CSIRO PUBLISHING

International Journal of Wildland Fire **2008**, *17*, 390–406 www.publish.csiro.au/journals/ijwf

Implementation of mid-scale fire regime condition class mapping

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Abstract. We used mid-scale Fire Regime Condition Class (FRCC) mapping to provide Hawthorne Army Depot in the Mount Grant area of Nevada, USA, with data layers to plan fuels restoration projects to meet resource management goals. FRCC mapping computes an index of the departure of existing conditions from the natural range of variability, and consists of five primary steps: (1) mapping the Potential Natural Vegetation Types (PNVT) based on interpretation of a soil survey; (2) refining PNVTs based on additional information; (3) modelling the natural range of variability (NRV) per PNVT; (4) using field verification, calculation and mapping of departure of current distribution of structural vegetation classes interpreted by remote sensing (IKONOS 4-m resolution satellite imagery) from the NRV; and (5) mapping structural vegetation classes that differ from reference conditions. Pinyon–juniper and mountain mahogany woodlands were found within the NRV, whereas departure increased from moderate for low and big sagebrush PNVTs and mixed desert shrub to high for riparian mountain meadow. Several PNVTs showed departures that were close to FRCC class limits. The common recommendation to reach the NRV was to decrease the percentage of late-development closed and cheatgrass-dominant classes, thus increasing the percentage of early and mid-development classes.

Additional keywords: DOD, fire management, Great Basin, LANDFIRE, Nevada, pinyon–juniper, rangeland, sagebrush, soil survey, state-and-transition, woodland.

Introduction

Fire managers across diverse landscapes recognise the need to reduce hazardous fuel loads, restore fire regimes and ecosystems, and decrease the threat of catastrophic wildfires. The United States Department of Agriculture (USDA) Forest Service recently published national-level, coarse resolution data to address the nature and degree of departure of current vegetation and fuels from natural conditions (Hann and Bunnell 2001; Hardy *et al*. 2001; Schmidt *et al*. 2002; Menakis *et al*. 2003). These data, termed Fire Regime Condition Class (FRCC), were important in integrating and mapping of biophysical, vegetation, fire occurrence, and ecological community information and providing an ecological basis for prioritising resources for fire regime restoration, fuels treatment, and biodiversity conservation. However, although these data were intended to be used for broad geographic regions, the lack of similar data at finer scales has led to misuse of these data for prioritisation and planning at the regional and project scales. Until recently, available FRCC data addressed prioritisation between regions and states, but did not consider specific land management projects.

The LANDFIRE project (www.landfire.gov/Documents/landfirecharter.pdf, accessed September 2007; Wildland Fire Leadership Council 2004) was implemented to consistently map FRCC using remote sensing and gradient modelling, but will not be completed for the entire USA until 2007 to 2010. The Rapid Assessment component of LANDFIRE was based entirely on expert rules applied to imagery interpretation for mapping of FRCC and was made available in 2006 for the entire USA, while the National-LANDFIRE maps will be produced by 2010, as the latter are dependent on plot data. Availability of continuous and nationally consistent spatial FRCC and associated data on reference and current vegetation conditions will help prioritise and coordinate restoration and fire hazard reduction in landscapes with multiple ownerships and from the watershed to regional scale.

The FRCC concept was readily adopted by the US Congress in 2003 (Healthy Forest Restoration Act 2003 – Congressional Bill H.R. 1904) and by public land managers as a useful landscape-scale metric to partially measure the success of hazardous fuels and ecosystem restoration projects. Locally, the FRCC mapping approach can be used to assess local issues, such as the modification of natural fire regimes by invasive weeds, and the likelihood that a landscape can conserve wide-ranging species of special management concern (e.g. Greater Sage-grouse, *Centrocercus urophasianus*). Contrary to public perception, however, FRCC is not a predictor of wildland fire hazard because fuels loadings are not used in the calculation of FRCC. Instead, FRCC measures departure of the vegetation structure from reference conditions. For example, fuel loads in some ecological systems are naturally high (e.g. *Pinus contorta* forests), whereas other ecological systems differ substantially from natural conditions because they might be managed to keep fuel loads low to protect human settlements (e.g. *Pinus ponderosa* woodlands).

The objectives of the present FRCC assessment were twofold: (1) map FRCC for the Mount Grant area on the United

 10.1071/WF07066 1049-8001/08/030390

States Department of Defence Hawthorne Army Depot in western Nevada based on methods proposed by Shlisky and Hann (2003), and (2) provide FRCC and associated data layers to Hawthorne Army Depot managers to address their key resource management priorities. These priorities included developing an interagency fire management plan to prioritise fire suppression activities, protecting water resources, planning fuels restoration and maintenance projects, implementing strategies for biodiversity protection, tracking success of restoration strategies, and revising the Hawthorne's resource land management plan. These key resource management priorities were defined in 2003 based on an initial conservation assessment by The Nature Conservancy where Hawthorne Army Depot staff and external natural resource specialists identified the risk of catastrophic fire due to long-term fire suppression as the highest threat to the integrity of surface water quality and the viability of sagebrush shrubland, pinyon woodlands, and Greater Sage-grouse habitat (J. Nachlinger, unpubl. data, 2003).

Methods

We adopted the mid-scale FRCC assessment process proposed by Shlisky and Hann (2003; additional references at www.frcc.gov, September 2006) because these resulting maps (FRCC and others) can be used to plan local fuels management projects based on the analysis of large landscapes. We incorporated remote-sensing based on high-resolution imagery, a soil survey, and field verification to the mid-scale FRCC assessment to increase its accuracy and applicability. The concept of scale is different among disciplines and a source of confusion (Quattrochi and Goodchild 1997); the discipline of fire and FRCC mapping uses its own meaning of scale. The scale in 'mid-scale' proposed by Shlisky and Hann (2003) means that the data can be used to design local-scale fuels projects, which often range from 80 to 5000 ha for public agencies. Henceforth, we replaced the term 'mid-scale' with 'local-scale'. The resolution of satellite imagery conventionally associated with the local-scale assessment in the field of fire mapping is $\leq$30 m (Hann 2004). Hann (2004) suggested that a coarse-scale assessment is inappropriate for anything finer than regional and national comparisons and is often associated with a satellite imagery resolution $\geq$1 km^2. The local-scale methodology is composed of five primary tasks (Fig. 1): (1) map initial Potential Natural Vegetation Types (PNVT); (2) refine PNVTs; (3) model the Natural Range of Variability (NRV); (4) calculate and map departure from the NRV; and (5) map vegetation classes that are over- or under-represented based on the NRV. These methods were based on mapping environmental gradients (Keane *et al*. 2002), using reference ecological conditions in ecosystem management (Kaufmann *et al*. 1994; White and Walker 1997; Swetnam *et al*. 1999), and calculating departure of current from reference conditions (Hann and Bunnell 2001; Hann *et al*. 2003*b*). Similar methods were described by Hann (2004) and McNicoll and Hann (2004) to classify FRCC at finer project sizes.

Two important points need to be made about these FRCC methods. First, qualitative methods are required to a certain extent for FRCC assessments because they use a high degree of qualitative assessments, expert opinion and modelling, and rule-based methodologies. Second, we did not incorporate departure of fire regimes (fire-free interval and intensity) for Mount Grant, although the complete FRCC methodology includes choosing the most departed values between structural vegetation classes and fire regimes based on reference conditions (Hann and Strom 2003). We lacked empirical data about fire on Mount Grant, which is a common fact for non-forestlands, although photography of some mountain slopes suggested old fire scars in pinyon–juniper woodlands.

Study area

The Mount Grant project area (North American Datum 1927 Universal Transverse Mercador for the Continental United States of America, latitude, 38°34′18″N; longitude 118°47′26″W) is 18 218 ha and contained within Hawthorne Army Depot, a 59 609-ha military installation in the Wassuk Range located in western Nevada, USA (Fig. 2). The Wassuk Range is representative of western Great Basin mountain ranges, with clearly defined zonal vegetation types distributed from the alpine summit of Mount Grant reaching 3426 m in elevation, to the valley bottoms at 1280 m of elevation. The Mount Grant project area is managed by Hawthorne Army Depot with surrounding areas in the Wassuk Range managed by the Bureau of Land Management, US Forest Service, and private owners. Much of the land at higher elevations is part of a 1930s public lands withdrawal where multiple uses and public access have been limited for years, including the removal of livestock grazing for surface water management.

Thirteen ecological systems occur on the slopes of Mount Grant. The nine upland ecological systems include mixed desert shrub, big sagebrush (*Artemisia tridentata*) semidesert, pinyon (*Pinus monophylla*)–juniper (*Juniperus osteosperma*) woodland (as defined by Miller *et al*. 2000), curlleaf mountain mahogany (*Cercocarpus ledifolius* var. *intermontanus*) woodland, mountain big sagebrush (*A. tridentata* ssp. *vaseyana*), low sagebrush (*A. arbuscula*), subalpine pine forest, and alpine (often dominated by low sagebrush). Subalpine pine forest, which is dominated by limber pine (*Pinus flexilis*) and whitebark pine (*P. albicaulis*), occupies small patches within the mountain big sagebrush–low sagebrush matrix. The four mesic ecological systems include cottonwood (*Populus fremontii*) forest, willow (*Salix* spp.) riparian shrubland, montane meadow, and aspen (*Populus tremuloides*) forest. The big sagebrush semidesert, mountain big sagebrush, and low sagebrush matrix communities are important for several sagebrush obligates, including Greater Sage-grouse, which is part of a genetically distinct California population of special concern.

