

Decision support tools to improve the effectiveness of hazardous fuel reduction treatments in the New Jersey Pine Barrens

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Abstract. Our goal is to assist the New Jersey Forest Fire Service and federal wildland fire managers in the New Jersey Pine Barrens evaluate where and when to conduct hazardous fuel reduction treatments. We used remotely sensed LIDAR (Light Detection and Ranging System) data and field sampling to estimate fuel loads and consumption during prescribed fire treatments. This information was integrated with data on prescribed fire treatments conducted by the New Jersey Forest Fire Service over the last 15 years to produce and interpret maps of current fuel loads. Forest productivity measurements and models were then used to estimate rates of fuel accumulation through time. We could then calculate return intervals for desired fuel load conditions. Through formal workshops and frequent discussions with state and federal fire managers, our results enhance the ability of these agencies to make key decisions regarding the effectiveness and longevity of hazardous fuels treatments.

Additional keywords: forest productivity, fuel accumulation, fuel load estimates, LIDAR, prescribed fire treatments.

Introduction

The Healthy Forest Restoration Act of 2003 (Public Law 108–148) mandates hazardous fuel reduction treatments throughout public forests in the United States. To comply, fire managers must: (1) quantify hazardous fuel loads; (2) evaluate the efficiency of hazardous fuel reduction treatments; (3) determine rates of fuel accumulation and changes in fuel structure through time; and (4) select appropriate return intervals for repeated fuel reduction treatments. Collectively, these activities are time-consuming, expensive, and typically beyond the scope of most wildfire management agencies. However, decision support systems exist within the scientific and policy communities to map forest structure and estimate forest productivity, with the ultimate goal of quantifying carbon sequestration from landscape to global scales. Decision support systems use a combination of field measurements such as Forest Inventory and Analysis data (FIA; <http://fia.fs.fed.us/>, accessed June 2007), information collected in the Ameriflux and Fluxnet forest carbon networks (<http://public.ornl.gov/ameriflux/>, accessed June 2007), ecosystem models such as PnET-CN (Pan *et al.* 2006) and Biome BioGeochemical Cycles (BiomeBGC) (Thornton *et al.* 2002), and remotely sensed products such as those derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Pan *et al.* 2006; <http://modis.gsfc.nasa.gov>, accessed June 2007) to estimate forest structure and productivity. Unfortunately, this

information is generally underutilized by the fire community, although it would assist managers to plan and maintain effective fuel reduction treatments.

Wildland fire managers in the Pine Barrens of New Jersey, specifically the New Jersey Forest Fire Service (NJFFS) and federal fire managers at Fort Dix Army Base, Warren Grove and other military installations, conduct prescribed burns on ~8000 to 12 000 ha of public forest per year. They have two major goals when using prescribed fire: to reduce fuels on the forest floor, and to reduce the occurrence of ladder fuels. Ladder fuels, consisting of shrubs and subcanopy foliage and branches, increase vertical and horizontal fuel continuity, and can facilitate the transition of surface fires to the canopy, where they are much more difficult and expensive to suppress. Although a framework exists to plan and prioritize fuel reduction treatments within the NJFFS and other agencies, information is limited regarding rates of hazardous fuel accumulation; thus the appropriate return intervals for fuel reduction treatments for each forest type are currently debated. However, a strong need exists to prioritize and maximize the effectiveness of fuel reduction treatments, because of the increasing cost of conducting treatments, and because conflicting goals of other agencies may reduce the ability of the NJFFS to achieve their goals. For example, the US Environmental Protection Agency has mandated a reduction in emissions of particulate matter, ozone and other pollutants from all sources in

the region, including wildfires and prescribed fire treatments. In addition, population densities at the margins of the Pine Barrens are steadily growing, thus the wildland–urban interface (WUI) is substantial and increasing (Lathrop and Kaplan 2004).

To assist the NJFFS and federal wildfire managers in the NJ Pine Barrens, we:

- (1) Estimated hazardous fuel loads at the landscape level, using Light Detection and Ranging (LIDAR) measurements of canopy height and field measurements to characterize forest structure and fuel loads. We then produced a spatially explicit database and maps of ladder fuels and fuel continuity in the Pine Barrens, and identified sites that could be prioritized for fuel treatments.
- (2) Evaluated the efficiency of prescribed fires in reducing ladder fuels and fuel continuity in the understory and fuels on the forest floor, using a combination of LIDAR data to estimate ladder fuel structure, and pre- and post-prescribed fire measurements to evaluate the consumption of fine and 10-h fuels. We produced LIDAR maps of ladder fuels and fuel continuity for selected areas in the Pine Barrens, focussing on federally and state-owned lands that have a well-characterized history of hazardous fuel reduction treatments.
- (3) Determined rates of fuel accumulation and changes in fuel structure through time, using three existing decision-support tools for the evaluation of forest production and carbon sequestration by forests: forest inventory and biometric measurements made in the field, forest productivity models, and remotely sensed information on forest productivity and fuel accumulation. By identifying areas where fuel reduction treatments have been conducted in the context of fuel accumulation measurements, we can calculate how long each treatment will fulfil the required objective of reducing fuels.

