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Abstract

An important element of resource management and conservation is an understanding of the tradeoffs between marketed products such as timber and measures of environmental quality such as biodiversity. In this paper, we develop an integrated economic – ecological spatial optimization model. The integrated model incorporates dynamic forest sector harvesting, oil and gas sector development, coarse filter or habitat based old-forest indicators, and a set of empirical forest bird models that predict bird abundance. Using our integrated model, economic tradeoff curves, or production possibility frontiers, are developed that illustrate the cost of achieving coarse filter targets by a set time (50 years) within a 100 year time horizon. We explore the production possibility frontier's relationship to the natural range of variation of old growth habitat. Our analysis illustrates the use of ecological criteria like the natural range of variation in providing guidance for the choice of preferred location on the frontier.

Keywords: Production possibility frontier, forest management, biodiversity, optimization, tradeoffs.

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1. Introduction

An important element of resource management and conservation is an understanding of the tradeoffs between marketed products such as timber and measures of environmental quality such as biodiversity. In policy circles a common question is how "costly" is an imposition or change in environmental regulation in terms of the impact on the economy. Since ecological goods and services such as biodiversity are not traded in markets, understanding the opportunity cost of maintaining biodiversity, in terms of the monetary value of foregone resource development, provides an illustration of the costs of policy to maintain various levels of environmental services. However, a further question relevant to policy is what level of environmental services is desirable and at what time in the future the level is to be achieved. This entails a social choice across the feasible set of alternatives for environmental and economic outcomes. Identification of the production possibilities between market and non-market goods and services gives decision makers important information required to make such choices about setting environmental objectives. In the context we examine – biodiversity forestry tradeoffs on publicly managed land in northern Alberta and northeast British Columbia, Canada – such tradeoff information is important to guide policy that provides access to private forest management agencies and to develop guidelines for conservation of biodiversity.

The literature contains previous studies of production possibility frontiers in the context of resource management and biological conservation (e.g. [30]). Our contribution here is to include an explicit evaluation of the effect of a set of regionally and nationally important forest policy options, namely appurtenancy and timber processing / quota restrictions, on the tradeoff relationship at a relevant spatial scale. In addition, we estimate the range of natural variation [26] in the biodiversity indicators, as determined by empirical models of the natural disturbance regime, to identify ecologically defensible criteria for management outcomes and to identify regions of the tradeoff curve which meet these criteria. Finally, we consider how changes in policy affect the ability to achieve such potentially acceptable outcomes. The examination of policy change requires modeling of many forest product firms and their response to policy and market changes which adds to the policy relevance of the analysis. The analysis of the range of natural variation in the context of the production possibilities frontier integrates an ecological concept that is being used in forest policy in Canada into the analysis of tradeoffs.

2. *Background*

The development of integrated ecological and economic models to support policy decisions is critical in the context of government decision making on public forest land. The boreal forest plains provide a case study for examining the application of such tools. Boreal landscapes in Alberta and northeast British Columbia have undergone dramatic change due to the expansion of the forest sector in this area since the 1980s and 1990s. In Alberta, most productive forest land has been allocated for timber production[1]. These lands are managed on a sustained yield basis by the determination of an annual allowable cut (AAC) which firms must maintain over time within a narrow allowable range of annual variation. Public interests in threatened wildlife such as woodland caribou and environmental protection are attempted to be accommodated through the forest management planning process, which is governed by numerous regulations on e.g. the

[1] Similar policies and resource conditions apply to the boreal forest region in northeastern British Columbia but to simplify the discussion we describe only the Alberta context.

size, adjacency, location and timing of harvest blocks. Less specific and less enforceable policy guidelines such as those set out in the *Alberta Forest Conservation Strategy* [2] recommend in addition that forest managers implement ecosystem based forest management which includes establishing ecological benchmarks, and maintaining the abundance of older forest age classes of within the natural range of variability [1].

In Alberta, the most productive forest lands have been fully allocated to timber production. As a result, Schneider [40] concludes that a reduction in cut levels is required to implement ecosystem based management and other conservation objectives. It is important to estimate the degree of reduction that might be necessary and what would be the corresponding opportunity cost. However, additional forest policy constraints lead to inefficiencies that must be accounted for in estimating such costs. For example, as in most of Canada's forest, the AAC is set without explicit consideration of the risk of fire which may impede the ability to meet both AAC and conservation objectives in the future [6]. The separate allocation of deciduous and coniferous rights to different firms operating independently on the same tenure area (or *landbase*) and restrictions on the movement of wood between mills are costly in terms of maximizing timber values [17]. Therefore the relevant questions facing policy makers include: what are the costs associated with biodiversity protection and implementation of ecosystem management objectives; and, is the forest being managed as efficiently as possible in order to minimize the costs of achieving multiple forest objectives? To address these questions we develop a production possibility frontier (PPF) to assess the tradeoffs between protection of old growth habitat and the net present value of timber harvests on public forest land in the boreal plains region.

Our objective is to develop a policy relevant analysis of conservation – forestry tradeoffs under the influence of alternate policy regimes. Such an analysis requires a relevant spatial scale and the inclusion of several forest product firms that interact in their forestry harvesting operations. Our model examines a large spatial extent (approximately 560,000 km^2), at a spatial resolution of approximately 10km x 10km grid cells (see Figure 1). The model includes 50 forest product firms at 26 locations within or on the periphery of the study region (see Figure 2). Each firm is characterized by a demand function for one of two sources of fiber which represent essentially softwood volume (used mostly for dimensional lumber) and hardwood volume (used for production of pulp and paper or oriented strand board).. The firms compete for timber thereby facilitating efficient land use from an economic perspective. The model provides spatial information on the impact of increasing conservation requirements and indicates forestry firm locations that are most likely to cease activities as conservation requirements are increased.

We examine the impact of alternative forest policy regimes on the production frontier for timber values and old growth habitat. The policy dimension we examine is the relaxation of restrictions on wood flows across administrative boundaries, shown in Figure 2. Appurtenancy and timber processing / quota restrictions, which include requirements that forest lands surrounding a mill to be used primarily to support that facility, are traditional elements of Canadian forest policy (see e.g. [33]). Such restrictions were imposed for security of supply for mills and to support economic development and employment in rural communities. However, appurtenancy and overlapping tenures also restrict wood resources from flowing to their most valued uses. Overlapping tenures in this context means that firms rights to fiber overlap on the landbase. In Alberta, for example, firms with area based rights (Forest Management Agreement or FMA holders) do not have complete rights over all merchantable forest within their management areas.

One or more firms with volume based rights, or quotas, are likely to operate on the same landbase and are guaranteed by statute periodic harvest volumes. Typically these rights differ in terms of the tree species' desired for processing (hardwood versus softwood). Furthermore, regeneration standards mandate stand-level reforestation to either softwood or hardwood dominance depending on pre-harvest conditions and the initial allocation to tenure holder and landbase. These rules, which can vary among tenure areas, introduce a potentially costly restriction on tenure holders. Quotas and appurtenancy impose restrictions on tenure holders' actions and restrict the flow of forest resources to the highest and best uses. Therefore, the "security" associated with appurtenancy and related restrictions comes at a cost to the economic value of wood products. As we shall see, these constraints also affect the ecological – economic tradeoffs between conservation and timber objectives.

We also explore the production possibility frontier's relationship to the natural range of variation of old growth habitat [21,5]. Our analysis illustrates the use of ecological criteria like the natural range of variation in providing guidance for the choice of preferred location on the PPF. Without guidance from other normative criteria, the natural range of variation provides an ecological benchmark from which to evaluate policy decisions about movements along the frontier.

We find that the tradeoff frontier has the classic shape found in other studies but we also find that policy changes have a significant impact on the position of the frontier. Areas of the study region that are likely to be implicit reserve areas, and product mills that are marginally profitable at various levels of the conservation target are identified through the spatial dimensions of the model. In the following section we review the literature on production possibility frontier approaches and then discuss the linkage between the PPF and the range of natural variation and coarse filter approach. We then explain the model formulation in more detail and describe the solution approach. The next section describes the results including the tradeoff frontiers and spatial depictions of the outcomes, under different policy regimes, and we assess these outcomes in terms of the range of natural variability. We then conclude the paper with a discussion of the policy implications and the limitations and potential extensions of the study.

3. Production Possibility Frontiers

The PPF is an efficiency frontier, illustrating the maximum feasible combination of outputs based only on technological and input availability assumptions. In this sense, the PPF represents an ‘unconstrained’ optimum which allocates available inputs efficiently given other output constraints. For example, forest land is allocated to maximize the net present value of timber production subject to habitat constraints. Traditional regulatory constraints on timber harvest such as adjacency, and restrictions on the flow of wood between demand sources are removed. While any point along the efficiency frontier is feasible, policy constraints and other barriers may lead to inefficient combinations of outputs. Construction of the PPF allows decision makers not only to assess the economic tradeoffs associated with any particular bundle of habitat and timber production, but also to evaluate the costs of current policies relative to the unconstrained optimum. The PPF is a convex set under standard assumptions of diminishing returns to fixed factors such as land and other natural capital. This means that the opportunity cost of increasing biodiversity or other environmental goods will be low at first, but will increase monotonically as more natural capital is allocated to this objective. Thus another interesting question is whether we are currently on the ‘flat’ initial part of the PPF, so that environmental goods can be increased at a relatively low cost. However, additional normative information is required to make judgments about the location of superior options on the frontier [46].

The construction of a PPF for ecological and economic outputs requires an integrated modeling approach. Integrated modeling of forest landscapes is a complex undertaking given the spatial and temporal dynamics affecting both economic and ecological systems. It is necessary to integrate process based simulation models that identify ecological outcomes such as species presence and absence based on landscape characteristics with optimization models used to identify efficient solutions [48]. Computational demands require modelers themselves to make tradeoffs about the degree of spatial and temporal resolution in the model, as well as the representation of the spatial and dynamic relationships within the model. Our understanding of the effects of these modeling decisions on tradeoff analysis is increased with each exploration in this area. This study illustrates the potential benefits of improving on the spatial and temporal dimensions of integrated forest sector modeling, in particular by allowing us to test the impact of some of the spatial regulatory restrictions such as appurtenancy / quotas on timber values, as well as reduced flexibility to achieve ecological objectives.

One approach to constructing the PPF emerges from the reserve design literature. This literature focuses on the spatial complexity of the problem from the ecological perspective. Initial approaches focused on developing algorithms to maximize biodiversity outcomes for given habitat constraints. These models are explicitly spatial in that they considered the marginal contribution of each site in the network to additional levels of biodiversity however the combinatorial nature of the problem remains numerically challenging for large problems. The solutions take advantage of the complementarity between sites, however are considered impractical in that they do not consider budget constraints associated with the optimal reserve strategy. By incorporating the opportunity cost of alternative sites, it is possible to increase biodiversity protection for a given budget constraint (e.g. [4,34]). Reserve design algorithms that include opportunity cost of land considerations can be considered a “dual” programming problem to the tradeoffs problem [39]. Alternately the maximization of net present value subject to habitat or species persistence constraints provides a spatial description of land use patterns in the solutions. These land use patterns can be interpreted as efficient reserve designs [35]. By iterating the solution for multiple constraints it is possible to trace out a PPF for conservation and economic objectives using these methods.

The reserve design approach is static. Opportunity costs of land are typically based on discounted present values assuming that the current and future productivity of land is capitalized in private land values (e.g. [4,8,34]). For example, Juutinen et al. [25] calculate the opportunity cost of foregone timber revenues using a stand level Faustmann rotation model. Similarly the discounted present values presented in Weber [49] are based only on site estimates of stand values. Both of these examples consider only permanent reserves. These approaches are restrictive for forest landscapes. Temporal dimensions that affect the costs and benefits of site selection include: the impact of harvest rates today on future fiber supply and risk, as well as the impact of current harvesting decisions on future habitat availability (e.g. availability of old growth forest). Spatial considerations relevant to the economics of forest management are largely related to access and the costs of regional road networks on delivered wood costs. These dimensions are not typically captured in land prices or public timber auctions due to externalities between forest tracts as one moves from stand level to regional level analysis (e.g. [32]).

