EXPLORING THE IMPACTS OF CLIMATE CHANGE AND ADAPTATION OPTIONS FOR BOREAL FOREST ECOSYSTEMS

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SUMMARY DOCUMENT

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INTRODUCTION

Observations over the last few decades, and projections of future climate based on general circulation model (GCM) simulations, indicate that significant climate warming will occur within the next 50-100 years in the Canadian Prairie Provinces. These changes are likely to cause serious impacts on forest growth, tree species composition, and productivity. The current approach to estimating timber supply entails modelling stand development and volume productivity based on empirical relationships between growth and tree or stand attributes observed from field measurements. This approach assumes that past growth is a reasonable predictor of future growth conditions. These traditional growth and yield models, however, will fail if changes in climate seriously influence future site conditions. An alternative to growth and yield models is process-based growth models that use physiological and physical principles to relate forest development and productivity to climatic conditions. Such models can then be used to simulate the likely impacts of plausible future climate scenarios on forest growth and development and to investigate the potential use of management actions to adapt to the projected changes.

Since 1995, the CFS Laurentian Forestry Centre (in Ste Foy, Québec) has pursued the ECOLEAP (Extended COllaboration for Linking Ecophysiology And forest Productivity) project, http://www.cfl.forestry.ca /ECOLEAP) where forest net primary productivity[1] (NPP) is modelled mechanistically, and then mapped at the landscape scale using spatial data (soils, climate and remote sensing imagery) to drive the model. One of the most important aims of this initiative is to generate estimates of forest productivity that are both of direct value to forest managers (e.g., merchantable volume production) and can be applied over areas comparable to typical forest management units (i.e., hundreds of square kilometres). The study summarised in this document, called ECOLEAP-West, builds on the ECOLEAP initiative for a study region in the Foothills Model Forest in west-central Alberta.

The primary objectives of this study were (1) to build the spatial data sets needed to develop and test process models of forest productivity and species succession, and (2) to use process models to assess the impacts of plausible changes in future climate on these key forest attributes. The main challenges of this project revolved around collecting and extracting as much information as possible from multiple data sources, including remote sensing, Geographic Information Systems (GIS), and computer modeling, as both extrapolation and validation tools. The end products, therefore, would include new tools, in terms of both models and data, to assess forest productivity and species composition under both present-day and anticipated future climates, and to investigate the potential for forest management to adapt to the potential negative and positive effects of climate change.
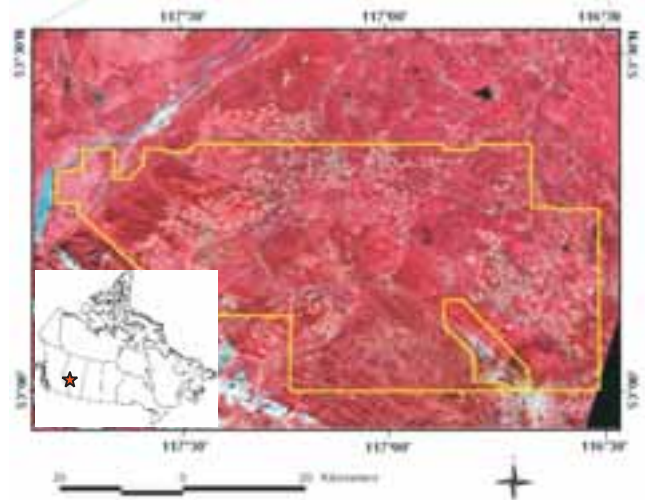

Figure 1. The study region in west-central Alberta.

STUDY REGION

A detailed description of the study region (Figure 1) can be found on the ECOLEAP website at: http://ww. cfl.forestry.ca/ECOLEAP/ pilot_regions/pilot_ regions.html. It covers about 2,700 km2 within the Foothills Model Forest in Western Alberta and comprises a large portion of a forest management unit managed by Weldwood of Canada Ltd (Hinton Division)[2]. The study region was selected for its range of topography and ecological diversity, and comprises portions of the Upper Foothills, Lower Foothills, Montane, and Sub-alpine natural regions.

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[1]Net Primary Productivity is the rate at which plant biomass is produced, after accounting for plant respiratory losses, typically expressed in dry biomass or carbon terms, in units of g m^{-2} yr^{-1}.

[2]Weldwood of Canada Ltd. was acquired by West Fraser Timber Co. Ltd. on 31 December, 2004.

SPATIAL DATASETS

One of the primary aims of the study was the collation of a range of datasets to establish a coherent spatial database of biophysical and inventory data, and then derive a number of intermediate data products that were important in testing and application of the process-based productivity models.

Input Data

Input data sets were obtained from numerous sources, including the Foothills Model Forest archives, Weldwood of Canada Ltd, the Province of Alberta and the Canadian Forest Service.

Elevation Data

A 25 m horizontal resolution DEM (Digital Elevation Model), derived from the Alberta Provincial DEM, was obtained for the Alberta study region from Alberta Sustainable Resource Development. In this study, the 25 m DEM was used to orthorectify the satellite remote sensing image. A second, approximately 50 m resolution DEM was derived from NTDB (National Topographic Database) digital contour data using ArcInfo GIS software.