Methods

Site description

Research was based at the Silas Little Experimental Forest of the US Forest Service, Northern Research Station, managed by Rutgers University as the Pinelands Field Station (38°54.90'N, 74°35.90'W), ~6 km south of New Lisbon, NJ. Established in 1933, the experimental forest has a long history of fire management research (e.g. Little and Moore 1949). Upland forest sites are located in Burlington and Ocean Counties in the Pinelands Management Area, southern New Jersey, USA. The Pine Barrens encompass 445 000 ha (1.1 million acres) of pine, oak and wetland forests, covering 23% of New Jersey, and are recognized by United Nations Educational Scientific and Cultural Organization (UNESCO) as a Man and the Biosphere Programme (MAB) Reserve. The climate is cool temperate, with mean monthly temperatures of 0.3° and 23.8°C in January and June respectively (1930–2004; State Climatologist of New Jersey, see <http://climate.rutgers.edu/njwxnet/>, accessed August 2007). Mean annual precipitation is 1123 ± 182 mm. Soils are coarse-textured, sandy, acidic, and have extremely low cation-exchange capacity and nutrient status (Tedrow 1986). Despite the widespread occurrence of sandy, well-drained, nutrient-poor soils, upland forests are moderately productive and fuels accumulate rapidly (Pan *et al.* 2006). Upland forests comprise 62%

Table 1. Major forest types in the Pinelands of New Jersey and their extent (adapted from Lathrop and Kaplan 2004)

Forest type	% of landscape	Area (km ²)
Upland forests		
Oak–Pine	19.1	726
Pine–Oak	13.1	497
Pitch Pine–Scrub Oak	14.3	542
Wetland forests		
Pitch Pine lowland	12.3	468
Mixed Hardwood–Conifer	8.6	326
Hardwood swamp	6.0	228
Atlantic White Cedar swamp	1.4	53

of forested lands in the Pine Barrens, and are dominated by three major communities: oak-dominated forests with scattered pines (Oak–Pine), pine-dominated forests with oaks in the overstorey (Pine–Oak), and pitch pine-dominated forests with scrub oaks in the understory (Pine–Scrub Oak) (McCormick and Jones 1973; Lathrop and Kaplan 2004; Table 1). For the analyses here, we classified dwarf pine stands as Pitch Pine–Scrub Oak forest. All upland forests have moderate to dense shrub cover in the understory, primarily *Vaccinium* spp., *Galussacia* spp., *Kalmia* spp., and *Quercus* spp., and sedges, mosses, and lichens also can be present.

There are strong seasonal effects on the occurrence and severity of wildfires in the Pine Barrens. For example, leafless conditions result in larger amounts of solar radiation reaching the forest floor, accelerating the moisture dynamics of fine and 10-h fuels. Needle moisture content of pitch pine can fluctuate up to 40% seasonally, with the minimum occurring in spring. Wind fields also differ seasonally, with the 1 November to 15 May period much windier on average than the summer months. On ignition during drought conditions in any season, abundant shrubs and ladder fuels can result in crowning and severe wildfire behavior. Upland forests are of major concern to fire managers, because of their occurrence adjacent to dense residential developments and key transportation corridors.

LIDAR and fuel loading measurements

LIDAR measurements were made using a portable airborne laser system described by Nelson *et al.* (2003), mounted on a Bell Jet Ranger helicopter operated by the NJFFS. We flew 63 LIDAR lines spaced at 1 km across ~202 500 ha, covering most of the Pinelands Management Area (see Skowronski *et al.* 2007 for details). The laser was programmed to record helicopter-to-canopy heights at 400 Hz by averaging raw 1200-Hz data. The helicopter flew at 100-m height at ~50 m s⁻¹; thus, LIDAR returns were spaced ~0.125 m apart along each line. A downward pointing video camera was used to record the area sampled, and a Geographical Positioning System recorded position to within 5–7 m. Data were recorded on a laptop computer running *Labview* data acquisition software (National Instruments, Austin, TX). Ground elevation was extrapolated from unvegetated surfaces (roads, water, etc.) at ~100 m intervals using cubic spline interpolation (Nelson *et al.* 2003), and was similar to the United States Geological Service (USGS)

Digital Elevation Map (DEM) elevations. Each LIDAR return was classified using a 2001 New Jersey land cover map generated from Landsat images in a Geographical Information System (GIS) database (Table 1; Lathrop and Kaplan 2004). LIDAR returns were then grouped into 80-m segments within each forest type for analysis.

Following Skowronski *et al.* (2007), LIDAR data were analyzed by grouping data into 1-m height classes by normalizing returns for each height class:

Number of returns for the 1st height class:

$$n = (R_n/R_{\text{total}}) \times 100$$

Number of returns for the 2nd height class:

$$n + 1 = (R_{n+1}/(R_{\text{total}} - R_n)) \times 100$$

where R_n is the number of returns from the upper 1 m of the canopy, R_{total} is the total number of returns along the segment, and R_{n+1} is the number of returns from the next lower 1-m layer of the canopy. We used normalized LIDAR returns from height classes 1–2, 2–3, and 3–4 m, because data from 0–1 m in height proved unusable owing to noise generated from the ground spline. We derived a scale from LIDAR measurements to rapidly detect the density of ladder fuels and horizontal fuel continuity by summing data for 1–4-m height classes. Cover classes were color-coded, using green dots to indicate 0–10% of normalized LIDAR returns at 1–4 m in height, which represented 0–10% cover value of shrubs, scrub oaks, and ladder fuels in the understorey along each 80-m segment, and red dots to indicate 40–100% of normalized LIDAR returns at 1–4 m in height, which represented the >40% cover values. Landscape-scale maps of the occurrence of ladder fuels derived from LIDAR measurements were produced to indicate the location and density of hazardous fuels.

Fine (1-h), 10-h, and 100-h fuels were sampled on the forest floor in 23 stands throughout the Pine Barrens. Fine fuels were defined as leaves, needles, and dead stems <0.625 cm diameter, 10-h fuels as dead stems with a diameter of 0.625 to 2.5 cm, and 100-h fuels as dead stems with a diameter of 2.5 to 7.6 cm. Stands were located in the Brendan T. Byrne State Forest, Greenwood Wildlife Management Area, Fort Dix, and Wharton State Forest. Fuel mass on the forest floor was sampled using ten 1-m² quadrats at random locations throughout each stand. We sampled the 'L' horizon, and samples were separated into fine, 10-h, and 100-h fuels, dried at 70°C, and weighed. Fuel depths were also measured at each site, using $n = 10$ to 20 measurements of the L horizon around each 1-m² quadrat. ANOVAs were used to determine significant differences in fuel loading among forest types (Sokal and Rohlf 1995).

