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Research article

Effects of intensive forest management on stand and landscape characteristics in northern New Brunswick, Canada (1945–2027)

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Abstract

Historical and future projected landscape patterns and changes caused by harvesting and silviculture were evaluated for a 189,000 ha, intensively managed forest in New Brunswick, Canada. We compared changes in species composition, age classes, and patch characteristics (area, size, density, edge, shape, and core area) between 1945, 2002, and projections to 2027 (based on the landowner's spatial forest management plan). In 1945, the landbase was 40% softwood, 37% mixed hardwood–softwood, 10% hardwood, and 9% softwood–cedar. From 1945 to 2002 and 2027, respectively, softwood forest area increased by 2 and 11%, mixedwood decreased by 19 and 20%, and hardwood area increased by 15 and 14%, and softwood–cedar increased by 6% and then decreased by 7%. In 1945, forest > 70 years old comprised 85% of the landscape, but declined to 44% in 2002 and was projected to encompass 41% in 2027. Increased area harvested, decreasing harvest patch size, and protection against natural disturbances resulted in progressively smaller mean and less variable patch sizes from 1945 to 2002. Based upon the 25-year forest management plan, this trend was projected to continue, with the exception of nine patches > 1000 ha created by 2027, eight of which were softwood plantations. Stand type successional dynamics were highly variable in both harvested and non-harvested areas, and in some cases were unexpected. Few of the 1945 stand types remained static by 2002, with 42 and 35% of mixedwood shifting to softwood as a result of harvesting, and to hardwood as a result of both harvesting and spruce budworm (*Choristoneura fumiferana* Clem.) outbreaks in the 1950s and 1970s. This study demonstrates the strong cumulative effect of forest management on landscape patterns, especially the socially mandated drive for smaller clearcuts resulting in the loss of large patches.

Introduction

Forest stand type and landscape patterns occur as a result of complex interactions between climate, soil, water availability, and disturbances (Krummel et al. 1987; Turner 1989; Forman 1995). Both natural disturbances (e.g., fires, insect outbreaks, and wind) and forest management influence stand type and age class distributions and patch characteristics over time, which in turn determine landscape patterns (Krummel et al. 1987; Russell et al. 1993; Axelsson et al. 2002). Forest management removes forest vegetation and may replace it with managed stands of altered structure, resulting in a mosaic of forest stands with different characteristics (Forman 1995). Landscape pattern largely determines a number of important ecological processes, such as animal movement and natural disturbances (Krummel et al. 1987; Lee et al. 2002). Therefore, understanding past, present, and future forest landscape patterns, and their influence on biodiversity and ecosystem function, is an important aspect of landscape ecology (Turner 1989; Axelsson et al. 2002; Löfman and Kouki 2003; Turner et al. 2003).

In areas where forest management has increased in intensity and extent, we must understand the role of landscape pattern in preserving, altering, or eliminating biological communities (Miller et al. 1997). One approach for maintaining healthy forest landscape conditions strives to retain spatial elements within the limits of the historical range of variability produced from past disturbances (Miller et al. 1997; Landres et al. 1999; Harvey et al. 2002). Characterizing the historical range of variability is often difficult due to lack of data, but it is possible to determine the influence of forest management on landscape pattern and identify trends of concern.

Direct effects of forest management on landscape pattern include increased fragmentation and increased edge caused by harvest blocks, and decreased core area (Wallin et al. 1994). With increased management intensity, the landscape is fragmented into smaller and simpler shaped patches (Mladenoff et al. 1993; Miller et al. 1997). Other studies have also found that management decreases interior forest habitat, decreases mean patch size, increases total number of patches, simplifies patch characteristics, decreases amount of old growth, and increases fragmentation (Iverson 1988; Pastor and Broschart 1990; Ripple et al. 1991; Spies et al. 1994; Hessburg et al. 1999; Staus et al. 2002; Turner et al. 2003). Forest management also indirectly affects landscape patterns through fire suppression and by minimizing insect outbreaks (Franklin and Forman 1987; Lehmkuhl et al. 1994; Radeloff et al. 2000), which may decrease landscape-scale diversity (Bender et al. 1998; Betts et al. 2003).

Few studies have determined the effect of management on forest landscapes over an extended period of time. Lehmkuhl et al. (1994) compared landscape pattern of 49 watersheds in Oregon and Washington from 1932 to 1992, and found less early seral and old stand types and more diverse and fragmented patterns. Hessburg et al. (2000) found decreased mean patch size and a shift from dominance by old growth to primarily young patches, from the 1930s to the 1990s. Most studies of changes in forest landscape pattern have been conducted at relatively coarse scale and used broad indicators of habitat types (Wallin et al. 1994; Tang et al. 1997).

Etheridge et al. (2005) compared species, age classes, and stand structure in 1945 and 2002, for a 189,000 ha industrial forest in northwestern New Brunswick, Canada. The area dominated by softwood remained relatively constant, with 40% in 1945 and 42% in 2002; however, mixed hardwood–softwoods decreased from 37 to 18% and hardwoods increased from 10 to 25%. As a result of management, the forest (1) became considerably younger, with 86% > 70 years old in 1945 vs. 44% in 2002; (2) developed denser stands, with 100–300 more stems/ha and 4–7 m^2/ha more basal area in 2002 than in 1945; and (3) had less balsam fir (*Abies balsamea* (L.) Mill.), which comprised 31–66% of basal area in stands with > 30% softwood in 1945, but only 4–38% by 2002. Forest management targeted purposeful balsam fir reduction because it sustains heavy mortality in spruce budworm (*Choristoneura fumiferana* (Clem.)) outbreaks. Management increased timber production while maintaining similar softwood species composition; however, age structures and areas of some forest types (e.g., mixedwood and hardwood) were altered.

In this paper, we examine the influence of forest management on landscape pattern of the same landbase examined by Etheridge et al. (2005). This industrial forest is intensively managed for timber production, includes > 60,000 ha of softwood plantations, and thus represents a good case study to determine the influence of management on patch size distribution and landscape metrics. Our objectives were to: (1) compare species composition and age class distributions in 1945 and 2002 with a modeled projection for 2027; (2) quantify changes in landscape metrics and patch size distribution; and (3) determine changes in stand type from 1945 to 2002 and 2027, for harvested and unharvested conditions. We expected that management would increase the degree of fragmentation, with more patches, smaller patches, less core area, and more edge.

Methods

Study area

Our study area was the 189,000 ha Black Brook District owned by J.D. Irving, Limited (JDI) in northwestern New Brunswick, Canada. JDI purchased the land in 1944 and it ranks among Canada's most intensively managed forests, with > 60,000 ha of softwood plantations and > 49,000 ha of high quality hardwoods managed by selection harvests. Plantations are managed on a 70–80 year rotation, with two or three commercial thinnings. The oldest plantations date from 1957 and commercial thinnings began in the early 1990s. About 20% of the area has harvesting restrictions, including no-harvest scientific reserves (3.5%), winter habitat for white tailed deer (*Odocoileus virginianus*) (4%), and partial harvesting only in watercourse buffers (10%).