Initial mapping of potential natural vegetation types

Potential natural vegetation types (PNVT) are one type of biophysical classification based on dominant and upper-layer plant species that are indicators of the natural disturbance regime, local climate, and topo-edaphic relationships (Schmidt *et al*. 2002; Shlisky and Hann 2003). Biophysical characteristics that to a large extent control fire regimes and the distribution of vegetation are reflected in the distribution of PNVTs (Keane *et al*. 2002). For example, fire-free landforms would be expected to support fire-sensitive species (Miller and Rose 1995). The PNVT represents the vegetation type that would exist under the natural regimes of ecological processes and natural disturbances,

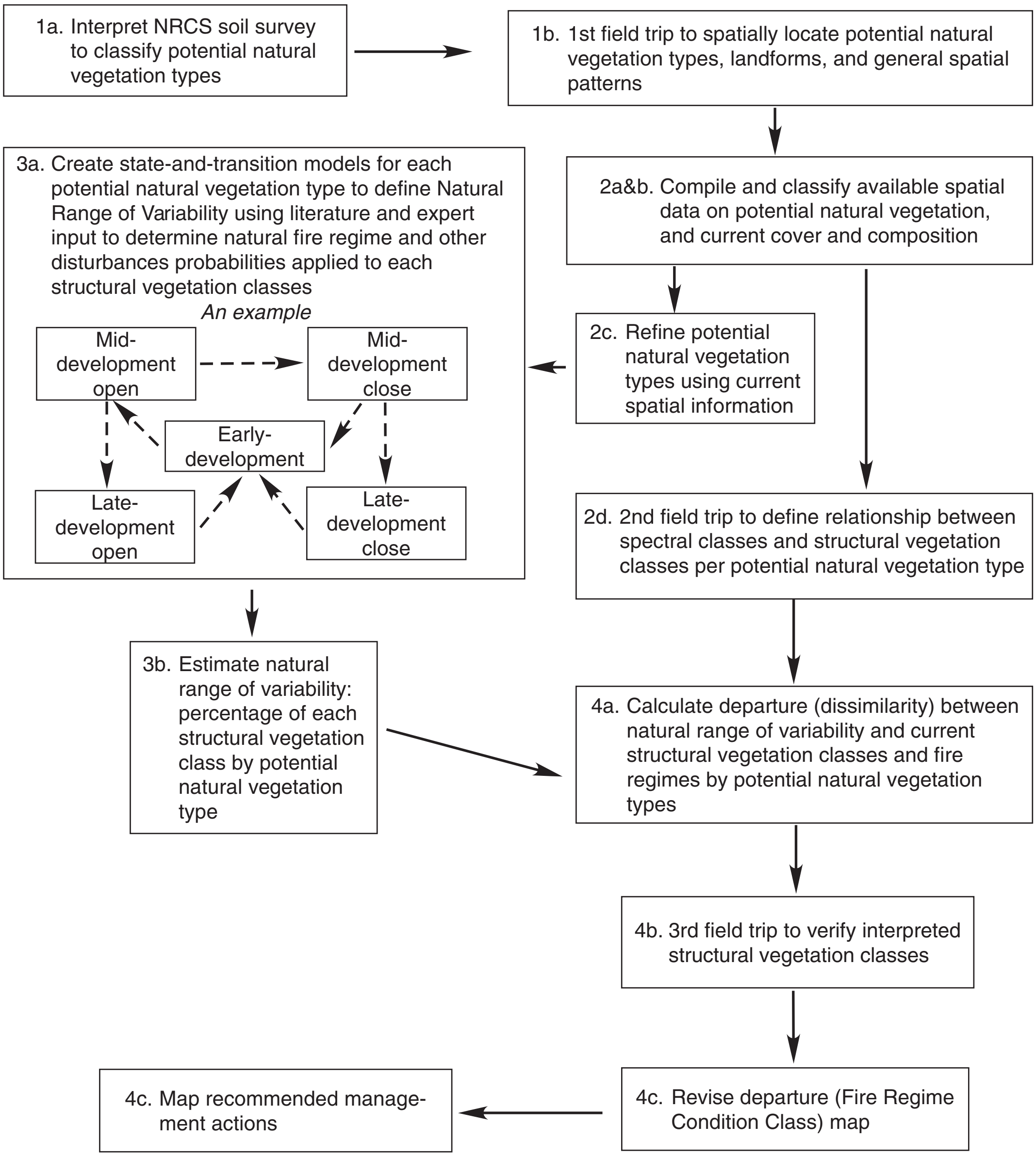

Fig. 1. Rapid Fire Regime Condition Class (FRCC) Assessment process (adapted from Shlisky and Hann 2003). The dashed arrows in Box 3a represent arbitrary succession and disturbance transitions among structural vegetation classes for a Potential Natural Vegetation Type example.

including Native American presettlement disturbances, in the absence of modern human interference (Schmidt *et al.* 2002; Shlisky and Hann 2003). Thus, the PNVT is informed by both pre-Euro-American settlement vegetation and current climate. For the present project, PNVTs were the foundation for stratification of reference and current vegetation, the development of reference models, and calculation of departures of current vegetation conditions from reference conditions.

PNVTs for Mount Grant were first identified by interpreting an order III soil survey completed in 1991 by the United States Department of Agriculture Natural Resources Conservation Service (NRCS) for Hawthorne Army Depot (No. 799; USDA Soil Conservation Service 1991). Soils take centuries to form as an interaction of climate, geology, and vegetation. Therefore, they can be used to approximate the natural, long-term ecological potential based on the best available science for soil–vegetation interactions (Haines-Young 1991; Franklin 1995). Given that the presettlement period ended ~150 years ago in the Great Basin, current soils should be reliable predictors of PNVTs unless soil horizons were removed mechanically or severely eroded owing to post-settlement land management practices.

There were no other comprehensive data layers that described PNVTs, except perhaps the coarse-scale PNV Group map published by the US Forest Service (www.fs.fed.us/fire/fuelman/pnv2000/maps.html, accessed October 2005). We did not use this coarse-scale map because its spatial scale (1-km resolution)

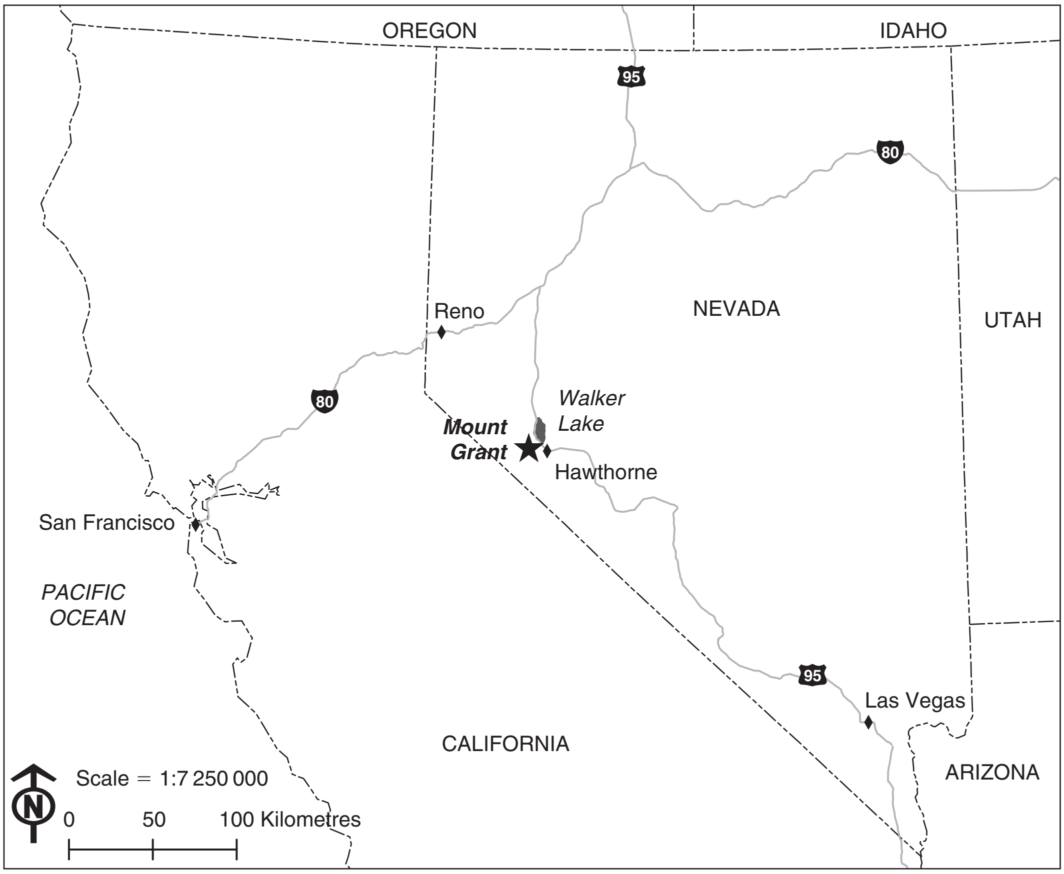

Fig. 2. Location of Mount Grant located in western Nevada, USA. The large star symbol is the location of Mount Grant.

was incompatible with local-scale FRCC mapping and displayed only one PNVT for the Mount Grant area, which has a net elevation change of ~2000 m, supporting at least seven PNVTs.

Soil survey interpretation is based on the natural, long-term ecological potential for a site defined as 'ecological site' by the NRCS (National Forestry Manual, www.nrcs.usda.gov/technical/ECS/forest/2002_nfm_complete.pdf, accessed November 2007). The NRCS defines ecological site as 'A distinctive kind of land with specific physical characteristics that differs from other kinds in its ability to produce a distinctive kind and amount of vegetation'. The ecological site generally represents a special case of PNVT based on biophysical characteristics. For example, mountain big sagebrush was a PNVT in our study; however, NRCS listed at least three different mountain big sagebrush ecological sites that differed by slope, average precipitation, or landform position.

