–
O-1[j]	0.50	2.29	7.74	7.66	54.49	44.65	5.22	7.29	1.91	8.10
Nonfuel	14.92	9.96	11.77	2.26	0.34	8.40	2.78	1.54	5.87	2.96
Water	1.58[k]	9.49	3.42	3.54	10.28	9.49	12.87	12.45	10.20	7.17
Other[l]	–	19.11T	–	0.50T	–	1.68T	3.24B	0.24T	–	0.09T

[a]FBP = Forest Fire Behavior Prediction System.
[b]TFTM = territorial fuel-type map.
[c]NFTM = national fuel-type map.
[d]PFTM = provincial fuel-type map.
[e]Percentages are based on total area excluding the bare dry and bare humid areas as defined by the Quebec agency.
[f]Value in parentheses includes M-1 and M-2 with 75% or more conifer.
[g]Dashes indicate fuel type not present in the province/territory fuel-type map and the national fuel-type map.
[h]Value in parentheses includes M-1 and M-2 with 25% or less conifer.
[i]Value in parentheses includes M-1 and M-2 with 50% conifer.
[j]Includes cropland.
[k]Includes the wetland category as defined by each province.
[l]T = tundra; B = bog.

from coniferous and deciduous fuel types. Different percentages of conifer composition have been used in determining the mixedwood fuel-type classifications on the various FTMs. In the Yukon, the three M-1 and M-2 categories are based on three discrete conifer composition levels (25%, 50%, or 75% conifer); in Alberta and Saskatchewan, mixedwood is defined as having about 50% conifer; in Ontario, the mixedwood fuel type is divided into nine categories with conifer percentages ranging in steps from 10% to 75%; finally, in Quebec, mixedwood conifer content varies from 35% to 70% (Pelletier et al. 2002). In comparison, the land-cover data used in the national FTM defined the mixedwood fuel type as one class having a conifer content between 25% and 75% (Joint Research Centre 2004; Natural Resources Canada 2004b). In addition, scaling had an effect on the M-1 and M-2 classification: if half of a 1-km cell on a finer-resolution provincial or territorial FTM is classified as D-1 and the other half as a coniferous fuel type, the national FTM might classify the cell correctly as M-1 and M-2, whereas the provincial or territorial map might identify the 1-km cell on its scaled-up map as D-1 or as a coniferous fuel type. Obviously, some disagreements between provincial and territorial and national FTMs are bound to occur for M-1 and M-2, D-1, and some conifer fuel types, particularly C-2 (Tables 4 and 7).

Relative to the Yukon, Alberta, Saskatchewan, and Ontario FTMs, the national FTM overestimated fuel type C-2 (Table 4) because C-2 was the default fuel type assigned to areas with dense conifer. A different fuel type was assigned for dense conifer only if the ecoregion map (Environment Canada) or the CanFI 2001 (Natural Resources Canada 2004a) map indicated a dominant conifer other than black spruce (*Picea mariana* (Mill.) BSP) or white spruce. In some remote northern areas of the country where no forest inventory exists, areas of dense conifer defaulted to C-2 regardless of the species present. A forest inventory of the same resolution as Land Cover 2000 will be essential in improving the accuracy of the new national FTM.

The following comparisons are presented by territory and province, starting from the west.

The most striking characteristic of the Yukon FTM was the abundance of M-1 and M-2, which accounted for 47.21% of the total area (Table 4). In contrast, on the national FTM, M-1 and M-2 covered only 0.26% of the Yukon. However, most of the mixedwood areas identified on the territorial map as having only 25% conifer cover were classified as deciduous (D-1) in the national FTM, and most of the areas with 75% conifer were classified as coniferous (C-2) (Table 7). Another striking characteristic was the area covered by water (Table 4) and the overlapping water percentage (Table-7): the area covered by water was six times greater on the national FTM. The imagery from which these maps were produced was obtained at different times (seasons and/or years and might have been misinterpreted), which resulted in different areas for the open water classification. Finally, the fuel types O-1 and C-1 (Spruce–Lichen Woodland) were more common on the national FTM than on the territorial FTM. Eighty-seven percent of the O-1 area on the national FTM overlapped with nonfuel or D-1 on the territorial FTM (Table 7). Sparse shrubs are often difficult to classify, since no classification in the CFFDRS represents shrubs. As a result, fire scientists do not always agree on the fuel type to which these best correspond in the FBP System. As for C-1, 63% of this fuel type on the national FTM overlapped with C-2 on the territorial FTM (Table 7). These areas had been classified as open evergreen forest with lichen understory (typical of fuel type C-1) by the Land Cover 2000 (Natural Resources Canada 2004b) input to the national FTM, which made it difficult to differentiate and classify this land-cover class as C-2 on the national FTM.

