Chapter 10
Assessing Knowledge Ambiguity in the Creation of a Model Based on Expert Knowledge and Comparison with the Results of a Landscape Succession Model in Central Labrador

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10.1 Introduction

Sustainable forest management (SFM) recognizes that the spatial and temporal patterns generated at different scales by natural landscape and stand dynamics processes should serve as a guide for managing the forest within its range of natural variability (Landres et al. 1999; Gauthier et al. 2008). Landscape simulation modeling is a powerful tool that can help encompass such complexity and support SFM planning (Messier et al. 2003). Forecasting the complex behaviors of a forested landscape involving patterns and processes that interact at multiple temporal and spatial scales poses significant challenges (Gunderson and Holling 2002). Empirical evidence for the functioning of key elements, such as succession and disturbance regimes, is crucial for model parameterization (Mladenoff 2004). However, reliable empirical data about the forest vegetation dynamics that arise in response to forest management and other disturbances may be scarce, particularly in remote areas where harvesting activity has been historically limited.

Expert knowledge-based (EKB) modeling is receiving more attention as a companion approach to empirical modeling, and attempts are now being made to formalize the process of eliciting and including expert knowledge during the development of decision-support systems (Johnson and Gillingham 2005; Murray et al. 2009; Chap. 3; and Chap. 4). Forestry experts with local knowledge collectively have considerable knowledge about forest succession and disturbance. Such collective knowledge can contribute greatly to our understanding of the vegetation transitions within a landscape that are so critical for informed SFM planning (Drescher et al. 2008).

Eliciting scientifically precise information from the collective knowledge of a group of experts remains a significant challenge. However, rigorous expression of latent knowledge that can be incorporated into an expert model can be achieved using a structured information-mining procedure. By examining convergent and divergent expert opinions about specific forest dynamics questions, researchers can obtain insights into uncertainties, knowledge gaps, and where complexity lies (Drescher et al. 2008). Comparisons between EKB models and other knowledge sources can offer a more comprehensive examination of the potential bias underlying each technique, and can reveal uncertainty and knowledge ambiguity that will suggest logical avenues for additional research and monitoring to support SFM planning.

Recognizing knowledge ambiguity is particularly important in natural resource planning because it lets planners assess the degree of uncertainty in the outcomes of various management options (Drescher and Perera 2010a).

In this chapter, we compare and contrast postdisturbance (fire and clearcut harvesting) vegetation transition probabilities (including the regeneration delay) based on knowledge derived from local experts in central Labrador with analogous information derived from a process-based landscape-dynamics model (LANDIS-II) that has been parameterized for the same area by scientists with expertise in boreal forests outside of Labrador. Expert self-assessment of their degree of uncertainty, combined with our analysis of similarities and differences among expert opinions and the relative agreement between the EKB model and LANDIS-II, can reveal the magnitude of the knowledge ambiguity.

10.2 Methods

10.2.1 Study Area

The study area is a 1.9 million ha forest management district (District 19a) in south-central Labrador (52°18′–54°0′ N, 62°05′–59°11′ W; Fig. 10.1) located at the transition between the closed-canopy boreal forest and the open-canopy taiga (Bajzak 1973; Bajzak and Roberts 1984). The central valley in District 19a contains the majority of Labrador's boreal forests, which are dominated by black spruce (*Picea mariana*) and balsam fir (*Abies balsamea*) (Foster 1984; Forsyth et al. 2003). Spruce–fir stands are embedded within a diverse mosaic of open sphagnum forest, lichen woodlands, mixed hardwoods (*Betula* spp., *Populus* spp.), black spruce bogs (with *Larix laricina*), lakes, and open wetlands. The topography is characterized by a moderate relief underlain by the bedrock geology of the Grenville formation, which is covered by glacial moraines and drumlins that support mostly podzols and gleysols (Batterson and Liverman 1995; Roberts et al. 2006). The climate is primarily continental, though it is moderated by the presence of Lake Melville, with long harsh winters, heavy snow accumulation, and annual precipitation ranging between 900 and 1,100 mm (Roberts et al. 2006). Fire is the dominant natural disturbance (Foster 1983) in Labrador.

The forestry potential of the region is impeded by slow growth of the forest (mean increment <1.0 m^3/ha/year), a long regeneration delay (sometimes lasting many decades), and conversion of productive forest into nonproductive forest after disturbance (Mallik 2003; Simon and Schwab 2005a, b). Some empirical studies have examined the response to different disturbances – for wildfire, Foster (1985), Foster and King (1986), and Simon and Schwab (2005a, b); for clearcutting, Simon and Schwab (2005a) and Elson et al. (2007). However, no studies have examined the mid- and long-term dynamics following disturbances (Roberts et al. 2006).