In 1945, the southern portion of the District had been under a cutting license for 40 years (Lussier and Grenier 1947), but there was no reported harvesting on the less accessible northern portion prior to 1939 (Grenier 1945). Forty-four percent of the southern portion had experienced diameter limit harvesting, with a limit of 30 cm on the stump for spruce (*Picea* sp.) and eastern white cedar (*Thuja occidentalis* (L.)), and 25 cm for balsam fir (Etheridge et al. 2005). Lussier and Grenier (1947) reported that species were remarkably sound and most exhibited vigorous growth. The exception was the birches (*Betula* spp.), which were in decline during the previous 5 years due to some unknown pathogen; Lussier and Grenier (1947) speculated that if the epidemic continued the birches would disappear entirely in overmature stands.

Based upon ecological land classification (New Brunswick Department of Natural Resources and Energy (NBDNRE) 1998), the area is in the Southern Uplands Ecoregion, with elevations of 180–600 m, increasing from south to north. The District includes parts of four Ecodistricts (Madawaska River, Restigouche-Upsalquitch, Sisson Branch Reservoir, and Saint John River Ecodistricts), with similar elevations, but differing topographic relief and rainfall (NBDNRE 1998). More details about the study area are provided in Etheridge et al. (2005).

Data for 1945

A detailed cruise of the District conducted by Grenier (1945 – northern half) and Lussier and Grenier 1947 – southern half), as well as a full set of 1945 aerial photographs that had been photo-interpreted and digitized specifically for this project, provided historical data. In this paper, we refer to the 1940s cruise and photo data as 1945. Parallel cruise lines were run every 400 m in the north and 800 m in the south, referenced to perpendicular base lines established by staff compass. Every 200 m along a cruise line, a 100×10 m^2 plot was established for trees ≥10 cm diameter at breast height (dbh), with a 200 m^2 sub-plot for trees <10 cm dbh. Data recorded included tree species, dbh, age class, and, if applicable, stand origin (burn or cutover). Species recorded included spruce, balsam fir, eastern white cedar, white birch (*Betula papyrifera* March.), aspen (*Populus* sp.), yellow birch (*Betula alleghaniensis* Britt.), American beech (*Fagus grandifolia* Ehrh.), maple (*Acer saccharum* Marsh. and *Acer rubrum* L.), and a fuel-wood category including poorer quality hardwoods but not distinguishing species.

We entered the 1945 data into an Access® database, converted from English to metric units, and calculated basal area per species and stand type. Stand types included five species groups: black spruce (*Picea mariana* (Mill.) B.S.P.), softwood–cedar, softwood, mixedwood (mixed softwood and hardwoods) and hardwood; and five age classes: 0–29, 30–49, 50–69, 70–89, and 90–120 years old. We calculated percent basal area (m^2/ha) by species for each stand type class, and determined that species composition was consistent: softwood (≥70% softwood species); hardwood (≥70% hardwood); mixedwood (31–69% softwood); softwood–cedar (≥70% softwood, ≥30% cedar); and black spruce (≥70% softwood, of which black spruce ≥75%).

Maps depicting stand types, burned areas, major water courses, and harvested areas from 1939 to 1946 identified in the 1940s cruise were scanned and digitized using ARCMAP®.

2002 and 2027 data

The 2002 GIS inventory was originally based upon interpretation of 1982 color aerial photographs (1:12,500) with re-interpretation of selected stands carried out in 1996, and annual updating for timber harvesting and silviculture. The inventory included ground sampling of 110 randomly selected stands (representing 20 cover type strata) with over 600 prism plots (2.0 m^2/ha BAF). Data included species, dbh, development stage (regeneration, young, immature, and mature), % crown closure, height, and ages.

Using the STAMAN stand growth model (Vanguard Forest Management Services Ltd. 1993), the 2002 cruise stand tables for each stratum were projected for 150 years, and stand tables (species in 2-cm dbh classes) were produced by 5-year period. These stand tables were averaged by age class and categorized by stand type as for the 1945 data. Each stand in the 2002 inventory was then assigned a stand type based on these species and age categories.

Projection of the landbase to 2027 was based on a 25-year spatial management plan prepared by JDI, where the 2002 stand types were projected into the future using a Woodstock® (Remsoft 1999) timber supply model. Planned future harvest blocks had been assigned by JDI using the spatial harvesting block scheduling software Stanley® (Remsoft 2000). The projected 2027 landbase was characterized in the same manner as for the 2002 data.

Harvest characterization

Past and planned future harvest blocks, by treatment, were compiled into two separate GIS coverages: 1939–2001 and 2002–2027. There were five harvest treatments: (1) clearcutting; (2) shelterwood harvesting (approximately 300 16 m^2 openings per ha); (3) partial cutting, including diameter limit harvest from 1939 to 1977, and later partial harvests (about 125 40 m^2 openings per ha), patch cuts (one 3330 m^2 opening per ha) or salvage harvests (about 25 200 m^2 openings per ha); (4) commercial thinning (45–55% reduction in basal area of softwood plantations); and (5) single-tree selection (about 75 40 m^2 or 125 25-m^2 openings per ha). These characterizations were provided by JDI (G. Pelletier, JDI, personal communication, 2004).

Adjacent harvest blocks with the same treatment and year were combined, and harvest patch and opening sizes were calculated by 5-year period. Distributions of number and area of harvest patches by 100 ha size class (including >1000 ha as a class) were determined, by harvest treatment, in four periods: 1942–1961, 1962–1981, 1982–2001, and 2002–2027. To further examine small patches, the <100 ha size class was further analyzed by 10 ha classes.

Clearcut opening sizes were based on the area of the GIS polygon, combining adjacent clearcuts within a given 5-year period. The total area clearcut (ha), and mean, maximum, and standard deviation of opening size (ha) were calculated by year and by 5-year period.

Landscape pattern changes from 1945 to 2027

We defined patches by stand type (softwood–cedar, softwood, mixedwood, or hardwood) and age class (0–29, 30–49, 50–69, 70–89, and 90–120 years), and combined similar adjacent polygons, within each of the 1945, 2002, and 2027 databases. Since few roads existed in 1945 and the locations of future roads (in 2027) are unknown, we eliminated roads from all three periods by converting all coverages from vector to a raster grid (1 ha, 100×100 m^2), assigning predominant stand type and age class, and then converting the grid back to a vector coverage. Polygons less than 1 ha were joined to the adjacent polygon with which it shared the longest border. When calculating core area metrics (total patch area minus edge area), an edge buffer distance of 100 m was used, based on the resolution of the raster grid pixels. Areas by stand type and age class in 1945, 2002, and 2027 were then summarized.