The incorporation of a spatially explicit cost structure in the forest management model is expected to increase the curvature of the PPF because of increased heterogeneity between sites over time as road networks and other infrastructure is diffused across the landscape. Overall we might expect increased spatial representation of costs will result in greater spatial specialization of harvested and non-harvested areas. As a result we expect habitat constraints to result in de-facto zoning which moves over time as the forest matures. At the same time, incorporating regeneration in the model relaxes the habitat constraint and overall we expect the costs of a particular conservation target to decrease relative to the case of permanent reserves. An explicit regional timber supply model is required to capture these tradeoffs. There have been several studies that examine a single economic agent (e.g. a forestry firm) that maximizes the net present value of forestry operations subject to constraints on alternative levels of the conservation goods. These agents respond to constraints by altering management variables such as the optimal rotation age, or the total area harvested (e.g. [29,5]). However these models lack spatial representation of both the economic and ecological processes.

The current study is most comparable to a recent study by Nalle et al. [30] that develops a PPF for three outcomes, the net present value of timber harvest, and the population levels for two species with conflicting habitat preferences: the great horned owl (mature forests), and the common porcupine (young forests). The authors generate an unconstrained PPF, and illustrate the costs two management scenarios; the first concentrating conservation effort on public land only, and the second a static reserve selection problem where allowing habitat patterns to shift over time is not allowed. Nalle et al. [30] take spatial restrictions on timber harvests as given. We examine the effects of relaxing spatial constraints on the ability to achieve conservation targets.

While the choice of the economic objective as the maximization of net present value from forest products is a relatively straightforward decision, the choice of the ecological criterion used to represent biodiversity is more difficult. Integrated models differ with respect to how ecological objectives are specified. Examples include wildlife population sizes [30], mature or old-growth forest [46], species persistence [28,35], and habitat suitability [7]. In most cases two-dimensional tradeoffs are analyzed (e.g. timber versus a conservation goal) while in some cases multidimensional tradeoffs are assessed (e.g. [30]). Like some of the previous analyses, our model explores two-dimensional tradeoffs between timber values and old growth constraints.

Canadian forestry has been characterized by a movement towards the use of coarse-filter objectives, or coarse-filter in combination with fine-filter objectives [44]. Coarse filter objectives are defined in terms of attributes such as age class structures and proportional abundances of land cover classes. In boreal forests these are often set in reference to landscape patterns potentially created by natural disturbances such as wildfire which are believed to offer a template for sustainable forest management [24]. Fine filter objectives, in contrast, are generally established in terms of the population size and distribution or the habitat requirements of individual species. We use old forest as a coarse filter criterion. The benefit of using old growth criterion is that is relatively easy to measure is directly linked to land use decisions. Perhaps more importantly, old forest conservation can be considered representative of natural disturbance management (NDM) (see [5]). Our approach allows us to identify the impact of management for the coarse filter objective on fine filter indicators. The coarse filter versus direct approach to biodiversity conservation has received some attention in the literature. For example, Juutinen et al. [25] test the difference between different specifications of conservation objectives in the reserve selection problem and find that the coarse filter approach which minimizes the costs of meeting habitat constraints does not work as well at achieving biodiversity for a given area constraint. However, as Weber [49] shows, a coarse filter approach may itself be more cost effective than the direct approach and thus result in greater biodiversity for a given cost.

In order to examine fine filter as well as coarse filter approaches, we embedded a suite of forest songbird abundance models into the overall framework and analyzed their predictions ex-post as a proxy for biodiversity (e.g. [20]). The songbird models were fit to data from a multi-year landscape-scale (≈100 km^2) observational study designed to support this application [43]. Conducting ex-post analysis within the PPF framework can test the efficacy of indirect, coarse filter management in achieving fine-filter or species-level objectives.

4. Model Formulation

Within the study area there are a number of relevant administrative levels and associated boundaries, which include forest management agreement (FMA) areas (timber supply areas or TSAs in BC), and sub-units of FMAs in Alberta called forest management units (FMUs)(see Figure 2). In this paper we concern ourselves only with the forested portion of that area, which is about 23.3 million ha. The remaining area is composed of non-forested or sparsely forested wetlands with a large inclusion of areas converted to agricultural land uses on either side of the Alberta/BC border, along the Peace River. We model ecological impacts over this area using a coarse filter indicator, area or proportion of old mesic forest; and a fine filter, forest bird counts. In this paper, we focus on ecological impacts and conservation objectives with respect to forest harvesting and management activities over the entire forested area. While oil and gas sector activities are important within the study area the number of wells in the area are held constant at existing levels in this paper, so as to isolate the ecological impact of the forest sector.

4.1 Forest Dynamics

Harvesting activities are represented spatially at a township level or 10x10 km grid cell. There are 5600 grid cells or locations in our model, which we index by *h*. Within each location, forest patches are represented aspatially. Forest patches are aggregated into classes defined by 44 five year age classes and 8 forest tree species types, which we index by *s* and *i* respectively. Each forest type is characterized by two timber types *j*, hardwood and softwood. The model is dynamic and time is divided into 10 year periods which are indexed by *t*. We denote the maximum time period as period *T*. At time *t*, the land area distribution of forest classes over locations, age classes, and species types is represented by X_{hist} over all *h*, *i*, and *s*. The initial forest land area for a particular combination is then denoted by X_{his0}.

In each time step of the model, the land area of each forest class X_{hist}, is transferred to a new forest class in up to three ways: growth into the next older age class, harvest, and natural forest fire disturbances. All three of these mechanisms are shown in the following dynamic equation:

$$X_{hi,s+1,t+1} = (X_{hist} - x_{hist})\theta_{hi} \tag{1}$$

where x_{hist} is the area of forest harvested in ha of type *i*, ageclass *s*, and grid cell *h* in period *t*. The expected portion of forest land of type *i* in grid cell *h* left after fire is denoted θ_{hi}. Forest area remaining after harvest and fire is transferred to the next oldest age class $X_{hi,s+1,t+1}$ in the next period.

Areas disturbed by harvesting are transferred to younger age classes according the following equation:

$$X_{hi1t+1} = \sum_{s>=m_i}^{S} x_{hist} + X_{hi0t} \tag{2}$$

and areas disturbed by fire are transferred using:

$$X_{hi,0,t+1} = \sum_{s=1}^{m_i} X_{hist}\theta_{hi} + \sum_{s\geq m_i}^{S} (X_{hist} - x_{hist})\theta_{hi} \tag{3}$$

where m_i is as minimum harvest age class and S is the maximum possible age. This construction of forest dynamics is similar to that of Reed and Errico [36].

4.2 Ecological Indicators and Constraints

As noted above, we evaluate a coarse filter approach to biodiversity management. The coarse filter indicator included in the model formulation measures the abundance of a focal avian habitat type associated with forest of a specific species composition and age class which we characterize as "old mesic" forest. In the boreal plains ecozone, sites can be stratified by soil nutrient and moisture regimes. The most productive sites from a forest management perspective can be called "mesic", referring to a soil moisture regime intermediate between poorly drained wetlands with organic soils and very well drained dry sites with coarse sandy soils. Mesic sites are also believed to be the most productive for forest songbirds in terms of both species richness and total abundances. These sites can be reliably identified from forest inventory attributes [37,9]. To a first approximation, they correspond to mapped stands with a canopy dominated by some combination of trembling aspen, balsam poplar, white spruce and balsam or subalpine fir, which are commercially the most valuable and most harvested tree species in the study region. Mesic sites with an estimated or projected canopy age above 90 years are considered "old." This is a compromise between the economic rotation ages of the two most important mesic tree species, trembling aspen (approximately 80 years) and white spruce (approximately 100years). It is also the age by which structural features characteristic of the old-growth condition begin to appear in aspen stands [12]. See Vernier et al [47] for further details of the underlying avian habitat classification from forest resource inventory attributes. Coarse filter habitat objectives are expressed in terms of the proportional area of focal habitat at some chosen period:

$$\frac{1}{A}\sum_{h}\sum_{s\geq s_o}\sum_{i\in F_m} X_{hist} \geq O_t \tag{4}$$

where O_t is the old mesic forest target in period t, s_o is the age at which mesic forest is defined as old, and F_m is the set of forest types that are defined as mesic.

For the ex-post fine filter analysis, we used the total predicted abundances of a number of songbird species, on mesic habitat. These were based on Poisson regression models of empirical count data using a number of landscape and patch level covariates. The observational data were collected in 2001 and 2002 by a standard survey protocol (dawn point counts of fixed duration and sampling radius; [42]) as part of a landscape-scale study designed to elucidate the effects of focal habitat abundance, configuration and industrial development on forest songbirds [43]. The landscape units were townships corresponding to the locations of this study, distributed over roughly 100,000km^2 in the southeastern portion of the present study region. The focal habitat type was old mesic forest[2]. Our modeling framework calculates summed expected bird abundances b_{hist} over each aggregation of patches X_{hist} as

[2] The landscape design variables for focal habitat were its proportional abundance and a measure of its spatial arrangement within landscapes, derived from the patch size distribution [16]. The design variables for industrial

$$b_{hist} = \frac{X_{hist}}{\pi} f\left(O_{is}^{m}, D_{is}^{m}, N_{h}^{1}, N_{h}^{2}, W_{h}, O_{ht}^{T}, \overline{P}, R_{ht}, E_{ht}; \beta\right)$$

where

O_{is}^{m}, an old mesic indicator which equals 1 if stand type *i* is old mesic at age *s* and 0 otherwise;

D_{is}^{m}, a deciduous mesic indicator which equals 1 if stand type *i* is deciduous at age *s* and 0 otherwise;

N_{h}^{1} and N_{h}^{2}, are indicators that capture geographic gradients in avian distributions specifically whether location *h* is north of latitude 55.6ºN and 56.6ºN respectively;

W_{h}, an indicator similar to N_{h}^{1} that indicates whether location *h* is west of longitude 113ºW;

O_{ht}^{T}, the percentage of old mesic forest in location *h*;

$\overline{P}_{ht}$, the mean log patch size of old mesic patches in location *h*; and

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development were the cumulative proportional area of harvest over the 30 years prior to survey, and the total number of drilled oil and gas wells measured as log density standardized to wells per 10,000 ha. The log of well density is a surrogate for the cumulative impact of energy sector activities, especially the densities of linear features such as roads, seismic lines and pipelines [18]. Post-hoc landscape variables included a year effect, and geographic location measured as factors partitioning the survey region extent into roughly equal thirds from south to north and by halves longitudinally. This was considered sufficient to capture the spatial gradients evident in the data whilst safeguarding out-of-sample prediction over the geographic range of the current simulation study. In the regression analysis developed for this application, we included also a number of stand or patch-level covariates. The most important of these were two indicators which stratify mesic habitat into four subclasses by dominant species (deciduous versus conifer) and canopy age (old or young; see explained). We also standardized the predictions for the effect of sampling data within year.

R_{ht}, the percentage of location *h* cut in the last 30 years

E_{ht}, the log of the number of wells (energy sector).

β is a set of estimated parameters, *f* is the model form, here exp($z'\beta$), and *z* is the vector of covariates. The constant 1/π scales predictions from 100m radius circular plots to expected count per ha. Predicted counts can be aggregated up to the township, b_{ht}, by summing over *i* and *s* and thence to the study region by summing over townships *h*, $b_t = \sum_{his} b_{hist}$. Some of the covariates, such as O^T_{ht} and $\overline{P}_{ht}$, must be computed for each location in each time period *t*, but these are simple summations of areas over each aggregated patch, X_{hist}. As noted, although it would be possible to constrain species' abundances directly, we leave this for future research. and opt instead for the coarse filter approach as represented in equation 4.