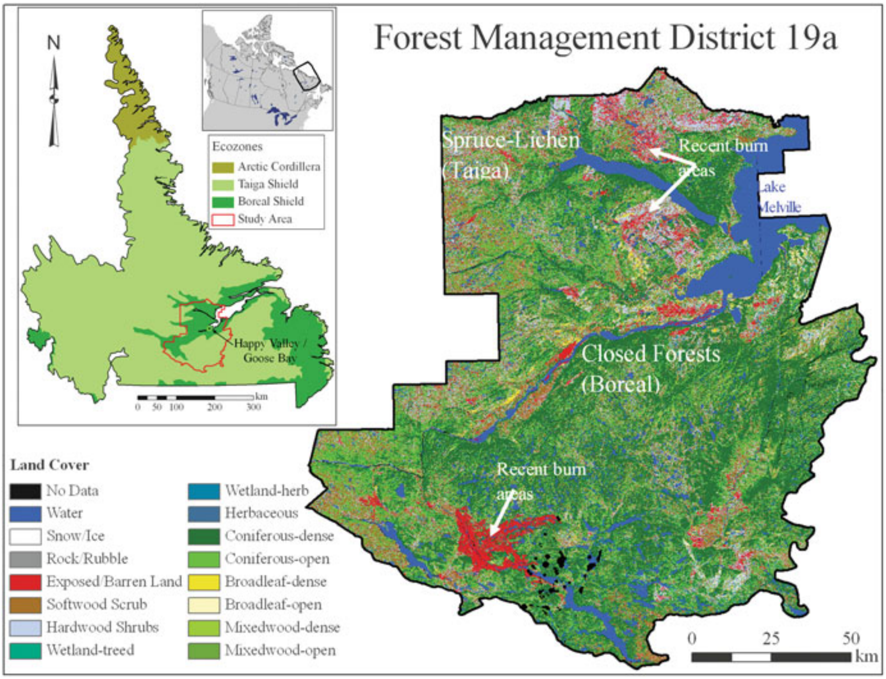


Fig. 10.1 The location of Forest Management District 19a in Central Labrador (Canada) straddles a major ecotone between closed-canopy boreal forest and open-canopy taiga systems

Although commercial harvesting has been limited in the district, a new forest management plan designed to stimulate economic growth and balance cultural and ecological values was recently approved (Forsyth et al. 2003). As clearcutting has been the only silvicultural system used in Labrador up to now, and will be according to the FM plan, expert knowledge was limited to this treatment.

10.2.2 Analytical Approach

We conducted two parallel analytical procedures for building succession models: the first (the EKB model) was based on expert knowledge, and the second used LANDIS-II, a well-established process-based succession model. Both approaches let us compare the predictions for postdisturbance succession, including transition probabilities, regeneration delays, and conversion of productive forest into nonproductive forest, and let us assess the uncertainty and level of agreement or disagreement among the experts and between the experts and LANDIS-II (Fig. 10.2).

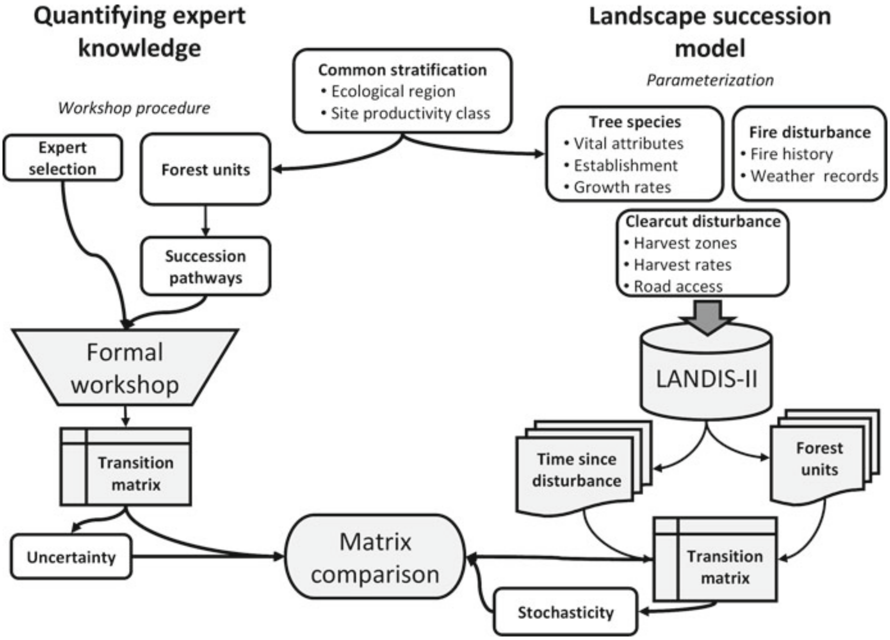


Fig. 10.2 Flowchart illustrating the process underlying the parallel development of vegetation transition matrices based on expert opinion (*left*) and the LANDIS-II model (*right*)

10.2.3 Estimating Vegetation Transition Probabilities Using Expert Opinion

10.2.3.1 Forest Units

The forest units were based on the Newfoundland and Labrador Department of Forestry stand-level inventory, in which forest units are defined by the combination of ecological region, site quality class, and forest type. Two broad ecological regions were defined (the High Boreal ecozone and the Low and Mid-Subarctic ecozone; Wiken 1986), each of which covered about half of District 19a. Of the two, the High Boreal ecozone is warmer and more productive. At finer (i.e., stand) spatial scales, forest productivity was classified into three site quality levels (good, medium, and poor). The forest types were pure balsam fir (Bf), balsam fir–black spruce (BfBs, with balsam fir dominant), black spruce–balsam fir (BsBf, with black spruce dominant), pure black spruce (Bs), softwood-dominated mixedwood (SwHw), hardwood-dominated mixedwood (HwSw), and pure hardwood (Hw). We restricted our modeling exercise to the 16 most prominent forest units (ten in the High Boreal ecozone and six in the Subarctic ecozone), which covered 95.4% of the forested landscape. In Labrador, a nonregenerated state can persist for decades after disturbance

(Simon and Schwab 2005a). To allow the experts to express such dynamics in the District 19a landscape, we added a nonproductive forest (NF) type as a possible vegetation state.

10.2.3.2 Postdisturbance Transition Probabilities

Experts assessed two different postfire situations: one in which the fire occurred during a sexually immature (nonseed-producing) stage and one during a sexually mature (seed-producing) stage. Only stand-replacing disturbances were considered. We assumed that harvesting occurred only when a stand was mature and capable of producing seed. Postharvest replanting is almost absent in Labrador, so we assumed in the model that no planting occurred. Vegetation transitions were defined for each selected forest unit after the two fire disturbance situations and after clearcutting by assigning a probability that each unit would develop into a given postdisturbance forest type (16 forest units × 3 disturbance types = 48 transitions). The experts (described in Sect. 10.2.3.4) identified two different transitions (potential postdisturbance forest types) for each disturbed forest unit. We provided no formal details of the disturbance size or shape, or of the residual forests surrounding the disturbed forest units; experts therefore had to assume that each unit had average conditions for the District 19a landscape.