We produced four GIS coverages for the above stand types, in 1945, 2002, and 2027, calculated the number of patches and area by stand type in

100 ha size classes. We analyzed the 12 coverages using Patch Analyst 2.2 (Rempel 1999), which produces a subset of the spatial statistics produced by FRAGSTATS (McGarigal and Marks 1995; Elkie et al. 1999). A total of 13 metrics in five categories of statistics were calculated: area, patch size and density (five metrics), edge (two metrics), shape (two metrics), and core area (three metrics). Percent change in landscape metrics from 1945–2002 to 2002–2027 was calculated:

$$\%\text{Change} = \left(\frac{\{\text{year B(Metric A)} - \text{Year A(Metric A)}\}}{\{\text{Year A(Metric A)}\}}\right) * 100 \qquad (1)$$

Changes in stand types over time were assessed by overlaying the 2002 on the 1945 coverage, and calculating percent changes among stand types for harvested and non-harvested categories. A similar method was used to determine projected changes from 2002 to 2027.

Results

Changes in stand type and age class distributions

From 1945 to 2002, the most dramatic shifts in stand types were increased hardwood area from 10 to 25%, decreased mixedwood from 37 to 18%, and increased softwood–cedar from 9 to 15% (Etheridge et al. 2005). In comparison, area changes from 2002 to 2027 are projected to be relatively minor: softwood to increase from 42 to 51%, softwood–cedar to decrease from 15 to 8%, and mixedwood and hardwood area remaining similar (Figure 1). Although the overall amount of softwood was similar in 1945 and 2002, nearly all of this area (88%) was comprised of plantations in 2002. These included 56% black spruce, 30% white spruce (*Picea glauca* (Moench) Voss), 9% Norway spruce (*Picea abies* (L.) Karst.), 3% pine (*Pinus* sp.), and 2% other species. Projections indicated that plantations will comprise 92% of all softwood stands by 2027.

In 1945, 85% of the forest was 70–120 years old (Figure 2a), but by 2002, 44% was younger than 70 years old (Figure 2b). The age-class distribution was more even in 2002 than in 1945, although there was still less area in mid-aged than young and older age classes (Figure 2b). In 2002, nearly all softwood (98%) was <70 years old, but this was projected to decrease to 59% by 2027, when 41% will be 70–120 years old (Figure 2c). As a result of plantations maturing, 0–29 year old softwood was projected to decrease from 76% in 2002 to 48% in 2027, in spite of 27,500 ha of plantations projected to be clearcut and replanted. Hardwood >70 years old was projected to increase from 77 to 97% by 2027, due to the use of single-tree selection and partial harvests that maintain relatively mature stand characteristics.

Mature (70–120 year old) natural softwood area was only 2% in both 2002 and 2027, but this is partly an artifact of the rasterization process used to remove roads from the coverages. This resulted in dissolving linear riparian buffers (60 m wide) into larger adjacent harvest blocks. To correct for this, we calculated area of stand types in riparian buffers using vector data, which showed 7600 ha (4% of the total landbase) of mature natural softwood in 2002 and 6000 ha (3%) in 2027, resulting in actual total areas of mature natural softwood of 6 and 5%, respectively.

Harvest trends

From 1945 to 2002, 64% of the District was harvested via clearcutting or partial harvesting, and 72% was projected to be harvested from 2002 to 2027 (Table 1). Partial harvesting, including commercial thinning and single-tree selection, is increasingly being used. Because of multiple-entry treatments, the area harvested increased from a mean of about 12,000 ha per 5-year period from 1939 to 1976, to 20,000 ha for 1977–2001, and 40,000 ha per period projected to 2002–2027 (Figure 3).

Harvesting prior to 1960 was nearly all diameter-limit partial cutting. Clearcutting commenced in 1957, increased to 1977–1981 and averaged about 11,000 ha/period from 1982 to 2001 (Figure 3). Commercial thinning of softwood plantations commenced in 1986, and was projected to be the most prevalent treatment from 2002 to 2027. Single-tree selection harvest of tolerant hardwood stands began in the mid 1980s, and it is projected that over 41,000 ha will be treated this way between 2002 and 2027.

Figure 1. Distribution of stand types and percent area (pie charts) for the Black Brook District in northern New Brunswick in (a) 1945, (b) 2002, and (c) 2027. Stand type abbreviations are: BS – black spruce; SWCE – softwood-cedar; SW – softwood; MW – mixedwood; HW – hardwood; BURN – burned. (a) and (b) were modified from Etheridge et al. (2005).

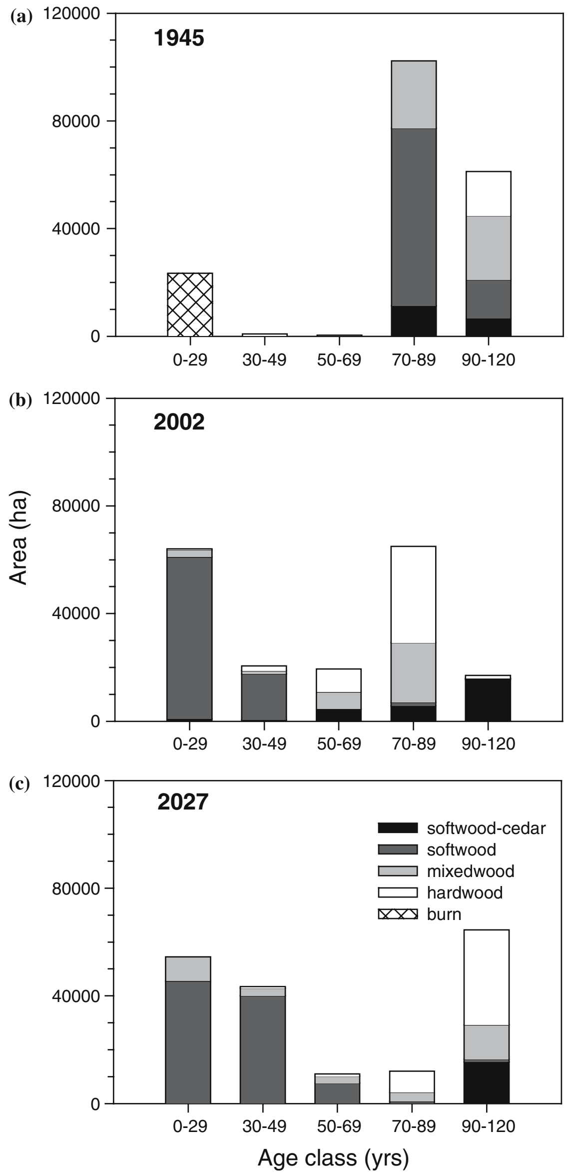

Figure 2. Age class distribution of forest in the Black Brook District in (a) 1945, (b) 2002, and (c) 2027.