For both Alberta and Saskatchewan, the occurrence of fuel types O-1 and D-1 and the nonfuel category was inconsistent between provinces and also between these provinces and the national FTM. Some areas straddling the Alberta–Saskatchewan border were classified as nonfuel on the Alberta FTM but as fuel type O-1 on the Saskatchewan FTM. On the national FTM the nonfuel category was underestimated for Alberta and overestimated for Saskatchewan (Table 4). In addition, the national FTM nonfuel category for Saskatchewan was mainly classified as fuel types D-1 and O-1 on the provincial FTM (Table 7). The difference may relate to the different data sources and classification methods used in creating the provincial FTMs and the national FTM.

For both Alberta and Saskatchewan, fuel type D-1 was underestimated by the national FTM (Table 4). In addition, the national FTM fuel type D-1 for Alberta overlapped with the nonfuel category of the provincial FTM (Table 7). The interpretation of shrubs as a fuel type is a factor in this discrepancy. For both provinces, the national FTM fuel type D-1 overlapped significantly with the provincial FTM fuel type M-1 and M-2 (Table 7).

For Ontario, the provincial FTM nonfuel category overlapped a large portion of the national FTM cropland category (Table 7), which indicates that the provincial agency decided to classify croplands as nonfuel.

For Quebec, fuel types O-1 and C-1 were overestimated by the national FTM (Table 4). Two categories (bare dry and bare humid fuel types) defined by the province are described as having scattered trees, but probably would be best described as either the C-1 or the O-1 fuel type. Bare humid land was found to be the best match for the fuel type C-1 on the national FTM (Table 5). These two categories covered 35% of the provincial FTM, overlapping with fuel types O-1, C-1, C-2, and D-1 and the nonfuel category to various extents.

Accuracy Assessment

Assessments of point data indicated a 55% to 70% agreement between each of the provincial or territorial FTM and the national FTMs (data not shown). The overall agreement was 60% (Table 5). However, map accuracy is not the only characteristic to be considered: the consistency of interpretation for the entire country could be just as important (Keane et al. 2001).

Designating as a mismatch the presence of fuel type C-3 and C-4 on the national FTM and fuel type C-4 on the provincial FTM for the same location may be questionable (Table 5) since they both represent the same forest species. Mismatches between C-2 and C-3 occurred in ecoregions where white spruce was the dominant species and no CanFI data were available. As a result, the user's accuracy for C-3 was low (Table 5). As expected, the fuel type M-1 and M-2 was also difficult to match between provincial or territorial and national FTMs (Table 5).

The magnitude of mismatches and the certainty of matches in Table 6 suggest that 17% of the mismatches (18 [Table 7] of 108—or 270 – [0.60*270] from Table 5) are significant (i.e., under the −1.0 to −0.8 column in Table 6), 12 of them being sites classified as nonfuel on the national FTM. Of the 12 sites, 8 were sites in the Yukon and northern Saskatchewan that were classified as D-1 on the provincial and territorial FTMs.

Nonfuel and water categories were classified with the most certainty (Table 6), whereas conifer fuel types were the most difficult to classify with any certainty. This situation is reflected in Fig. 3, where possibility values ranged from 0.4 to 0.6 in an east–west band spanning central Canada's boreal forest zone, dominated by dense conifer forests.

The magnitude of mismatches averaged −0.51, whereas the certainty of matches averaged 0.26, for an overall arithmetic mean of −0.05 (Table 6). This value reflects the fire experts' confidence in the rules that they produced for the fuzzy logic computer program, as well as the low number of inputs used to produce the national FTM. The identification of fuel types can be very complex, and there is a lack of confidence in "choosing" a fuel type based on limited characteristic data.

The distribution of possibility values (Fig. 3) gives insight into where better data for classifying the existing fuel types with more certainty are required in Canada or, conversely areas that might need better-defined fuel types that are not currently recognized within the FBP System. The tundra–alpine, cropland, and nonfuel (e.g., snow or ice) land-cover types had generally high possibility values, whereas shrubs, dense conifer forests, and wetlands had lower possibility values.