10.2.3.3 Regeneration Delay

The postdisturbance regeneration delay and conversion of productive forest into nonproductive forest, which are believed to be important phenomena in this region (Bajzak 1973; Bajzak and Roberts 1984; Simon and Schwab 2005a), were also estimated by the experts. Regeneration delay was defined as the time following a disturbance that was required before the stand had sufficient regeneration to develop into a future merchantable stand. Experts were instructed to define the regeneration delay associated with a vegetation transition in 5-year classes. A regeneration delay of 60 years or more was defined as effectively "permanent" in terms of future SFM planning purposes, and was then considered to represent a conversion from productive forest into nonproductive forest (the NF type).

10.2.3.4 Workshop Procedures

Making expert knowledge explicit requires the use of an elicitation method that can help experts communicate their tacit knowledge in explicit terms (Ford and Sterman 1998). For this exercise, we used simultaneous interviews of several experts to elicit their knowledge of the forest vegetation dynamics of the study area during a 2-day workshop (similar to Drescher et al. 2006). The experts who we invited to the workshop were defined as individuals with a minimum of 10 years of local expertise in forestry or natural resource management. Seven experts participated, all of whom had a college degree in natural resources or in environmental education; they represented a combined total of 121 years of forest-related experience. Two-thirds of this experience was acquired in Labrador, primarily as part of their professional work and secondarily through other outdoor activities. On average, the experts spent 34.5 days in the field each year. All were familiar with the concept of forest succession and with the processes underlying forest dynamics, as well as with the autecology of Labrador's forest species. One aboriginal expert, in addition to contributing traditional Innu knowledge, also had conventional Western training. We used cross-validation of peer-recognized expertise among the individuals to ensure that we had successfully selected true experts.

The workshop was organized in three phases. In Phase I, the experts reviewed the workshop procedures, the definitions of terms, and local scientific studies on forest ecology and dynamics. In Phase II, they assigned vegetation transition probabilities to the different vegetation types in response to disturbance, as outlined by a workbook provided by the workshop coordinator (Doyon). In Phase III, the experts described their expertise in forestry, forest ecology, and succession via a questionnaire that determined the kinds of activities they had engaged in (professional, educational, academic, or nonprofessional) and the number of years of experience in each area.

10.2.3.5 Self-Assessment of Uncertainty

Uncertainty about an expert's opinion of any given transition probability arises from two components: the expert's degree of confidence in their knowledge and the perceived uncertainty (variability) in the system (Drescher et al. 2008). Confidence reflects the expert's knowledge, experience, and background, specifically with respect to the succession transition being assessed. System variability reflects the natural stochasticity of conditions that influence the processes involved in any given transition. Experts had to jointly evaluate these two components to "qualify" the level (low = 1, moderate = 2, and high = 3) of uncertainty in their opinion. This self-assessment was accomplished for all postdisturbance vegetation transitions, and included the step in which they estimated the regeneration delay.

10.2.3.6 The EKB Succession Model

Vegetation transition probabilities were calculated by averaging the estimates provided by all of the experts. Probabilities were then assembled into a vegetation transition matrix organized by disturbance type versus forest type, and further stratified by ecological region and site quality.

10.2.4 Deriving Vegetation Transition Probabilities from LANDIS-II

10.2.4.1 Overview and Parameterization

LANDIS-II is a process-based, spatially dynamic model of forest succession and disturbance in which the landscape is represented as a grid of interacting cells (Scheller et al. 2007; http://www.landis-ii.org). Cells have homogeneous light environments and are aggregated into "land types" with similar environmental conditions. In this study, the land types were defined based on the same ecological regions and forest site quality classes that we used to stratify forest units within the EKB succession model. Forest composition at the cell level was represented as age cohorts of individual tree species that interact via a suite of vital attributes (i.e., shade tolerance, fire tolerance, seed dispersal, ability to sprout vegetatively, and longevity) to produce nondeterministic successional pathways that are sensitive to disturbance type and severity.

We applied version 2 of the Biomass Succession extension (Scheller and Mladenoff 2004), which calculates competition among cohorts and their respective aboveground dynamics. We modified this extension to explicitly simulate the light environment that would affect species establishment and to better capture the light gradient from open- to closed-canopy forests in central Labrador. Tree species cohorts become established on new sites in the model based on a spatially explicit algorithm for seed dispersal (Ward et al. 2005) and based on establishment probabilities specific to each land type. The latter probabilities were estimated based on two soil properties (texture and available nitrogen) and two climate parameters (temperature and precipitation). Initial conditions were defined by assigning inventory sample plots to cells stratified by forest type, age class, and site quality class using a combination of classified satellite imagery, stand inventory data, and records of disturbance history. Tree species biomass information was translated into the standard fuel types (Forestry Canada Fire Danger Group 1992) used by version 1.0 of the Dynamic Fire extension to estimate fire spread rates, burn patterns, and resulting tree cohort mortality (Sturtevant et al. 2009). Timber harvesting was simulated using version 1.0 of the Harvest extension (Gustafson et al. 2000). We assumed that young (10-year-old) cohorts of balsam fir survived the clearcutting disturbance as advance regeneration. Each process was simulated using a 10-year time step and a 1-ha cell size.