Evaluation of fuel reduction treatments

We first developed a GIS database of prescribed fire treatments conducted by the NJFFS and fire managers at Fort Dix from 1990 to 2006, located in the forest areas described above for fuel loading measurements. LIDAR data for 1–4-m heights were integrated with maps produced from the prescribed fire database. We then sampled 17 prescribed burns in upland forests from 2004 to 2006 to quantify fuel combustion during treatments. Sampling encompassed stands with a wide range of tree densities and fuel loadings, and prescribed fires were conducted over a

range of fuel moisture and fuel temperature conditions. Pre- and post-treatment forest floor measurements (ten 1-m² quadrats at random locations within each treatment block) were used to calculate the consumption of fine, 10-h, and 100-h fuels at each site. Pre- and post-fire forest floor depth measurements ($n = 10$ to 20) were made around each 1-m² quadrat. Meteorological data, fuel moisture contents and temperatures, and other ancillary data were recorded from fire weather towers in the Pine Barrens.

Rates of fuel accumulation

Three methods were used to estimate forest productivity and fuel accumulation rates in the Pine Barrens: forest census measurements to estimate fuel production and decomposition, validated models of aboveground net primary production (ANPP), partitioned into fuel types, and remotely sensed predictions of NPP and fuel accumulation. Carbon flux sites in the Ameriflux and Fluxnet networks use extensive forest census measurements in concert with eddy covariance measurements from towers to quantify carbon sequestration and its partitioning into various components (see <http://public.ornl.gov/ameriflux/>). Currently, the United States Forest Service (USFS) operates three flux sites in representative upland forests in the Pine Barrens: an Oak–Pine stand at Silas Little Experimental Forest, a Pine–Oak stand at Fort Dix, and a Pine–Scrub Oak stand at Cedar Bridge (Skowronski *et al.* 2007).

We used forest inventory measurements to quantify the accumulation of live, fine, 10-h, and 100-h fuels at each site. Tree inventories and measurements of diameter at 1.3 m (diameter at breast height, DBH) and height were conducted annually in five 200-m² plots located within 100 m of the tower at each site. Tree biomass and growth increments were estimated from published allometric relationships (Whittaker and Woodwell 1968) and destructive sampling at each site (Wright *et al.* 2007). Annual aboveground biomass production of understorey oaks, shrubs and herbaceous plants was estimated using clip plots (1.0 m²; $n = 10$ to 20 plots per site). Samples were separated into leaf and stems for seedlings, saplings and shrubs, and sedges and herbs, dried at 60°C, and weighed. Accumulation of fine and 10-h fuels on the forest floor was estimated from litterfall collected monthly from ten 0.42-m² traps located at random locations within 100 m of the tower at each site. Litterbags (10 × 20 cm, 1-mm mesh size) containing 5 g of pine needles, oak foliage, or shrub foliage were used to estimate decomposition of fine fuels. Litterbags ($n = 40$ for each component) were placed at random locations within the vicinity of each tree census plot. Collectively, these measurements were used to estimate accumulation and loss rates of live, fine, 10-h, and 100-h fuels.

Our second method to estimate forest productivity and its partitioning into fuel types was using PnET-CN, a process-based model of stand carbon dynamics (Pan *et al.* 2006). We used field measurements and literature values to estimate parameters for PnET-CN, and model predictions were evaluated against eddy covariance measurements made at the tower sites. We then used the model to estimate current rates of forest productivity in the major upland forest types, and partitioned these into individual fuel types. We assumed that allocation to foliage and fine roots was similar, and that allocation to coarse roots below ground was ~20% of that to stems above ground (Whittaker and

Woodwell 1968; Gholz *et al.* 1994). In conjunction with field measurements to estimate allocation, partitioned model predictions can be used to estimate fuel accumulation rates at landscape to regional scales, much larger areas than can be measured realistically in the field. We used a similar approach for the remotely sensed estimate of forest production, and partitioned Moderate Resolution Imaging Spectroradiometer (MODIS) satellite

estimates of NPP for the Pine Barrens into fuel types based on results from field measurements.

Results and discussion

LIDAR and fuel loading measurements

Sites with heavy fuel loads, dense fuel bed depths >2 m in height, and high horizontal continuity (40–100% shrub and ladder fuel