4.3 Economic Equations, Constraints and Objectives

Harvest volumes are computed using yield curves that are specific to each forest type *i*. Thus v_{ijs} represents the merchantable volume of timber of species j (hardwood or softwood) that can be obtained from forest type *i* and age class *s* by harvesting 1 ha. The total amount of wood of species *j* harvested from location *h* is V_{jht}, which is defined by:

$$V_{jht} = \sum_{is} v_{ijs} x_{hist} \qquad h \in A \qquad (5)$$

where A is a set of all locations that have road access (we return to the next section). Another important aspect of our model is that demand for timber is spatially represented by multiple mill locations. This allows us to more effectively determine spatial harvesting patterns and the costs of conservation objectives such as constraints on old forest. Harvested timber is shipped to *M* possible mill destinations (each associated with a particular location *h*), the choice of mill being governed by the objective function described below. Then z_{jmht} is the amount of wood of species *j* that is shipped to mill *m* from location *h* in period *t*. The amount of wood shipped to each mill *m* from location *h* cannot exceed the amount of wood harvested from location *h*:

$$\sum_{m \in M_j} z_{jmht} \leq V_{jht} \qquad h \in A \tag{6}$$

where M_j is a subset of the *M* mills that demands wood of type *j* (i.e., hardwood or softwood). The amount of wood delivered to a particular mill *m*, or y_{jmt}, is captured by the equation:

$$y_{jmt} = \sum_{h} z_{jmht} \qquad h \in A \tag{7}$$

Harvesting activities are driven by demand for wood at each of the *M* mill locations. Each mill generates benefits from the wood delivered to it, y_{jmt} according to a revenue function $R_{mjt}(y_{jmt})$. This is defined by the area under the mill's inverse demand curve for wood. The costs of delivering wood to the mills are from transport, harvesting, regeneration activities, and road building. Denote *T* as the number of time periods in the model. In this type of model, if ending inventory has no value the model will tend to exhaust all the resources in the final periods. We solve this problem by introducing ending inventory values. Ending inventory value per ha of forest area X_{hisT+1} is denoted E_{his}. When these are added to the revenues generated at all mills we have the following net benefit equation:

$$B = \sum_{jt} \sum_{,m \in M_j} R_{mjt}\left(y_{jmt}\right) - \sum_{jt} \sum_{h \in A} \sum_{m \in M_j} C_{mht} z_{jmht} - \sum_{h \in A} \sum_{ist} H_{ist} x_{hist} + \sum_{his} X_{hisT+1} E_{his} \qquad (8)$$

where C_{mht} is the per unit volume transport cost of wood delivered to mill *m* from location *h* and H_{ist} is the per ha harvesting cost plus regeneration cost for stand type *i*, age class *s* in period *t.* Cost and revenue components are subscripted with a *t* to denote that costs and revenues are different in each period due to discounting of future values and possible changes in technology.

4.4 Forest Access

One important aspect of our study area is that substantial portions of it are currently unaccessed by roads[3]. We address the access problem by assuming that enough roads are built within an accessed township to access all adjacent townships. In other words, we do not model roads as links that connect a set of nodes. This means that wood may flow from township to township as long as the two townships are adjacent and they are accessed.

We define a set *A* that contains all locations accessed, a set *U* of locations that are not accessed previous to our model time horizon, and A^U is a set of location in A that are adjacent to at least one location in U. Major access decisions are captured (i.e., presence of major logging haul roads or highways) through the integer variable I_{ht}, which indicates the time period *t* that location *h* is accessed. A location can be accessed only once and we assume that the access is permanent. Hence, we require:

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[3] In our model we account for the timing and cost of forest access decisions but in a simpler way than conducted in studies focused on timing and access decisions (e.g. [38,3]). These authors were focused on solving forest access problems and integration of the forest access decisions into timber supply models, but on a much smaller scale. Even so, when the spatial and temporal dimensions of road construction are incorporated into such models the problem becomes complex and difficult to solve as acknowledged by these authors. Our focus here is not on solving this problem but to simply account for forest access timing decisions in as simple a way as possible.

$$\sum_t I_{ht} = 1 \qquad (9)$$

For locations $h \in U$, harvesting cannot take place until access is present. Hence we require:

$$V_{jht} \leq \sum_{s=0}^{t} I_{hs} M \qquad h \in U \qquad (10)$$

where M may represent the maximum road capacity (see [3]) or simply a number larger than the largest conceivable V_{jht}. For unaccessed areas the eventual path from locations to access points or locations that are permanently accessed cannot be predetermined. Hence, the transport costs C_{hmt}, which are based on the minimum cost route from supply locations h to mills m , will vary depending on the overall access plan. To account for this we define the set of valid access plans

$$A^P = \left\{ \left(I_{ht}\right)_{\forall ht} \in \{0,1\}^{n(U)\times T} \left| \sum_{s}^{T} I_{hs} = 1, \text{ if } I_{ht} = 1 \text{ then } h \in P_h \right. \right\}$$

Where $n(U)$ is the total number of locations not accessed at the beginning of the time horizon and P_h is the set of all feasible paths from h to a location in A^U, the set of all locations accessed at the beginning of the planning horizon. A feasible path is a sequence of locations $h^0, h^1, \ldots, h^N$ such that: h^{i+1} is adjacent to h^i $i = 0,...,N-1$; $h^N \in A$ and adjacent to U. Let a be one possible access plan (i.e. $a \in A^P$). Then define C^a_{hmt} as the minimum transport cost from location h to m in period t for access plan a. The objective function given a and including access costs is then

$$B^a = \sum_{jt} \sum_{,m \in M_j} R_{mjt}\left(y_{jmt}\right) - \sum_{jht} \sum_{m \in M_j} C^a_{mht} z_{jmht} - \sum_{hist} H_{ist} x_{hist} - \sum_{t} \sum_{h \notin A} D_t I^a_{ht} + \sum_{his} X_{hisT+1} E_{his} \qquad (11)$$

Given *a*, equations (1)-(7), and (10) form a non-linear programming problem. An optimal solution, $\left(y^a_{jmt}\right)_{\forall jmt}$, $\left(z^a_{jmht}\right)_{\forall jmht}$, $\left(x^a_{hist}\right)_{\forall hist}$, and $\left(X^a_{hist}\right)_{\forall hist}$, given *a*, is obtained by maximizing (11) subject to (1)-(7). To obtain an overall optimal solution we would need to solve:

$$\max_{a \in A^P} B^a \tag{12}$$

4.5 Regulations and Wood Flow Constraints

Figure 2 is a map of administrative boundaries or forest management units and mill locations. Wood quotas arising from appurtenancy, wood processing constraints, and forest tenure requirements are defined and enforced according to these boundaries and mill locations. Let *k* be an index of forest management units and H_k be the set of grid cells in forest management unit *k*. Then for each tree species *j*, each mill $m \in M_j$, and each *t* quota constraints can be defined as:

$$q_{jmkt} \le \sum_{h \in H_k} z_{jmht} \tag{13}$$

where q_{jmkt} is the quota for mill *m*, species *j*, from forest management unit *k*, in time *t*.

4.6 Solving the Model

The problem of maximizing (11) subject to equations (1)-(7) and (13) is a large linear or non-linear programming problem, depending on the form of the revenue functions for each mill location. This problem is large and time consuming to solve using conventional methods. Hence we employ a Lagrangian Relaxation method (see [22, 23, 31]) to significantly reduce computation times. The method works by relaxing strict primal feasibility requirements for selected constraints. In this case the relaxed constraints are the old mesic forest constraint (equation 4), the market clearing constraint (equation 7), and the quota constraints (equation 13). The method yields optimal solutions although equations (4) and (7) will not be satisfied exactly. We also utilize the method described by Larsson et al [27] in conjunction with the Lagrangian relaxation method to generate solutions that are closer to primal feasibility and optimality and to improve convergence. Solving (12) for the optimal access plan is a difficult problem to solve because it is a mixed integer problem. Andalaft et al. [3] formulate a similar but smaller scale problem and describe and demonstrate a series of complex procedures for solving it. Richards and Gunn [38] use a different method to solve a forest access problem with volume constraints, again on a smaller spatial scale than the problem described here.

We use a simple heuristic for generating alternative access plans. It is based on the solving a small access problem for each un-accessed grid cell. Each un-accessed grid cell may be permanently accessed in one of 10 periods. For each potential access period it is simple to compute an estimate of the maximum net present value of harvest. Let this maximum be NPV_{it}. If $\bar{t}_i$ is the earliest access time of neighboring townships to i then the access time for i can be determined by choosing t to solve:

$$\max_{t \geq \bar{t}_i} NPV_{it}$$

We employ this as a simple to implement heuristic which we know will not guarantee global optimal results[4].

4.7 Estimating the Natural Range of Variation of Ecological Indicators

The natural range of variation of old mesic forest over the study area was estimated by Monte-Carlo simulation of forest dynamics in the absence of forest management. A multi-stage stochastic fire model was adapted from Cumming and Armstrong [17] to capture spatial variation in the fire regime over the study region[5]. One thousand 200 year simulations of forest development were made starting with the initial forest conditions from the same forest inventory used with the optimization model. The harvesting sub-model was turned off and the energy sector wells were removed from the landscape so that the only disturbance was the simulated pre-suppression fire regime. The percentage old mesic forest at the end of a 200 year simulation was taken to be a realization of the natural disturbance regime independent of initial conditions and prior history. The distribution of ending values over the 1000 simulations is the estimated natural range of variation in the indicator.

5. *Model Data*:

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[4] With the heuristic, unaccessed townships are only opened when the NPV for that specific township is positive. However, it may be worthwhile to open a township that itself yields a negative NPV so that unaccessed areas beyond with positive NPVs may be opened up for harvest.

[5] The empirical data were The Canadian Large Fire Database [45] which records the location, size and attributed cause of all large fires (>200ha) from 1959 through 2001. Lightning fires were referenced to a 10,000 km^2 hexagonal grid, and the observed fire regime for each cell was characterized by three estimated parameters: the frequency of large fires (expected count per unit area and time assuming Poisson errors) and the shape and truncation parameters of a truncated Pareto fire size distribution. [13]. The resultant parameter maps were intersected with the simulation grid to assign parameters to each township. The composition of areas burned by simulated fires is calculated from multivariate regression models [15] that we assume to be approximately correct over the study region. To represent historical and current fire regimes, we corrected the observed frequencies to account for changes over the period of record in the probability that a detected fire will become large [19, Table B2]; these changes measure increasing effectiveness of wildfire suppression by initial attack.

The forest inventory data are primarily Alberta's phase 3 forest inventory. Some more recent Alberta Vegetation Inventory (AVI) is also included. The forest inventory data are the source for the initial areas of forest cover, X_{his0}, described above. The inventory data were classified into 7 forest cover types, indexed by *i*, and 44 five year age classes, indexed by *s*. Timber yields, v_{ijs}, were obtained from forest products companies with licenses in the study region. The parameters, θ_{hi}, which give the average proportion of land that is unburned were estimated from prior simulations using the fire regime parameters described above, except for the probability of escape to 200ha which was set to represent current fire management effectiveness in Alberta [19]. Revenue functions $R_{mjt}(.)$ were estimated as the area under inverse demand curves for wood at each mill location. The demand curves were estimated from provincial and national Statistics Canada data sets (various CANSIM time series). Estimated demand curves are for representative mills in the pulp and paper, the waferboard and the sawmill industries. The individual demand curves were calibrated to individual mill capacities and wood flows using data provided by the Government of Alberta's Department of Sustainable Resources Development. Logging and transport costs data (C^{a}_{hmt}, H_{ist}, and D_t) used in this study are as described in Cumming and Armstrong [14]. We used a discount rate of 0.04.