Opening size characteristics

The number of harvest openings that created new forest patches increased substantially over time, with 650 from 1942 to 1961 (91% of which were diameter-limit harvests), 1060 from 1962 to 1981 (80% clearcuts and 20% partial harvests leaving 5–15 m^2/ha of residual basal area (G. Pelletier, JDI, personal communication, 2004)), 2960 from 1982 to 2001 (63% clearcuts and 17% shelterwood cuts), and 8660 projected for 2002–2027 (37% clearcuts, 36% commercially thinned plantations, and 19% single-tree selection harvests) (Figure 4). The large projected increase in number of harvest patches from 2002 to 2027 resulted from increased use of multiple-entry harvest treatments. Percentage of small harvest patches (<100 ha and ≤10 ha, respectively) steadily increased, at 84 and 40% from 1942 to 1961, 88 and 57% from 1962 to 1981, 96 and 53% from 1982 to 2001, and 95 and 64% from 2002 to 2027 (Figure 4).

Clearcutting affects landscape pattern more than do partial harvest treatments. The 5-year mean clearcut opening size was 9–22 ha from 1957 to 1976; peaked at 59 ha in 1977–1981, in response to salvage harvesting of spruce budworm defoliated stands and pre-salvage harvesting of vulnerable stands; and declined to 11–19 ha from 1992 to 2026 (Table 2). Maximum opening sizes showed a similar trend, increasing to a peak in the late 1970s and declining thereafter. Future harvest plans implicitly assume the use of insecticide protection to prevent mortality during the next spruce budworm outbreak, expected within the next decade.

Forest landscape metrics

The total number of patches increased from 970 in 1945 to 5230 in 2002, and is projected to increase to 13,460 by 2027 (Table 3). Patches in 1945 were evenly distributed, with 20–29% in each stand type. From 1945 to 2002, the number of patches per stand type increased 2.8–7.7 times (Table 4), and from 2002 to 2027, they were projected to increase another 1.5–3.9 times.

From 1945 to 2002, mean patch sizes decreased by 37–90%, and projections to 2027 indicated further decreases of 53–75% (Tables 3 and 4). In 1945, the patch size standard deviation was large, especially for softwood stands (Table 3). From 1945 to 2002, patch size standard deviation decreased by 15–90%, and it is projected to decrease 40–76% from 2002 to 2027 (Table 4).

From 1945 to 2002, total amount of edge and edge density increased by 100%, and these metrics were projected to increase by 30% from 2002 to 2027 (Table 4). Total edge increased

Table 1. Percent change of stand types from 1945 to 2002 and projected to 2027 in the Black Brook District. Values for unchanged stand types are shown in bold.

Comparison years	Initial stand type[a]	Harvested	Area (ha)	% area by end of period stand type[a]			
				SWCE	SW	MW	HW
1945–2002	SWCE	Yes	12350	**21**	56	13	10
		No	4700	**58**	18	10	14
	SW	Yes	47390	14	**58**	17	11
		No	25420	23	**29**	18	30
	MW	Yes	40210	4	51	**16**	29
		No	11840	13	13	**18**	56
	HW	Yes	10770	2	44	14	**40**
		No	8470	50	4	9	**37**
	BURN	Yes	6450	17	28	30	25
		No	15870	27	3	33	37
2002–2027	SWCE	Yes	17820	**32**	56	9	3
		No	10460	**55**	25	16	4
	SW	Yes	62530	1	**95**	2	2
		No	14960	7	**81**	7	5
	MW	Yes	12610	4	52	**9**	35
		No	20570	3	8	**81**	8
	HW	Yes	35480	1	7	16	**76**
		No	10600	4	8	10	**78**

[a]Stand types: SWCE softwood–cedar, SW softwood, MW mixedwood, HW hardwood.

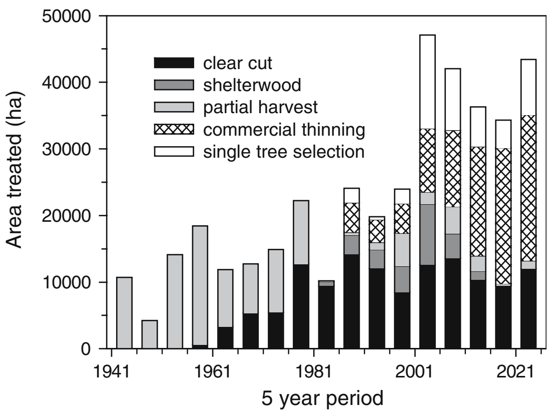

Figure 3. Area by harvest type in 5-year periods from 1937 to 2026. Data from 2002 to 2026 are based upon projections in the Black Brook District spatial forest management plan.

220–270% for softwood–cedar and hardwood from 1945 to 2002, due to their increased total area, but edge increases of 29–67% for softwood and mixedwood resulted from increased number of patches and decreased patch sizes. Projections indicated that from 2002 to 2027, total edge will increase another 14–84% for softwood, mixedwood, and hardwood, due to increasing numbers of small patches, but will decrease 25% for softwood–cedar due to area reductions (Table 4). Similar trends were observed for edge density (Table 4). Area-weighted mean shape index decreased by 8–49% from 1945 to 2002 for softwood–cedar, softwood, and mixedwood, types, but increased 26% for hardwood (Table 4). Continued decreases (37%) are projected for softwood, but mean shape index will remain similar (±10%) for the other stand types.

From 1945 to 2002, total core area (polygon area minus 100 m edge area) decreased by 9%, and it is projected to decrease 12% from 2002 to 2027. Among stand types, total core area decreased by 59% for mixedwood from 1945 to 2002, due to decreased mixedwood area, remained similar for softwood–cedar and softwood, but increased 114% for hardwood due to increased hardwood area (Table 4). Total core area was projected to decrease further by 54 and 28% for softwood–cedar and mixedwood by 2027, due to less area of these stand types, but remain similar for softwood and hardwood (Table 4). Mean core area in 1945 was 45–210 ha among stand types, decreased by 44–90% from 1945 to 2002, but only softwoods were projected to decrease (62%) from 2002 to 2027 (Table 4).

