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Simulating Site-Specific Effects of a Changing Climate on Jack Pine Productivity Using a Modified Variant of the CROPLANNER Model

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This study evaluated the site-specific effects of projected future climate conditions on the productivity of jack pine (*Pinus banksiana* Lamb.) plantations over the next 50 years (2011-2061). Climatic parameters as predicted by the Canadian Global Climate Model in association with a regional spatial climatic model, under 3 emissions scenarios (no change (NC), B1 and A2), were used as input values to a biophysical-based site-specific height-age model that was integrated into the CROPLANNER model and associated algorithm. Plantations managed under a basic silvicultural intensity on two site qualities at each of two geographically separated sites (northeastern and northwestern Ontario, Canada) were assessed. The results indicated that the stands situated on low-to-medium quality sites at both locations were largely unaffected by the predicted increase in temperature and precipitation rates. Conversely, however, stands situated on good-to-excellent quality sites grown under the B1 and A2 scenarios experienced consequential declines in stand development rates resulting in decreases in rotational mean sizes, biomass yields, recoverable end-product volumes, and economic worth. In addition to providing a plausible range of site-specific climate change outcomes on jack pine productivity within the central portion of the species range, these results suggest that future predictions that do not account for potential climate changes effects may overestimate merchantable productivity on the higher site qualities by approximately 15%. As demonstrated, incorporating biophysical-based site index functions within existing forest productivity models may represent a feasible approach when accounting for climate change effects on yield outcomes of boreal species.

Keywords: B1 and A2 Emission Scenarios; Low-to-Medium and Good-to-Excellent Site Qualities; Basic Silvicultural Intensity Regimes

Introduction

Jack pine (*Pinus banksiana* Lamb.) occupies a wide range of sites throughout the northern temperate forest region of North America (Rudolph & Yeatman, 1982). Ecologically, jack pine exhibits an ability to: 1) tolerate environment constraints (e.g., moisture and nutrient limitations); 2) temporarily exploit environments following severe disturbance (e.g., rapidly colonization of recently-disturbed wildfire-burned sites due to its early maturity (cone-bearing at 3 - 5 years of age), cone serotiny and associated seed-dispersal habit (aerial dispersal of abundant viable seeds following heat-induced opening of serotinous cones), and favorable germination and seedling establishment conditions following wildfire (e.g., exposed mineral soil and temporary lack of competing species)); and 3) intensely compete for environmental resources and/or physical space, as evident by its asymmetric size-distributions and rapid rates of self-thinning as observed within monospecific density-stressed populations. Jack pine is one of the most economically important and intensely managed species within the Canadian Boreal Forest Region (Rowe, 1972). Specifically, in Canada's largest province, Ontario, jack pine represents 33% of the annual softwood volume harvested (OMNR, 2008). The principal products derived from this harvest are northern bleached softwood kraft pulp used to produce paperboard, tissue products and newsprint, dimensional lumber (studs, structural joists and planks), and composite wood products that are used in wood-frame residential house construction (Zhang & Koubaa, 2008).

The effects of a changing climate on boreal ecosystems have been estimated using a variety of different modeling approaches (e.g., Myneni et al. (1997), Shaw et al. (2006), Girardin et al. (2008), Kurz et al. (2009), Ise and Moorcroft (2010)). Although contradictory tendencies have been reported, results from these analyses have been useful in delineating a range of plausible outcomes. At the regional level, recognition that the jack pine resource will be impacted by rapid changes in climate is well appreciated throughout the forest management and scientific communities (e.g., Parker et al., 2000; Colombo et al., 2007). Although climate change projections vary by the type of model used, emissions scenario considered, and locality assessed, the consensus is that the climate within northeastern and northwestern Ontario will undergo a consequential change over the next century (Colombo et al., 2007). Given that jack pine exhibits a large degree of phenotypic plasticity and has the ability to tolerate a wide range of climatic and site conditions, it is important to estimate how this valuable resource will fair under a changed climate. Consequently, the objectives of this study were to simulate climate change effects on the productivity of jack pine plantations across a range of site qualities and locations. The approach employed the CROPLANNER decision-support model (Newton, 2009) which was modified through the incorporation of a biophysical-based site-specific height-age function. This enabled an empirical assessment of the effects of localized changes in climate on jack pine productivity.