Soils Data

Many ecosystem models require at least a representation of surface soil texture (top 15 cm) to simulate seasonal or annual water balances and to determine the availability of soil moisture to vegetation. The available soils coverages, however, did not contain a soil texture attribute. Instead, "averaged" soil textures were derived from generalized, modal soil profiles characterised within the Canadian Soil Information System (CanSIS) database for various soil associations. These soil textures were subsequently mapped for the study extent by assigning the appropriate texture to soil polygons in the GIS, based on the soil association attribute for each polygon. The accuracy of the texture information resulting from this procedure was considered coarse at best and can only be used with caution.

Forest Inventory Data

An Alberta Vegetation Inventory (AVI) data layer was obtained from Weldwood of Canada Ltd. for the study region. The AVI layer was used initially to explore, characterise, and display the location and spatial distribution of forest stand characteristics across the study region. For forested areas, stand-level GIS data were first classified by species composition, year of origin, stand height, and crown closure. As the main source of spatial vegetation data, the AVI dataset provided crucial forest measurement data for both empirical and process-based model development and application.

Climate Data

Climate surfaces for the Alberta study area were derived using a new implementation of the daily weather generation algorithm originally developed as a component of the BioSIM, Pest Management Planning Decision Support program (Régnière et al. 2001). The climate generator program is a Microsoft Windows-based application that interpolates monthly climate statistics for a series of user-specified point locations using a database of 1961-90 Canadian climate normals. Input data consist of latitude, longitude and elevation, with slope and aspect derived from the DEM. The output is a spatial representation of the temperature and precipitation regimes for a given area. For the purposes of this study, a grid comprised of 100 m $\times$ 100 m cells was set up over the study region, and the climate generator used to simulate a set of daily values for each variable for a one-year period based on the 1961-90 monthly climate statistics observed at local stations. After completing the interpolation, the daily values for each variable were averaged to create monthly statistics for each 100 m pixel and imported back into a GIS to create individual climate variable surface grids. Data produced by the climate generator were used as input data in simulations of species succession and productivity in subsequent process modelling for the Alberta study region.

Permanent Sample Plot Data

The purpose of permanent sample plots is to provide periodic measurement data (typically 5-10 year intervals) for the development of growth and yield tables. The Weldwood FMA has a particularly well-developed grid of permanent growth sample (PGS) plots, with tree measurement data maintained in a relational database. Tree measurements have been recorded within the plots for all live and dead free-

standing trees above 1.3 m height, including: diameter at breast height, stem height to top of live foliage, site index (SI), stand age, and tree condition. Other data were collected at a stand level, such as canopy closure and species composition. These data are also linked to the AVI GIS data, thereby enabling them to be located geographically.

The PGS plot data were used in the study for: (i) calculation of plot-level biomass, ultimately used for the scaling-up and mapping of biomass at stand level; (ii) estimation of tree sapwood basal area, used in the estimation of leaf area index (LAI); and (iii) calibration, validation, and modelling of forest productivity with the FORSKA-M process-based model.

Derived Spatial Products
Forest Biomass Mapping

Many process models attempt to simulate ecosystem productivity, typically meas-ured in mass terms (e.g., tonne ha-1 y-1). Therefore, deriving empirical estimates of forest biomass through statistical model-ling provides an important linkage between forest inventory data and the outputs of process models.