10.2.4.2 Converting LANDIS-II Output into Vegetation Transition Matrices

Three 250-year simulations were run with LANDIS-II and the outputs were summarized by decade. Species cohort information from the simulations was converted into forest types and 20-year age classes using the rules for defining stand types in the Temporary Sample Plot Program (Newfoundland Forest 1995), but with biomass substituted for basal area. Sites with total biomass values (ignoring shrubs) that were less than the stocking threshold of 39.34 Mg/ha (i.e., the minimum value recorded within the District 19a stand inventory) were assigned to the NF type. We used the time since the last disturbance to assign the stand age class, and for each disturbance type, we recorded the forest types before the disturbance and for each decade of a 60-year period following the disturbance. Postfire observations were restricted to those cells that experienced a stand-replacing fire, which would result in a biomass less than the minimum stocking threshold. We applied a threshold age of 30 years for all forest types to distinguish fire disturbances that occurred within seed-producing (>30 years) versus nonseed producing (<30 years) situations. Postdisturbance transition probabilities 60 years after the disturbance were used for comparison with the transition matrix produced by the expert panel. The postdisturbance regeneration delay was estimated by recording the time after disturbance required for at least 75% of the cells to switch from an NF type to a given forest type based on the minimum stocking threshold. Cells that were still classified as NF after 60 years were considered to indicate a conversion from productive forest into nonproductive forest.

10.2.5 Data Analysis

We quantified the extent of the agreement both among the experts and between the EKB and LANDIS-II models using Pearson's correlation coefficient of the probability value for all pairwise transitions between forest types before and after disturbance. Correlations were computed for all transitions together, then by ecological region, by site quality class, by disturbance type, and by forest types before disturbance. Nonsignificant correlations were considered to represent disagreement between the sources of knowledge. An expert involved in many (more than half) nonsignificant correlations was considered an outlier of the group, and was excluded for the comparison analysis between the EKB and LANDIS-II.

We used the transition probabilities obtained from averaging of the estimates provided by all of the experts to compute a Shannon–Weaver diversity index (Shannon 1948) for each postdisturbance transition ($n = 48$):

$$\text{Diversity} = -\sum_{i=1}^{8} p_i \log(p_i) \tag{10.1}$$

where p_i is the averaged probability among all experts of transiting to forest type i after a disturbance for a specific transition.

This measure of concentration of information is used to express the relative agreement among experts for a given transition; low diversity would indicate that experts have chosen to assign similar probabilities to the same forest types, showing a common understanding of the forest dynamics for a particular successional transition, whereas a high diversity would indicate disagreement among the experts. Uncertainty perceived by the experts within the transitions was summarized by averaging the rank order of their individual uncertainty assessments (low uncertainty = 1, moderate = 2, high = 3). We used ANOVA (PASW v.18.0.0; SPSS Inc. 2009) to assess the effects of the ecological region, individual expert, site quality class, disturbance type, forest type before transition, and forest type after transition on uncertainty and on the probability of having an expert assigning a regeneration delay to a given transition. We evaluated mean differences using the *post hoc* least-significant-difference test where significant differences were indicated by the ANOVA.

10.3 Results

10.3.1 Postdisturbance Transitions

10.3.1.1 Expert-Based Transition Probabilities

Postdisturbance transition probabilities estimated by the experts varied considerably both by disturbance type and site quality, but varied less by ecological region (Table 10.1). The assigned transition probabilities suggested that clearcutting favored a transition to stands with a higher balsam fir content, whereas fire in mature stands favored black spruce. The experts agreed that postdisturbance succession on sites with good quality tended toward increased balsam fir, whereas postdisturbance succession on poor sites favored black spruce, irrespective of the ecological region. The EKB succession model clearly identified more conversion of productive forest into the NF forest type on poor-quality sites and after fires in immature stands. Indeed, in the Subarctic ecological region, the experts expected some conversion to a nonforested state for two-thirds of the 18 transitions.

10.3.1.2 Variability and Uncertainty in Expert Opinion

The diversity index of transition paths did not differ between ecological regions ($P = 0.582$), among site classes ($P = 0.196$), or among forest types before disturbance ($P = 0.309$), but did differ significantly among disturbance types ($P = 0.006$). The diversity in transitions given by the experts was greater after clearcutting and fire in immature stands than after fires in mature stands (Fig. 10.3 and Table 10.1), suggesting a better agreement among the experts for succession after fires in mature stands. Variability in opinion among experts was lower for transitions on medium-quality sites than on sites with good quality and on poor sites and for those involving forest types before disturbance dominated by black spruce (data not shown).

We found that expert opinions were significantly ($P < 0.05$) correlated, with Pearson's r ranging from 0.17 to 0.70 and a mean of 0.47 (Table 10.2). Although the average correlation coefficient among the experts was higher for the Subarctic

Table 10.1 Comparison of the mean postdisturbance transition probabilities between the EKB and LANDIS-II succession models for all transitions, by disturbance type and by site quality class

			Transition probability (%)									
Disturbance	Site quality class	Model	Bf	BfBs	BsBf	Bs	SwHw	HwSw	Hw	NF	SW*I*[a]	Uncertainty[b]
All transitions		EKB	2	12	11	43	16	4	4	7	0.415	1.92
		LANDIS	3	2	0	43	1	1	6	43	0.564	
Clearcut	Good	EKB	13	37	20	5	23	1	0	1	0.500	1.68
		LANDIS	14	4	1	46	3	3	7	21	0.577	
	Medium	EKB	1	50	20	7	19	1	0	1	0.398	1.92
		LANDIS	9	4	1	50	2	2	4	27	0.585	
	Poor	EKB	1	8	42	34	6	0	0	9	0.486	2.10
		LANDIS	6	7	1	68	0	1	1	14	0.518	
Fire in immature stands	Good	EKB	0	3	7	44	24	10	11	1	0.508	1.99
		LANDIS	0	0	0	37	2	1	12	49	0.472	
	Medium	EKB	0	2	5	53	17	6	10	7	0.486	2.01
		LANDIS	0	0	0	36	1	1	8	54	0.448	
	Poor	EKB	0	0	0	58	0	0	6	35	0.346	1.94
		LANDIS	0	0	0	49	0	1	2	47	0.387	
Fire in mature stands	Good	EKB	0	0	5	62	22	6	5	0	0.375	1.74
		LANDIS	0	0	0	36	2	2	11	49	0.408	
	Medium	EKB	0	2	0	68	19	7	2	1	0.298	1.97
		LANDIS	0	0	0	37	1	1	5	55	0.586	
	Poor	EKB	0	0	0	71	4	0	0	25	0.301	1.98
		LANDIS	2	2	0	50	0	1	2	43	1.249	