6. Results

A production possibilities frontier can be derived by progressively increasing the ecological indicator target, in this case the old mesic forest target in equation 4, and maximizing the objective function subject to the other constraints. Higher old forest targets will yield lower objective function values. The model, used in this way, will provide estimates of the impact of alternative conservation strategies / targets in terms of the foregone economic activity. Figure 3 shows the resulting production possibilities frontier between net present value of forest harvesting activity and old mesic forest over the entire study region. It does not include any of the spatial processing constraints that are current policy and as such represents the solution to an unrestricted maximization, except for the old mesic constraints. The left most point on the curve shows the objective function value as plotted on the smallest old mesic forest level over the last 5 periods in the planning horizon. This point does not constrain old mesic forest. Harvest policy without old mesic constraints results in a minimum old mesic forest level of 23% over the last 5 periods of the planning horizon. Other points show objective function values plotted on the old mesic forest target or minimum old forest percentage required in each of the last 5 planning periods. Also shown in Figure 3, is the range of natural variation of old mesic forest, derived from the forest fire simulation model. Current management policy results in an old mesic forest level that is less than the median and outside the range of natural variation. However, since the range of natural variation encompasses the flattest part of the possibilities frontier, achieving old forest targets equivalent to the median or even the 90th percentile of natural variation in old mesic forest could be done with relatively little expense in terms of forgone forest harvesting value. Note, however, that this target is being imposed over a very large area. Maintaining states within the natural range of variation over this scale carries little cost. In further studies, we will examine the how the costs of maintaining this condition vary with the size of management unit. We conjecture that the costs at the forest management unit extent will be significantly larger.

Figure 4 shows the relationship between four selected bird species and the objective function values from the production possibilities frontier. In this case the coarse filter approach works to increase the bird counts in the "correct" direction. That is, use of the coarse filter requirement to increase old mesic forest also increases bird abundance. However, the bird counts may not be optimized for each bird species. Optimizing bird counts would require that they be constrained rather than (or in addition to) the coarse filter indicator. The three selected bird species shown in Figure 5, have a negative relationship between old mesic forest cover and bird counts. Hence bird counts increase as the objective function increases.

Figure 6 shows the effect of spatial timber processing restrictions, which restrict wood flows across administrative boundaries. Again, the level of old mesic forest when no coarse filter constraint is applied is not within the range of natural variation, but a position within the natural range of variation may be obtained without substantial cost. However, the curve labeled “with quotas” shows a drop in net present value of approximately 8% from the case where no constraints on wood flow are applied and where both scenarios do not constrain old mesic forest which increases to about 27% when the old growth constraint is set to its maximum. Figure 6 also shows that a target old mesic forest level equivalent to the upper range of natural variation can be achieved at minimal cost if spatial timber processing restrictions are maintained. It is even possible to increase overall timber benefits and target the highest level of old mesic forest in the range by relaxing the spatial timber processing restrictions.

Figures 7, 8, and 9 illustrate the spatial implications of biodiversity constraints. In Figure 7 the area of old mesic forest is shown under no old forest constraint and the area when a constraint of 46% is imposed. The locations of old forest in the constrained case are illustrative of a least cost approach to attaining the target, or a least cost protection strategy. A time sequence of such illustrations provides an illustration of floating reserves or dynamic conservation networks that is the most cost effective means of achieving the coarse-filter conservation target and which is also arguably more consistent with the natural dynamics of this ecosystem than is any static system of protected areas [11].

Figures 8 and 9 show the abundance of two different bird species, the Canada Warbler and the White-throated Sparrow respectively, under old mesic forest constrained and unconstrained situations. The Canada Warbler is more abundant when the old mesic constraint is imposed while the White-throated Sparrow is less abundant. This is not surprising given the different habitat preferences of the two bird species. These results suggest that the coarse filter approach will have positive effects on some species but negative effects on others and that there will be changes in the spatial distribution of individual species as a result of the coarse filter policy.

Figures 10-13 illustrate the effect of the coarse filter old forest constraints and spatial timber harvesting constraints on 4 individual bird species. In the case of Canada Warbler, Ovenbird and White-throated Sparrow, spatial harvesting constraints have negative effects on counts. This is due to the rearrangement of the harvest area under the constraints, which can shift harvesting into or out of the preferred habitats. However, the Yellow-rumped Warbler actually does better under the quota constraints than with no quota constraints (see Figure 12). The natural range of variation is also shown for each species. For the Canada Warbler the current policy is outside the natural range of variation, but points within the range up to the 90th percentile can be achieved at minimal cost. For Ovenbird the natural range of variation does not overlap the tradeoff curves (see Figure 11). This result is primarily due to the negative effects of harvesting on forest stands near Ovenbird old forest habitat. Even when old mesic forest is fully constrained at 44% there is still nearby harvesting on non-mesic sites and since there is no harvesting in the range of natural variation these negative effects are excluded. This is why the range of natural variation is shifted to the right of the tradeoff curves. It appears that harvesting would have to be severely restricted or completely excluded from certain areas to ensure that this species' abundance is within its natural range. The current policy yields higher abundance for the Yellow-rumped Warbler than the range of natural variation. Hence, increasing old mesic forest could potentially reduce abundance to within the natural range for this species, while increasing abundance to within the natural range for birds such as Canada Warbler, which prefer old mesic forest. The natural range of variation for White-throated Sparrow is far higher than the range of the tradeoff curves (see Figure 13). This is due negative effects of oil and gas wells on this species, which are not present in the natural range. Hence, for this species abundances cannot be increased to within the natural range by changes in forestry activity alone, it would be necessary to adjust oil and gas activity as well.

7. Discussion

The main contributions that we feel this study makes are (1) the development of a tradeoff frontier for a large spatial scale and a multi-firm economic environment, thus making it relevant for provincial scale policy analysis, (2) the incorporation of insights from the natural range of variation of our coarse filter target into the tradeoff analysis and (3) the empirical assessment of the impact of appurtenancy / spatial timber processing constraints.

The incorporation of the natural range of variation suggests that current levels of our biodiversity indicator are outside the range of natural variation but that increasing the percent of old mesic forest to extend to the median of natural variation would be quite inexpensive in opportunity cost terms. However, this analysis only considers the biodiversity indicator and the range of variation evaluated at a large spatial scale. If the ecological objective is to be examined and implemented at smaller spatial scales (e.g. where each FMA is required to maintain a proportion of old mesic forest) the tradeoffs are expected to be quite different. At present many detailed forest management agreements (developed by FMA holders) describe efforts to incorporate natural range of variability objectives or targets into management plans. Future uses of this modeling framework will assess the impact of smaller spatial scale objectives in economic and ecological terms. Furthermore, these results do not include considerations of energy sector expansions (discussed below).

The empirical assessment of the impact of appurtenancy, timber processing and administrative boundary constraints revealed a significant cost associated with this constraint. Potential net present values decreased by nearly 10% with the constraint. Alternately, without the constraint, achieving biodiversity targets is much less expensive. Our exercise provides not only the aggregate costs of the policy constraint, but can also be used to examine the spatial location of the areas expected to be affected by a change in the policy. Both pieces of information provide important input into policy analysis of the benefits and costs of spatial constraints. Historically spatial constraints were viewed as critical to community stability and resource utilization. Consideration of whether these benefits still exist today, and if so whether their benefits outstrip the costs, frame the policy debate that our results provide input into.

Currently our modeling framework maximizes net present values (NPV) from forestry subject to the coarse filter constraint. The fine filter objectives (birds) are tracking the landscape outcomes from this optimization problem. In future work we plan to optimize over NPV and the fine filter indicators in an attempt to assess how optimization over fine filter indicators differs from the coarse filter approach. An assessment of whether coarse filter objectives address fine filter targets, whether fine filter objectives may address coarse filter targets, or if a combination of targets is required, will inform the on-going debate on coarse filter or natural disturbance based forest management. In addition, a likely extension is to include other fine filter indicators, particularly threatened species like woodland caribou. Examining the opportunity cost of various objectives and management strategies for threatened species will provide valuable information for policy makers and land managers.

A significant forest disturbance agent that is not fully incorporated into our model is the energy sector. Energy sector activity (oil, natural gas, oilsands) has been increasing rapidly in the areas of the boreal forest that we study [41]. These activities have significant cumulative effects in terms of habitat loss, creation of linear features on the landscape, and disturbance. The present stock of well sites is incorporated in our model. However, we have not included projections of energy activities in this paper nor have we incorporated the profits from energy resource extraction into the objective function. These are important tasks for future research. The number of well sites present in a township has a significant effect on several bird species. The contributions of the energy sector to royalties and provincial revenue is currently orders of magnitude greater than the forestry sector. The tradeoffs between the two overlapping economic sectors (forestry and energy) and the variety of ecological indicators will provide a much more relevant assessment of the challenges of land use management in the boreal forest. Incorporating energy into the objective function will be difficult because of the uncertain nature of energy reserves and the complex exploration – extraction behavior of the sector.

A final aspect of the model that has not been fully employed is the role of natural disturbances (fire, insects) and the stochastic nature of the problem. Future analysis will provide distributions of production possibility frontiers based on the fire dynamics already present in the model. Given the recent significant impact of Mountain Pine Beetle in British Columbia's forests [10], extensions to include the impact of this insect species are warranted. These disturbances, coupled with climate change, form the major uncertainties affecting the western boreal forest and the forest industry.

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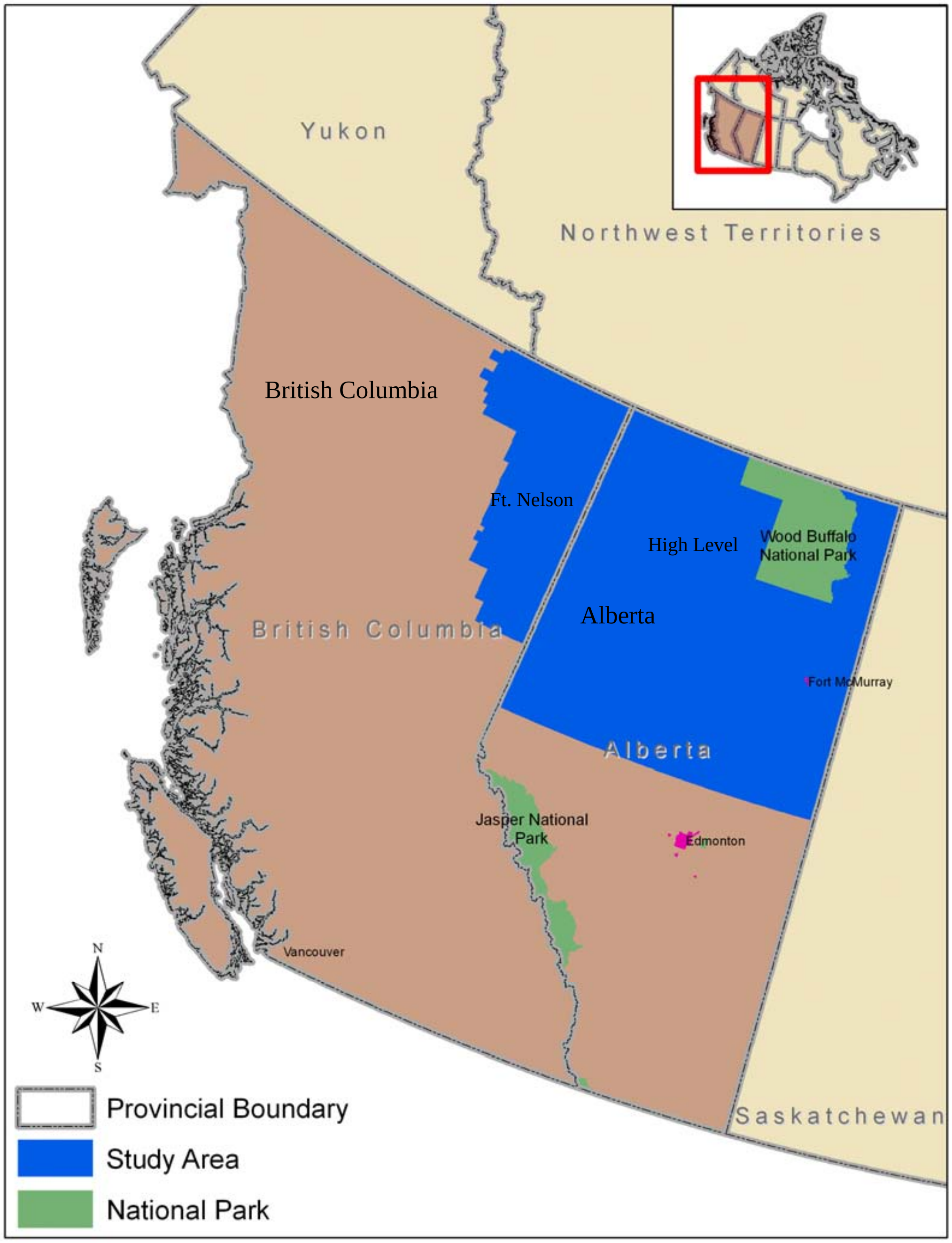

Figure 1. Map showing the location of the study region.