Stand-level biomass was mapped by: (1) deriving species-specific equations for estimating individual tree biomass; (2) applying the derived equations to PGS plot trees to estimate tree biomass for all trees in each field plot; (3) aggregating tree biomass to a stand-level biomass density (t ha-1) at each PGS plot location; (4) deriving equations relating stand-level biomass to forest stand structural characteristics; and (5) applying the stand-level functions to the AVI polygons. The resulting map (Figure 3) shows that average biomass density generally increases from west to east, suggesting that mean annual productivity is higher towards the eastern (lower elevation) portion of the study region.
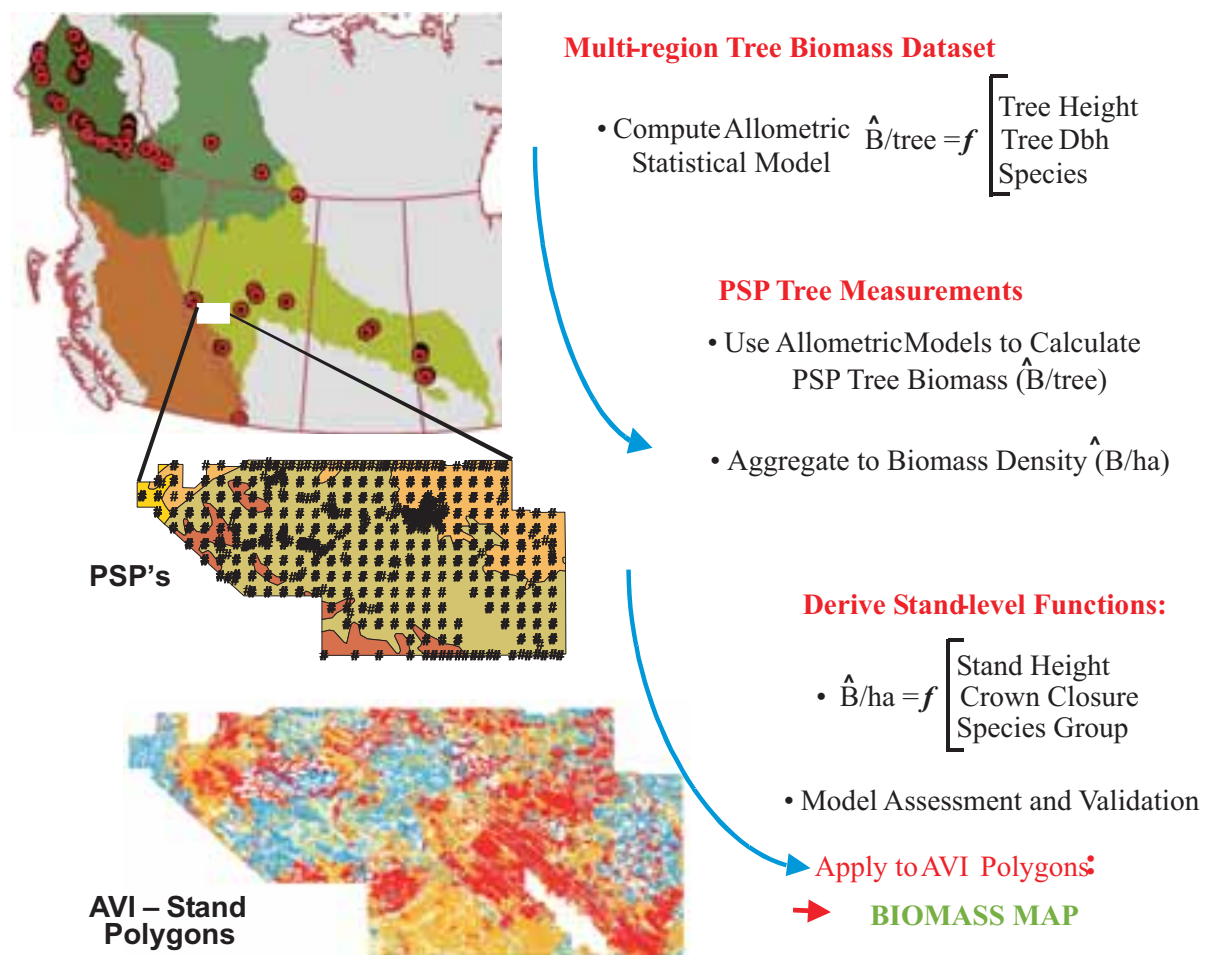

Multi-region Tree Biomass Dataset

- Compute Allometric Statistical Model $\hat{B}/\text{tree} = f \begin{bmatrix} \text{Tree Height} \\ \text{Tree Dbh} \\ \text{Species} \end{bmatrix}$

PSP Tree Measurements

- Use Allometric Models to Calculate PSP Tree Biomass ($\hat{B}/\text{tree}$)

- Aggregate to Biomass Density ($\hat{B}/\text{ha}$)

Derive Stand-level Functions:

- $\hat{B}/\text{ha} = f \begin{bmatrix} \text{Stand Height} \\ \text{Crown Closure} \\ \text{Species Group} \end{bmatrix}$

- Model Assessment and Validation

Apply to AVI Polygons:

BIOMASS MAP

PSP's

AVI – Stand Polygons

Figure 2. Diagram showing the flow of biomass calculation, modelling, and mapping for the ECOLEAP-West Alberta study region.

Empirical Biomass Productivity Estimates

We tried to confirm the hypothesis that the biomass data shown in Figure 3 suggested a decreasing eastwest gradient in productivity. To produce maps of estimated average productivity (t ha-1 yr-1) across the study region, both biomass density data, and merchantable volume estimates taken directly from the AVI data set, were each divided by the stand age reported in the AVI (Figure 4). It should be recognized, however, that the ratio of biomass to age can vary appreciably, with the highest values typically occurring in semi-mature stands and lower values occurring at younger and older stages.