Bf pure balsam fir, *BfBs* balsam fir–black spruce, *BsBf* black spruce–balsam fir, *Bs* pure black spruce, *SwHw* softwood-dominated mixedwood, *HwSw* hardwood-dominated mixedwood, *Hw* hardwood

[a] Shannon–Weaver index

[b] Uncertainty = mean expert uncertainty score based on individual self-assessments. Uncertainty values ranged from low (1) to high (3)

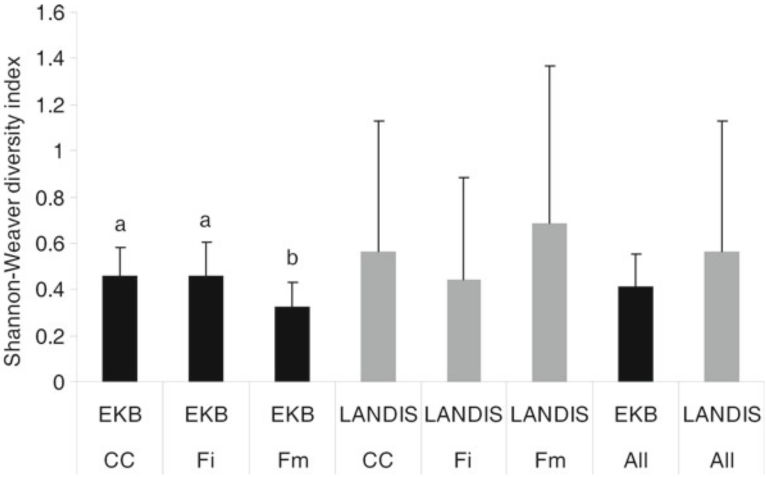


Fig. 10.3 Shannon–Weaver diversity index for transitions after three types of disturbance based on expert opinion (*EKB*) and the *LANDIS-II* model for Labrador's District 19a. Values (mean ± SD) labeled with *different letters* differ significantly ($P<0.05$). *CC* clearcutting, *Fi* stand-replacing fire in a sexually immature stand, *Fm* stand-replacing fire in a sexually mature stand

ecological region than for the Boreal region, the range of coefficients was also wider and included five nonsignificant correlations. Expert G was least experienced and was also rated as least knowledgeable by the other experts. This may explain why Expert G's answers were consistently different from the others, to the extent that removing Expert G increased the overall average correlation from 0.47 to 0.58. We therefore considered Expert G to be an outlier, and removed his assessments from the database for all subsequent analyses. It is possible, however, that this may have eliminated a perspective that was important to the understanding of this system.

The uncertainty perceived by the experts differed significantly among the participants ($F5,566=5.35$, $P<0.001$), with some experts significantly less certain than others. Uncertainty was significantly lower ($F2,566=7.10$, $P<0.001$) for sites with good quality than for those with medium or poor quality (Table 10.1 and Fig. 10.4). Experts had significantly less confidence (perceived more inherent variability) when they were assigning transition probabilities to disturbed SwHw stands or when a stand transitioned to mixedwood forest types ($F7,566=7.07$, $P=0.045$). Surprisingly, uncertainty was not correlated with the Shannon–Weaver diversity index of transition paths (Pearson's $r=0.19$, $P=0.19$).

10.3.1.3 Comparison Between the Experts and LANDIS-II

Postdisturbance vegetation transitions derived from expert opinion and LANDIS-II were significantly ($P<0.001$) correlated, but the Pearson's r was low (0.33; Table 10.2). Agreement between the two transition matrices was higher for the Subarctic ecological region than the Boreal region, for poor-quality sites, and for

Table 10.2 Correlation coefficients among experts for the postdisturbance vegetation transition probabilities, and correlations between the average expert response and the LANDIS-II prediction

		Among experts				Experts vs. LANDIS-II	
		Pearson's *r* [Mean (range)]	NS[a] corr.	Outlier	*n*	Pearson's *r*	*n*
Overall		0.47 (0.17 to 0.70)	0	–	192	0.33*	384
Ecological regions	High Boreal	0.45 (0.15 to 0.69)	2	G	125	0.24*	240
	Subarctic	0.52 (0.04 to 0.82)	5	G	67	0.47*	144
Site quality class	Good	0.39 (0.08 to 0.69)	6	F and G	80	0.17*	144
	Medium	0.56 (0.28 to 0.79)	0		73	0.24*	144
	Poor	0.46 (–0.16 to 0.88)	6	G	39	0.62*	96
Disturbance	Clearcut	0.37 (0.06 to 0.66)	4	G	68	0.04	128
	Fire in immature forest	0.39 (–0.14 to 0.76)	6	G	67	0.44*	128
	Fire in mature forest	0.65 (0.34 to 0.88)	0	–	57	0.45*	128
Forest type before disturbance	SwHw	0.36 (–0.02 to 0.84)	8	A, B and D[b]	26	0.16	48
	BfBs	0.25 (–0.25 to 0.64)	12	B, D and G	26	0.46*	144
	Bs	0.55 (0.12 to 0.85)	4	G	68	0.34*	144
	BsBf	0.54 (0.22 to 0.77)	1	G	72	–0.14	48

BfBs balsam fir–black spruce, *BsBf* black spruce–balsam fir, *Bs* pure black spruce, *SwHw* softwood-dominated mixedwood

*Significant at $P<0.05$

[a] Number of nonsignificant correlations

[b] Expert G did not assess this forest type

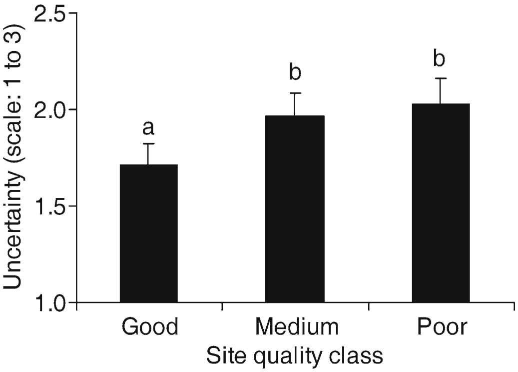


Fig. 10.4 Effect of site quality class on the uncertainty score associated with transitions among forest types after disturbance proposed by the experts for Labrador's District 19a. Values (mean ± SD) labeled with *different letters* differ significantly ($P < 0.05$)

succession after a fire (Table 10.2). The successional states produced by the experts and by LANDIS-II following clearcutting were not significantly correlated ($P = 0.69$).