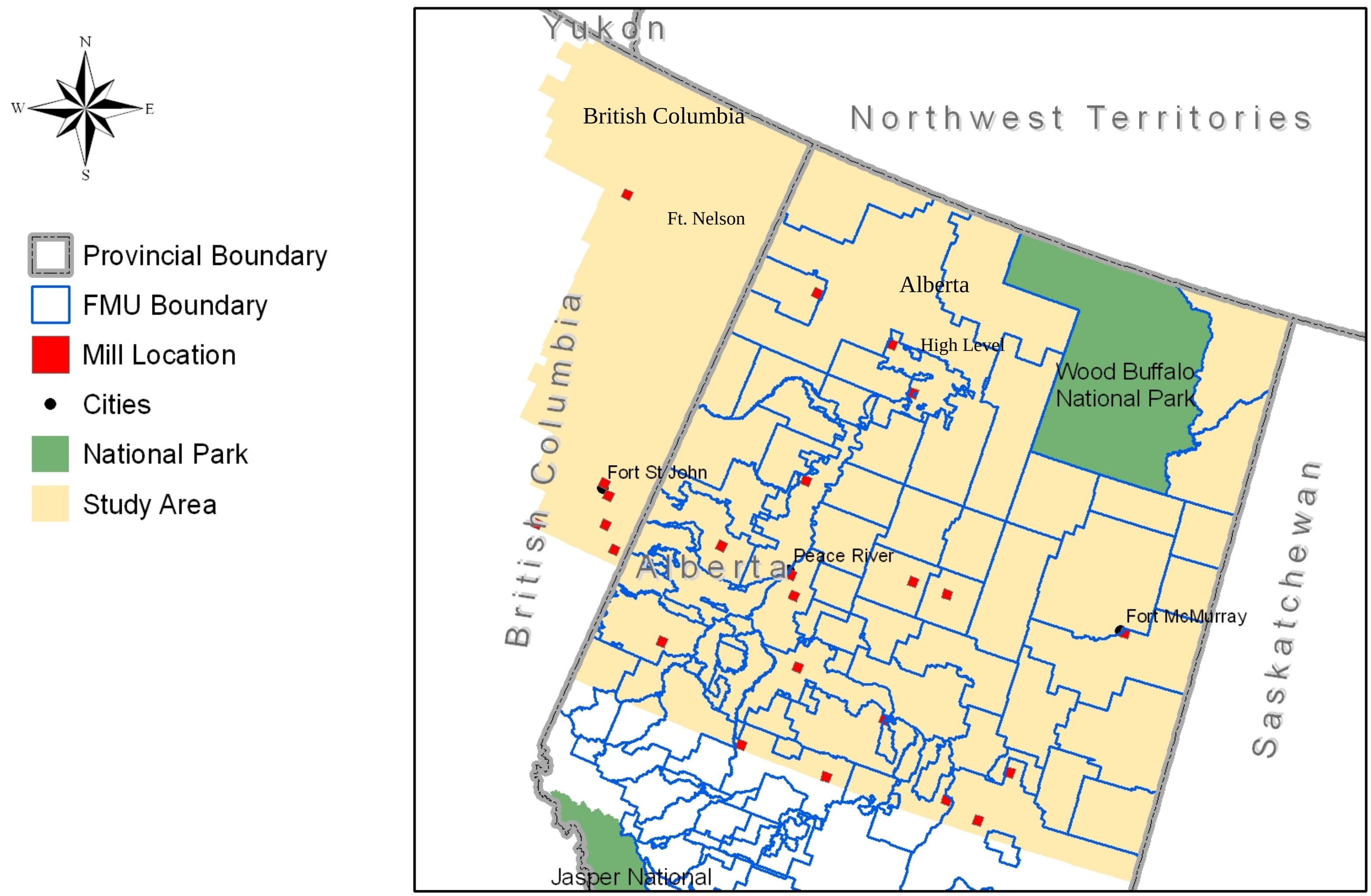

Figure 2. Map of the study region showing mill sites and administrative boundaries (provincial, forest management units, forest management agreements).

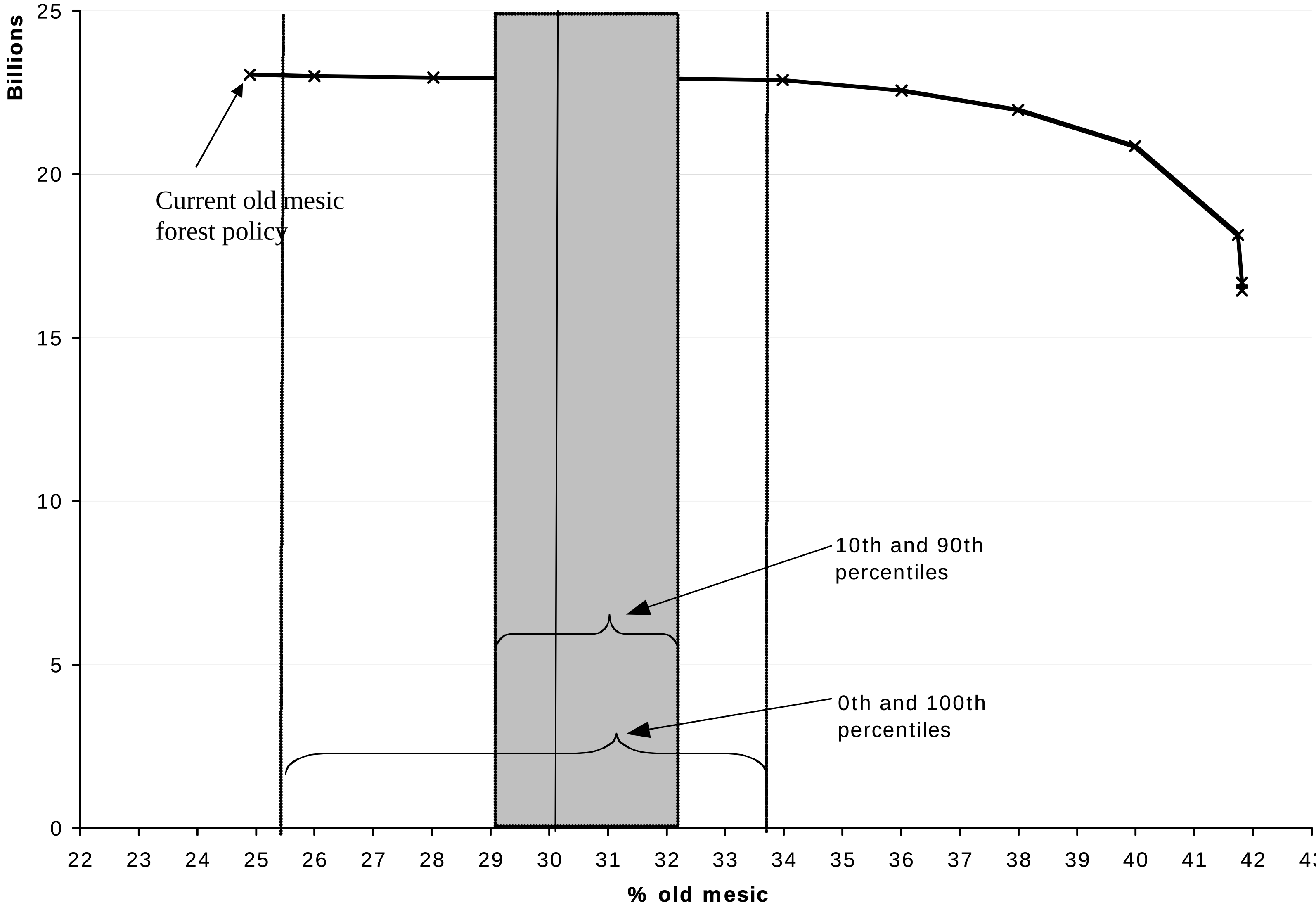

Figure 3. Objective function in dollars plotted against old mesic forest over the entire study region. Also shown are the 0th, 10th, 50th, 90th and 100th percentiles for old mesic forest from the natural fire disturbance regime.

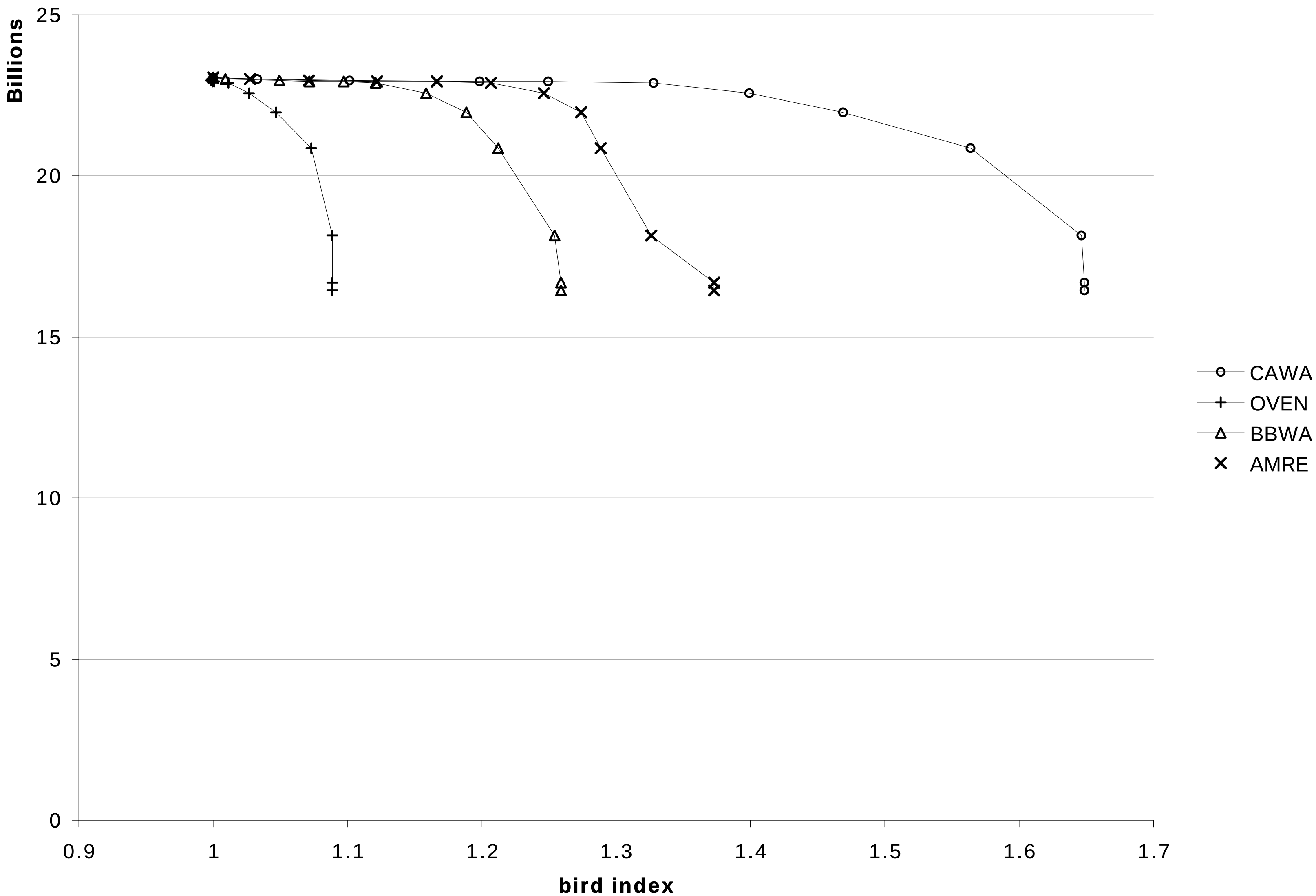

Figure 4. Bird count indexes for three selected species with a positive relationship between bird counts and old mesic forest cover. AMRE: American Redstart, BBWA: Bay Breasted Warbler, OVEN: Oven Bird, CAWA: Canada Warbler.