Order III soil surveys do not map ecological sites <4.04 ha, which are termed inclusions, but these small ecological sites are listed as imbedded in the ecological site. Soil survey polygons, each describing a soil association, were mapped. A soil association might contain anywhere from one to three ecological sites, but it is shown as one polygon in an order III survey (see below *Refinement of PNVT map using current spatial data*). Dominant upper-layer species were matched with each ecological site. The dominant upper-layer species were obtained from the list of characteristic species per ecological site supplied by NRCS's attribute tables. All ecological sites sharing the same dominant species in the upper layer (e.g. mountain big sagebrush) were combined into a PNVT. In more recent soil surveys, the potential ecological community associated with a soil type (i.e. the ecological site) is provided and can be directly translated into a PNVT.

Refinement of PNVT map using current spatial data

We found that order III soil surveys need to be refined because NRCS map polygons commonly contain multiple soils and inclusions, thus multiple ecological sites per mapping unit (polygons) that primarily depend on landform position and slope. When mapping units are not refined to single PNVTs, it is impossible to define the vegetation reference condition to calculate FRCC. A first field survey in November 2003 confirmed that the initial map of PNVTs based on the NRCS soil survey was too coarse because it did not consistently separate many ecological sites. For example, fine-scale patterns between low sagebrush and mountain big sagebrush were commonly observed in the field.

Current vegetation imagery was used to refine NRCS ecological sites only for PNVTs that were edaphically controlled and whose dominant upper-layer species were not prone to at least moderately rapid expansion or contraction because of modern human interference. Also, current imagery was used to map ecological sites that were already identified within existing polygons by NRCS. In a few cases, current imagery was used to correct polygons that were incorrectly identified by NRCS, such as when an ecological site was mapped at an elevation that was biologically incompatible with the growth of the dominant upper-layer species. Vegetation types that were edaphically controlled were low sagebrush, curlleaf mountain mahogany, and mixed desert shrub. Low sagebrush is the only sagebrush that survives waterlogged soils caused by a claypan that prevents infiltration of water to deeper soil layers (USDA-NRCS 2003). Therefore, the presence of low sagebrush today was an excellent predictor of this species' dominance during the long process of soil formation. This criteria made the separation of low and mountain big sagebrush relatively easy for most of Mount Grant above 2133 m. Curlleaf mountain mahogany is similarly dependent on a few soil types (USDA-NRCS 2003) and because this species is slow-growing and a long-lived species ($>$500 years lifespan), it could be reliably mapped as potential vegetation wherever found: these ecological sites were often inclusions. Mixed desert shrub could also be mapped with current imagery because no other vegetation types could survive in the dry and saline soils at some elevations.

Other PNVTs could be very carefully refined with current imagery. These included: (1) Wyoming big sagebrush and mountain big sagebrush PNVTs that may appear smaller than their potential because of pinyon and juniper encroachment with fire exclusion, and (2) the pinyon–juniper woodland PNVT that may appear larger than its potential owing to the same encroachment process. This mapping difficulty only occurred when the NRCS soil survey listed, but did not map, a big sagebrush type and woodland type in the same soil association polygon. Examination of landforms and slope, and field visits generally resolved this problem because big sagebrush shrublands should be found on deeper soils of alluvial fans with shallow to moderate slopes whereas pinyon–juniper woodlands should be found on shallow soils with moderate to steep slopes. The challenges with using current imagery to refine a soil survey for Wyoming big sagebrush, mountain big sagebrush, and pinyon–juniper woodlands were mainly a difficulty associated with the upper and lower elevation limits of pinyon and juniper establishment. Therefore, mountain big sagebrush could be considered edaphically controlled above pinyon–juniper woodlands and its spatial distribution refined with current imagery.

We also refined the NRCS soils data with a 1990 plant community description and mapping based on aerial photography and field surveys for Mount Grant (J. Nachlinger, unpubl. data, 1990) and current vegetative conditions identified from IKONOS satellite imagery. For example, in many areas along the slopes and drainages of Mount Grant, narrow bands of mountain big sagebrush in deeper soils extended into areas identified only as low sagebrush by the NRCS data. Most likely, patches of mountain big sagebrush were the inclusions described in the soil survey. It was determined by the 1990 mapping effort (J. Nachlinger, unpubl. data, 1990) and local ecologists that these narrow bands of mountain big sagebrush were indeed representative of the mountain big sagebrush PNVT and should be mapped as such. The interpretation of the IKONOS imagery clearly identified the presence of mountain big sagebrush; therefore, the draft map was revised to include the more spatially detailed mountain big sagebrush PNVT. Similar processes were used to spatially refine the low sagebrush and mountain mahogany PNVTs as described above. We also refined the infrequent-fire pinyon–juniper PNVT, but mostly by excluding barren areas formed by talus slopes and bedrock, and inclusions of low sagebrush and curlleaf mountain mahogany. In a few cases, inclusions of Wyoming big sagebrush and mountain big sagebrush without any trees were located and mapped within the infrequent-fire pinyon–juniper PNVT because the cover of shrubs was uncharacteristic for this PNVT.

Modelling the NRV

The NRV was defined as the distribution of structural vegetation classes and mean fire return intervals expected under natural ecological conditions, including ecologically acceptable human fire use (as characterised by Native American burning) (Shlisky and Hann 2003). The NRV is also referred to as the reference condition by the LANDFIRE project, Shlisky and Hann (2003), and by fire practitioners in general. Henceforth, we use 'vegetation reference condition' instead of 'reference condition' to indicate that our study does not include presettlement fire regimes. Structural vegetation classes were defined for each PNVT and were composed of vegetation attributes of development time (e.g. succession described by either early-, mid-, or late-development), cover of the dominant and upper layer plant species (open or closed canopy), plant height, and common plant species. Modelled structural vegetation classes were identified using standard US interagency terminology (Shlisky and Hann 2003; Hann 2004; The Nature Conservancy *et al*. 2006) as early development, mid-development open, mid-development closed, late-development open, and late-development closed. We also added a non-standard structural vegetation class termed late-development wooded found only in Wyoming big sagebrush. This simple classification is consistent with local-scale spatial data likely to be available for vegetation structure and composition.

Because quantitative fire history and vegetative data are generally lacking for the presettlement period, particularly for non-forested land, the NRV is often modelled. State-and-transition modelling (Westoby *et al*. 1989; Bestelmeyer *et al*. 2004) was used to estimate the distribution of structural vegetation classes Fig. 1, Box 3*a*) and fire return intervals (Shlisky and Hann 2003). Where presettlement data are available for all PNVTs in a landscape to predict the NRV, they should be used preferentially or in tandem with modelling (The Nature Conservancy *et al*. 2006). Estimating the NRV by modelling is also at the heart of the LANDFIRE methodology.

We modelled the NRV because quantitative data about the distribution of structural vegetative classes and fires were absent for Mount Grant. Models were developed using Vegetation Dynamics Development Tool software (*VDDT* from ESSA Technologies, Inc., http://www.essa.com/downloads/vddt/download.htm, accessed January 2005; Barrett 2001; Beukema *et al*. 2003) and methods were based on the LANDFIRE Vegetation Dynamics Modelling Manual (The Nature Conservancy *et al*. 2006; http://www.landfire.gov/participate_veg_workshops.php, hyperlink: vegetation modelling manual, accessed August 2006). Seven LANDFIRE VDDT models were parameterised with succession and fire disturbance probabilities reflecting either

Table 1. Potential natural vegetation types (PNVT) of Mount Grant and equivalent LANDFIRE ecological systems used to obtain the natural range of variability (NRV)

Original PNVT	LANDFIRE ecological system	LANDFIRE mapping zone	LANDFIRE code
Infrequent fire pinyon–juniper	Juniper steppe and pinyon–juniper steppe woodland (infrequent fire)	Great Basin Region	R2PIJU[A]
Low sagebrush	Intermountain basins montane sagebrush steppe (low)	16	1126 Low[B]
Curlleaf mountain mahogany	Intermountain basins mountain mahogany woodland and shrubland	12 and 17	1062[B]
Mountain big sagebrush (no tree invasion)	Intermountain basins montane sagebrush steppe	Great Basin Region	R2SBMT[A]
Wyoming big sagebrush with potential for pinyon–juniper invasion	Intermountain basins big sagebrush shrubland	16, 12 and 17	1080[B]
Riparian mountain meadow	Rocky Mountain riparian herbaceous (crosswalk requires interpretation and compromise with old PNVG)	16	1164[B]
Mixed desert shrub	Intermountain basins semi-desert shrub steppe	16	1127[B]

[A]From LANDFIRE's Rapid Assessment modelling for the Great Basin Region.
[B]From National-LANDFIRE models developed for the Great Basin Region Mapping Zones 12, 16, and 17. Within the LANDFIRE process, coarse-scale Rapid Assessment modelling preceded finer-scale National-LANDFIRE modelling.

presettlement or natural post-settlement conditions and run with 10 Monte Carlo replicates for 500–1000 years, or until the distribution of structural vegetation classes of each PNVT stabilised. The most important outputs of these models were the percentage of each structural vegetation class on the landscape (e.g. percentage of the mid-development open class in low sagebrush), the fire return intervals for replacement, mixed severity, surface fires, and the total fire return interval.