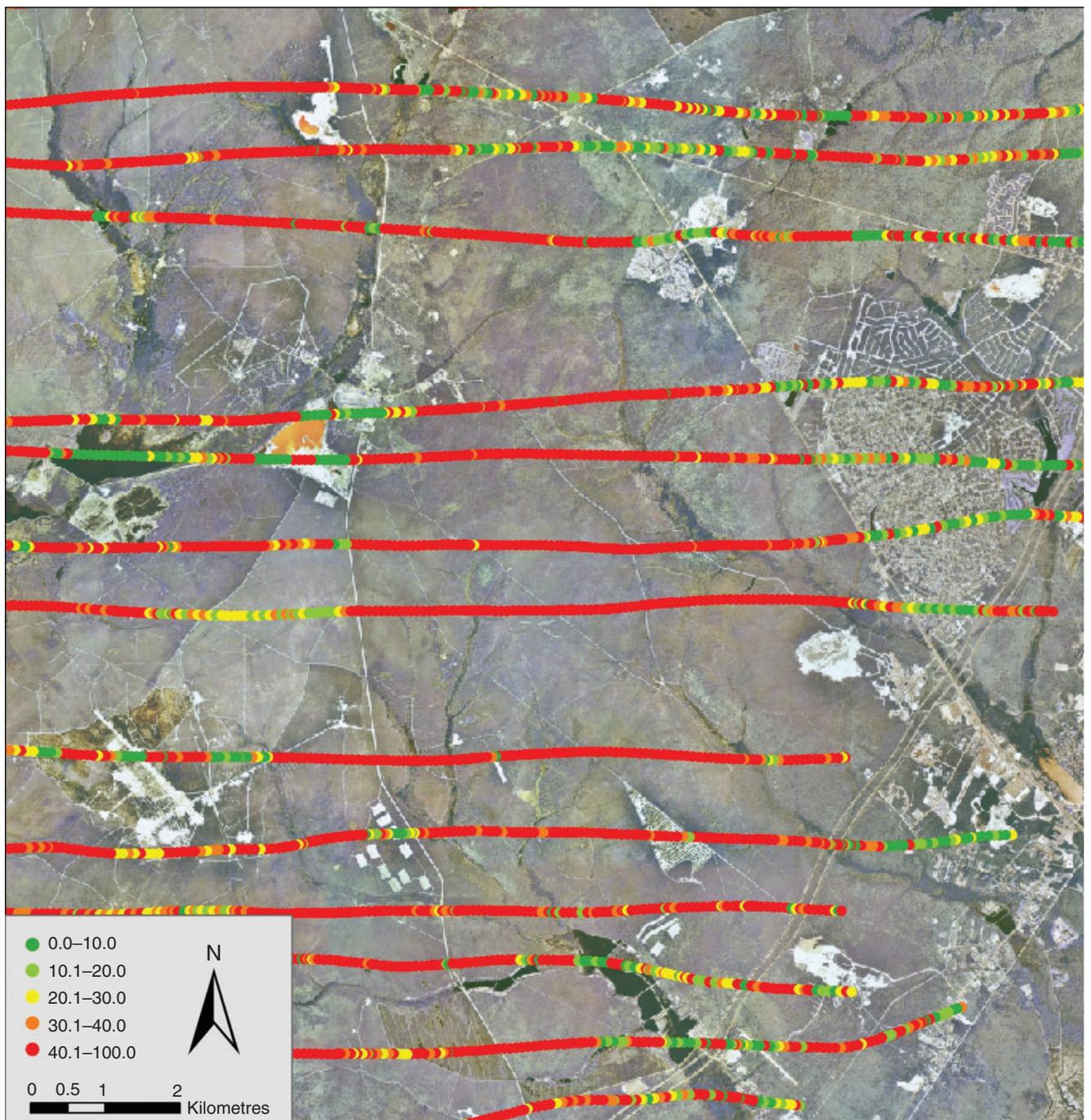


Fig. 1. A map of pooled 1–4-m height normalized LIDAR returns, color-coded to indicate cover classes in 10% increments, superimposed on an aerial photo indicating large fuel accumulations near Stafford Township.

cover) were readily detected on maps generated from binned LIDAR data (red LIDAR lines in Fig. 1). We identified at least five areas in the Pine Barrens with heavy to very heavy fuel loads adjacent to WUI. For example, Fig. 1 shows accumulated hazardous fuels in a large Pine–Scrub Oak stand near Stafford Township in the central Pine Barrens. LIDAR data indicate a nearly unbroken 7-km stretch of forest with abundant ladder fuels, and fuel continuity $\geq 40\%$ in the understorey. Following this analysis, the majority of the area with heavy fuel loads in Fig. 1 burned in a severe wildfire on 15–19 May 2007. The Warren Grove wildfire consumed ~ 8200 ha of forest and damaged or destroyed 41 structures. Areas such as this could be prioritized for treatment, using a combination of prescribed fire and mechanical fuel treatments.

Field sampling indicated that 1-h and 10-h fuels on the forest floor ranged from low values of 4.8 ± 2.6 and $1.3 \pm 0.6 \text{ t ha}^{-1}$ (mean ± 1 s.d.) in fuel treatment strips to 14.6 ± 2.9 and $4.8 \pm 2.6 \text{ t ha}^{-1}$ in a Pitch Pine–Scrub Oak stand that had not burned since at least 1963, respectively (Table 2). Oak–Pine and Pine–Oak stands had lower 1-h and 10-h fuel loadings than Pitch Pine–Scrub Oak stands (ANOVAs: $F = 14.9$, $P < 0.001$ for 1-h fuels, $F = 5.6$, $P < 0.05$ for 10-h fuels, $F = 13.5$, $P < 0.001$ for total loading). A second ‘old’ forest floor that occurred in a Pitch Pine–Scrub Oak stand that had not burned since at least 1963 was characterized by large 1-h fuel loads ($12.4 \pm 1.6 \text{ t ha}^{-1}$), and the greatest 10-h fuel loads ($11.1 \pm 5.4 \text{ t ha}^{-1}$). Values reported in Table 3 are similar to those obtained in previous measurements in the Pine Barrens (Burns 1952; Wright *et al.* 2007).