Briefly, CROPLANNER is an algorithmic analogue of the structural stand density management model (SSDMM) which was developed by expanding the stand density management diagram modelling framework through the incorporation of distribution recovery modules for diameter, height, biomass, carbon, end-products, value and wood quality attributes (Newton, 2009). Structurally, the model consists of a number of functional and empirical quantitative relationships, which collectively represent the cumulative effect of various underlying competition processes on tree and stand yield parameters. The temporal dependency of these processes is governed by the intensity of competition and site quality as expressed by relative density index and site index, respectively. As with most tree and stand simulators, the site-specific mean dominant height—age function largely governs the rate of stand development. Consequently, accounting for the cumulative effect of climate change through the use of a biophysical-based site-specific height-age function was considered a prudent approach and is in accord with similar approaches used with other tree and stand simulators (e.g., O'Neill & Nigh, 2011).

CROPLANNER, for a given density management regime, site quality, rotation length, cost profile and set of merchantability specifications, enables the estimation of overall productivity (e.g., mean annual volume, biomass and carbon increments), volumetric yields (e.g., total and merchantable volumes per unit area), log-product distributions (e.g., number of pulp and saw logs), biomass production and carbon sequestration outcomes (e.g., oven-dried masses of above-ground components and associated carbon equivalents), recoverable end-products and associated monetary values (e.g., volume and economic value of recovered chip and dimensional lumber products) by sawmill-type (stud and randomized length processing protocols), economic efficiency (e.g., land expectation value), duration of optimal site occupancy, structural stability, and fibre attributes (e.g., wood density and branch diameter). For a complete analytical description of the approach used in the development and calibration of the modular-based SSDMM, refer to Newton (2009).

The scope of this analysis includes the consideration of the effects of B1 and A2 emission scenarios (Nakicenovic et al., 2000) relative to the null case of no climate change (NC). These scenarios cover the plausible range normally considered by policy makers and forest planners within the Province of Ontario (Colombo et al., 2007). Specifically, the NC scenario was based on climatic norms observed during the 1970-2000 period. As defined by Nakicenovic et al. (2000), the B1 emission scenario arises from a convergent world that is characterized by global-based collaborative approaches to solving economic, social, and environmental problems (i.e., best-case scenario). The transition from conventional oil and gas resources to alternative energy systems is expected to be uneventful. Globally, the population is expected to increase to 8.7 billion by 2050 but then decline to 7.0 billion by 2100. The global gross domestic product (GDP) is expected to increase to 136 billion (1990 US$/yr) by 2050 and then to 328 billion (1990 US$/yr) by 2100. Proactive nation-based environmental measures and associated policies are expected to result in relatively low anthropogenic GHGs and aerosols emissions, reaching a maximum concentration of approximately 600 ppm by 2100 (IPPC, 2007). Relative to the 1980-2000 period, the mean global temperature is expected to increase 2.4˚C by 2100 (IPPC, 2007).

Conversely, the A2 emission scenario is based on a hetero- geneous and regionally differentiated world in terms of econo- mic development, productivity, social structures and income equa- lity, where the self-reliance and preservation of local identities is paramount (i.e., worst-case scenario; Nakicenovic et al., 2000). Although attempts to control local environmental degradation will occur, international co-operation in mitigating the effects of climate change will be limited. The global population is expected to increase to 11.3 billion by 2050 and then to 15.1 billion by 2100. Global GDP is projected to increase to 82 billion (1990 US$/yr) by 2050 and then to 243 billion (1990 US$/yr) by 2100. This increase in population growth combined with concurrent changes in land use, and consumption of natural resources including the rapid depletion of fossil fuels, will substantially increase GHGs and aerosols emissions, reaching a maximum concentration of approximately 1250 ppm by 2100 (IPPC, 2007). Resultantly, the mean global temperature is expected to increase by approximately 3.4˚C by 2010, relative to the 1980-2000 period (IPPC, 2007).