The overall spatial distributions of biomass density (Figure 3) and estimated productivity (Figure 4) appear quite similar, indicating that the age-class distribution is
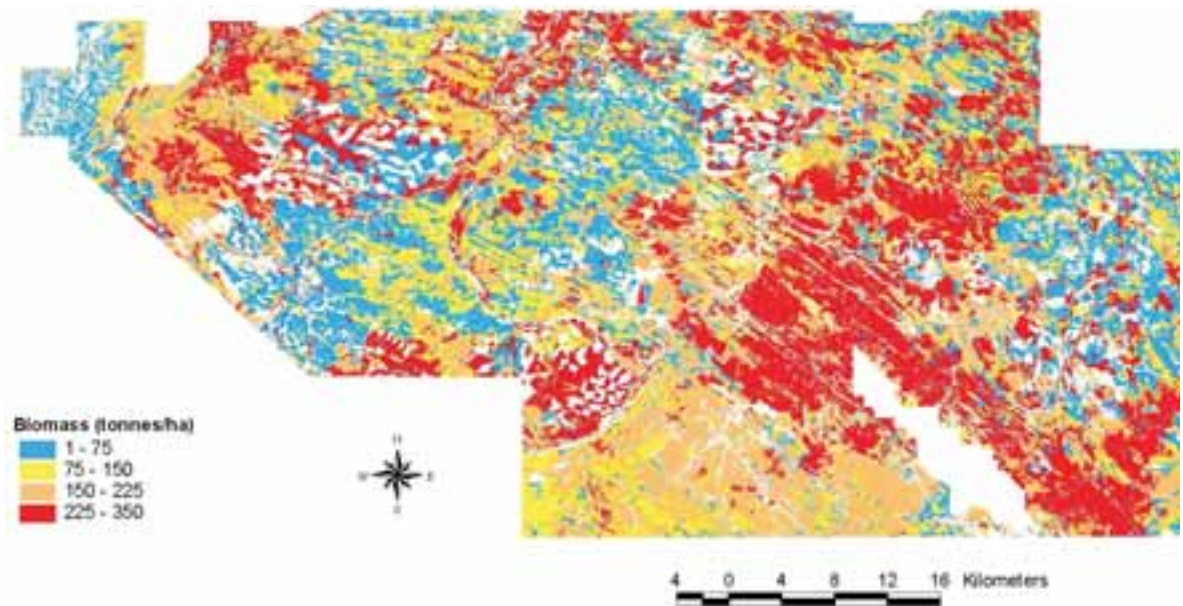
Figure 3. Biomass map obtained from stand-level regression models relating biomass (Mg ha^{-1}) estimated from allometric relationships at PGS plot locations to the crown closure and height attributes in the AVI.
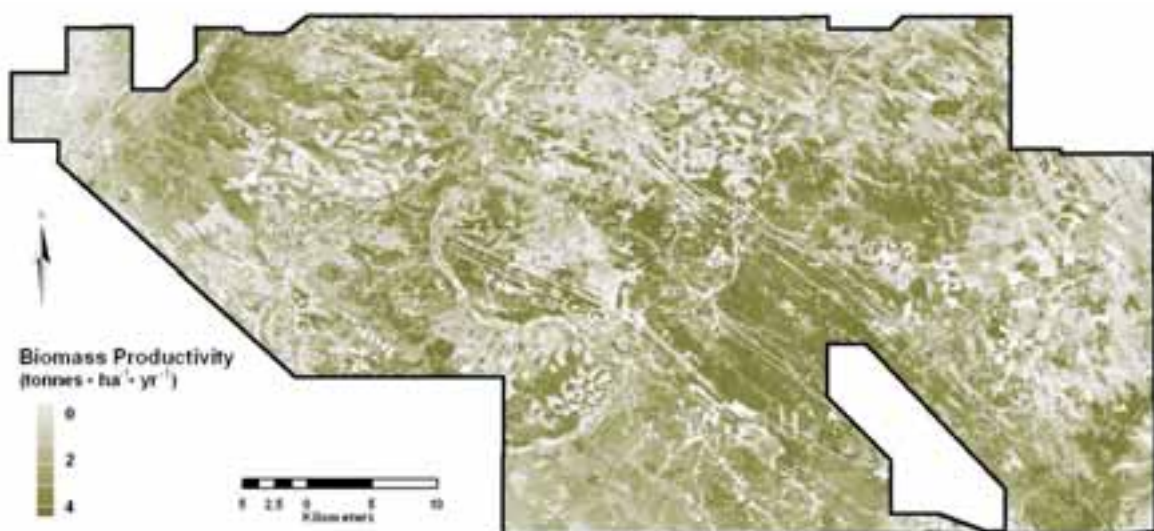

Figure 4. Distribution of stand productivity expressed in aboveground biomass terms (t ha^{-1} yr^{-1}). Data were calculated by dividing total aboveground biomass estimates in each polygon by the stand age (the latter estimated as the difference between year of inventory and year of origin reported in the Alberta Vegetation Inventory).

broadly similar across the region and across forest types. These GIS-based spatial productivity estimates were subsequently compared to the results of productivity modelling.

Leaf Area Index

Leaf area index (LAI), defined as one half the total intercepting leaf area per unit ground surface area, is an important measure of forest canopy structure, and often a crucial component of many process-based ecosystem models. For this study, methods for measuring and mapping LAI, from the plot-level to the landscape level, were investigated for the Alberta study region. At the plot-level, LAI measurements were carried out using hand-held optical instruments at 27 PGS plot locations distributed across the Alberta study region (Figure 5). The optical devices provide a relatively fast and cost-efficient way to estimate LAI at given locations.