The seven VDDT models for Mount Grant were obtained from two sources (Table 1) used to model the NRV: (1) The LANDFIRE Rapid Assessment models (www.landfire.gov/ModelsPage1.html, accessed November 2007) were developed based on a series of regional expert workshops in 2004–2005, was the source of two models (Infrequent Fire Pinyon–Juniper and Mountain Big Sagebrush Without Tree Invasion). (2) National-LANDFIRE models (www.landfire.gov/VegetationModels.html, November 2007), which were developed for mapping zones 16 (Utah High Plateau), 12 (Western Great Basin), and 17 (Eastern Great Basin) through series of regional expert workshops, peer-reviewed, and completed in 2005 were used for the remaining five models. LANDFIRE models were designed for a specific region and incorporated the most recent ecological knowledge on estimated successional transition times, fire frequency and severity, and disturbance probabilities between a relatively simple set of structural vegetation classes (PNVT classes) expected to occur historically, and representing vegetation reference conditions (Table 2). The description of each PNVT, models, and parameter values are downloadable from www.landfire.gov/reference_models.php (accessed November 2007) for the Rapid Assessment products (PNVTs will soon be downloadable from National-LANDFIRE as Biophysical Settings) or obtained from L. Provencher for National-LANDFIRE. These descriptions include sections on the geographic distribution, biophysical setting, vegetation composition, disturbance regimes, comments by experts, structural vegetation classes (i.e. early, mid-closed, mid-open, late-open, and late-closed) and their dynamics, and the mean fire return intervals for surface, mixed severity, and replacement fire.

Classifying and mapping current vegetation development and canopy cover

We used IKONOS satellite imagery (4-m multispectral resolution; SpaceImaging Corporation, Dulles, VA, USA; Taylor 2005) to classify and map vegetation types, vegetation development, and canopy cover. IKONOS satellite imagery of the Mount Grant area was obtained on 10 July 2004, during a period of maximum vegetation productivity.

For the majority of the assessment, an unsupervised classification of the IKONOS satellite imagery resulted in mapping spectral classes (defined in Lilles and Kiefer 2000) obtained by thematic stratification that were evaluated against field-based data, and existing Geographic Information System (GIS) data, aerial imagery, or any other available ancillary data to determine the relationship between the spectral classes from the satellite imagery and current structural vegetation classes listed in Table 2. As spectral classes were defined, the unsupervised classification was repeated for the remaining undefined spectral classes. Other ancillary data included GIS data such as the US Geological Survey's (USGS) Digital Elevation Model and USA Environmental Protection Agency's GAP classification data used to aid in refining the resulting map through minor GIS modelling. The US Geological Survey GAP vegetation data had limited usefulness because it misclassified PNVTs and did not resolve fine spatial patterns among them. GIS models included the use of elevation and aspect zones to correctly assign a structural vegetation class depending on whether or not a PNVT was correctly defined. For example, any wooded structural vegetation classes of pinyon–juniper woodland could be found on a steep slope, whereas significant cover of pinyon and juniper on a shallow slope would generally be assigned to a late-development closed

Table 2. Natural range of variability (NRV) percentages per potential natural vegetation types (PNVT)
The terms early-, mid-, and late-development referred to the succession age of a PNVT recovering from a stand-replacing disturbance, and were determined by experts and the literature. The conditions 'open' and 'closed' refer to the upper layer plant species, not necessarily the dominant plant species, and were not based on an absolute cover value, but are relative to the potential natural maximum canopy closure of a PNVT. PJ, pinyon–juniper

Structural vegetation classes	PNVT: Infrequent fire PJ (%)	Low sagebrush (%)	Mountain mahogany (%)	Mountain big sagebrush (%)	Wyoming with PJ (%)	Riparian mountain meadow (%)	Mixed desert shrub
Early	5	10	10	20	15	5	10
Mid closed	5	N/A	15	35	25	70	40
Mid open	15	35	10	45	50	10	50
Late open	35	N/A	20	N/A	N/A	N/A	N/A
Late closed	40	55	45	N/A	5	15	N/A
Late wooded (for Wyoming/ PJ invasion)[A]	N/A	N/A	N/A	N/A	5	N/A	N/A

[A]Late-development wooded is not used in LANDFIRE terminology.

or wooded class of either Wyoming or mountain big sagebrush PNVT on loamy soil depending on elevation.

The most important and early step of the unsupervised classification was the collection of field data from 29 to 31 July 2004 for 94 preselected sites corresponding to specific spectral classes of interest that could not be classified or that were tentatively identified to a combination of PNVT and structural vegetation classes. At each field site, a set of digital photographs was taken and specific visual estimates of existing vegetative cover were made to fully characterise the current vegetation type, current structural vegetation class (i.e. early-, mid-, or late-development), and current vegetative canopy cover (i.e. open, closed, or wooded).

The field data, which also included subjective field notes and expert opinion, were combined, when necessary, with ancillary GIS data to create a penultimate map of structural vegetation classes that was designed to be verified in the field. Also, for areas exhibiting spectral anomalies or known errors that could not be efficiently and effectively corrected through further automated image processing techniques, manual editing was infrequently employed after field visits to enhance the thematic accuracy of the final map.

The penultimate draft of the structural vegetation class map was qualitatively verified with 61 preselected plots on 23 June, 21 July, and 13 October 2005. Additional unplanned plot visits also contributed to verification. Although estimates of error rates between the previous and penultimate maps were calculated, they were likely biased because a formal quantitative assessment using a statistically robust sampling design, such as random and stratified random, was not feasible and would have cost more than the current study. Our field assessment used targeting sampling by qualitatively locating plots to represent the range of spectral classes or thematic attributes. Verification plots were preferentially situated close to roads and trails, or accessible roadless terrain and there was not a direct relationship between the verification of interpreted spectral classes and the frequency of those spectral classes throughout the landscape. At each plot, we determined whether or not the mapped PNVT and structural vegetation class were correct. We also briefly described the vegetation and bare ground cover and other characteristics such as soil colour and slope, and we photographed the plot. Field data were used in a final iteration of thematic characterisation of structural vegetation classes. The last iteration in the final draft map of structural vegetation classes was used to calculate the FRCC.

Calculating and mapping departure in vegetation, and fire frequency and severity

The departure in vegetation development classes was calculated by comparing the structural vegetation class proportions obtained from the modelled NRV by PNVT to the proportions of structural vegetation classes in the current vegetation condition. The general methodology employed is described by Hann *et al.* (2003*a*) and can be applied at any spatial scale.

Percentage area coverage of each structural vegetation class (i.e. early development, mid-development closed, mid-development open, late-development closed, late-development open, or late-development wooded) for each PNVT was computed from the final structural vegetation class map for the current condition and indicated the cover of the current structural vegetative class within each PNVT. These current vegetative condition cover proportions were directly compared with the NRV proportions (Table 2) calculated through VDDT modelling for each PNVT. By summing the lowest of the two area coverage percentages between the NRV and current conditions for each structural vegetation class combination, a measure of 'similarity' was obtained. Subtracting this similarity measure from '100' rendered a measure of 'dissimilarity' between the NRV and current conditions:

$$\text{Fire Regime Condition} = 100\% - \sum_{i=1}^{n} \min\{Current_i, NRV_i\}$$

where n is the number of structural vegetation classes used in the analysis for each PNVT, $Current_i$ is the percentage of pixels in the current vegetation class i, and NRV_i is the percentage of pixels that should be in vegetation class i according to VDDT models.

Following US interagency protocols and publications on FRCC (Hann and Bunnell 2001; Schmidt *et al.* 2002; Hann and Strom 2003), dissimilarity measures (i.e. combined vegetation and fire regime departures, which we lacked) ranging from 0 to 33% per PNVT were classified as 'intact' or unaltered (FRCC 1). Departures ranging from 34 to 66% and 67 to 100% were classified as 'moderate' (FRCC 2) or 'high' (FRCC 3) departure, respectively.

Mapping departed structural vegetation classes

Maps of FRCC are less informative and practical to managers than a PNVT-specific map of departure that identifies the over- and under-represented structural vegetation classes in a landscape. Although users understand that a whole PNVT is assigned one FRCC value (i.e. every pixel in a given PNVT has the same FRCC value), they do not always grasp that each pixel also belongs to a vegetation development class that may be either similar, under-represented, or over-represented compared with the NRV regardless of its FRCC value. Therefore, in addition to the calculation of FRCC across the Mount Grant study area, we identified vegetation structural classes that departed from vegetation reference conditions by comparing percentages between the current conditions and NRV values. We evaluated each 4-m pixel on the map based on the relationship between current conditions and NRV. If the current percentage of a class is ±5% within the NRV, the vegetation development class is similar to the vegetation reference condition and the percentage should be *maintained*. Otherwise, the vegetation development class differs from reference conditions and its percentage needs to be either *decreased* or *increased* depending on whether it is, respectively, too abundant or too under-represented compared with the vegetation reference condition. These data are referred to as the Management Action Map when plotted spatially. The terms 'decreased', 'maintained', and 'increased' do not apply to fuels loads, but to the percentage of the structural vegetation class throughout the landscape. Therefore, not all pixels that differ from reference conditions require management because these data only indicate that a pixel belonged to a structural vegetation class that departed from the NRV by more than 5%. The 5% buffer around the NRV percentage was arbitrary and chosen based on trial-and-error experimentation and practical considerations. The point of the 5% buffer is to show true difference in departure, but not disqualify structural vegetation classes that are only moderately departed. In practical terms, we might want to identify structural vegetation classes that at least differed moderately because the amount of corresponding area that is treatable after management constraints are applied can shrink so much as to limit the manager's ability to restore a landscape to a lower FRCC. Moderately departed structural vegetation classes might also be easier or cheaper to treat than highly departed classes (Forbis *et al*. 2006) and contribute just as much to an improved FRCC. The Management Action Map used in conjunction with the FRCC map can provide strong guidance for identifying alternative areas needing management action, such as fuels reduction.