Material and Methods

Firstly, the CROPLANNER decision-support model (Newton, 2009) was modified through the inclusion of a biophysical-based height-age model developed for jack pine plantations in Ontario (Sharma et al., 2012). Specifically, the original site-based height-age function developed by Carmean et al. (2001; Equation (23) in Newton, 2009) was replaced by Equation (1):

$$H = 1.3 + \hat{\beta}_0 \Big/ \left(1 - \left(1 - \left(\hat{\beta}_0 / S_I\right)\right)\left(25/\left(A_{bh} - 0.5\right)\right)^{\hat{\beta}_1}\right) \qquad (1)$$

where

$$\hat{\beta}_0 = 196.47 + 0.3209P_w - 0.3762P_d - 14.2779T_g + 0.0014P_aT_a,$$

$$\hat{\beta}_1 = -1.3757 - 0.0058P_w + 0.0114P_d + 0.2153T_g,$$

H (m) is mean dominant height, S_I is site index (mean dominant height at a breast-height age of 25 yr), A_{bh} is mean breast height age (yr), P_w and P_d are total precipitation (mm) during the wettest and driest period, respectively, T_g is the mean temperature (˚C) during the growing season, P_a is the total precipitation (mm) during the entire year, and T_a is the mean annual temperature (˚C) during the entire year.

Secondly, climatic parameters (P_w, P_d, T_g, P_a and T_a) were predicted by the Canadian Global Climate Model (V. 3.1; Environment Canada, 2011) in association with a regional spatial climatic model (McKenney et al., 2007). Two emissions scenarios (B1 and A2; Nakicenovic et al., 2000) for the 2011-2040 and 2041-2070 periods at two geographic locations (Kirkland Lake, ON (Forest Section B7 Missinaibi-Cabonga (Rowe, 1972)) and Thunder Bay, ON (B.9 Superior (Rowe, 1972))) were specified. For the no change scenario (NC), corresponding climatic variables for the 1970-2000 period were obtained from the regional spatial climatic model (McKenney et al., 2007) for the same locations. The 2011-2040 and 2041-2070 values were combined and means obtained for the entire 2011-2070 period in order to avoid abrupt changes at the 2040-2041 transition point. **Table 1** lists the derived parameters for each location by scenario and time period.

Thirdly, the simulations consisted of inputting the resultant climatic values into the modified CROPLANNER model and implementing density management regimes consistent with a basic silvicultural intensity (Bell et al., 2008) on poor-to-medium

Table 1.
Climatic input parameters for the modified CROPLANNER model: climatic variables corresponding to the NC, B1 and A2 emission scenarios by period and location.

Input	Location (Forest Section)[a]													
Parameter	Kirkland Lake, ON (B.7 Missinaibi-Cabonga)							Thunder Bay, ON (B.9 Superior)						
[Denotation]	NC	B1			A2			NC	B1			A2		
	1971 - 2000	2011 - 2040	2041 - 2070	2011 - 2070	2011 - 2040	2041 - 2070	2011 - 2070	1971 - 2000	2011 - 2040	2041 - 2070	2011 - 2070	2011 - 2040	2041 - 2070	2011 - 2070
Total precipitation during wettest period (mm) $[P_w]$	98	99	98	99	107	100	104	87	91	91	91	97	87	92
Total precipitation during driest period (mm) $[P_d]$	47	49	59	54	61	59	60	28	32	38	35	38	36	37
Mean temperature during growing season (˚C) $[T_g]$	11.2	12.5	13.6	13.1	12.9	13.8	13.4	11.3	12.7	13.6	13.2	13.1	14.0	13.6
Annual precipitation (mm) $[P_a]$	865	885	951	918	951	964	958	720	765	816	791	811	811	811
Annual mean temperature (˚C) $[T_a]$	1.54	2.71	4.01	3.36	3.33	4.85	4.09	2.74	3.98	5.25	4.62	4.50	6.14	5.32

All forecasted values of the climatic parameters were derived from the Canadian Global Climate Model (Version 3.1; Environment Canada, 2011). Specific estimates for the 2 locations were derived from the web-based customized spatial climatic model as described by McKenney et al. (2007). [a]Longitude and latitude in decimal degrees for Kirkland Lake, ON and Thunder Bay, ON: –80.0333 and 48.1500, –89.2500 and 48.3833, respectively. Forest Section after Rowe (1972).

and good-to-excellent sites within each of the two locales. The underlying objective of the basic silvicultural intensity is to shorten the rotation length and increase product value. The actual crop plan consisted of site preparation and vegetation management treatments preceding the planting of 2000 seedlings per hectare and allowing 500 seedlings per hectare to establish naturally as ingress. **Table 2** lists the input variables and model parameters that were used.