When superimposed on the land cover classification (Lathrop and Kaplan 2004), binned LIDAR data indicated that Oak–Pine stands had the lowest density of understorey vegetation and ladder fuels at 1–4 m in height ($30.5 \pm 22.3\%$), whereas Pine–Oak and Pine–Scrub Oak stands had higher densities ($44.9 \pm 24.1\%$

Table 2. Summary of 1-h and 10-h fuel loading measurements in upland forests in the Pine Barrens

Data are mean $\text{t ha}^{-1} \pm 1$ s.d. of mean values calculated from ten 1-m^2 plots located at random points throughout each stand. Stand types with different superscripts are significantly different at $P < 0.001$ for 1-h fuels, $P < 0.05$ for 10-h fuels, and $P < 0.001$ for total loading

Forest type	<i>n</i>	1-h	10-h	Total
Fuel break	1	4.8 ± 2.6	1.3 ± 0.6	5.8 ± 2.8
Oak–Pine	3	8.4 ± 1.4^a	1.8 ± 1.0^a	10.7 ± 1.5^a
Pine–Oak	12	9.1 ± 1.8^a	2.1 ± 0.7^a	11.5 ± 2.3^a
Pine–Scrub Oak	7	11.9 ± 1.6^b	4.1 ± 3.2^b	16.2 ± 4.1^b

Table 3. Summary of fuel loading measurements made in upland forest types

Data are from Wright *et al.* (2007); Skowronski *et al.* (2007); K. L. Clark and N. Skowronski, unpubl. data. Fuel model fire behavior models from Scott and Burgan (2005)

Forest type	% of landscape	Fine fuels (t ha^{-1})	Fuelbed depth (m)	Fuel model
Oak–Pine	19.1	<1.0 to 4.4	0.3 to 1.0	TU2, SH3, SH4
Pine–Oak	13.1	1.7 to 8.4	0.5 to 1.7	SH4, SH6, SH8
Pine–Scrub Oak	14.3	2.2 to 12.0	0.5 to 2.1	SH6, SH8, SH9

and $42.8 \pm 23.2\%$, respectively). Areas treated using repeated prescribed fires are clearly visible in all upland forest types. We used the forest classification by Lathrop and Kaplan (2004), canopy height maps derived from the Eastern LANDFIRE prototype, forest floor measurements, and fuel photoseries data (Wright *et al.* 2007) to tentatively assign fuel models developed by Scott and Burgan (2005) to forests in the Pine Barrens (Tables 1 and 3). Fuel bed depths range from 0.6 to 2.0 m, and surface fuel loads from 3.9 to 12.0 t ha^{-1} in the humid climate shrub models proposed by Scott and Burgan (2005), similar to fuel loadings in the Pine Barrens (Skowronski *et al.* 2007; Wright *et al.* 2007; Table 3). High fuel load (SH8) and very high fuel load (SH9) humid-climate shrub models reflect fuel loadings in many Pitch Pine–Scrub Oak and dwarf pine stands well, as do observations of fire behavior in these forests. However, one limitation to this approach is that only a static fuel model map is produced. Because fuels can accumulate rapidly and the NJFFS and other agencies have an active fuel reduction program, it is important to quantify transition rates among models for an accurate representation of fuel loadings in the Pine Barrens.

Evaluation of hazardous fuels reduction treatments

Using a map of prescribed fires conducted by the NJFFS from 1990 to 2005 in Wharton Forest (Fig. 2; $n = 48$ prescribed fires, range of 20 to > 500 ha) and LIDAR data from 1 to 4 m, we could detect areas where repeated prescribed fires had been conducted when compared with less-frequently burned areas (Fig. 3). Percentage normalized LIDAR returns (mean $\% \pm 1$ s.d.) across the Pine Barrens, and in single and multiple prescribed burn blocks in Wharton Forest are shown in Fig. 4. Results indicate that understorey vegetation and ladder fuels are less dense in treatment blocks compared with the average loading across all upland forest types in the Pine Barrens, and that repeated treatments led to a near-linear decrease in fuel loading at 1–4 m in height (Fig. 4; $y = 34.55 - 5.19 \times (\text{number of prescribed burns})$, $r^2 = 0.89$).

Prescribed fires conducted in stands with a wide range of fuel loadings, fuel moisture contents, and meteorological conditions reduced 1-h and 10-h fuels in the litter layer by 0.2 to 10.5 t ha^{-1} ($5.4 \pm 0.8 \text{ t ha}^{-1}$, mean ± 1 s.e.), but had little effect on humus (O horizon) on the forest floor (Fig. 5). Reductions were greatest for sites with the highest initial loadings, but meteorological conditions during the prescribed fire also exerted an effect on rates of fuel consumption. Lettered blocks in Figs 2, 3, and 5 allow us to track fuel consumption and thus fuel loading on the surface following prescribed fire treatments in a GIS database.