Results

Mapping PNVTs

Seven PNVTs were interpreted from the NRCS soil survey: mixed desert shrub, Wyoming big sagebrush (*Artemisia tridentata* spp. *wyomingensis*) with pinyon–juniper, infrequent-fire pinyon–juniper, curlleaf mountain mahogany, low sagebrush, mountain big sagebrush, riparian mountain meadow. Models and descriptions of these PNVTs were ultimately obtained from the FRCC Guidebook and LANDFIRE (Table 1).

The draft map of PNVTs (Fig. 3*a*) was refined with the 1990 map from J. Nachlinger (unpubl. data, 1990; Fig. 3*b*) and IKONOS imagery (Fig. 3*c*) to separate those PNVTs that might belong to different landforms, slopes, and soils. The result of this process provided a broad-scale characterisation of PNVTs throughout the Mount Grant study area that more closely and appropriately matched the spatial resolution of the 4-m IKONOS satellite imagery (Fig. 3*c*). The greatest challenge encountered in using current imagery to separate PNVTs was to differentiate shrubland inclusions from the first two vegetation development classes of pinyon–juniper woodlands. This problem represented only a small fraction of the area on Mount Grant. Shrub cover in pinyon–juniper woodlands is generally much lower and mineral soil more exposed than in both of the big sagebrush PNVTs.

Non-random field verification results showed an overall mislabelling rate of 11% for PNVTs (Table 3). Low sagebrush and Wyoming big sagebrush were mislabelled most often (21.4 and 20.0%, respectively), whereas mountain big sagebrush, mixed desert shrub, and riparian mountain meadow were always correctly identified. Infrequent-fire pinyon–juniper woodlands and curlleaf mountain mahogany were both incorrectly classified at an intermediate rate of 11%.

Modelling the NRV

Table 2 contains the modelled NRV values based on vegetation structure and composition. The infrequent-fire pinyon–juniper, curlleaf mountain mahogany, and low sagebrush PNVTs were dominated by late-development classes that were both open (5–30% cover for mountain mahogany and 11–30% for pinyon–juniper) and closed (10–55% cover for mountain mahogany and 21–40% for pinyon–juniper) for the woodlands and closed (11–20% cover) for low sagebrush. The mixed desert shrub, Wyoming big sagebrush, mountain big sagebrush, and riparian mountain meadow PNVTs were dominated by mid-development classes, which were open for the upland PNVTs (5–15% cover for mixed salt desert shrub, 11–25% cover for Wyoming big sagebrush, and 6–25% for mountain big sagebrush) but closed (80–100% herbaceous cover) for the riparian mountain meadow.

Classifying and mapping structural vegetation class and canopy cover

The current conditions land cover map using the PNVT terminology (Fig. 4) and the structural vegetation class map (Fig. 5) were derived from the processed 4-m IKONOS satellite imagery. Non-random field verification results showed an overall mislabelling rate of 16.7% for structural vegetation classes, provided that the PNVT was correctly identified (Table 3). The percentages of mislabelled structural vegetation classes varied from 100% for mixed desert shrub, 40% for Wyoming big sagebrush, and 33.3% for riparian mountain meadow to 0% for curlleaf mountain mahogany (Table 3). Cheatgrass detection was the greatest source of mislabelling of structural vegetation classes for mixed desert shrub and Wyoming big sagebrush PNVTs. Also, one unplanned visit to large areas of pinyon–juniper woodlands revealed that one spectral class that

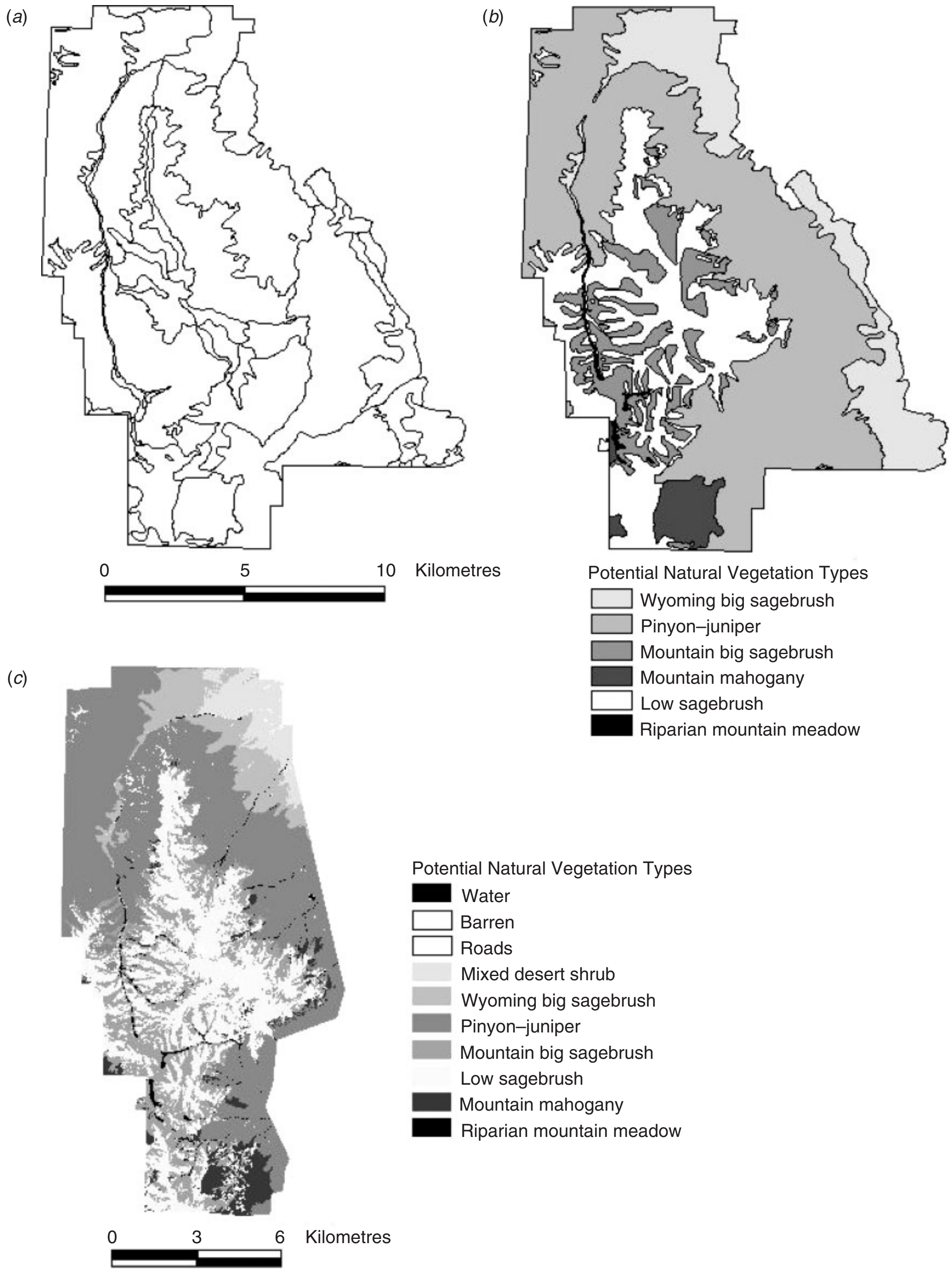

Fig. 3. Potential Natural Vegetation Type (PNVT) map developed from Natural Resources Conservation Service (NRCS) soils data, The Nature Conservancy plant community classification mapping (J. Nachlinger, unpubl. data, 1990), and IKONOS satellite imagery (10 July 2004). (*a*) First draft of the interpreted USDA NRCS soil survey showing only polygons of soil associations; (*b*) improved PNVT map obtained by overlaying the interpreted soil survey and vegetation mapping conducted by Nachlinger (1990); and (*c*) final PNVT map obtained by refining the map shown in (*b*) with IKONOS satellite imagery. Note that the boundary of final map differed from those of (*a*) and (*b*) as a tradeoff between the cost of IKONOS imagery and shape requirements imposed by SpaceImaging Corporation.

Table 3. Percentage of verification plots where (1) potential natural vegetation types (PNVTs) were incorrectly identified, and (2) structural vegetation classes were incorrectly identified by imagery interpretation given the correct PNVT was found on site

A total of pre-assigned 61 plots were visited. Plots were chosen because imagery interpretation indicated ambiguous colour or texture characteristics; therefore, plots were not randomly chosen and were generally located close to roads and trails for convenience

PNVT	Percentage PNVT incorrect	Percentage of structural vegetation classes incorrect given PNVT was correct	Number of verification plots
Infrequent fire pinyon–juniper	11.1	11.1	9
Low sagebrush	21.4	7.1	14
Curlleaf mountain mahogany	11.1	0.0	18
Mountain big sagebrush (no tree invasion)	0.0	10.0	10
Wyoming big sagebrush with potential for pinyon–juniper invasion	20.0	40.0	5
Riparian mountain meadow	0.0	33.3	3
Mixed desert shrub	0.0	100	2
Percentage of total plots incorrect	11.5	16.7	

was initially interpreted as mid-development closed vegetation was, in fact, a late-development open class. Because this spectral class was very common, it changed the FRCC from 3 to 1. Fig. 5 represented the final version.