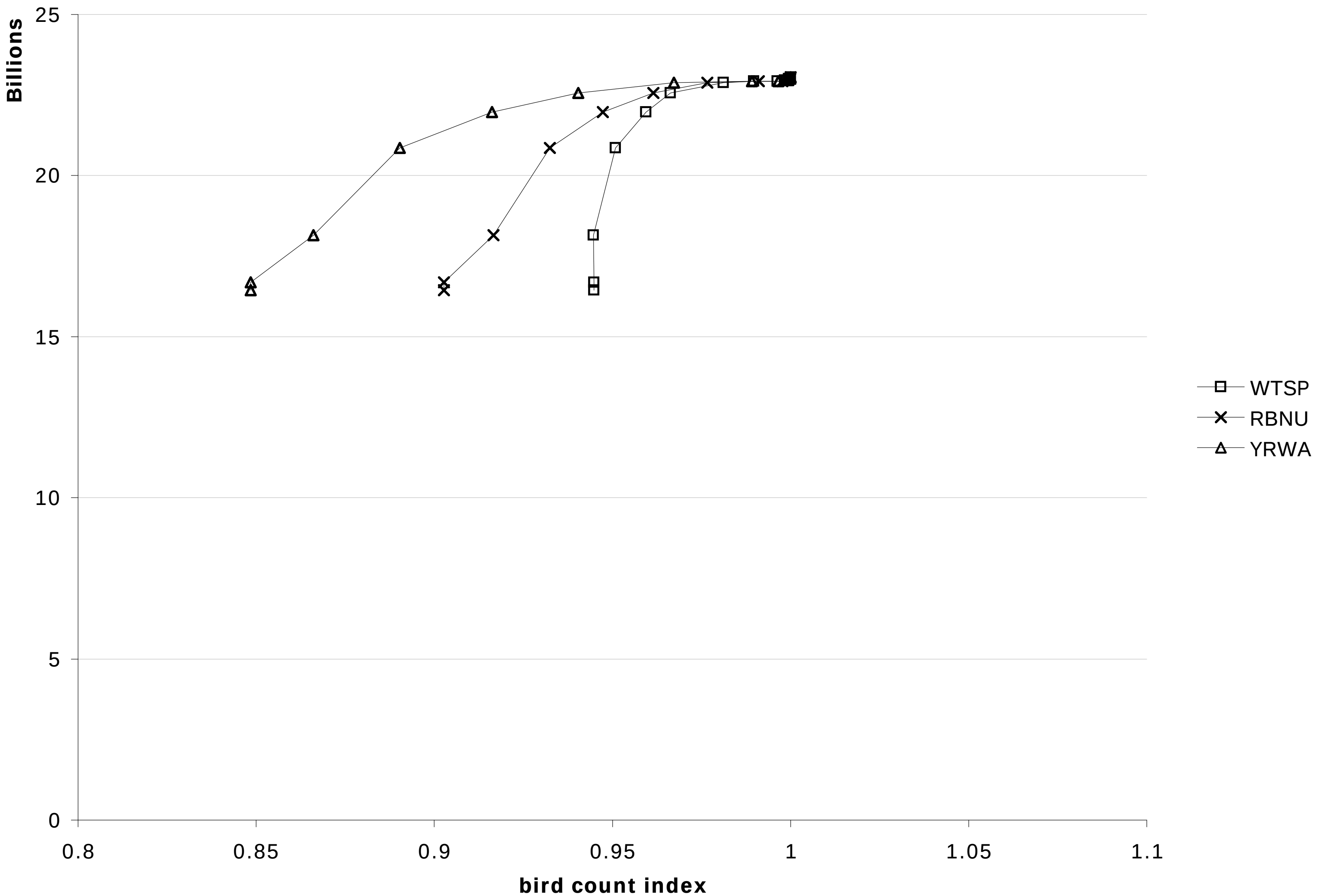

Figure 5. Bird count indexes for 3 selected species with a negative relationship between bird counts and old mesic forest cover. YRWA: Yellow-rumped Warbler; RBNU: Red-breasted Nuthatch, BOCH: Boreal Chickadee.

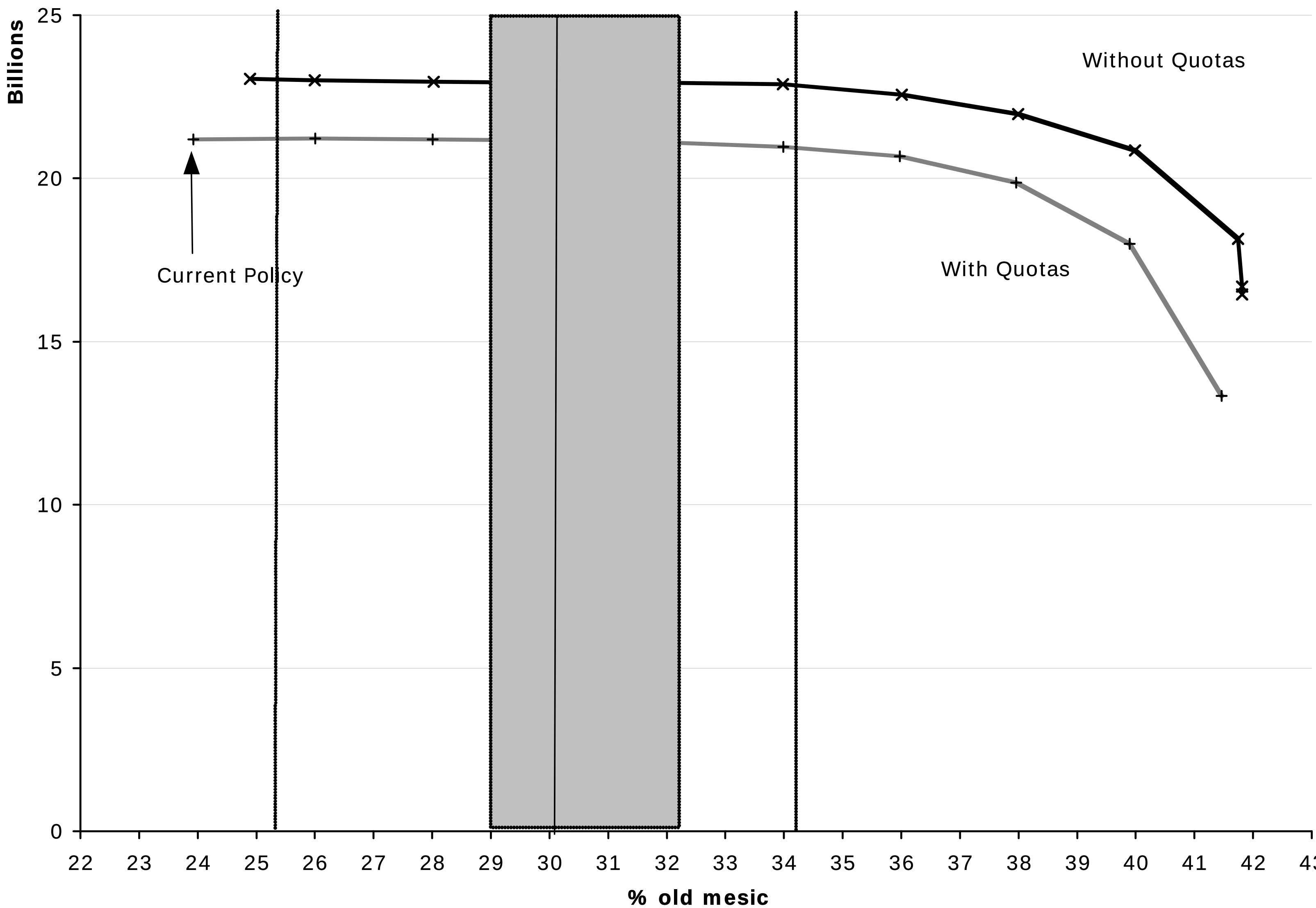

Figure 6. Production possibilities frontiers with and without forest regulatory constraints.

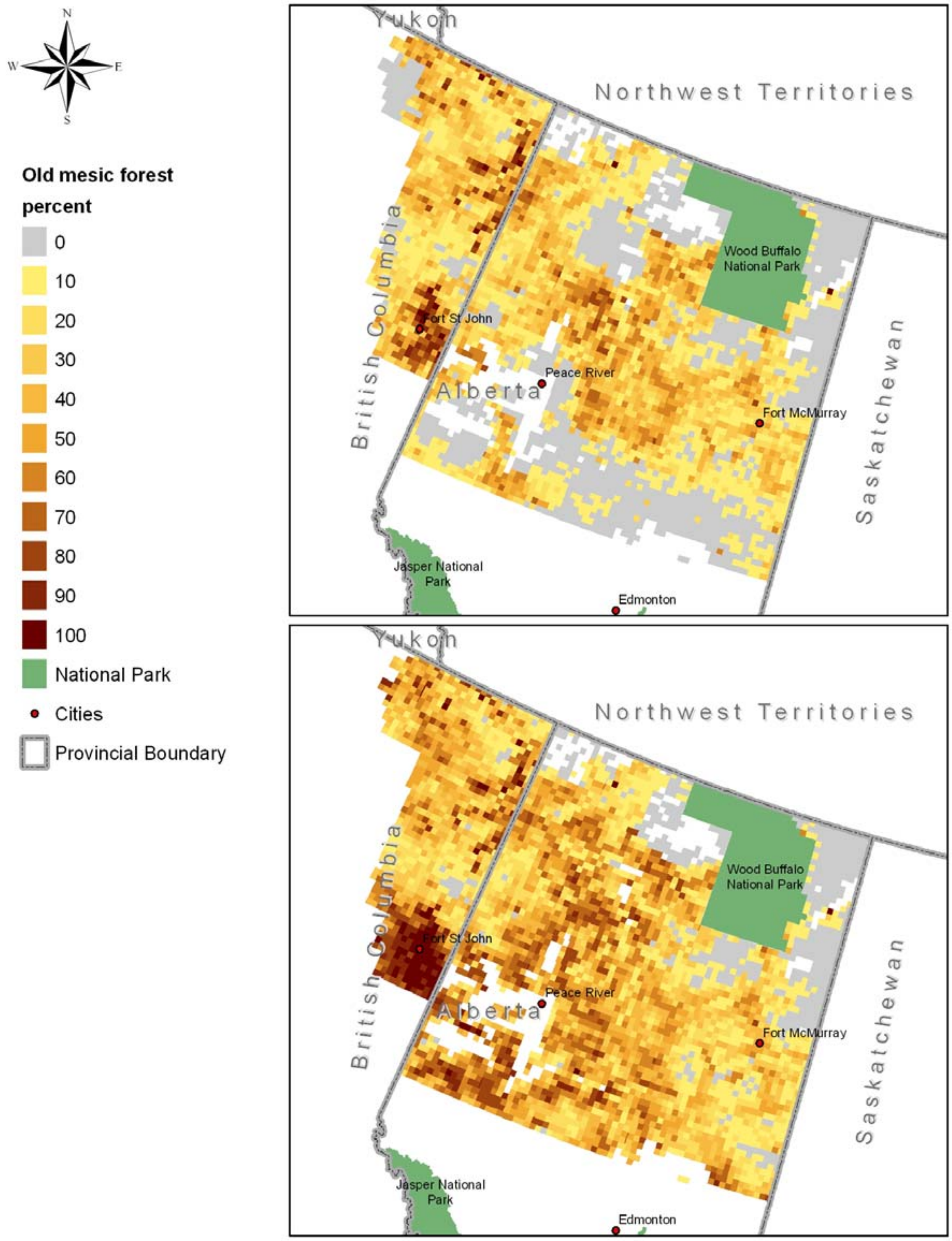

Figure 7. Map of study region showing old mesic forest for each grid cell after 90 years. The top picture shows the distribution of old mesic forest when there is no constraint on old mesic forest. The bottom picture shows the distribution when old mesic forest is constrained to be at least 44% of the total forest area.