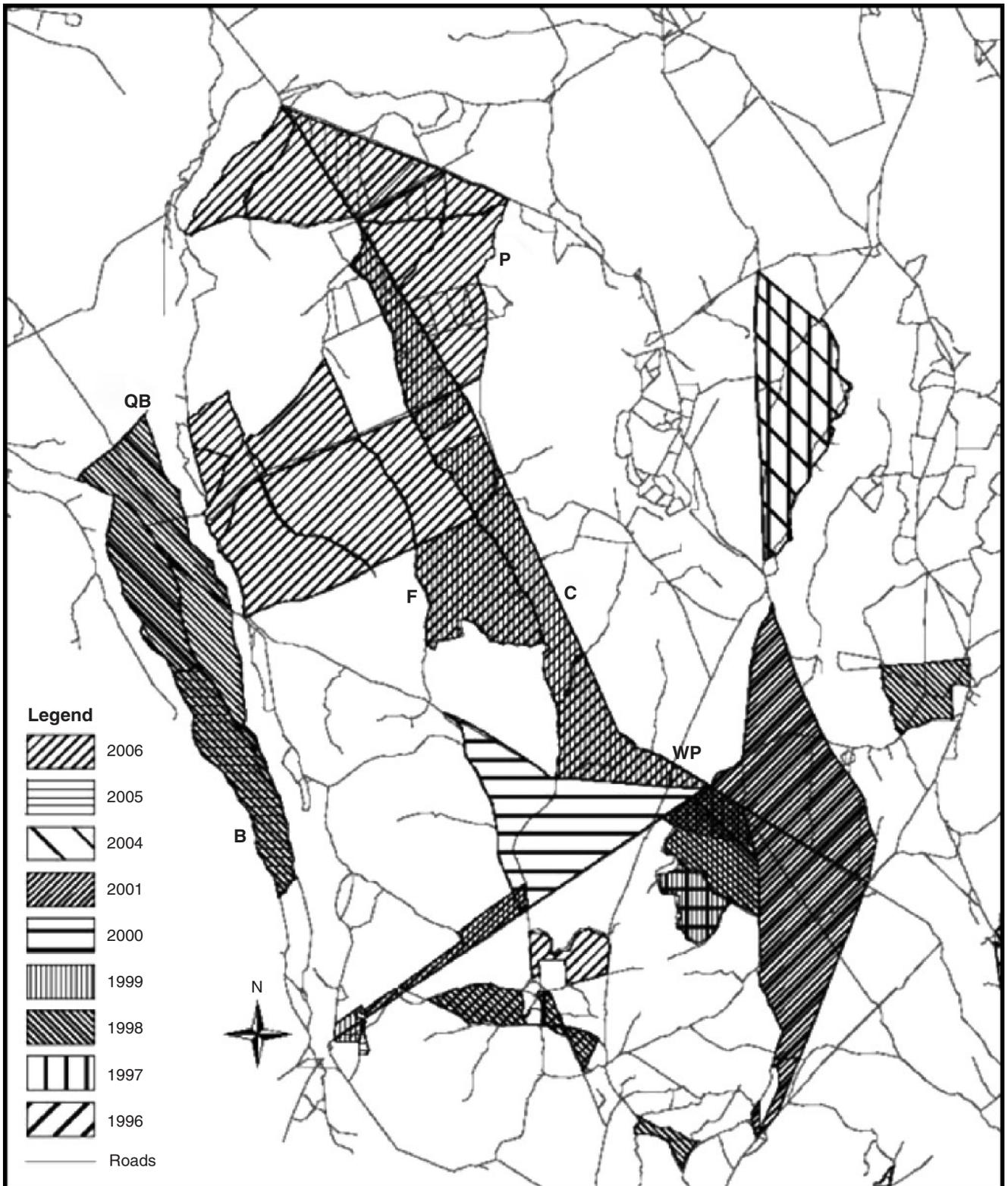


Fig. 2. A Geographical Information System map showing a 10-year history of prescribed fires conducted in Wharton State Forest in the Pine Barrens of New Jersey. Prescribed burns from 1990 to 1995 were omitted from the figure for clarity. Lettered blocks correspond to data presented in Figs 3 and 5 and are discussed in the text.