Table 5. Confusion matrix of 270 data points[a] used for validation purposes (comparison of the provincial and territorial fuel-type maps with national fuel-type map) (*Kappa* = 0.53)

Provincial or territorial fuel type	National fuel type															
	C-1	C-2	C-3	C-3 and C-4	C-4	C-5	C-6	C-7	D-1	M-1 and M-2	M-3 and M-4	S-1	O-1	Nonfuel	Water	Total	Map user's accuracy (%)
C-1	**13**	2	0	0	0	0	0	1	0	1	0	0	0	0	0	17	76
C-2	4	**33**	0	0	1	0	0	0	1	1	0	0	1	0	0	41	80
C-3	2	11	**4**	0	3	1	0	0	0	0	0	0	0	0	0	21	19
C-3 and C-4	0	0	0	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0
C-4	1	3	1	2[b]	**4**	0	0	0	0	0	0	0	1	0	0	12	33 (50)[c]
C-5	0	0	0	0	0	**0**	0	0	0	0	0	0	0	0	0	0	0
C-6	0	1	0	0	0	0	**0**	0	0	0	0	0	0	0	0	1	0
C-7	0	0	0	0	0	0	0	**0**	0	0	0	0	0	0	0	0	0
D-1	1	1	0	0	0	0	0	0	**34**	4	0	0	3	8	0	51	67
M-1 and M-2	2	8	0	1	0	0	0	0	5	**11**	0	0	0	1	3	31	35
M-3 and M-4	0	1	0	0	0	0	0	0	0	2	**0**	0	0	0	0	3	0
S-1	0	2	0	0	0	0	0	0	0	1	0	**0**	0	0	0	3	0
O-1	2	2	0	0	0	0	0	0	6	0	0	0	**26**	5	0	41	63
Nonfuel	1	1	0	0	0	0	0	0	4	0	0	0	5	**18**	3	32	56
Water	0	1	0	0	0	0	0	0	0	0	0	0	0	0	**16**	17	94
Total	26	66	5	3	8	1	0	1	50	20	0	0	36	32	22	**270**	N/A[d]
Map producer's accuracy (%)	50	50	80	0 (67)[c]	50	0	0	0	68	55	0	0	72	56	73		**59 (60)[c]**

[a]Forty-five data points were collected for each of the Yukon, Alberta, Saskatchewan, and a portion of Quebec southeast of James Bay, and 90 data points were collected for Ontario.
[b]Questionable error.
[c]Value in parentheses considers the questionable mismatch as representing a match.
[d]N/A = not applicable.

Table 6. Magnitude of mismatches and certainty of matches for 270 data points[a] comparing the provincial and territorial fuel-type maps (FTMs) with the national FTM

Provincial or territorial FBP fuel-type designation	Magnitude of mismatch or certainty of match with national FTM[b] (as no. of data points)									
	−1 to −0.8	−0.8 to −0.6	−0.6 to −0.4	−0.4 to −0.2	−0.2 to −0.2	0.2 to 0.4	0.4 to 0.6	0.6 to 0.8	0.8 to 1.0	Mean
C-1	0	0	7	1	18	0	0	0	0	−0.15
C-2	0	0	23	10	18	15	0	0	0	−0.15
C-3	0	0	1	0	4	0	0	0	0	−0.10
C-3 and C-4	0	0	2	0	1	0	0	0	0	−0.33
C-4	0	0	3	1	4	0	0	0	0	−0.23
C-5	0	0	1	0	0	0	0	0	0	−0.50
C-6	0	0	0	0	0	0	0	0	0	0
C-7	0	0	1	0	0	0	0	0	0	−0.50
D-1	2	0	7	6	13	22	0	0	0	−0.01
M-1 and M-2	1	3	0	7	0	9	0	0	0	−0.12
M-3 and M-4	0	0	0	0	0	0	0	0	0	0
S-1	0	0	0	0	0	0	0	0	0	0
O-1	0	5	2	1	20	0	8	0	0	−0.22
Nonfuel	12	0	0	0	4	0	0	5	11	0.08
Water	3	3	0	0	0	0	0	16	0	0.29
Total	18	11	47	26	82	46	8	21	11	−0.05
Mean	Magnitude of mismatches: −0.51					Certainty of matches: 0.26				

[a]Forty-five data points were collected for each of the Yukon, Alberta, Saskatchewan, and a portion of Quebec southeast of James Bay, and 90 data points were collected for Ontario.
[b]Mismatches indicated by negative values in column headings; matches indicated by positive values in column headings. Mismatches with lower values are more serious; matches with higher values are more reliable.