Despite quantitative differences between the transition outcomes, we observed many qualitative similarities (Table 10.2). Both the experts and LANDIS-II indicated higher postdisturbance forest type diversity following clearcutting and fire in immature stands, and this diversity increased from poor-quality sites to sites with good quality (Table 10.1). The probability of postdisturbance transitions to the Bs forest type increased on poor sites in both the expert opinions and LANDIS-II. However, LANDIS-II indicated a much higher likelihood of the Bs forest type following clearcutting than was predicted by the experts, but the experts predicted a higher likelihood of the Bs forest type after fires. This difference resulted mainly from (1) lower transition probabilities to mixed forest types after clearcutting in LANDIS-II, (2) the absence of any Bf forest types after a fire in LANDIS-II, and (3) a much higher importance (frequency and probability) of conversion of productive forest into nonproductive forest after fires within LANDIS-II. The latter is probably the most important difference between the two methods. In LANDIS-II, 60 years after disturbance, all of the 48 transitions had some probability of conversion into NF, whereas the experts predicted this for only 40% of the transitions. Moreover, the average probability of transitioning into the NF type was much higher in LANDIS-II (43%) than was predicted by the experts (7%) (Table 10.1). This may explain why diversity in succession pathways was much higher and more variable among the transitions in LANDIS-II than in the EKB succession model (Fig. 10.3).

10.3.2 Regeneration Delay

Experts assigned a regeneration delay to 55% of the transitions. The probability was significantly ($P < 0.001$) higher for poorer site classes (Fig. 10.5) and significantly higher ($P = 0.005$) after a fire (in both immature and mature stands) than after a clearcut (Fig. 10.6). In addition, the higher the proportion of black spruce after the disturbance, the higher the likelihood of having an expert assign a regeneration delay to that transition ($P < 0.001$).

Fig. 10.5 Effect of site quality class on the likelihood (between 0 and 1) that experts would associate a regeneration delay with the transition probability after a disturbance in Labrador's District 19a. Values (mean ± SD) labeled with *different letters* differ significantly ($P < 0.05$)

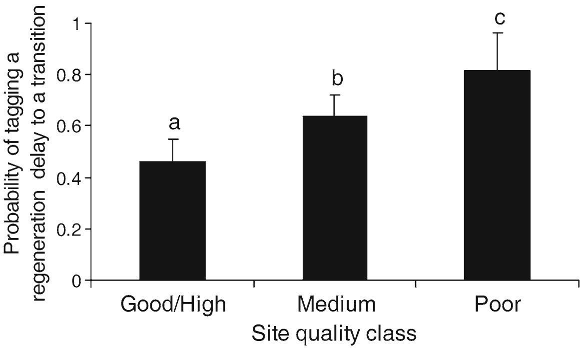
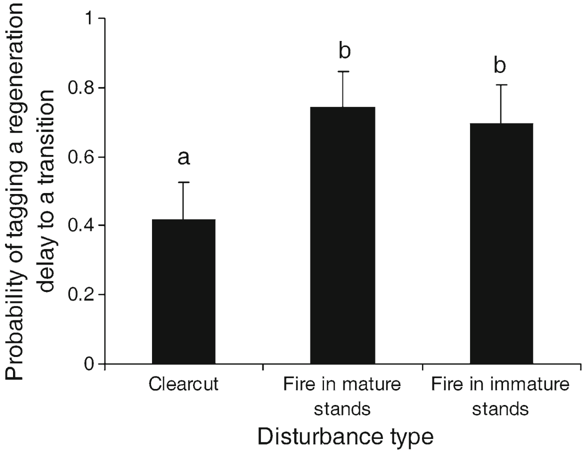


Fig. 10.6 Effect of disturbance type on the likelihood (between 0 and 1) that experts predicted a regeneration delay when assigning succession transition probabilities by disturbance type in Labrador's District 19a. Values (mean ± SD) labeled with *different letters* differ significantly ($P < 0.05$)



10.3.2.1 Variability Among Experts

The likelihood of assigning a regeneration delay to a transition after disturbance differed significantly among the experts ($P < 0.001$). Most of the experts assigned a regeneration delay in about 50% of the transitions, but one expert almost always assigned a regeneration delay to the postdisturbance succession. However, where experts agreed that a regeneration delay would occur after disturbance, the estimated duration did not differ significantly (an average of 16 years).