Results

During the 2011-2070 period, both precipitation and temperatures are predicted to increase at both the eastern and western Ontario locations with the greatest increases occurring under the A2 emission scenario (**Table 1**). Specifically, relative to the 1971-2000 period (**Table 1**): 1) annual precipitation is forecasted to increase 6.1% and 10.8% and mean annual temperatures by +1.8˚C and +2.6˚C under the B1 and A2 scenarios, respectively, at the north-eastern locale; and 2) annual precipitation is forecasted to increase 9.9% and 12.6% and mean annual temperatures by +1.9˚C and +2.6˚C under the B1 and A2 scenarios, respectively, at the north-western locale. Simulating the effect of these increases on jack pine plantations established at nominal initial spacing across a range of site qualities using the CROPLANNER model (**Table 2**), enabled a comparative analysis of 50 yr rotational productivity outcomes for each emission scenario. **Table 3(a)** and **Table 3(b)** list the yield estimates for the northeastern and northwestern locales, respectively. Similarly, **Tables 4(a)** and **(b)** provide a set of relevant performance metrics for the northeastern and northwestern locales, respectively. Site-specific representations of the expected size-density trajectories within the traditional stand density management graphic for each scenario by site quality and geographic location are shown in **Figures 1** and **2**: **Figures 1(a)** and **(b)** illustrate the trajectories for the poor-to-medium and good-to-excellent site qualities at the north-eastern locale, respectively, whereas **Figures 2(a)** and **(b)** illustrate the corresponding trajectories at the north-western locale, respectively.

Table 2.
Density management input parameters for the modified CROPLANNER model.

Parameter (units)	Value
Simulation Year	2011
Site Index (S_I)	8 & 12
Rotation Age (yr)	50
Initial Density (stems/ha)	2500
Ingress Density (stems/ha)	500
Pulp Log Length (m)	2.59
Pulp Log Diameter (cm)	10
Saw Log Length (m)	5.03
Saw Log Diameter (cm)	14
Merchantable Top Diameter (cm)	4
Inflation Rate (%)	2
Discount Rate (%)	4
Operability Target for $S_I = 8$: Quadratic Mean Diameter (cm)	14
Operability Target for $S_I = 12$: Quadratic Mean Diameter (cm)	18
Site Preparation (CAN$/ha)	300
Planting (CAN$/seedling)	0.6
Operational Adjustment Factor (%)	1
Product Degrade Factor (%)	15
Harvesting + Stumpage + Renewal + Transportation + Manufacturing Costs (CAN$/m^3)	75

Lower Site Qualities

The stands established on the poor-to-medium site qualities differed only slight in terms of their dynamics over the 50 yr rotations (**Figures 1(a)** and **2(a)**). However, for the northeastern stands, these slight differences in the size-density trajectories translated into greater rotational mean sizes (quadratic mean diameter and mean volume) and per unit area yields (total and merchantable volumes, and component-specific biomass and carbon yields), and end-product volumes (volume of recoverable chip and lumber volumes), for stands grown under the NC and B1 scenarios, relative to the stand grown under the A2 scenario (**Table 3(a)**). Conversely, however, the trajectories for the northwestern stands grown under the B1 and A2 scenarios actually attained a slightly greater size-density condition at rotation than that obtained within the stand grown under the NC scenario. These differences translated into greater rotational mean sizes and per unit area yields, and preferred end-product volumes, relative to the NC scenario (**Table 3(b)**). In terms of the performance indices, merchantable volume, biomass productivity and carbon yields, and the proportion of preferred end-products (number of saw-logs and volume of recoverable dimension lumber), were slightly greater for northeastern stands growing under the NC and B1 scenarios relative to the stand grown under the A2 scenario (**Table 4(a)**). Apart from a decline in economic worth under the A2 scenario, differences in the duration of optimal site occupancy, stand structure, wood quality metrics, and time to operability, were largely inconsequential (**Table 4(a)**). The corresponding values for the northwestern stands established on a poor-to-medium site quality, indicated that productivity and the percentage of preferred end-products increased slightly under the B1 and A2 scenarios, resulting in a consequential increase in economic worth relative to the NC scenario (**Table 4(b)**). Similar to the northeastern stands, differences in the duration of optimal site occupancy, stand structure, wood quality metrics, and time to operability, were minimal. Although, the stand grown under the NC scenario exhibited a slight increase in its rate of development as evident by a 3 yr differential (reduction) in the time to operability status (**Table 4(b)**).