The optical measurements were compared to estimates of leaf area derived using known allometric relationships between tree sapwood cross-sectional area and tree leaf area at each sample plot. Overall, results showed that allometric and optical LAI were positively
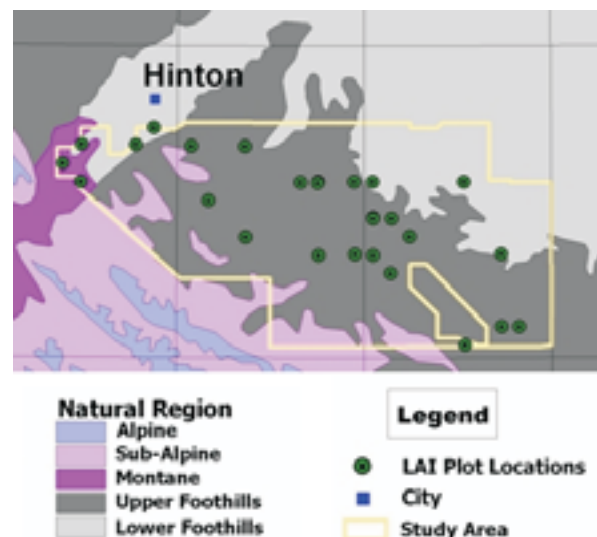

Figure 5. The location of 27 PGS plots for which both optical and allometric LAI values were estimated.

and significantly correlated (Figure 6). Based on the distributions for each species groups (aspen, mixed conifer, mixed deciduous, lodgepole pine, black spruce, white spruce), plots for lodgepole pine (Pl) displayed the greatest variation, with the allometric estimates often underestimating the optical measurements. Some of the variation in these results is likely due to limitations in
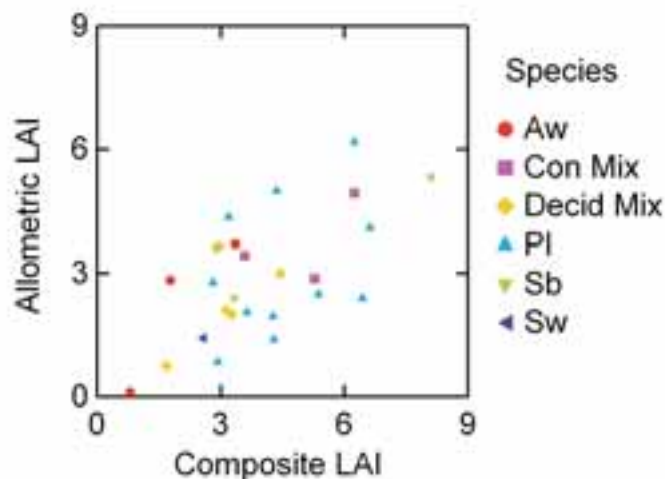

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Figure 6. The relationship of allometrically-derived LAI with optically-measured LAI, organised by species group, for the 27 sites.

applicability of the allometric functions obtained from the literature to the study region. A further possible factor is the limited sampling precision of the optical measurements.

To explore ways of modelling LAI at the landscape level, the plot-level optical estimates of LAI were correlated to spectral response data sampled from a Landsat-TM satellite image. There was a statistically significant relationship between optical LAI and LAI derived from the satellite imagery ($r = 0.68$, $p < 0.0001$), from which an image map of LAI was produced (Figure 7).

PROCESS-BASED MODELLING

Two models, StandLEAP and FORSKA-M were tested and applied to the Alberta study region.

StandLEAP

StandLEAP is a forest productivity model based on 3PG (Landsberg and Waring 1997), with modifications to simulate NPP in Canadian forests (Bernier et al. 1999). The model is driven primarily by leaf area index and the estimated fraction of photosynthetically active solar radiation (fpar) at the tree canopy level, as well as by other climate factors influenced by topography. StandLEAP was calibrated for lodgepole pine in the Alberta study region using data from the literature with some physiological data for the closely related jack pine species measured in the BOREAS experiment (carried out in southern Saskatchewan in 1994 and 1996). Calibrations for other major species in the areaincluding black spruce, trembling aspen and white sprucewere derived from the literature, from data obtained from the BOREAS experiment, and from other study sites in eastern Canada.

In general, when tested at the plot scale, StandLEAP tended to overestimate aboveground biomass increment by around 10%, but it still predicted acceptable values of accumulated biomass, when calculated as the initial plot biomass plus the biomass increment.
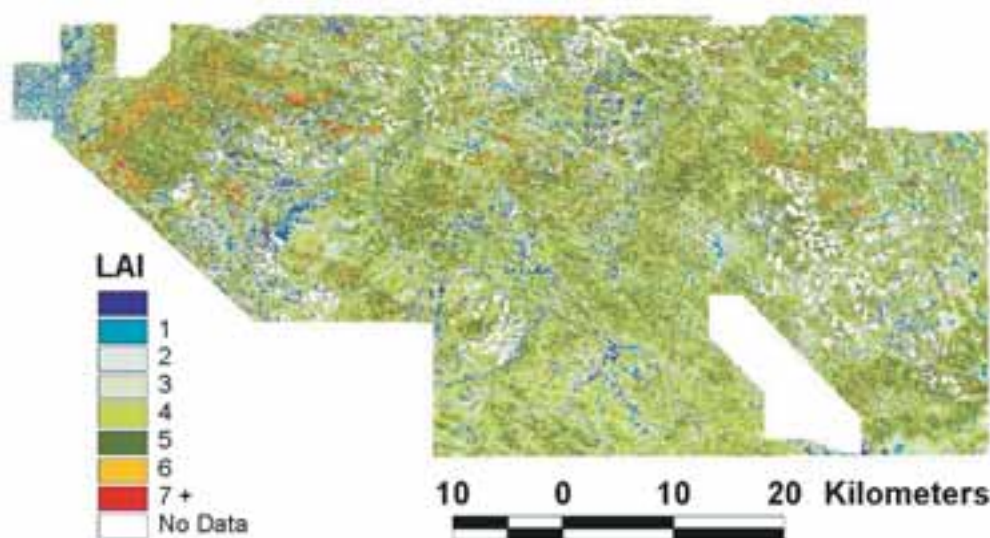