10.3.2.2 Comparison Between Experts and LANDIS-II

LANDIS-II predicted a regeneration delay for 96% of the postdisturbance transitions. If we consider only the transitions for which experts assigned a transition probability, the regeneration delay after the disturbance was 26 years shorter than that predicted by LANDIS-II. Hence, there was poor agreement between LANDIS-II

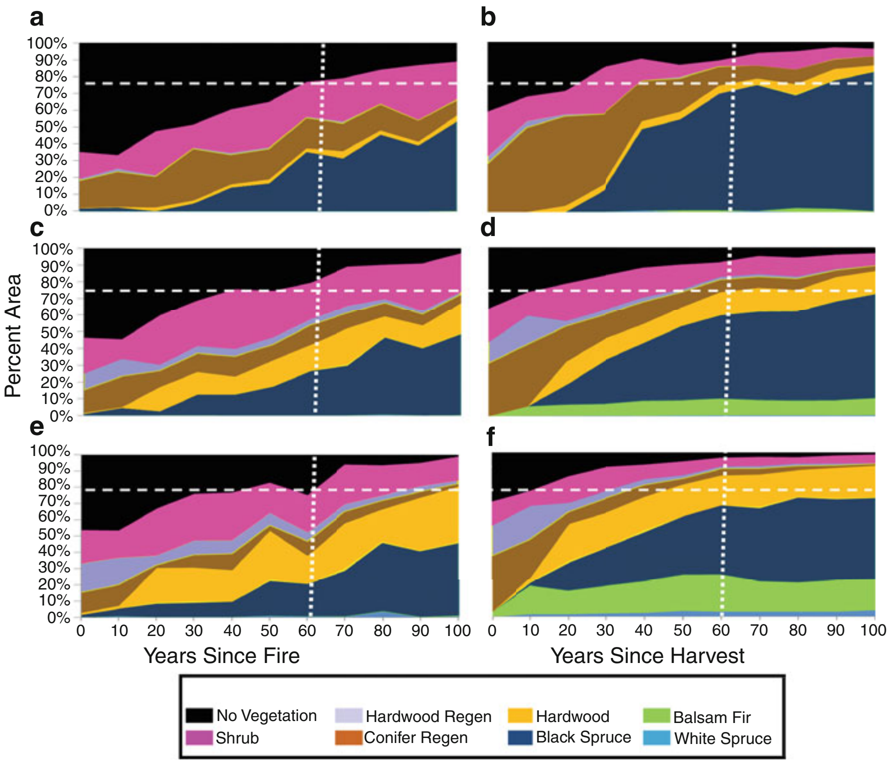


Fig. 10.7 Regeneration delay and composition trends following a fire or clearcutting on sites with (**a**, **b**) poor, (**c**, **d**) medium, and (**e**, **f**) good quality based on the LANDIS-II output. The *dashed horizontal line* indicates the 75% threshold used to assign a regeneration delay (NF) to a forest transition 60 years (*vertical line*) after the disturbance. *Regen* regenerating forest vegetation that remains below the minimum stocking level

and the experts on the regeneration delay; the overall correlation was significant but low ($r = 0.24$, $P = 0.002$). Nonetheless we observed similar qualitative trends from both methods: the regeneration delay was predicted to be frequent and of longer duration on poorer sites and after fires (Fig. 10.7).

10.4 Discussion

10.4.1 Insights from the Expert Workshop

In general, expert knowledge was strongly convergent; that is, the experts generally agreed about the postdisturbance transitions. Their level of agreement was only moderate for the postdisturbance regeneration delay. Informal discussions by the experts after the workshop suggested that such agreement was not the result of groupthink, which can lead to “bandwagon” reasoning, as they were often referring to different examples they had experienced during their career. It was also apparent during the workshop that experts paid strong attention to the consistency of their own mental models by looking back at their previous answers while answering the workshop questionnaire; they often asked to change an answer after they had had time to think about subsequent questions.

In general, group opinion on succession was more variable for the mixed forest types (BfBs, BsBf, and SwHw) than for the Bs forest type. Experts recognized that variability in the successional response increased with increasing diversity of the forest cover. Such variability translated into both a higher diversity of expert opinion and greater expert uncertainty for the transitions involving mixed forest types. Agreement among experts varied depending on ecological factors and the diversity of the forest community. Drescher et al. (2008) found that succession of monospecific stands under relatively extreme environmental conditions (dry sands and wet bogs) was more predictable than succession of mixed stands on sites with a good site quality. We observed similar results within the resource-limited landscape of central Labrador, where more species can become established on richer and warmer sites, leading to more variability in the successional response.

Although the diversity of expert opinion on postdisturbance succession was higher for richer sites, we were surprised that the expert uncertainty was lowest for sites with good site quality. We suspect that this inversion was due to the important roles that the regeneration delay and the conversion from productive forest into nonproductive forest play on poor sites and the variability of these phenomena perceived by the experts. Such insights demonstrate the importance of identifying whether the variation among the experts arises from perceived variability in the system’s response to disturbance or from a lack of expert knowledge or experience with specific ecological patterns, as Drescher et al. (2008) pointed out.

Agreement was also lower after clearcutting and fire in immature stands than after fire in mature stands. Commercial harvesting in this district has been limited to a few thousand hectares thus far. Experts therefore had little experience with succession after clearcutting, but considerable experience with catastrophic wildfires in mature stands. Moreover, harvesting has mostly occurred at the most productive sites, which are closest to Goose Bay and Happy Valley. Since better site quality is expected to lead to more variability in the successional response, this disturbance history may have introduced additional uncertainty in the EKB model.

Distinguishing between postfire succession in mature seed-producing stands and that in immature nonseed producing stands proved to be important for the experts. First, the transition probabilities for conversion into the NF type and the regeneration delay differed somewhat between the two types of fire. Perhaps more importantly, agreement among experts was lowest and uncertainty was highest for fires in immature stands. The conversion process from productive forest into nonproductive forest occurs over long time scales that likely fall outside the experience of the experts. Nonetheless, the experts recognized that such conversions occur, perhaps frequently, and that they have important implications for forest sustainability.