Calculating and mapping departure in vegetation

Infrequent-fire pinyon–juniper and curlleaf mountain mahogany were largely intact relative to modelled vegetation reference conditions (FRCC 1), whereas low sagebrush, mountain big sagebrush, Wyoming big sagebrush, and mixed desert shrub were moderately degraded owing to a greater than expected proportion of either late-development vegetation classes or uncharacteristic classes (FRCC 2; Table 4; Fig. 6). Only riparian mountain meadow was highly departed from the NRV (FRCC 3) owing to the under-representation of the younger vegetation class and the dominance of woody (shrubs and trees) vegetation cover, the older vegetation development class. The Fire Regime Condition, which is a continuous percentage value representing ecological departure between the current conditions and NRV, was close to the class limits between different FRCCs for many PNVTs (Table 4). Low sagebrush and mountain big sagebrush, respectively, were within 1–2 percentage points from being in FRCC 1 and 3, respectively, whereas Wyoming big sagebrush and riparian mountain meadow were within 4 percentage points from being in FRCC 3 and 2, respectively. The FRCC 2 for low sagebrush, which has a long fire return interval, was the result of a combination of encroachment of mostly pinyon into high-elevation low sagebrush and over-representation of late-development structural vegetation classes of low sagebrush compared with the NRV. The FRCC 2 for the mountain big sagebrush PNVT was consistent with an early field survey that revealed the predominance of late-development closed shrub cover.

Mapping departed structural vegetation classes

For all shrubland PNVTs and the riparian mountain meadow, the most common recommended action for reaching the NRV was to decrease the percentage of late-development closed vegetation states and cheatgrass (in Wyoming big sagebrush) and increase the percentage of early and mid-development open (closed for the riparian mountain meadow) pixels (Table 2 *v.* Table 4; Table 5). In other words, late-development structural vegetation classes are currently too abundant in these PNVTs. For woodlands sites (infrequent-fire pinyon–juniper and curlleaf mountain mahogany), the recommended action was primarily to increase the percentage of late-development structural vegetation classes.

Discussion

Currently, Hawthorne Army Depot does not have a fuels crew to implement prescribed burns and other fuel reduction operations or fire management plan for Mount Grant – complete fire suppression is the default policy. We mapped FRCC as a first step of data acquisition for Hawthorne Army Depot to develop an interagency fire management plan to address the practical need of attacking wildfire incidents within and outside its ownership and to protect surface water and conservation of natural resources by managing fuels. We supported this effort by implementing the methodology of Shlisky and Hann (2003) and incorporated additional data from a soil survey, field verification, and high-resolution imagery to refine maps.

Lessons learned

Three lessons were learned during the present project and all greatly affected FRCC calculations.

(1) Verifying interpreted spectral classes using field data during various stages of the project greatly improved the accuracy of the mapping project. However, field verification is often the first task eliminated or reduced in scope when financial resources are limited. We conducted three field surveys to broadly define large landforms and PNVT types, to define ranges for vegetation development and cover, and finally to verify the interpretation of spectral classes to structural vegetation classes. As a result of the third field verification, we were able to more accurately identify the spectral

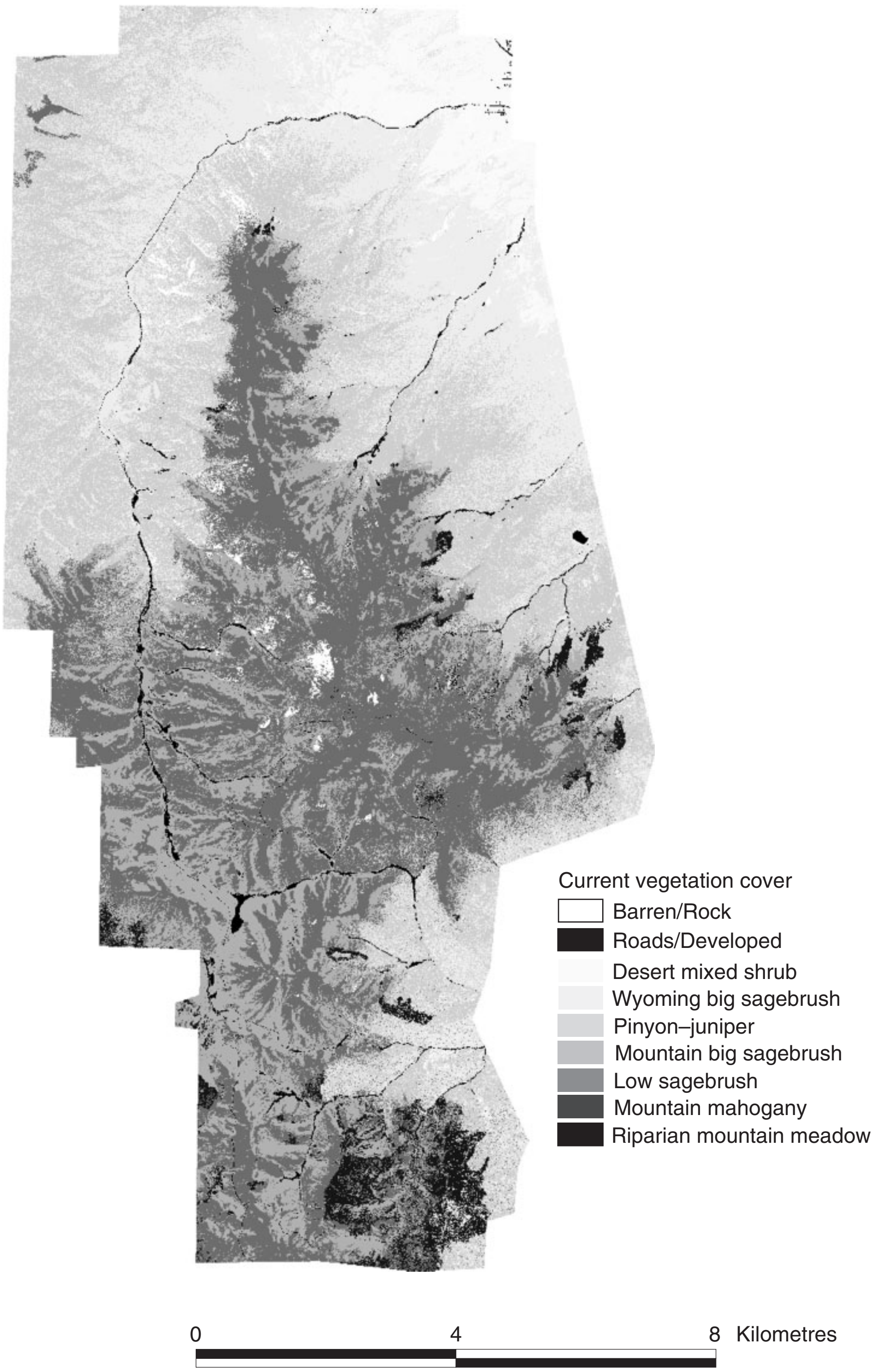

Fig. 4. Current Land Cover Classification developed from IKONOS satellite imagery. The map is based on raster data.

classes dominated by cheatgrass and the FRCC of four PNVTs changed substantially. Other local-scale FRCC mapping projects (Hann and Strom 2003; Shlisky *et al*. 2003; Hann 2004; McNicoll and Hann 2004) have used available field data or expert knowledge to classify spectral classes *a priori*, but did not describe field methods or results to test the accuracy of their maps after completing of the mapping process.