Figure 7. Map of Leaf Area Index (LAI) for the Alberta study region, derived from Landsat TM imagery.
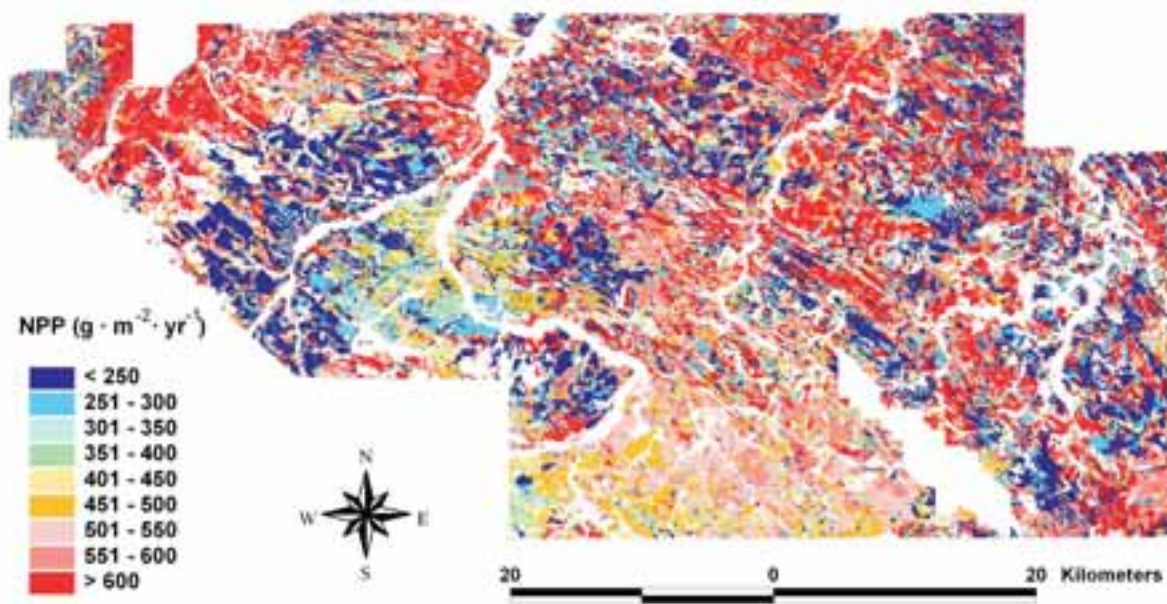
Figure 8. Map of net primary productivity estimated for the Alberta study area using the StandLEAP model.

Final Product Maps of NPP

Using the data sets described above, a simulation of net primary productivity was performed for some 80,000 AVI polygons distributed across the Alberta study region. This allowed creation of a map of the spatial distribution of productivity (Figure 8) derived directly from physically-based inputsincluding climate, soil conditions, and topography and remotely-sensed estimates of LAI and species composition. The range of simulated NPP values was consistent with observations (though no local measurements of NPP were available for comparison).

There was general agreement in relative terms, compared spatially, between the NPP map product (Figure 8) and the mean annual increment (MAI) of biomass computed from the biomass map (Figure 7). We beleive Figure 8 demonstrates the potential of the process-based modelling approach to predict productivity at the regional scale from physical data and biological principles, and therefore to incorporate the impact of climate change on growth. The work also demonstrated the problems encountered in scaling knowledge obtained at the plot scale over short time steps to perform regional simulations over periods of years to decades.

FORSKA-M

FORSKA-M is a forest gap model derived from the original FORSKA2 model (Prentice et al. 1993) that simulates competition among boreal tree species for water and light. Once calibrated for an area, the model can be used to investigate the effects of climate and forest management on forest composition and productivity. Weldwood PGS plot data were carefully surveyed and a set of 45 sites was selected, representative of the range of combinations of ecosystems and soil types found in the study region. Eight of these sites were used to calibrate the individual species parameters for the model, with the remaining 37 sites used for validation. FORSKA-M was able to replicate both the species composition and height-over-diameter relationships observed at most of the test PSP sites satisfactorily, although aspen growth rates were generally overestimated.