Table 3.

(a) Rotational yield estimates for jack pine plantations managed under a basic silvicultural intensity in northeastern Ontario by emission scenario and site quality. (b) Rotational yield estimates for jack pine plantations managed under a basic silvicultural intensity in northwestern Ontario by emission scenario and site quality.

(a)

Attribute[a]	Site quality[b]					
(Unit)	Poor-to-medium			Good-to-excellent		
	Emission scenario[c]			Emission scenario[c]		
	NC	B1 vs NC (% Δ)	A2 vs NC (% Δ)	NC	B1 vs NC (% Δ)	A2 vs NC (% Δ)
Mean dominant height (m)	16.2	0.0	–2.5	21.7	–7.8	–13.4
Quadratic mean diameter (cm)	15.9	0.0	–4.4	23.1	–10.4	–16.9
Total basal area per stand (m^2/ha)	29	0.0	–6.9	35	–5.7	–11.4
Mean volume per tree (dm^3)	140	0.0	–11.4	393	–26.0	–39.7
Total volume per stand (m^3/ha)	202	0.5	–7.9	326	–13.2	–22.1
Total merchantable volume per stand (m^3/ha)	190	0.5	–8.9	313	–13.4	–22.7
Total density per stand (stems/ha)	1445	0.8	3.8	829	17.2	29.3
Relative stand density (%/100)	0.64	1.6	–6.3	0.86	–8.1	–15.1
Total number of pulp logs per stand (logs/ha)	2313	0.7	–6.4	1550	35.7	47.5
Total number of saw logs per stand (logs/ha)	172	0.6	–31.4	1323	–32.9	–53.0
Total residual tip volume per stand (m^3/ha)	49.9	0.8	–6.8	21.3	24.9	57.3
Total bark oven-dried biomass per stand (t/ha)	10.9	0.9	–5.5	12.1	0.0	–1.7
Total stem oven-dried biomass per stand (t/ha)	119.8	0.8	–8.7	180.3	–12.4	–19.9
Total branch oven-dried biomass per stand (t/ha)	10.2	0.0	–8.8	18.3	–15.3	–24.0
Total foliage oven-dried biomass per stand (t/ha)	6.1	0.0	–8.2	9.4	–11.7	–18.1
Total above-ground oven-dried biomass per stand (t/ha)	147.0	0.6	–8.4	220.0	–11.8	–19.1
Total bark carbon per stand (t/ha)	5.5	0.0	–7.3	6.0	1.7	0.0
Total stem carbon per stand (t/ha)	59.9	0.7	–8.7	90.2	–12.4	–20.0
Total branch carbon per stand (t/ha)	5.1	0.0	–9.8	9.1	–14.3	–24.2
Total foliage carbon per stand (t/ha)	3.0	0.0	–6.7	4.7	–10.6	–19.1
Total above-ground carbon per stand (t/ha)	73.5	0.5	–8.4	110.0	–11.8	–19.2
Total chip volume per stand—stud mill (m^3/ha)	74.2	0.8	–8.6	106.8	–11.7	–19.0
Total lumber volume per stand—stud mill (m^3/ha)	83.9	0.8	–12.9	189.8	–23.4	–35.8
Total chip volume per stand—randomized length mill (m^3/ha)	46.1	0.9	–8.9	69.5	–12.8	–20.6
Total lumber volume per stand—randomized length mill (m^3/ha)	112.6	0.8	–11.5	227.2	–21.1	–32.4

[a] Predicted values; [b] Poor-to-medium and good-to-excellent site qualities correspond to site indices of 8 and 12 m at a breast-height age of 25 yrs, respectively (Sharma et al., 2012); [c] As defined in the text.