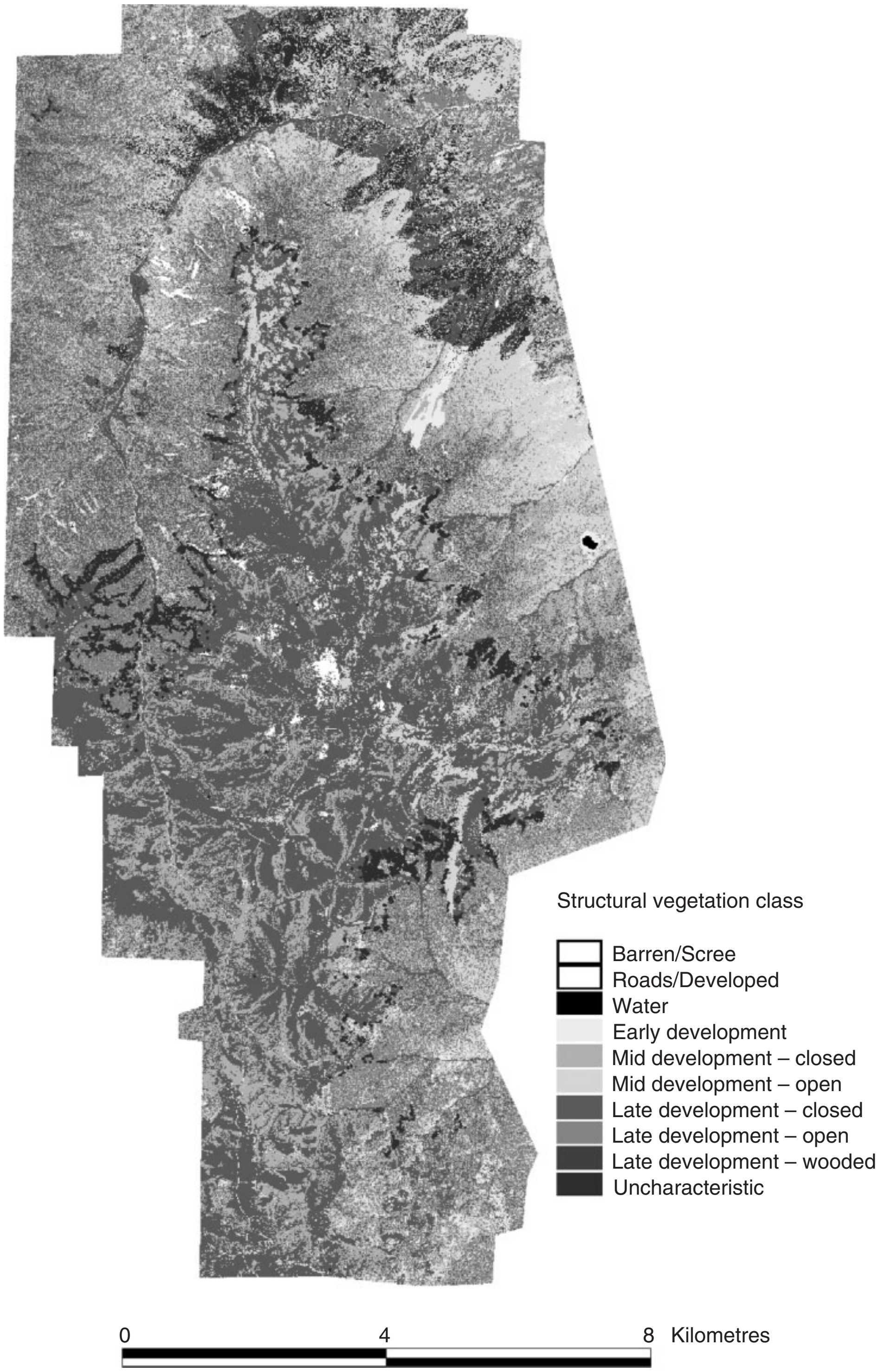

Fig. 5. Current structural vegetation class classification developed from IKONOS satellite imagery.

(2) Soil surveys from the USDA NRCS are often the only data available to create a first approximation of a complete PNVT map for local-scale assessments and, therefore, these data are invaluable for mapping FRCC. For relatively intact landscapes that function naturally today, the PNVT map should theoretically be the current vegetation type map. Previous FRCC mapping efforts have followed the local-scale methodology using current vegetation data layers as

Table 4. Percentages for the current condition of structural vegetation classes by potential natural vegetation type (PNVT) at Mount Grant
Fire regime condition class is given in bottom line where 1 represents intact condition, 2 is moderate departure condition, and 3 is high departure condition. PJ, pinyon–juniper; FMCC, Fire Regime Condition Class

Structural vegetation classes	PNVT						
	Infrequent fire PJ	Low sagebrush	Mountain mahogany	Mountain big sagebrush	Wyoming with PJ	Riparian mountain meadow	Mixed desert shrub
Early	3.0	0.8	11.4	0.6	0.2	0.2	2.0
Mid closed	22.0	N/A	21.3	54.5	8.7	11.2	2.9
Mid open	24.0	11.0	21.2	0.1	20.5	2.7	41.2
Late open	24.0	N/A	25.3	N/A	N/A	N/A	26.3
Late closed	26.0	82.6	20.8	35.3	32.8	85.9	12.0
Late wooded (for Wyoming/ PJ invasion)	N/A	N/A	N/A	N/A	3.3	N/A	
Late – uncharacteristic					0.1		
Early – uncharacteristic	1.0				34.4		15.6
PJ invaded – uncharacteristic		5.6		9.5			
Sum of lower percentages (SIMILARITY)[A]	73.0	66.8	75.8	35.7	39.4	29.1	46.1
DISSIMILARITY	27.0	33.2	24.2	64.3	60.6	70.9	53.9
FRCC	1	2	1	2	2	3	2

[A]Similarity was based on differences between reference values from Table 2 and actual current values provided here and calculated using index from Shlisky and Hann (2003).

the potential vegetation with either USDA Forest Service vegetation mapping data (Hann and Strom 2003), USGS GAP mapping data (McNicoll and Hann 2004), USDA Forest Service vegetation mapping and field assessments (Hann 2004), or classified digital orthophoto quadrangles (Shlisky *et al*. 2003). None of these studies used NRCS soil surveys to map the vegetation reference condition, probably because soil surveys were unavailable on the US Forest Service lands where these studies were conducted. Maps of PNVTs should be distinct from current vegetation maps for altered landscapes, otherwise part of the departure between natural and current conditions due to species expansion or contraction caused by management will not be included in calculations of FRCC.

For altered landscapes, we know of only two sources of information to map vegetation for local-scale assessment that, by definition, might have existed at presettlement. One option is to model the position of vegetation types based on biophysical rules using GIS software and data layers (Keane *et al*. 2002). The GIS option was not available to us because those rules and the data were largely non-existent. The second option is to interpret a soil survey using the correlation between soil type and vegetation type proposed by NRCS. A single soil survey at the county level can take years to complete because it requires extensive field visits to identify plant species, dig and analyse soil pits and characterise landforms, remote sensing analysis of aerial photography and satellite imagery, and extensive internal agency quality control. Despite the effort invested in soil surveys, application of the local-scale FRCC mapping method required further refinement of soil associations to distinguish PNVTs, especially where fire regimes or vegetation structures were significantly different from natural conditions.

(3) In addition to modelling PNVTs and estimating NRV values, ecologists must fully describe the PNVT and, especially, the cover values, vegetation height, dominant and upper-layer plant species, and dominant signature species. Without these descriptions, the remote sensing specialist lacks the needed information to separate structural vegetation classes. At the onset of the project in 2004, we did not have this information and this resulted in confusion and additional costs. The descriptions of PNVT from LANDFIRE's Rapid Assessment (PNVT) or National-LANDFIRE (Biophysical Settings) provide comprehensive information that can be locally modified.

Spatial scale

Calculated FRCC values can theoretically vary with spatial scale if the size of the stratification unit greatly changes the proportion of vegetation structural classes (Hann 2004). In the present study, current condition percentages and FRCC values were calculated by PNVT considering the entire study area as one stratification unit. We also could have summarised structural vegetation class percentages for the current condition and calculated FRCC values at several spatial stratification units (e.g. sub-watershed, first order hydrologic units). An approach of this sort would have rendered a more spatially robust characterisation of FRCC; however, there is a lower area limit below which FRCC calculation becomes nonsensical because a few development classes dominate current condition as an artefact of size. We encountered the problem of insufficient PNVT size with Wyoming big sagebrush and mixed desert shrub. These systems were extensive outside of the project area, but the artificial ownership boundary forced us to assess small portions of these shrublands found at the lower elevations. For Wyoming big sagebrush, a simple remedy

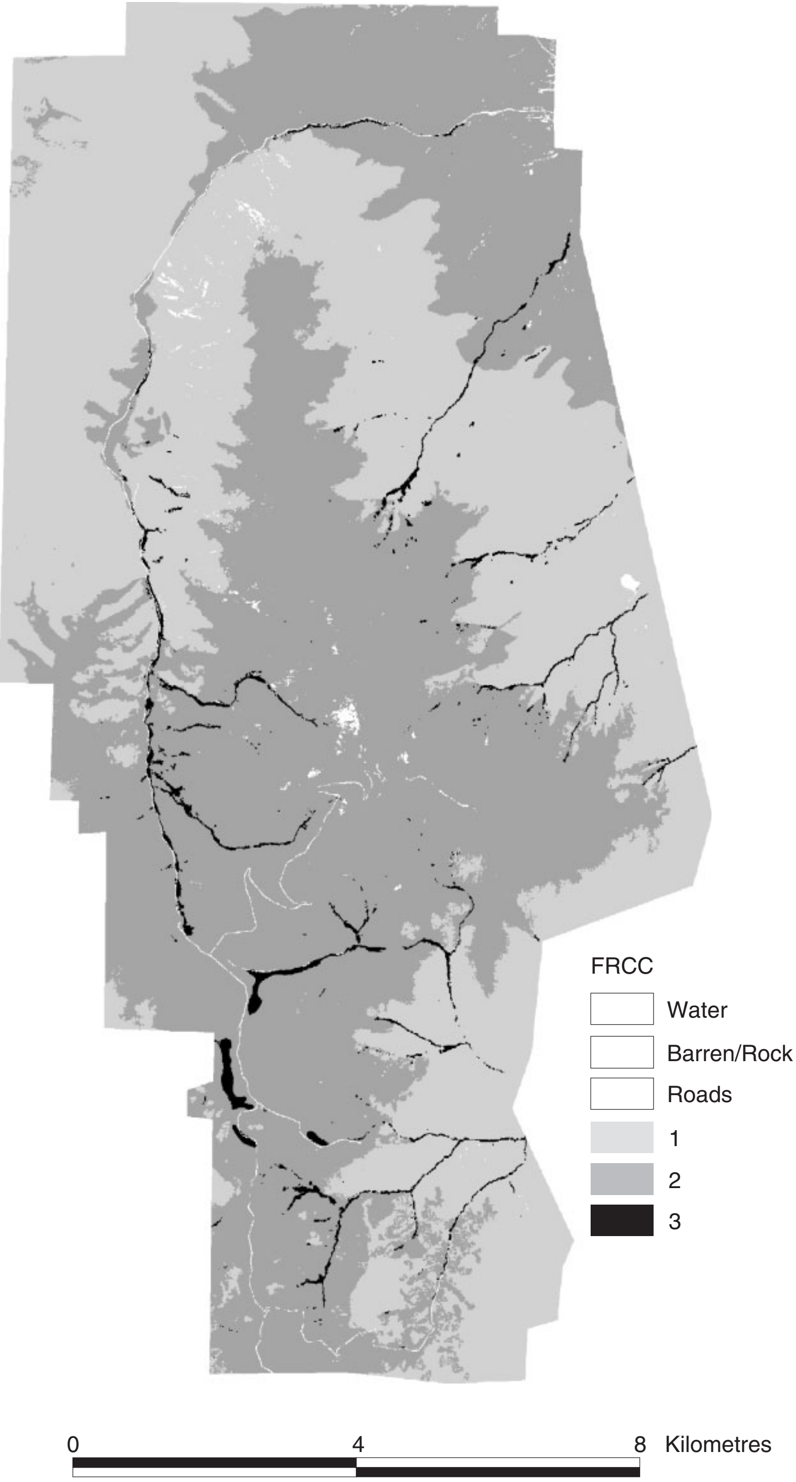

Fig. 6. Fire Regime Condition Class (FRCC) Map for Mount Grant. FRCC 1 is considered intact, whereas FRCC 2 and FRCC 3 are interpreted as moderate and high departure from natural range of variability, respectively.

to increasing area would have been to add a narrow belt of vegetation below pinyon–juniper woodlands, assuming additional funding. The more appropriate action for mixed desert shrub would have been to exclude it or merge it with Wyoming big sagebrush. Although Hawthorne Army Depot managers should critically evaluate the FRCC 2 for Wyoming big sagebrush and mixed desert shrub, their main challenge is controlling extensive cheatgrass invasion at the lower elevations.