Subsequently, the model was used to investigate the effects of different disturbance rates, and of changes in climate, at all 45 sites. Mean disturbance intervals (50, 100, 150 and 200 years) were based on those considered typical for the Canadian boreal forest. The three climate scenarios were representative of the typical range of predictions derived from general circulation model (GCM) simulations.
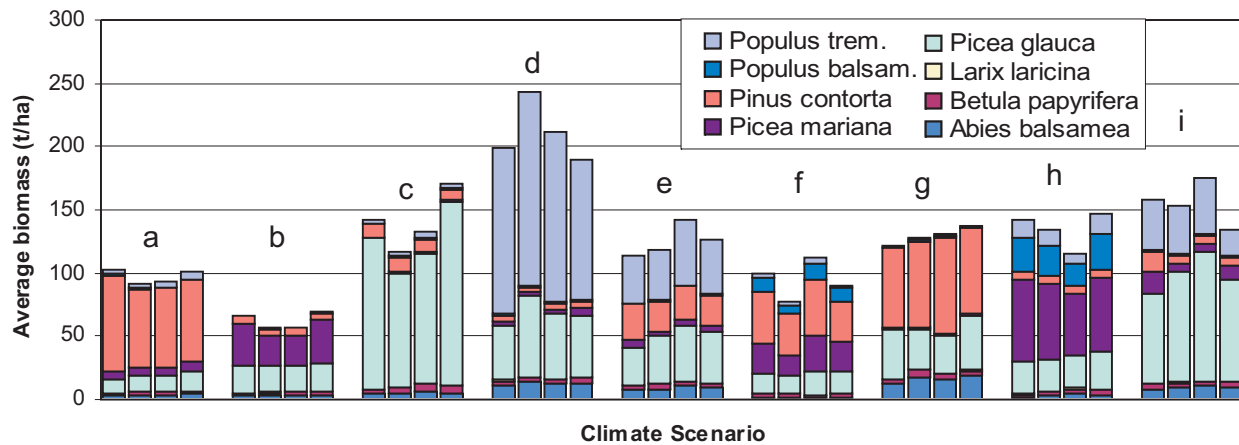
Figure 9. Biomass density simulated by FORSKA-M for the major forest types in the Alberta study region, under current climate and three alternative scenarios of future climate. The four climate scenarios are (left to right): current (based on 1961-90 climate normals); normals with 2 ºC increase in temperature and 10% reduction in average precipitation; normals with 2 ºC increase in temperature and no change in average precipitation; and 2 ºC increase in temperature and 10% increase in average precipitation. Disturbances were set to a 100-year return interval for all simulations. The forest types are (a) lodgepole pine; (b) black spruce; (c) white spruce; (d) aspen; (e) aspen-pine; (f) black spruce-pine; (g) pine-white spruce; (h) black spruce-white spruce; (i) aspen-white spruce.

Effects of climate change

The growth responses of lodgepole pine to climate dominated all the regional weighted averages (Figure 9) because the model parameterization was clearly successful in simulating the abundance of this species in the study region. The primary determinant is the relatively low precipitation regime, which generally favours lodgepole pine compared to other species. Balsam fir was parameterized to grow slowly, but the process-based formulation of the growth function in FORSKA-M gave a strong competitive advantage to shade-tolerant species wherever they could compete successfully and grow.

These simulations suggested that there should be only minor impacts on average biomass production, with a tendency for species composition to shift towards increased occurrence of lodgepole pine and trembling

Figure 10. FORSKA-M results showing the effects of varying disturbance interval on simulated area-weighted average biomass density in the Alberta study region under current climate conditions.

aspen and reduced abundance of spruces and firs. This interpretation should, however, be treated with caution: first it is based on the results from only one model of stand-level competition (which StandLEAP does not capture), and second it presupposes that there would be no impact of climate change on the natural disturbance regime. Based on these simulations, the most sensitive forest types are spruce-dominated, which suggests that lodgepole pine and trembling aspen should be favoured in long-term management of the more sensitive sites. However, an increase in the occurrence of fires, or catastrophic losses of lodgepole pine, due to mountain pine beetle, for example, could greatly alter this picture.