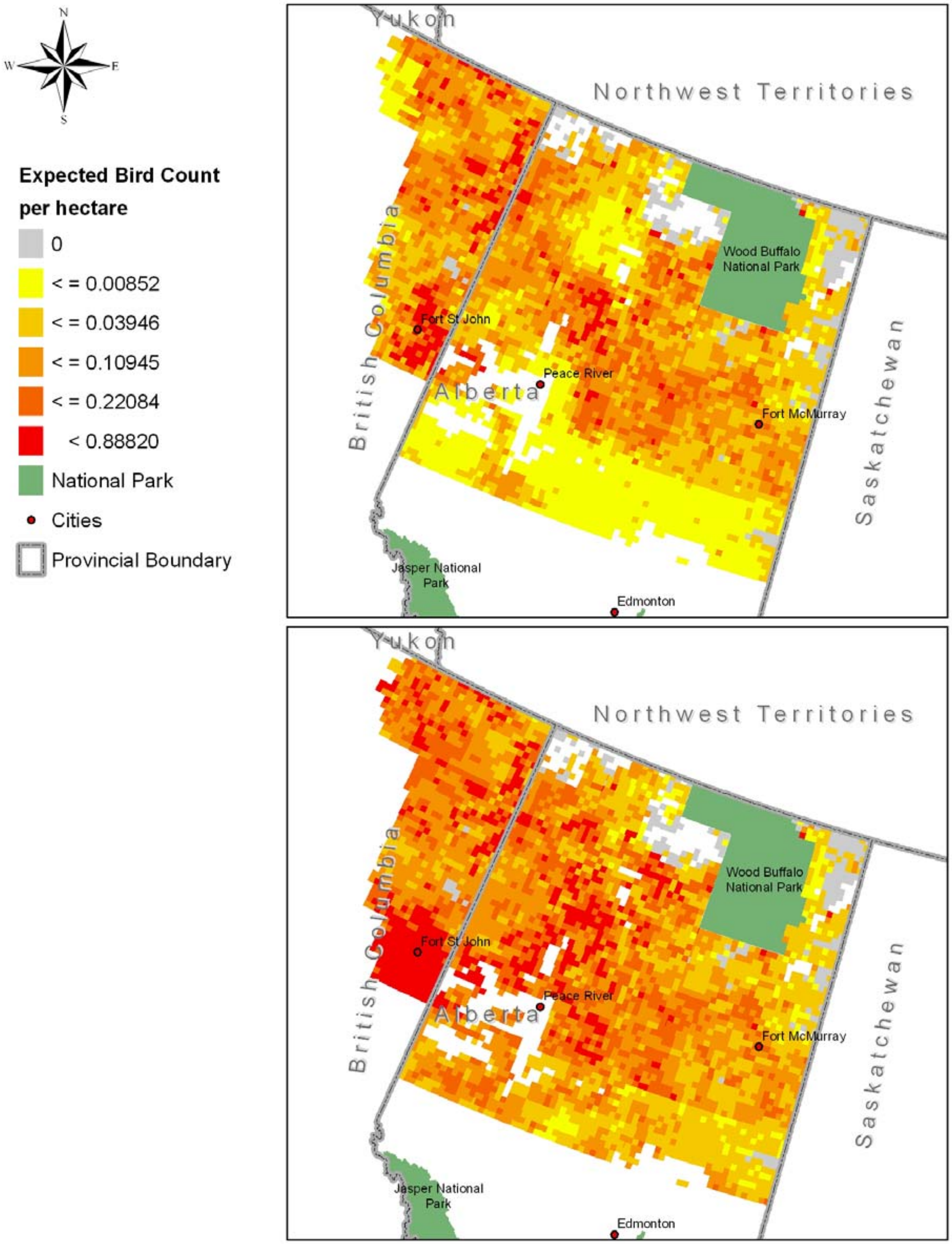

Figure 8. Expected bird counts for Canada Warbler in counts per ha for each grid cell. The top picture shows bird counts for the case where old mesic forest is unconstrained. The bottom picture shows old mesic forest where old mesic forest is constrained to 44%.

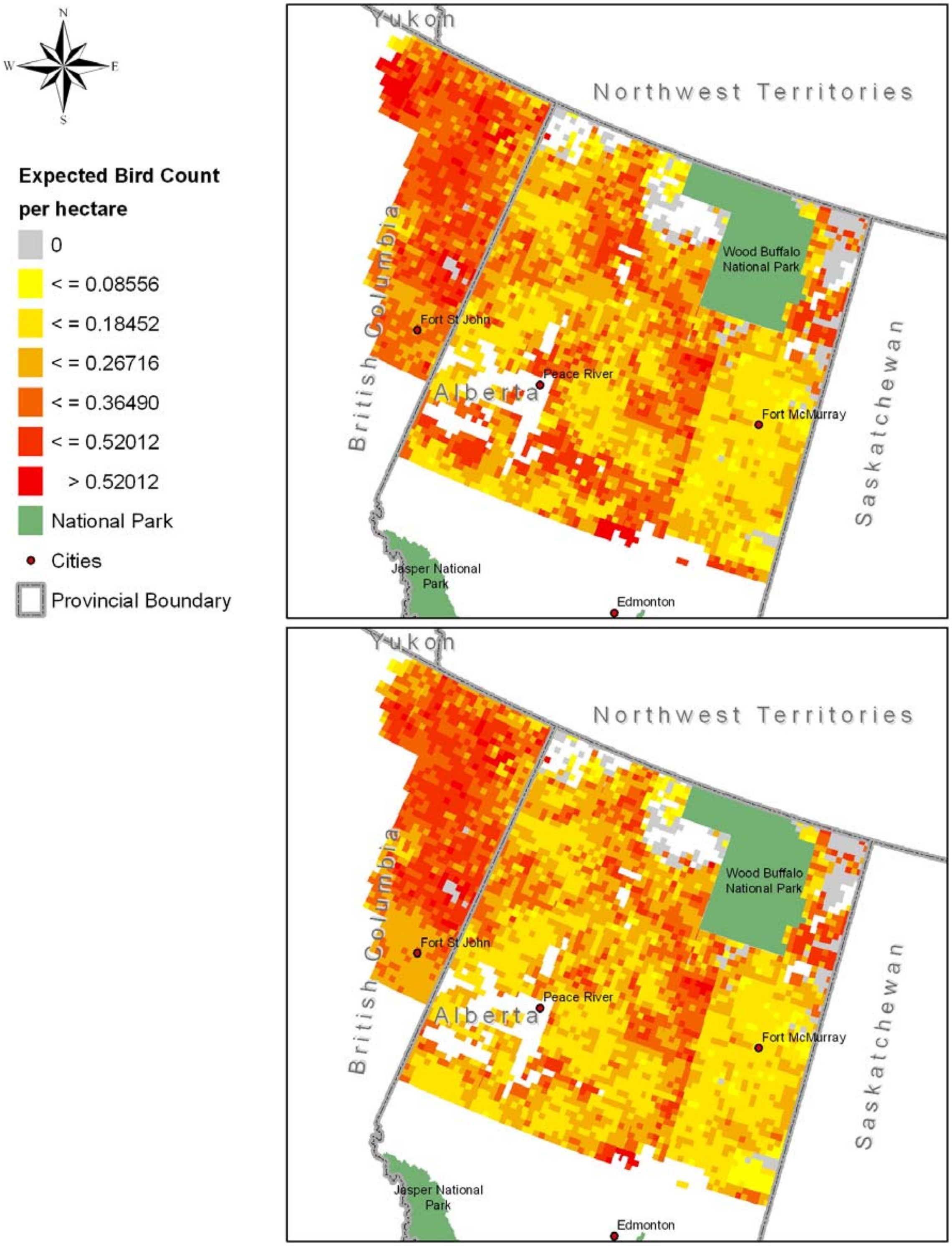

Figure 9. Expected bird counts for White-Throated Sparrow in counts per ha for each grid cell. The top picture shows bird counts for the case where old mesic forest is unconstrained. The bottom picture shows old mesic forest where old mesic forest is constrained to 44%.

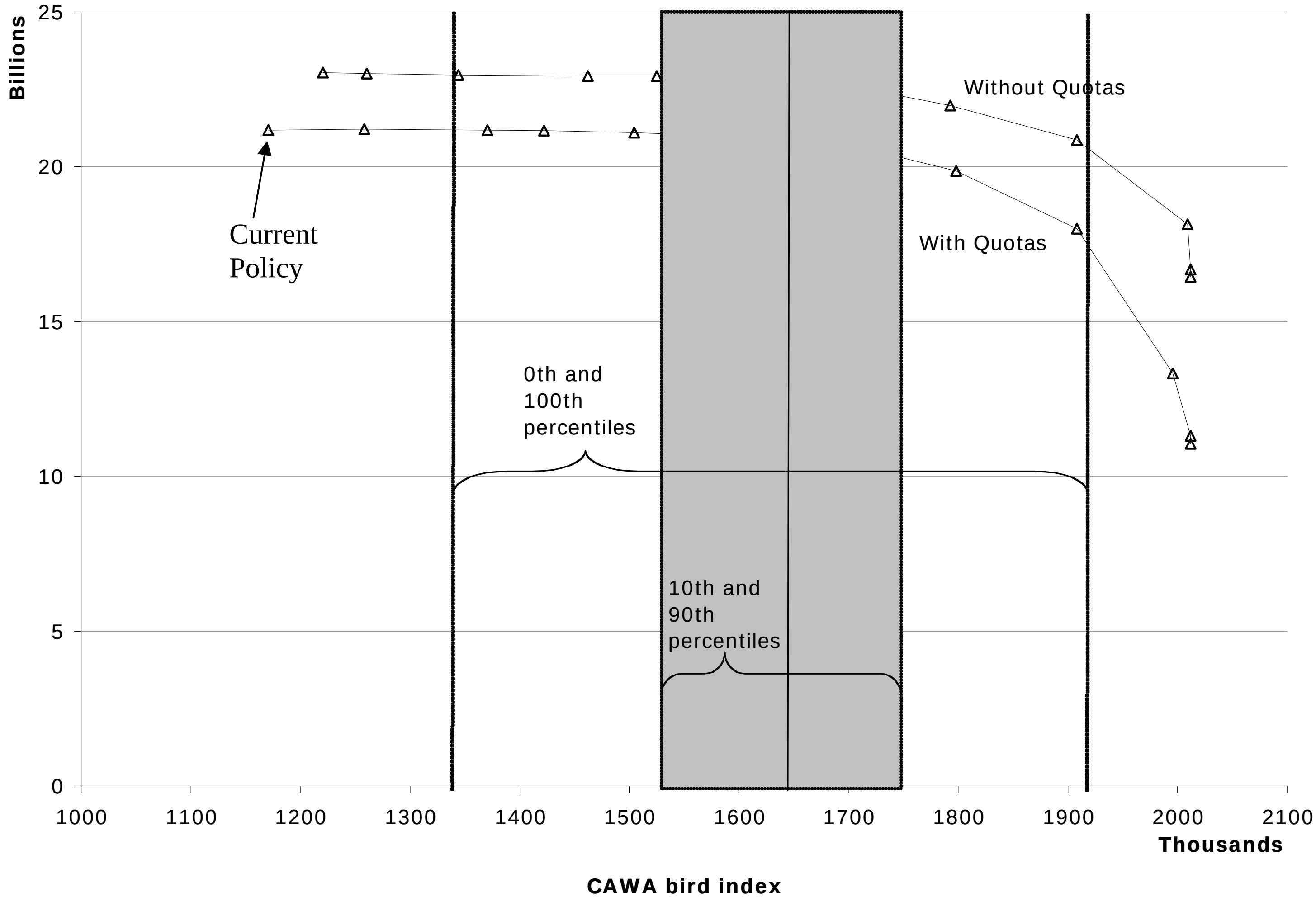

Figure 10. Abundance of Canada Warbler with and without quota constraints and under the natural disturbance regime.