Table 5. Recommended actions obtained by comparing the current condition to the natural range of variability (NRV) by structural vegetation classes for each potential natural vegetation type (PNVT) at Mount Grant

PJ, pinyon–juniper

	Infrequent fire PJ	Low sagebrush	Mountain mahogany	Mountain big sagebrush	Wyoming with PJ	Riparian mountain meadow	Mixed desert shrub
Early	Increase	Increase	Maintain	Increase	Increase	Maintain	Increase
Mid closed	Maintain	N/A	Maintain	Decrease	Increase	Increase	Increase
Mid open	Maintain	Increase	Decrease	Increase	Increase	Increase	Increase
Late open	Increase	N/A	Increase	N/A	N/A	N/A	Decrease
Late closed	Decrease	Decrease	Maintain	Decrease	Decrease	Decrease	Decrease
Late wooded (for Wyoming/ PJ invasion)	N/A	N/A	N/A	N/A	Maintain	N/A	
Late – uncharacteristic					Decrease		
Early – uncharacteristic					Decrease		
PJ invaded – uncharacteristic		Decrease		Decrease			

FRCC v. *Management Action Map*

Much attention is placed on FRCC maps because the information is used to prioritise wildland fuels management funding under the 2003 Healthy Forest Restoration Act in the USA (Congressional Bill H.R. 1904). For fuels management project planning, however, FRCC maps are less useful than a PNVT-specific Management Action Map. We have not shown the Management Action Map here because we found that managers (and the authors) have difficulty understanding it because too much information is summarised in a few management classes, whereas they easily grasp the results per PNVT in tabular form (Table 5) or when one Management Action Map is presented per PNVT; thus at most seven maps would be required for the current project. FRCC is a landscape-scale metric with true meaning at a scale that captures the full distribution of all vegetation development stages and fire regimes, whereas the Management Action Map shows the structural vegetation classes that might be targeted for fuels management because their proportions in the landscape depart from the NRV. Fuels management projects may be planned by applying constraints and decision rules to the Management Action Map, such as Wilderness Areas restrictions, military restrictions, inaccessible landforms, degree of departure, availability of methods to treat a fuel type, and so on. In the case of Hawthorne Army Depot, the next step would be to use the FRCC map and, especially, the Management Action Map data to identify restoration projects that support the military mission through natural resources management.

Management implications based on tested assumptions

FRCC results were counter-intuitive for Mount Grant and suggested several management activities different than initially anticipated.

First, we assumed that Mount Grant's pinyon–juniper woodlands would at least moderately depart from the NRV because other Great Basin woodlands show higher than expected tree density. The main cause of pinyon–juniper woodland densification (recruitment of younger trees under the older trees; Burkhardt and Tisdale 1976; Tausch *et al*. 1981; West 1999; Weisberg *et al*. 2007) is apparently decreased competition between grass and pinyon or juniper seedlings due to the removal of grasses by historic livestock grazing, mostly by domestic sheep. Active management would be required to counter the effect of densification, especially to prevent post-fire sedimentation into perennial water corridors. Our assumption proved wrong as pinyon–juniper woodlands had an FRCC of 1 and required no special management, including prescribed fire, because the mean fire return interval is long (>200 years for replacement fire). In fact, the mountain slopes supporting pinyon–juniper woodlands were sufficiently steep as to preclude future mechanical operations and past anthropogenic disturbances, including livestock grazing.

Second, we expected that the riparian mountain meadow PNVT should be protected from fire to maintain surface water quality by preventing sedimentation. The primary concern was that fire within the riparian corridor or from pinyon–juniper woodlands on surrounding slopes would cause massive sedimentation and affect the untreated water supply of Hawthorne Army Depot. Both the FRCC Map and Management Action data, however, identified a need for more urgent management attention, perhaps in the form of prescribed burning of shrub-dominant cover in riparian corridors to increase the herbaceous component. Greater cover of native bunchgrasses would form a barrier to sedimentation.

Third, we did not expect low sagebrush to moderately depart from the NRV because this PNVT, which is found mostly at higher elevation, experiences only infrequent fire (Table 4), and hence was assumed to be less affected by fire exclusion practices. Tree encroachment and over-representation of the late-development structural class were the causes of departure for low sagebrush. It is possible that naturally low cover values for low sagebrush rendered separation of the mid- and late-development classes more difficult; thus it may be a source of misclassification between these types (Table 3). The more serious concern for managers, however, should be the encroachment of pinyon from below, often from tree-encroached mountain big sagebrush, into high-elevation low sagebrush, because trees would make this habitat type unsuitable for Greater Sage-grouse (Connelly *et al*. 2000). The extent of this problem on Mount Grant is small enough to be reasonably remedied with mechanical thinning of trees in the low sagebrush PNVT and mosaic prescribed burning of low sagebrush by starting fire in mountain big sagebrush encroached by trees. The problem of tree encroachment into low sagebrush is, however, a more widespread problem in other regions of the Intermountain West, especially where a greater number of conifer species can encroach into low sagebrush.

Fourth, we assumed that fire exclusion was the source of more late-development closed mountain big sagebrush than expected under the NRV. This PNVT is close to becoming highly departed from the NRV and is important Greater Sage-grouse nesting and winter habitat. The 'typical' mountain big sagebrush can experience mean fire return intervals from 40 to 80 years (Burkhardt and Tisdale 1969, 1976; Houston 1973; Miller and Fowler 1994; Miller and Rose 1995; Miller *et al*. 2000; Crawford *et al*. 2004), which is a range consistent with the 50-year mean fire return interval used in the LANDFIRE VDDT model of the current project. The mountain big sagebrush PNVT on Mount Grant, however, is frequently found in elongated patches on concave landforms surrounded by large patches of low sagebrush (Fig. 3), which act as a fire break. We are uncertain, therefore, if the VDDT model for mountain big sagebrush is adequate or needs to be adjusted to reflect a naturally longer fire return interval caused by the spatial influence of low sagebrush, which could change the NRV. A prudent management approach given this uncertainty would be to conduct small, patchy prescribed burns to increase herbaceous and insect productivity for Greater Sage-grouse chick rearing and minimise the size of the early development vegetation class, which cannot be used as winter habitat by Greater Sage-grouse (Connelly *et al*. 2000; Crawford *et al*. 2004).

Conclusions

We implemented the local-scale FRCC methodology proposed by Shlisky and Hann (2003) to help Hawthorne Army Depot managers address their key resource management priorities for Mount Grant. Our analysis for Mount Grant used information not usually incorporated in published FRCC studies: interpreted NRCS soil surveys, high-resolution satellite imagery, and field visits to verify the interpretation of satellite imagery. Although soil surveys may not be readily available, high to moderate resolution imageries are available and field verification is generally feasible. The accuracy of these projects is limited by funding to purchase and, especially, analyse imagery and to pay field crews. The small investment we made in field visits before and after interpretation of imagery was probably the most important contribution to improve the accuracy of maps for Mount Grant. The greatest challenge to mapping FRCC is the development of the PNVT map, which should not be the current vegetation type map unless ecological systems are functioning naturally in the landscape of interest. In places where soil surveys or LANDFIRE products are not available, users will have little choice but to combine GIS modelling and current imagery to map PNVT. We found that local soil scientists who study the interaction between vegetation types and soil properties often have the best understanding of biophysical rules needed in GIS modelling for PNVT mapping. Soil scientists also work at a level of spatial analysis that is often finer than required by FRCC mapping; therefore, interdisciplinary teams that include a soil scientist, an ecologist with experience developing more general VDDT models, and a GIS and remote sensing expert are more likely to succeed in mapping PNVTs than any of these individuals working independently.

Acknowledgements

Research was funded by the USDA Forest Service, Department of the Interior, and The Nature Conservancy's 'Restoring Fire Adapted Ecosystems' cooperative agreement (No. 02-CA-11132543–037) and the Department of Defence, Legacy Resource Management Program (No. DACA87–00-H-0002). Brian McMenamy and Mike Polly provided GIS assistance, and Ayn Shlisky supplied riparian VDDT models. We are especially grateful to Jim Purrell and John Peterson from Hawthorne Army Depot for support, logistic help, and participation, and to Ayn Shlisky, Doug Zollner, and Lynn Decker from TNC's Global Fire Initiative. Ayn Shlisky, Doug Zollner, Kelly Pohl, Andrea Litt, and two anonymous reviewers generously reviewed earlier drafts of the manuscript. Mention of a proprietary product does not constitute a guarantee or warranty of the product by the Department of Defence or the authors and does not imply its approval to the exclusion of the other products that also may be suitable.

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Manuscript received 31 May 2007, accepted 18 December 2007