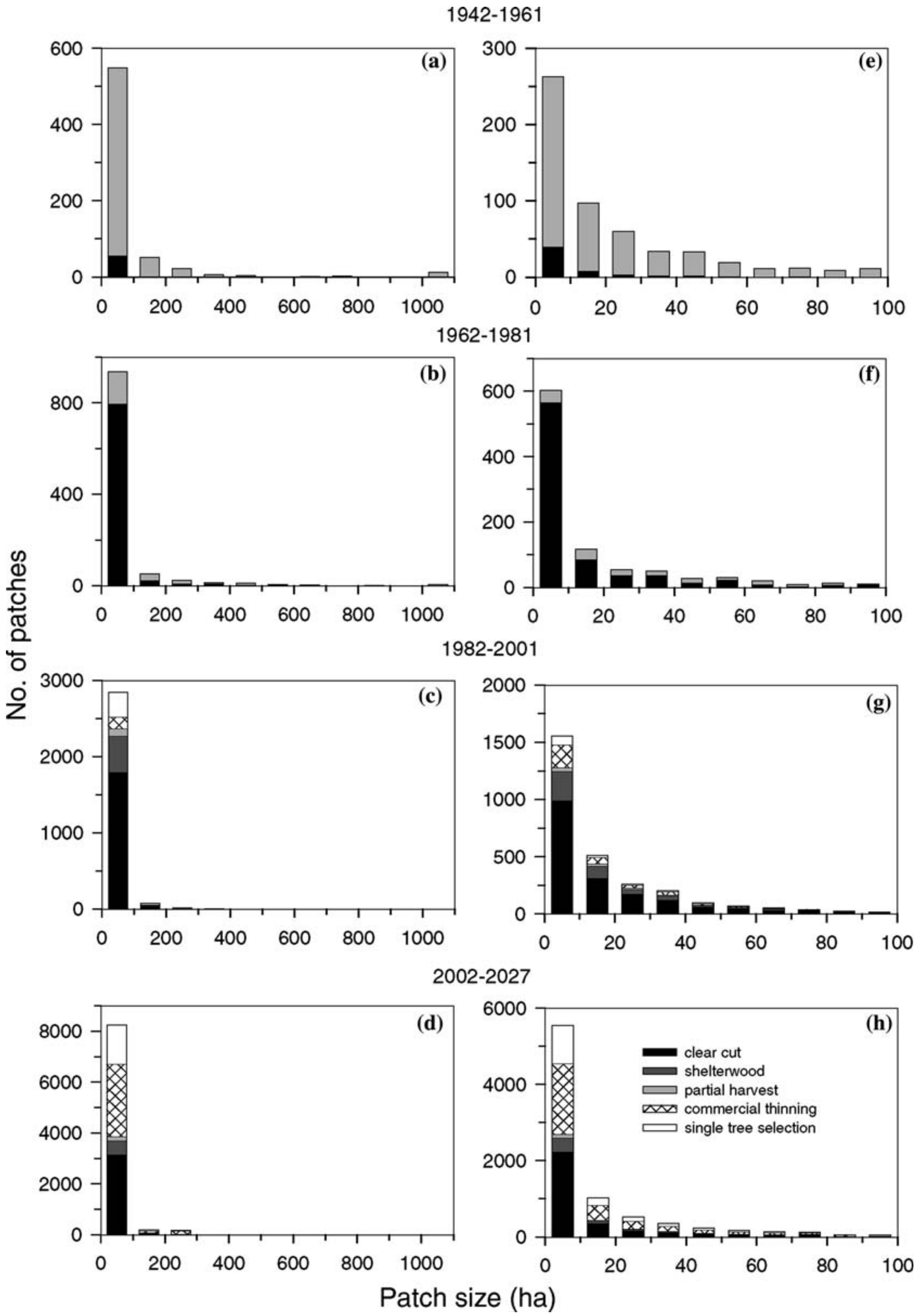

Figure 4. Patch size distributions by harvest type in four periods from 1942 to 2027. (a–d) present all patches and (e–h) expand the 0–100 ha class in 10 ha intervals.

Table 2. Clearcut area and opening sizes from 1957 to 2002, and projections to 2026, on the Black Brook District.

Harvest period (years)	Total area clearcut (ha)	Mean opening size (ha)		Maximum opening size (ha)		Opening size standard deviation (ha)	
		Annual[a]	Period[b]	Annual	Period	Annual	Period
1957–1961	610	7–11	9	34–79	79	12–17	15
1962–1966	3350	9–15	18	57–180	360	14–30	45
1967–1971	5380	10–13	21	106–240	490	21–30	53
1972–1976	5490	12–27	22	117–389	600	21–68	58
1977–1981	12740	29–51	59	324–918	2900	75–148	230
1982–1986	9460	13–30	38	68–494	870	18–68	100
1987–1991	14220	15–31	30	80–329	870	18–50	65
1992–1996	12060	10–22	18	94–187	230	14–23	26
1997–2001	8490	7–13	11	35–167	170	9–17	15
2002–2006	12590	–[c]	19	–	540	–	37
2007–2011	13610	–	18	–	610	–	39
2012–2016	10320	–	17	–	610	–	45
2017–2021	9480	–	13	–	260	–	24
2022–2026	12010	–	11	–	90	–	16

[a]Range of annual values.
[b]Adjacent clearcuts within a 5-year period were combined to calculate opening sizes.
[c]Projected values were only available by 5-year period.

Table 3. Landscape metrics for four broad stand types in the Black Brook District in 1945, 2002, and projections to 2027.

Metrics	Softwood–cedar			Softwood			Mixedwood			Hardwood		
	1945	2002	2027	1945	2002	2027	1945	2002	2027	1945	2002	2027
Area (ha)	17050	28280	15510	72810	77490	94270	52050	33180	30290	19240	46080	44580
No. patches	193	1685	2547	209	736	3593	282	1715	5080	288	1098	2243
Patch size (ha)												
Mean	88.3	16.1	6.0	348.8	107.0	26.4	184.6	19.0	5.9	66.8	42.4	19.9
Median	33.7	7.0	1.4	32.4	16.0	3.0	62.8	8.0	1.3	27.6	11.8	2.7
Standard deviation	220.1	32.6	19.4	1610.0	591.5	141.4	409.6	40.6	18.3	122.0	104.1	62.1
Total edge (*1000 m)	887	3245	2429	2536	4231	7767	2684	3472	4628	1041	3338	3809
Edge density	4.8	17.4	13.1	13.7	22.7	41.7	14.4	18.7	24.9	5.6	17.9	20.5
Area-weighted mean shape index	2.4	2.0	1.9	5.7	5.2	3.3	3.7	1.9	1.7	1.8	2.2	2.1
Mean shape index	1.5	1.4	1.3	1.8	1.6	1.4	1.8	1.4	1.3	1.4	1.5	1.3
Core area (ha)												
Total	12030	10960	5020	58080	55080	54860	36500	14990	10730	13410	28680	25720
Mean	60.1	6.4	5.9	210.4	61.3	23.6	89.5	9.1	6.2	44.8	24.9	20.7
Standard deviation	175.6	17.2	16.3	1190.1	385.9	111.9	220.6	27.3	18.6	97.3	66.4	52.3

Patch size and area distributions

Patch size distributions were dominated, in terms of numbers, by small patches < 100 ha (Figure 5a–c). However, patches < 100 ha represented only one-seventh of the landscape area in 1945, but increased to more than half by 2002, and nearly half by 2027 (Figure 5d–f). In contrast, large patches >700 ha represented the majority of the area in 1945 (Figure 5d) vs. only one-twentieth in 2002 (Figure 5e) and about one-fifth in 2027 (Figure 5f). Projections to 2027 indicated that nine very large (>1000 ha) patches (eight softwood plantations, and one hardwood) (Figure 5c) covering 20,100 ha would exist, vs. only two softwood patches >1000 ha encompassing 2300 ha in 2002 (Figure 5f). Harvesting in small patches and protection of the landbase from natural disturbance has virtually eliminated large patches.