10.4.2 Similarities and Differences Between Expert Opinion and LANDIS-II

We found more agreement among the experts than between the mean expert response and the predictions of LANDIS-II. Quantitative disagreements between the two models were attributed primarily to the length of time required for forest regeneration, resulting in greater conversion of productive forest into nonproductive forest, a higher probability of assigning a regeneration delay to a transition, and a longer average regeneration delay period in LANDIS-II. The longer regeneration delay in LANDIS-II can be partly explained by the model's more conservative definition of a "regenerated stand," which uses a minimum biomass threshold that we suspect would require more time to reach than the experts' mental picture of a regeneration state sufficient to produce a future merchantable stand. Including a clarification of fuzzy terms such as "regenerated stand" or "stand-replacing disturbance" in Phase I of the knowledge elicitation procedure would probably have helped to narrow the semantic differences, leading to less ambiguous thresholds in the EKB model used for comparison with the LANDIS-II model. A higher probability of regeneration delay might also have resulted from differences in the scale of the assessment; the LANDIS-II results were based on 1-ha cells, whereas the experts were generally thinking in terms of forest stands (tens of hectares). Such discrepancies highlight the difficulty of adequately comparing models that have been developed under frameworks that use different scales and concept definitions. Nonetheless, the fact that the qualitative trends in the regeneration delay were consistent between the EKB model and LANDIS-II (i.e., longer after a fire than after a harvest; more prevalent delays at sites with lower quality) suggests that these trends are both robust and important to forest dynamics in Labrador.

Both LANDIS-II and the experts predicted higher proportions of the balsam fir and hardwood species as components of the landscape after clearcutting, leading to higher forest type diversity after this disturbance type (Table 10.1 and Fig. 10.7). Similarly, both methods predicted that postdisturbance tree species diversity should increase from poor to good sites. Such a convergence of results gives us confidence in the general trends represented by these relationships. Nonetheless, there were key differences in the response to different disturbances that will have consequences for the future composition of District 19a's landscape. The experts anticipated that a relatively high proportion of clearcut sites would contain some balsam fir component, whereas LANDIS-II predicted that the majority of these sites would be dominated by black spruce (Table 10.1). Central Labrador is located at the northern range limit for balsam fir, which explains its low probability of establishment within LANDIS-II (Sturtevant et al. 2007). Although local experience suggested the range limits for balsam fir in LANDIS-II may have been too conservative, sites dominated by balsam fir nonetheless produced the highest disagreement among the experts (Tables 10.1 and 10.2). The experts also predicted a much higher frequency of mixed stand conditions than LANDIS-II predicted. Part of this discrepancy may be a consequence of differing resolution (i.e., small adjacent cells with different vegetation types within LANDIS-II may be aggregated into larger “mixed” stands by the experts). However, it may also be explained by the current dominance of black spruce in the landscape, and the explicit simulation of regeneration limited by seed sources within the LANDIS-II software. Such spatial interactions tend to reinforce the inertia of the current landscape composition within the process-based model, whereas experts, by excluding any spatial context for their transition probabilities, may have missed an important process (i.e., seed source limitation) that would affect the likelihood of transition to a mixed forest condition.

10.5 Conclusions

This study is among the first to formally compare EKB and process-based ecological succession models. Moreover, it is the first time that an EKB model was developed to address regeneration delays and the conversion of productive forest into nonproductive forest during forest succession. Comparing models has proven to be an important heuristic process in science to develop a broadly accepted body of knowledge that can support decision-making (Robertson et al. 2003; Drescher and Perera 2010b). In this case study, understanding the convergences and divergences between the two methods helped to identify the limitations, uncertainties, and needed improvements in both models, as well as the gaps in our knowledge of Labrador’s forest dynamics.

The knowledge ambiguity we identified concerning the relative importance of balsam fir after clearcutting, of the conversion of productive forest into nonproductive forest, of the effects of spatial heterogeneity in seed sources on future forest composition, and of the regeneration delay after disturbance all have important consequences for our ability to sustainably manage these forests. Indeed, we believe the choice of which transition matrix (expert-based or LANDIS-II) to use in developing SFM strategies would lead to very different sustainable timber yields and would have important impacts on all the other decisions that follow, as was observed by Drescher and Perera (2010a). This is particularly true if one considers that most of the coming changes that will result from application of the SFM plan to District 19a will lead to increased use of clearcutting; important knowledge ambiguities have not yet been resolved about the succession that will occur after this disturbance. Part of the stakeholder debate over the SFM plan stems from the unknown impact of clearcutting on both timber and nontimber values (Berninger et al. 2009). Because of the importance of the differences of opinion and the high uncertainties expressed by the experts on these processes, Newfoundland and Labrador should prioritize acquiring scientific knowledge on the conversion to the NF type, on regeneration delays, and on succession after clearcutting.

Expert modeling provides a complementary approach that can support data-driven development of scientific models. It offers an opportunity to quickly identify, during a first step, the critical elements of uncertainty that must subsequently be scrutinized by empirical research and other modeling approaches. In this study, we demonstrated that our comparison of the two models provided new insights that could not be achieved by either knowledge source alone. EKB models are often easier and less costly to develop than empirically validated models; with a surprisingly limited amount of resources and effort, we were able to derive the critical inputs necessary to drive a complete succession model using only expert knowledge, and the results showed strong consistency among the experts. The value of the insights we gained amply justified the investment in conducting parallel EKB modeling. We believe that there are many other situations in natural resource planning that could benefit from this approach. However, given the limited number of studies of such a combined approach, it appears that such benefits have not yet been fully recognized.

Developing an EKB model also brings indirect benefits. Involving stakeholders and planners in the process of developing a model enhances the likelihood of its use, since experts who participated in the model development are often involved in its subsequent use (Gustafson et al. 2006), and increases the likelihood that the model will be used properly, based on an improved understanding of its scope and limitations (as pointed out by Drescher and Perera 2010a). This approach also helps to structure and formalize the exchange of knowledge among participants. Hence, after such collective heuristic exercises, the experts can better express their mental models of the processes involved and better understand the mental models of other experts. Such a shared understanding facilitates further development of forest management planning. Finally, EKB models encourage formal retention of the expertise of all participants in a way that makes this knowledge easier to transfer to younger workers with less experience. In remote areas such as Labrador, where there is often a rapid turnover of personnel and where retaining expertise is a real challenge, this collection and sharing of knowledge becomes an important asset.

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