Table 7. Areas of fuel types from provincial and territorial fuel-type maps that matched the national fuel-type map (NFTM) after removal of buffer areas along boundaries

	% match with provincial or territorial map[a]				
Comparison	Yukon	Alberta	Saskatchewan	Ontario	Quebec section
Area compared (% of province or territory)	8	8	30	5	2 (0.7)[b]
Total % match with NFTM	71[c]	54 (64)[d]	90	83	24 (64)[b]
FBP[e] fuel type					
C-1	0 (63)[f]	0.3	14	83	88[g]
C-2	14 (91)[h]	72	30	78 (79)[i]	11 (92)[b]
C-3	23	41	85	80	–[j]
C-4	18	2	–	0	–
C-3 and C-4	–	12	82	6	100
C-7	–	33	–	–	–
D-1	9 (36)[k]	28 (68)[l]	25 (99)[m]	10 (14)[n]	0
M-1 and M-2	100	0.1 (96)[d]	0.5 (49)[d]	43[o]	0
O-1[p]	0 (87)[q]	28	100	22	0
Nonfuel[r]	89	78	3 (96)[s]	30[t] (45)[p]	17[u] (94)[b, u]
Water	28	97	99	98	92 (98)[b]

[a]Except as otherwise indicated.
[b]Value in parentheses does not include provincially defined fuel types “bare dry” and “bare humid.”
[c]Uses the values in parentheses identified by footnotes f and h.
[d]Value in parentheses includes D-1 as M-1 and M-2.
[e]FBP = Forest Fire Behavior Prediction System.
[f]Value in parentheses includes C-2.
[g]Value is for the bare humid fuel type, as defined by the provincial agency.
[h]Value in parentheses includes M-1 and M-2, 75% conifer, as defined by the territorial agency.
[i]Value includes mixedwood with 75% or more conifer, as defined by the provincial agency.
[j]Dashes indicate no value available for the provincial or territorial fuel type.
[k]Value in parentheses includes M-1 and M-2, 25% conifer, as defined by the territorial agency.
[l]Value in parentheses includes nonfuel.
[m]Value in parentheses includes M-1 and M-2.
[n]Value includes mixedwood with up to 25% conifer, as defined by the provincial agency.
[o]Value includes mixedwood with greater than 25% and less than 75% conifers, as defined by the provincial agency.
[p]Includes cropland.
[q]Value in parentheses includes nonfuel and D-1.
[r]Includes tundra.
[s]Includes O-1 and D-1.
[t]Value includes bogs, as defined by the provincial agency.
[u]Value is for the burnt fuel type, as defined by the provincial agency.

SUMMARY AND CONCLUSIONS

A rule-based approach incorporating expert opinion is not new in fire studies (Morgan et al. 2001). This approach accommodates situations where data are limited, as was the case in developing a new national FTM. In such situations, the uncertainty of outputs increases as the inputs become sparse or nonexistent (Morgan et al. 2001), but the product can easily be upgraded as fuzzy logic is improved or new data become available.

This approach was used to produce an updated national FTM for Canada. The new FTM still has limitations: its resolution is similar to the older FTM, and its similarity to provincial and territorial FTMs could be improved. Overall agreement between the new national FTM and the provincial and territorial FTMs was 60%; the main causes for the difference were the difference in map resolution of the original maps used in the comparison, which resulted in different boundaries for each fuel type after scaling changes, and the origin of the provincial and territorial FTMs and the map layers used to produce the national FTM. These differences in turn reflect the various image sources (aerial photography and different satellite outputs) obtained on different dates (i.e., seasons and/or year), which would affect boundary placement and sometimes classification (e.g., the water category in the Yukon).

The most evident constraint to the production of the national FTM is the small number of inputs (data) currently available for its development. Fuel types depend on many more characteristics than just Land Cover 2000, ecozones, ecoregions, and CanFI 2001, which were used in constructing the current national FTM. However, these are the only comprehensive national spatial data now available for determining fuel type. Canadian forest inventory data of the same resolution as Land Cover 2000 (Natural Resources Canada 2004b), would be essential in improving the accuracy of this national FTM. Input on stand structure would also be helpful because it would describe the vertical arrangement of dead and live biomass above the soil surface, which affects fire behavior (Keane et al. 2001; Sandberg et al. 2001). Dead standing stems and down woody fuels are attributes not easily captured by aerial photography or satellite imagery, because the forest canopy often hides these understory features. Even if aerial sensors were able to reach the ground, it would be difficult to distinguish between fuel on the ground and fuel suspended in the canopy (Keane et al. 2001). Determining ground truth for these attributes would be necessary, but doing so at a national level would be difficult and costly.

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