Table 4. Percent change of landscape metrics of four broad stand types (softwood–cedar (SWCE), softwood (SW), mixedwood (MW), and hardwood (HW)) on the Black Brook District from 1945 to 2002 and projected from 2002 to 2027.

Metrics	1945–2002				2002–2027			
	SWCE	SW	MW	HW	SWCE	SW	MW	HW
Area (ha)	*66*	8	−37	**142**	−45	20	−7	−4
No. patches	**773**	**252**	**508**	**281**	*51*	**388**	**196**	**104**
Patch size (ha)								
Mean	*−82*	*−69*	*−90*	*−37*	*−63*	*−75*	*−69*	*−53*
Median	*−79*	*−51*	*−87*	*−57*	*−80*	*−81*	*−84*	*−77*
Standard deviation	*−85*	*−63*	*−90*	−15	−40	*−76*	*−55*	−40
Total edge (*1000 m)	**266**	*67*	29	**221**	−25	*84*	33	14
Edge density	**265**	*67*	29	**220**	−25	*84*	33	14
Area-weighted mean shape index	−17	−8	−49	26	−1	−37	−10	−5
Mean shape index	−3	−9	−22	8	−12	−15	−12	−10
Core area (ha)								
Total	−9	−5	*−59*	**114**	*−54*	0	−28	−10
Mean	*−89*	*−71*	*−90*	−44	−8	*−62*	−32	−17
Standard deviation	*−90*	*−68*	*−88*	−32	−5	*−71*	−32	−21

Bold values show change > ± 100% and italicized values show change from ± 50–99%.

Stand type transitions with and without harvesting

Over the past 59 years, the four broad stand types were very dynamic (Figure 6). In fact, a portion of the area assigned to every classified stand type in 1945 was assigned to every other type by 2002 (Table 1). Only 16–58% of the four stand types in 1945 remained in the same stand type by 2002, regardless of whether they had been harvested or not. Major transitions, with ≥50% of a given stand type from 1945 to 2002, included: harvested softwood–cedar to softwood, unharvested softwood–cedar remaining the same, harvested softwood remaining the same, harvested mixedwood to softwood, unharvested mixedwood to hardwood, and unharvested hardwood to softwood–cedar (Table 1). The 1945 burned area that had been harvested by 2002 was fairly evenly distributed (17–30%) to softwood–cedar, softwood, mixedwood, and hardwood, while unharvested burned area was 27–37% softwood–cedar, mixedwood, and hardwood types in 2002 (Table 1).

Projections of expected stand type transitions from 2002 to 2027 were less variable than those observed from 1945 to 2002. One-third of harvested 2002 softwood–cedar is expected to remain the same type, while 56% will change to softwood (Table 1), whereas 55% of non-harvested 2002 softwood–cedar will remain the same type. Ninety-five and 81% of harvested and unharvested softwood are projected to remain softwood. Half of harvested 2002 mixedwood is projected to be planted to softwood, with 35% changing to hardwood; in contrast, 81% of the non-harvested mixedwood will remain as such. Three-quarters of the 2002 hardwood, harvested or not, is expected to remain hardwood, with 10–16% becoming mixedwood (Table 1). Overall, projections indicated that management from 2002 to 2027 will tend to change softwood–cedar to softwood, and mixedwood to softwood and hardwood, but that 55–81% of all unharvested stand types will remain the same.

Discussion

We used three contrasting data sources, a detailed timber cruise (with associated mapped stands) from the 1940s, a modern photointerpreted forest inventory for 2002, and a projection of the forest inventory to 2027, incorporating modeled stand development and planned harvesting, silviculture, and stand transitions. Comparing these varied data sources raises uncertainties, particularly in terms of the accuracy of the 1945 data. We evaluated this by qualitatively comparing two independent sources: the mapped 1944–1947 cruise data used in this study, with an independent photo-interpreted inventory created in 2003 by modern photointerpretation and digitizing of a full set of 1945 black and white aerial photographs.