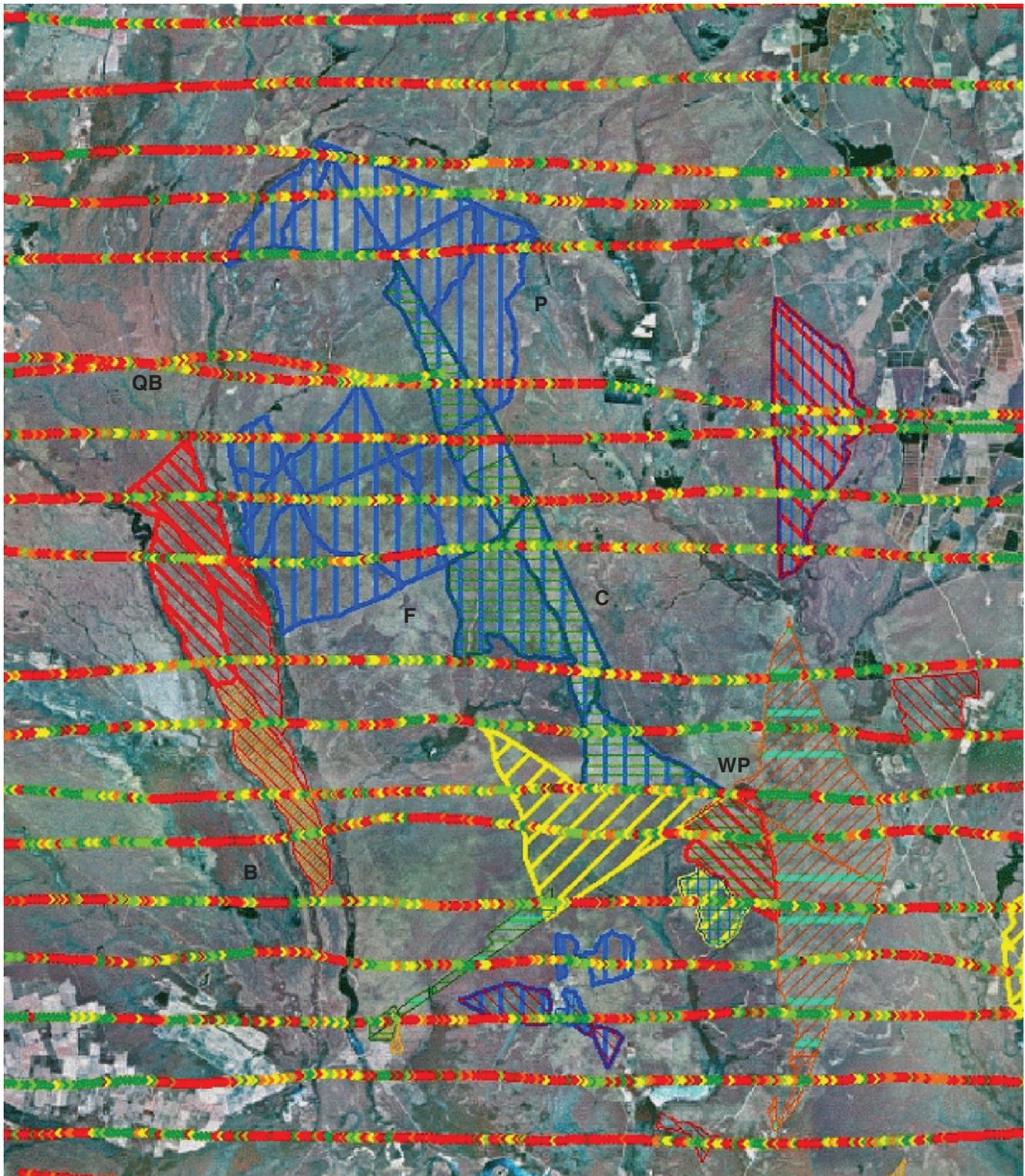


Fig. 3. A map of pooled 1–4-m height normalized LIDAR returns, color-coded to indicate cover classes in 10% increments, superimposed on prescribed fire blocks in Wharton State Forest. Blocks where repeated prescribed fires have been conducted have reduced ladder fuel and shrub cover at 1–4 m in height, whereas unburned areas are orange and red, indicating near-continuous ladder fuels and shrub cover at 1–4 m in height.

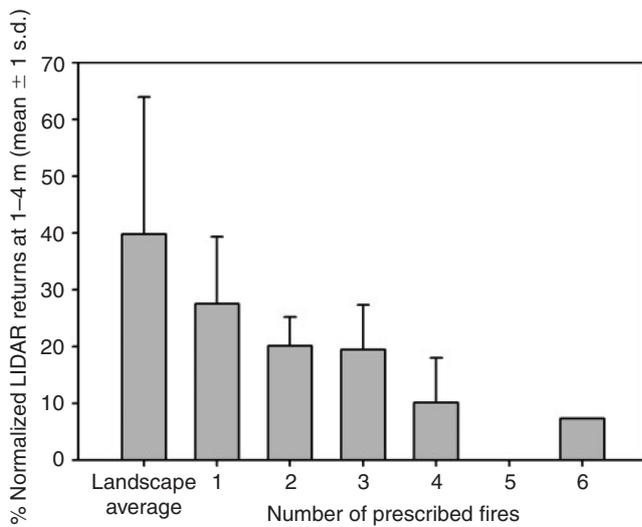


Fig. 4. Percentage normalized LIDAR returns at 1–4 m in height (mean \pm 1 s.d.) across the Pinelands Management Area, and in prescribed fire treatments. Samples sizes are $n = 18, 7, 19, 3,$ and 1 for one, two, three, four, and six prescribed burns conducted from 1990 to 2006, shown in Figs 2 and 3. Ladder fuel reduction = $34.55 - 5.19 \times (\text{number of prescribed burns})$ %, $r^2 = 0.89$.

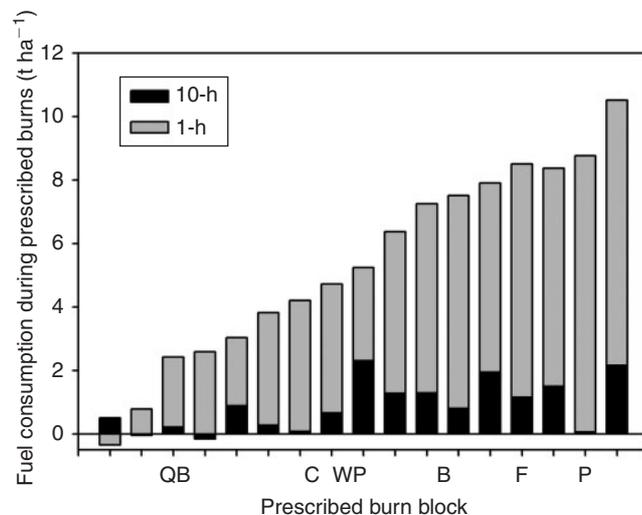


Fig. 5. Consumption of 1-h and 10-h fuels during prescribed fire treatments conducted by the New Jersey Forest Fire Service and fire managers at Fort Dix from 2004 to 2006 in the Pine Barrens of New Jersey. Values are means of 10 1-m² before and after measurements of the L horizon per treatment, and are ranked from low to high consumption values. Negative values occasionally resulted when randomly located before and after measurements were compared, and are attributed to sampling error when consumption was low. Letters indicate prescribed burn treatment locations on Figs 2 and 3.

Rates of fuel accumulation

Despite striking differences in species composition of the overstorey and in litterfall composition (i.e. oak v. pine litter), production of 1-h and 10-h fuels was similar among the three stands (Table 4). When aboveground overstorey productivity

is partitioned into fuel types, all sites are characterized by a relatively large fine and a smaller 10-h fuel production. Tree stem increment, which eventually leads to 100-h and 1000-h fuels, represents less than 33% of annual aboveground productivity. Shrub foliage production was also the major portion of total aboveground shrub production. These patterns are reflected in forest floor composition, with much greater fine fuel than 10-h and 100-h fuels in all but the 'oldest' forest floors in upland stands (Table 2). Overall, litterfall measurements averaged for all years, clip plots, and litter decomposition bags indicated that the net accumulation of fine and 10-h fuels is 3.2 ± 0.3 and $0.6 \pm 0.2 \text{ t ha}^{-1} \text{ year}^{-1}$ at all sites.

Average forest productivity (NPP) across the Pinelands Management Area estimated using PnET-CN was $8.4 \text{ t ha}^{-1} \text{ year}^{-1}$, and ranged from 7.5 to $11.7 \text{ t ha}^{-1} \text{ year}^{-1}$ (Pan *et al.* 2006). These estimates are consistent with eddy covariance measurements, and although they occur on nutrient-poor soils (Tedrow 1986), these forests maintain moderate rates of productivity compared with many other mature forests in the eastern USA (e.g. Pan *et al.* 2006; <http://public.ornl.gov/ameriflux/>). Partitioned into accumulated fuels, we estimated that fine and 10-h fuels accumulated at 3.0 ± 0.3 and $0.6 \pm 0.1 \text{ t ha}^{-1}$ across the Pinelands Management Area (Table 4). Using MODIS NPP data corrected for the effects of sandy soils and drought on rates of forest productivity in the Pine Barrens (Pan *et al.* 2006), accumulation of fine and 10-h fuels was estimated at 3.0 ± 1.2 and $0.7 \pm 0.3 \text{ t ha}^{-1}$, respectively. Both of these estimates were consistent with accumulation rates measured at the three tower sites (Table 4), illustrating the utility of this approach. However, it is important to model allocation to the various fuel types correctly.