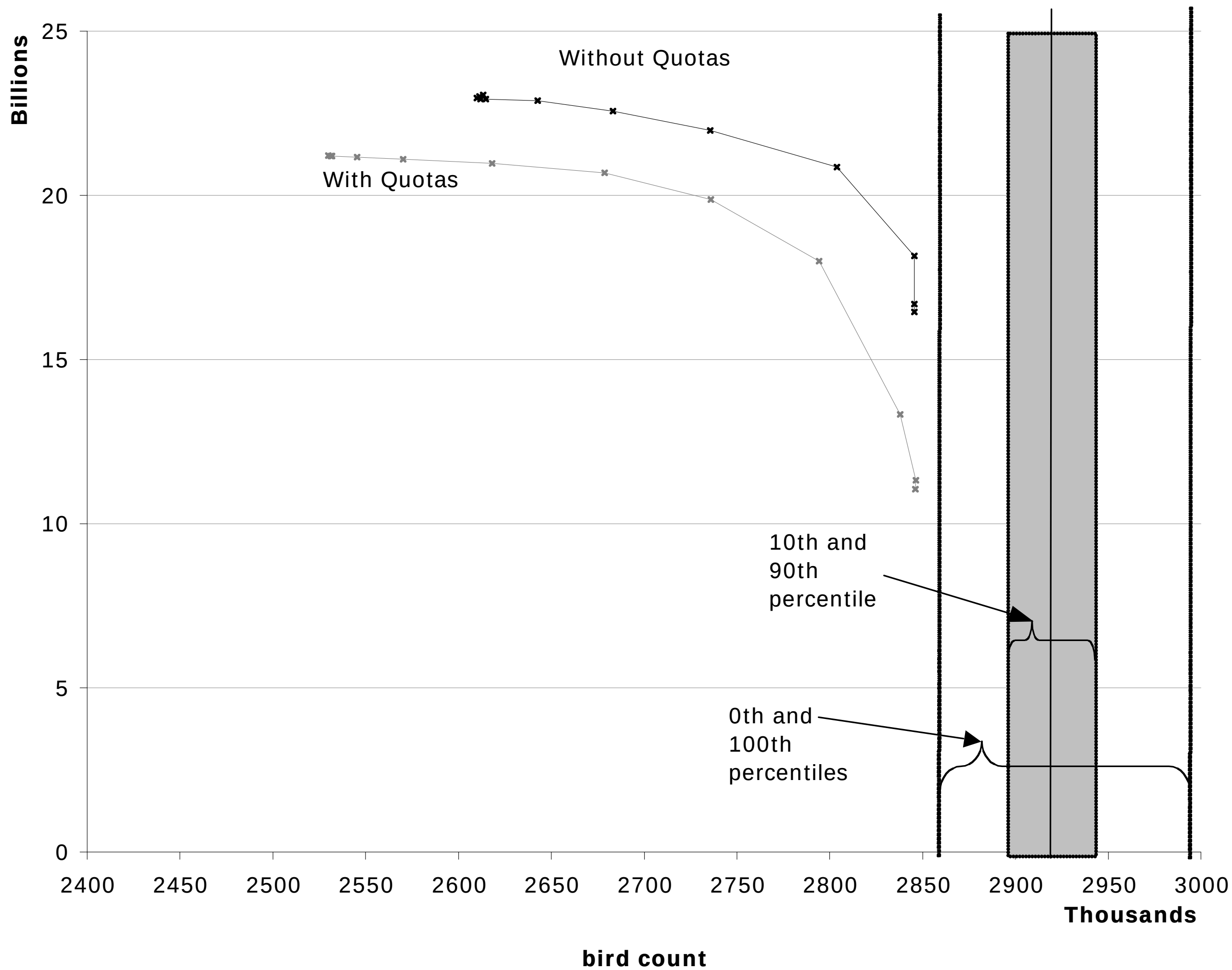

Figure 11. Abundance of Ovenbird with and without quotas and under the natural disturbance regime.

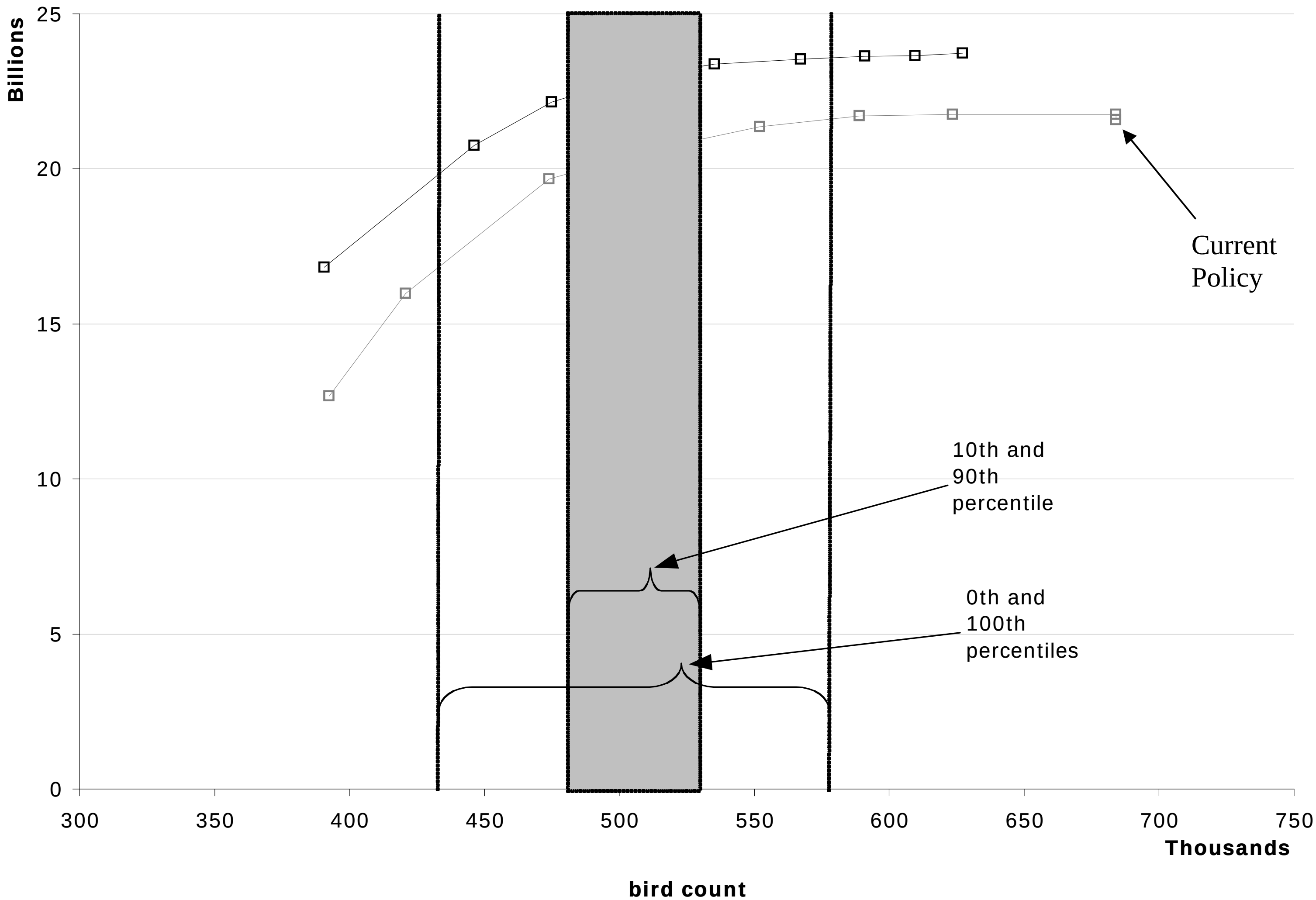

Figure 12. Abundance of Yellow-rumped warbler with and without quotas and under a natural disturbance regime.

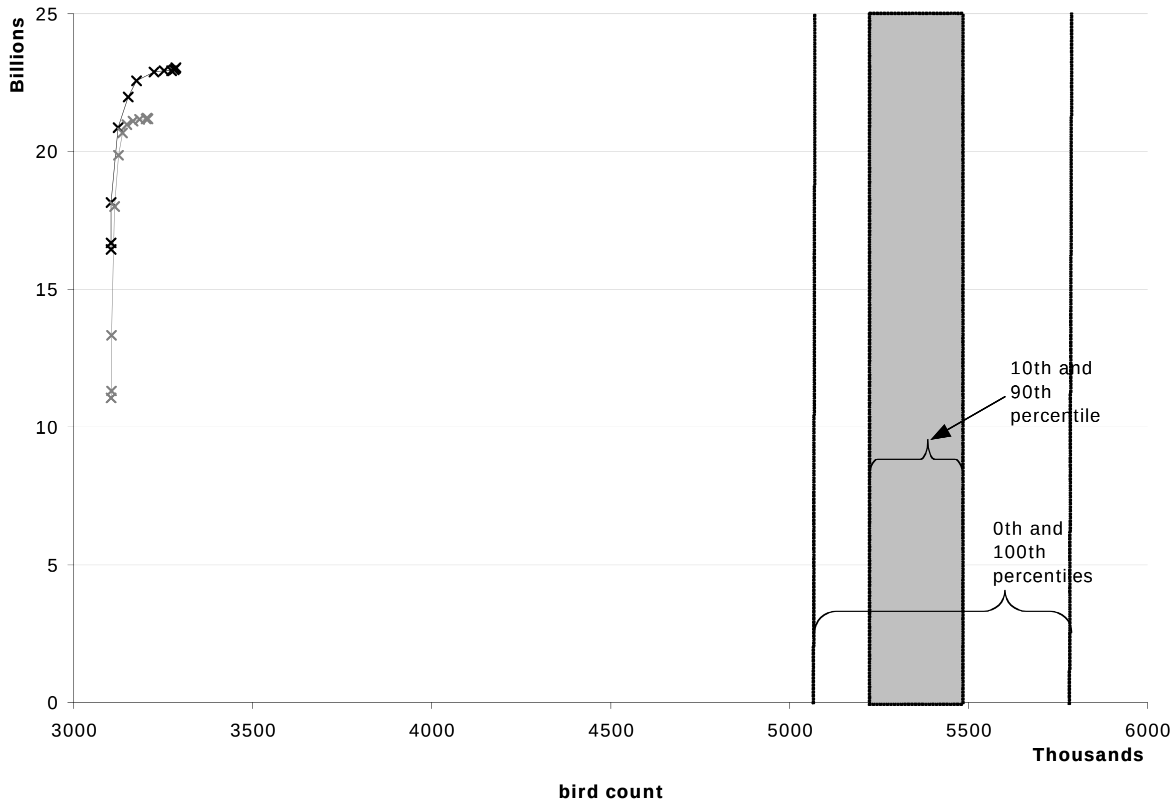

Figure 13. Abundance of White-throated Sparrow with and without quotas and under the natural disturbance regime.