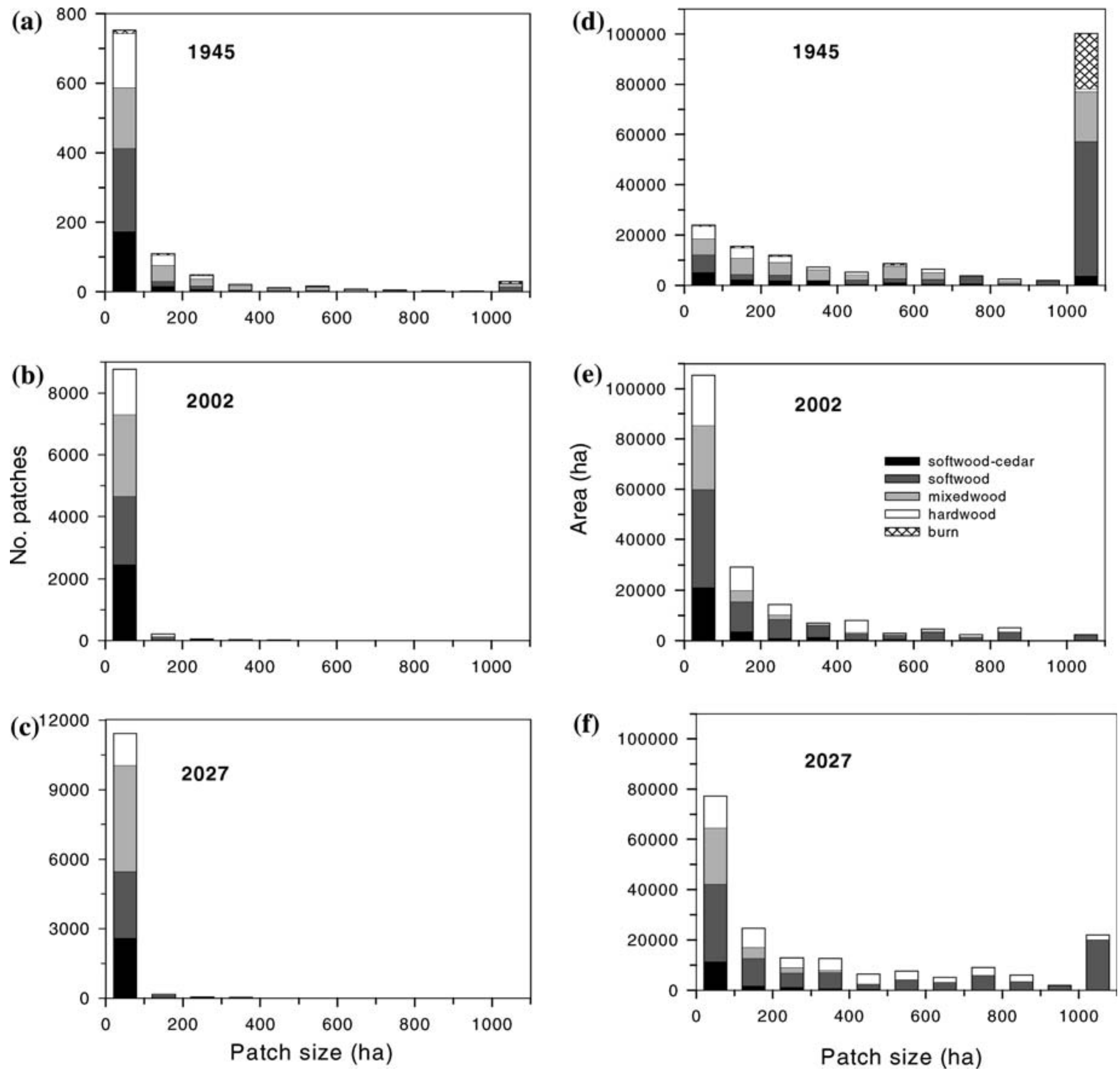

Figure 5. Number and area patch size distributions, by stand type, on the Black Brook District in 1945, 2002, and 2027.

Stand boundaries and species composition were closely aligned between the cruise and photo data. The 1945 species characterization was less detailed than in 2002 (fewer species identified per stand, some lumped classes such as 'spruce' and 'fuelwood' combining species), and thus the 1945 characterization scheme was used for comparisons. We compared data from cruise plots (species composition and dbh distribution) with the photointerpreted data, and overall, we are confident in the consistency and accuracy of the 1945 data. It is likely that the 1945 polygon differentiation had coarser spatial resolution than in the 2002 inventory, but the pattern of increased number of patches (5.3 times increase from 1945 to 2002 and a further 2.3 times from 2002 to 2027) is undoubtedly real.

Over the past half century, the proportion of softwood on the Black Brook District remained relatively constant, while hardwood increased, in spite of the establishment of 60,000 ha of softwood plantations. The amount of mixedwood declined as a result of conifer plantation establishment, plus the effects on mixedwood of selective harvesting,

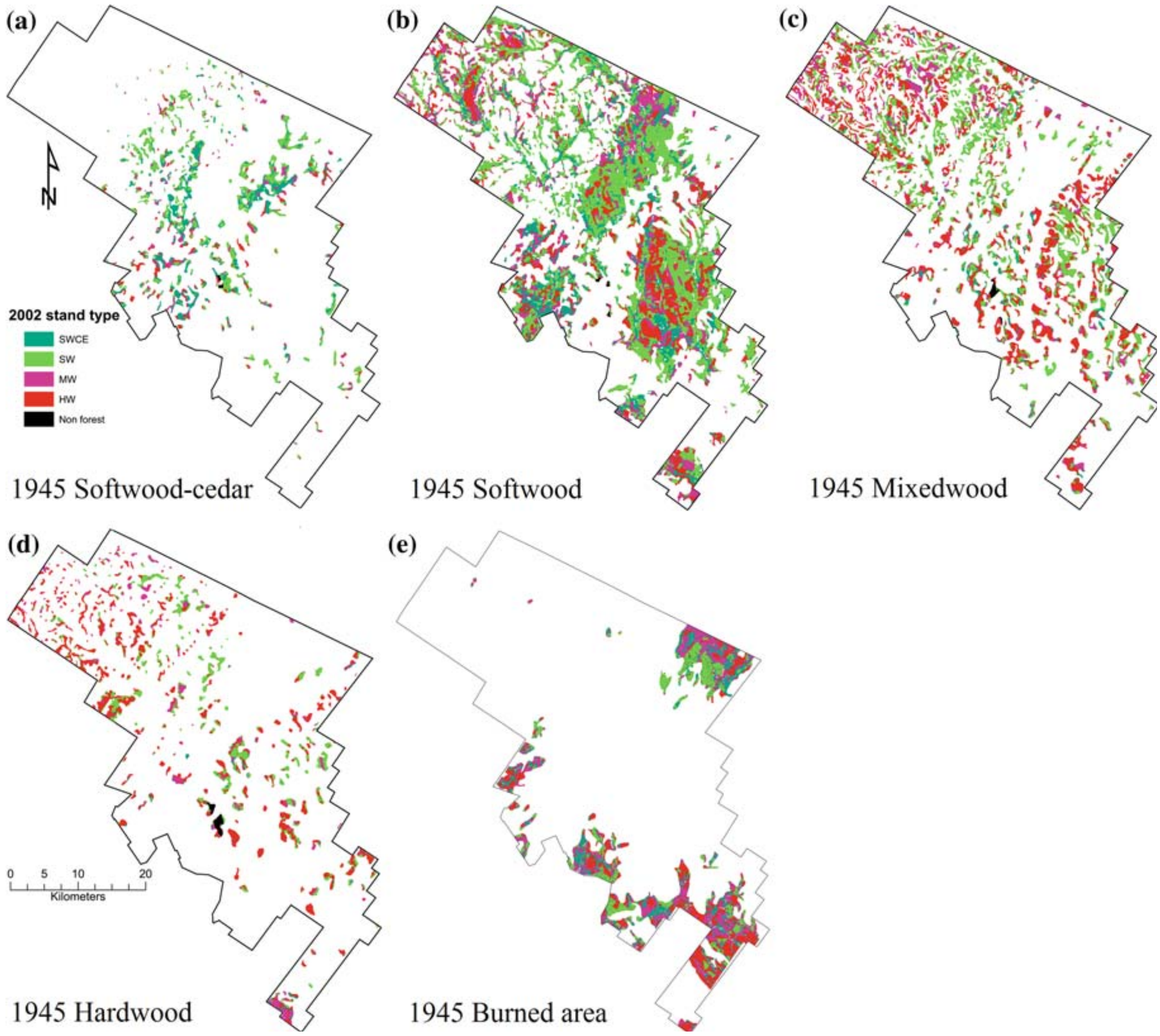

Figure 6. Maps of 1945 stand types on the Black Brook District, showing stand types present in 2002.

spruce budworm outbreaks killing mature balsam fir trees, and softwood salvage harvesting. The forest age class structure shifted from being dominated by mature stands in 1945 to a substantial proportion of younger softwood plantations by 2002. Lehmkuhl et al. (1994) and Hessburg et al. (2000) also found that forest management decreased the amount of mature and old growth stands on the landscape. A major spruce budworm outbreak in the 1870s–1880s (Tothill 1921) evidently initiated many of the softwood and mixedwood stands that were 70–120 years old in 1945. Following this outbreak in the 1880s, over half of the District would have been in the 0–29 year age class, actually exceeding the level observed in 2002.