Effects of natural disturbance

The responses of the FORSKA-M model to simulated disturbance regimes were generally consistent with reality. When disturbance effects were included, the model predicted total biomass densities for individual species that were consistent with observations. The FORSKA-M simulations suggested that average biomass would tend to stabilize with a disturbance interval between 100 and 150 years (Figure 10). With shorter disturbance intervals, the mean simulated biomass was much lower. In general terms, the range of biomass densities estimated by the model were somewhat lower than the area-weighted mean biomass estimates derived from spatial data. Average biomass density estimated from AVI stand level data and PGS
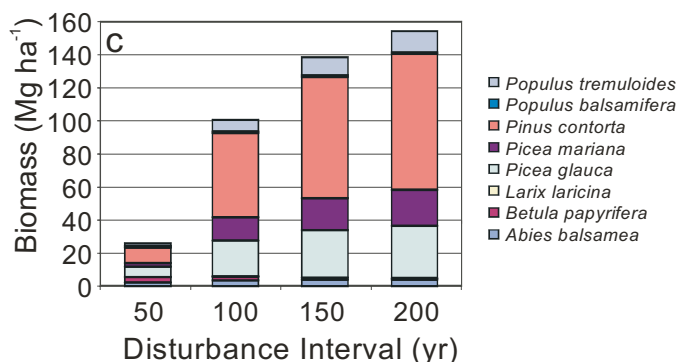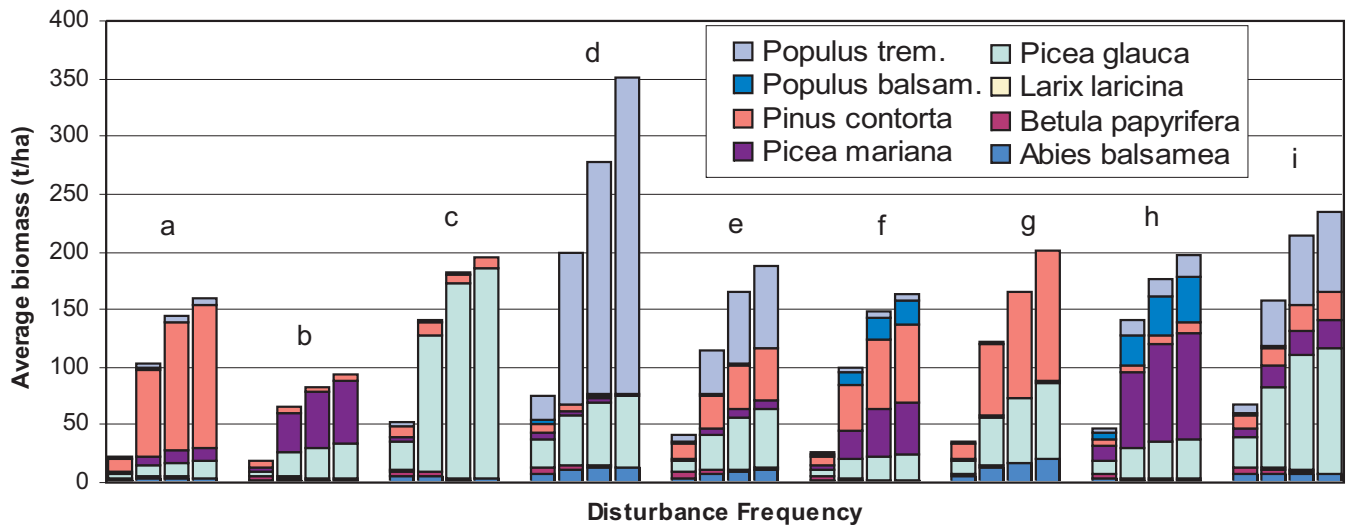
Figure 11. Effect of varying the disturbance interval on biomass density simulated by FORSKA-M for the major forest types in the Alberta study region. The four disturbance regimes are expressed in terms of the mean return interval: (left to right) 50 years, 100 years, 150 years and 200 years. Climate regime was derived from 1961-90 normals. The forest types are as in Figure 9.

observations lay in the range 160-190 Mg ha-1, with the exception of the black spruce-dominated systems, where it was approximately 60 Mg ha-1. By comparison, assuming a 100-year return interval, FORSKA-M typically predicted biomass densities of 100 to 150 Mg ha-1 (Figure 11), although in the specific case of black spruce-dominated systems, FORSKA-M predicted about 60 Mg ha-1 (Figure 11b).

CONCLUSIONS AND FUTURE WORK

We believe this study was the first attempt at developing comprehensive and spatially detailed data sets that can be used to drive high resolution models of forest processes over extensive regions. As such it proved to be an ambitious project with very challenging objectives. In particular, the project was successful in:

- Creating spatial data sets needed to develop and test many process models of forest productivity and species succession, and
- Performing simulations with different models of forest responses to climate.

The spatial datasets provide a firm basis for both simulating spatial variability and for validating predictions made with any ecosystem model over an extensive region in the western boreal biome.

To date, only limited explorations of the impacts of climate change on productivity and succession have been completed from use of the StandLEAP and FORSKA-M models. The work revealed several weaknesses in our ability to model specific processes linked to forest productivity, and the impact of environmental factors on these processes. Several model components, including the modelling of mortality and self-thinning within forest stands, require improvement. Further, given the possibility of decreased water availability in the Boreal Plains ecozone as a result of a warmer and possibly drier climate, we think that further work should be carried out to better capture this process. At the same time, local soil conditions in general, and profile drainage in particular, influence forest growth in a non-linear but predictable fashion. Better spatial representation of these properties, and proper representation of these processes in the models will likely improve the simulations.

Future work will be undertaken in the following areas:

1. Improvements to spatial data inputs to the statistical models used to estimate the spatial distributions of variables such as LAI, biomass, soil attributes, and stand density.
2. Refinements to process model parameters.
3. Use of different scenarios of future climate to simulate and assess the potential impacts on regional forest productivity.
4. Compilation of data for other study regions, notably in central Saskatchewan, to provide wider opportunities for developing and testing methods of combining ground-based datasets with remote sensing and computer models.

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