We can now approximate the accumulation of fine, 10-h and 100-h fuels on the forest floor following prescribed fire treatments in a GIS database. Specifically, the accumulation of fuel loads on the forest floor shown in the lettered prescribed burn blocks in Figs 2 and 3 can be tracked accurately through time. Although these measurements quantify the dynamics of surface fuels, they do not characterize changes in shrub cover and ladder fuel structure through time. Because LIDAR data can be used to detect subtle changes in leaf area and forest structure (Lefsky *et al.* 2002; Parker and Russ 2004; Riaño *et al.* 2004), sequential flights combined with field measurements would be an ideal method for estimating changes in understorey and ladder fuel structure. However, using a 'time since last disturbance' approach also allows an estimation of recovery of shrub and ladder fuel structure following prescribed fire. For example, we used this approach to detect differences in fuel loading between stands where repeated fuel treatments had been conducted, with the most recent occurring 3 months previous to LIDAR flights, and an adjacent stand that had not burned for ~ 10 years (Skowronski *et al.* 2007). The proportion of LIDAR returns from vegetation at 1–4 m in height was 14.2% in the recently burned area and 39.9% in the unburned area, and we calculated that ladder fuel cover increased at $\sim 2.9\%$ per year. Similarly, total shrub and sapling cover (%) measured using Fire and Environmental Research Applications Team (FERA, see www.fs.fed.us/pnw/fera/, accessed August 2007) protocols was 36.5 ± 4.9 and $0.0 \pm 0.0\%$ in the burned site, and 72.0 ± 14.4 and $21.9 \pm 13.7\%$ in the unburned sites, respectively, a calculated increase of 2.4 and 3.9% per year. Thus, a single LIDAR

Table 4. 1-h and 10-h fuel accumulation calculated from litterfall, stem production and total production at the Oak–Pine, Pine–Oak, and Pine–Scrub Oak tower sites in the New Jersey Pine Barrens

Landscape averages of 1-h and 10-h fuel, stem and total accumulation were calculated from PnET-CN predictions of net primary productivity (mean \pm s.d.) and corrected MODIS data for the entire Pinelands Management Area (Pan *et al.* 2006; see text). All units, $\text{t ha}^{-1} \text{ year}^{-1} \pm 1$ s.d.

	1-h	10-h	Stems	Total	% 1-h
Site					
Oak–Pine	3.4 \pm 0.4	0.9 \pm 0.9	1.2 \pm 1.1	5.4	62
Pine–Oak	2.9 \pm 1.2	0.4 \pm 0.5	1.2 \pm 0.6	4.5	64
Pine–Scrub Oak	3.2 \pm 0.9	0.5 \pm 0.4	1.7 \pm 0.3	5.4	59
Stand mean	3.2 \pm 0.3	0.6 \pm 0.2	1.4 \pm 0.3	5.2 \pm 0.5	62
PnET-CN	3.0 \pm 0.3	0.6 \pm 0.1	1.4 \pm 0.1	5.0	59
MODIS	3.1 \pm 1.2	0.7 \pm 0.3	1.5 \pm 0.6	5.2	59

flight can assist in calculating increases in ladder fuels and fuel continuity at sites where hazardous fuel reduction treatments have been conducted. Fire managers can use similar calculations to make informed decisions concerning the maintenance of landscape-scale fuel breaks throughout the Pine Barrens.

Measurements of forest productivity and fuel accumulation are ongoing at many sites in the US. By integrating estimates into GIS layers, it is possible to track fine, 10-h, and 100-h fuels. Quantification of fuel reduction treatments, including before and after measurements of shrubs and saplings to estimate understorey and ladder fuel combustion, would allow a more accurate calibration of LIDAR data. A further helpful addition to this approach would be to assess crown scorch using light attenuation measurements and upward-looking LIDAR before and after fire. Much of the data presented here can be used to parameterize and validate predictions of fuel consumption models to better predict the effects of fuel reduction treatments.

We benefit from a close working relationship with the NJFFS and federal fire managers in the Pine Barrens. We provide these agencies maps of hazardous fuel loads and their connectivity, such as in Figs 1 and 3, and discuss their interpretation. We also participate in formal workshops two to three times a year, and in numerous informal discussions with fire managers. Through these channels, our results enhance the ability of these agencies to make decisions regarding the location and timing of hazardous fuel reduction treatments.

Summary

LIDAR data from 1–4 m in height can be used to detect understorey vegetation and ladder fuel structure. The combination of LIDAR data and ground measurements can be used to help guide decisions for prioritizing fuel reduction treatments, and contribute to the selection of appropriate fuel models to simulate fire behavior. Field measurements of 1-h and 10-h fuel accumulation were consistent with modeled (PnET-CN) and remotely sensed (from MODIS) estimates of forest productivity when they were partitioned into fuel types using a simple allocation scheme, allowing landscape-scale estimates. Although repeated LIDAR images would be ideal, ‘time since last treatment’ analyses can also be used to estimate the accumulation of understorey vegetation and ladder fuels. Our approach integrates a variety of decision support tools, and can assist fire managers

make important decisions regarding the efficacy and longevity of hazardous fuel reduction treatments.

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