Since 1957, clearcutting has been a major harvesting system, used in conjunction with plantation establishment. As a result of the past two spruce budworm epidemics (1949–1958 and 1971–1987), during which up to 97% of the landbase was defoliated (Porter et al. 2004), JDI chose to reduce the overall spruce budworm vulnerability of forests in the District. This included reducing the balsam fir (most vulnerable species) in all stand types, especially softwood, via plantation management with less susceptible spruce species, and by harvesting balsam fir in mixedwood stand types to create more pure hardwood stand types (Etheridge et al. 2005).

As a result of natural disturbances, the 1945 landbase was characterized by large forest patches. From 1945 to 2002, the average patch size of softwood, mixedwood, and hardwood stands decreased by roughly 70, 90, and 40%, respectively. Even in the mid-1970s when extensive budworm outbreak salvage logging occurred and the maximum opening size reached 2900 ha, the mean clearcut size was only 59 ha. From 1982 to 2002 and for projections to 2027, the average clearcut opening was 11–38 ha; most harvest openings were < 60 ha, and the patch size standard deviation decreased for all stand types from 1945 to 2002, indicating homogenization. Past studies have also shown that forest management tends to increase the number of patches via small, dispersed harvest patches (Mladenoff et al. 1993; Miller et al. 1997). Several studies have also shown similar trends of decreasing mean patch size from forest management (Wallin et al. 1994; Hessburg et al. 1999; Turner et al. 2003). Forest management, for both social and economic reasons, has reduced harvest block sizes, dividing larger patches into smaller patches, and resulting in a patch size distribution different from the apparent historical norm. Mladenoff et al. (1993) observed a decreased range of patch sizes resulting from forest management. Given that some wildlife species require large patches and interior forest habitat to survive, management planning needs to incorporate the creation of some large patches.

In conjunction with smaller stands, stand edge increased from forest management, as shown elsewhere (Wallin et al. 1994; Tinker et al. 1998). Mean shape index declined with management (the closer the value is to 1.0, the more circular the patches), demonstrating a trend toward simplifying patch shapes over time, with the exception of hardwood stands, which increased in area. A long history of rectangular-shaped clearcuts and to a lesser extent partial harvesting, from the 1960s to the late 1980s, resulted in this trend. Since the 1990s, JDI has developed policy to create harvest blocks that follow natural stand boundaries and now retention islands are routinely left within clearcuts.

Core area decreases observed were similar to the results of other studies that have examined trends under forest management (Ripple et al. 1991; Tinker et al. 1998). The increased total number of patches over time led to patches having smaller perimeter-to-area ratios, decreasing total core area. Core area analyzed in this paper was standard across all stand types, but if analyzed by wildlife species, results might differ for some. However, decreasing patch sizes directly correlate, on average, to decreased core areas.

The decrease in total mixedwood and large mixedwood patches may be a limiting factor for wildlife species that need large patches and interior forest habitat to survive (Higdon et al. 2005). A question that arises is whether patches of intensively managed softwood may meet habitat requirements at a coarse landscape level, but may not have some of the stand-level structural characteristics necessary for certain wildlife species survival (Higdon et al. 2005).

The most surprising result of our stand type transition analysis was how pervasive the changes were, with every broad stand type class in 1945 transitioning to every other stand type by 2002. Many of the transitions make sense, given the human-caused and natural disturbance history. The transition of 44–58% of 1945 softwood–cedar, softwood, mixedwood, and hardwood that had been harvested to a softwood stand type in 2002 is clearly a function of plantation establishment. Much of the 1945 mixedwood (56% of the unharvested, 29% of the harvested) changed to hardwood, as a result of the softwood component being killed by spruce budworm defoliation, blowdown, or salvage. Similarly, nearly half of the unharvested 1945 softwood shifted to mixedwood (18%) or hardwood (30%), probably as a result of spruce budworm-caused softwood mortality and hardwood becoming more dominant.

The most puzzling stand type shift observed was undoubtedly the 50% of unharvested hardwood in 1945 that transitioned to softwood–cedar by 2002. We hypothesize that this might have resulted from the combined effects of birch dieback, which extensively killed yellow and white birch from central New Brunswick to Quebec from the 1930s to 1950s, and spruce budworm defoliation, which killed balsam fir and spruce (Balch 1952; Hatcher 1963). Stands impacted by birch dieback would release understory balsam fir, which was ultimately defoliated by the 1950s spruce budworm outbreak (Hatcher 1963). This might have allowed the unaffected cedar component to increase enough for the stand to be classed as softwood–cedar (≥70% softwood, ≥30% cedar). Also surprising was the diversity of 2002 stand types resulting from the unharvested 1945 burns, with about one-third softwood–cedar, mixedwood, and hardwood.

The extent of dynamic shifts of stand types resulting from both management and natural forest development was unexpected, raises questions about our understanding of forest development, and deserves further study. Some of the stand type transitions observed might have resulted from the classification scheme used, and we intend to study this further via a combination of: (1) field verification of the appropriateness of 1945 and 2002 stand typing; (2) interpretation of 1950s–1980s aerial photos and inventory records to verify changes; (3) field sampling and historical reconstruction of unharvested stands to elucidate stand development patterns; and (4) determination of the role of the classification scheme in the results (i.e., analysis based upon species gradients rather than classes with specific break-points).

Although the total area of softwood remained relatively constant between 1945 and 2002, mature balsam fir–spruce shifted to young planted spruce, and only 6% mature softwood remained. This was a purposeful strategy to replace natural balsam fir with spruce plantations that are faster growing and less vulnerable to future spruce budworm outbreaks. Being able to compare forest species composition, age class distribution, and patch sizes for a reference time period, in our case 1945, facilitated evaluation of human-caused changes in the forest.

Ecological and management implications of our results primarily relate to the substantial decrease of mixedwood forest and old forest required by some wildlife species, plus the magnitude of the cumulative effect of forest management on landscape patterns. The socially mandated drive for smaller clearcuts resulting in the loss of large patches has implications for ecology, especially for species that need large patches and interior forest. JDI is integrating the results into its management plan in four ways: (1) setting minimum areas for key vegetative communities (hardwood, softwood–cedar, mixedwood) and defining a maximum area in plantations; (2) setting more sophisticated objectives and measures of patch size distribution than the current 60 ha maximum clearcut size; (3) supporting research to understand the complex stand dynamics of balsam fir–mixedwood stands and to determine their use by wildlife species and the importance of landscape context; and (4) determining target levels for various old habitat types and the contribution of managed stands to habitat and diversity.

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