(b)

Attribute[a]	Site quality[b]					
(Unit)	Poor-to-medium			Good-to-excellent		
	Emission scenario[c]			Emission scenario[c]		
	NC	B1 vs NC (% Δ)	A2 vs NC (% Δ)	NC	B1 vs NC (% Δ)	A2 vs NC (% Δ)
Mean dominant height (m)	15.5	3.2	1.9	20.9	–5.3	–7.2
Quadratic mean diameter (cm)	15.0	4.0	2.7	22.0	–6.8	–9.1
Total basal area per stand (m^2/ha)	27	3.7	3.7	33	–3.0	–3.0
Mean volume per tree (dm^3)	119	11.8	7.6	342	–17.5	–22.8
Total volume per stand (m^3/ha)	179	8.9	5.6	302	–8.3	–11.3
Total merchantable volume per stand (m^3/ha)	166	10.2	6.6	290	–8.6	–11.7
Total density per stand (stems/ha)	1498	–1.8	–0.9	883	11.4	14.9
Relative stand density (%/100)	0.58	6.9	5.2	0.82	–4.9	–7.3
Total number of pulp logs per stand (logs/ha)	2087	8.0	5.4	1791	7.5	20.6
Total number of saw logs per stand (logs/ha)	103	42.7	25.2	1116	–24.6	–32.3
Total residual tip volume per stand (m^3/ha)	44.6	8.7	6.1	26.1	23.4	33.0
Total bark oven-dried biomass per stand (t/ha)	9.9	8.1	5.1	12.4	–3.2	–1.6
Total stem oven-dried biomass per stand (t/ha)	104.8	10.2	6.7	172.3	–10.4	–10.9
Total branch oven-dried biomass per stand (t/ha)	9.0	8.9	5.6	17.8	–14.6	–15.2
Total foliage oven-dried biomass per stand (t/ha)	5.5	7.3	3.6	9.3	–11.8	–11.8
Total above-ground oven-dried biomass per stand (t/ha)	129.2	9.8	6.3	211.8	–10.4	–10.8
Total bark carbon per stand (t/ha)	5.0	6.0	4.0	6.2	–3.2	–1.6
Total stem carbon per stand (t/ha)	52.4	10.1	6.7	86.1	–10.3	–10.8
Total branch carbon per stand (t/ha)	4.5	8.9	4.4	8.9	–14.6	–15.7
Total foliage carbon per stand (t/ha)	2.8	3.6	3.6	4.6	–10.9	–10.9
Total above-ground carbon per stand (t/ha)	64.6	9.8	6.3	105.9	–10.4	–10.8
Total chip volume per stand—stud mill (m^3/ha)	65.0	10.0	6.5	101.3	–9.2	–9.6
Total lumber volume per stand—stud mill (m^3/ha)	69.0	14.9	9.4	170.9	–18.3	–20.5
Total chip volume per stand—randomized length mill (m^3/ha)	40.1	10.7	7.0	65.8	–10.2	–10.8
Total lumber volume per stand—randomized length mill (m^3/ha)	94.3	13.5	8.7	206.7	–16.4	–18.2

[a,b,c] As defined in **Table 3(a)**.

Table 4.
(a) Stand-level performance indices for jack pine plantations managed under a basic silvicultural intensity in northeastern Ontario by emission scenario and site quality. (b) Stand-level performance indices for jack pine plantations managed under a basic silvicultural intensity in northwestern Ontario by emission scenario and site quality.

(a)

Index[a]	Site quality[b]					
(Unit)	Poor-to-medium			Good-to-excellent		
	Emission scenario[c]			Emission scenario[c]		
	NC	B1 vs NC (% Δ)	A2 vs NC (% Δ)	NC	B1 vs NC (% Δ)	A2 vs NC (% Δ)
Mean annual merchantable volume increment (m^3/ha/yr)	3.8	0.0	–7.9	6.3	–14.3	–23.8
Mean annual biomass increment (t/ha/yr)	2.9	3.4	–6.9	4.4	–11.4	–18.2
Mean annual carbon increment (t/ha/yr)	1.5	0.0	–13.3	2.2	–13.6	–18.2
Percentage of sawlogs produced	6.9	0.0	–24.6	46	–35.4	–53.5
Lumber volume recovered—stud mill (%)	53.1	0.0	–2.3	64	–5.2	–8.6
Lumber volume recovered—randomized length mill (%)	70.9	0.0	–0.8	76.6	–2.5	–3.9
Land expectation value—stud mill (CAN$K/ha)	1.0	2.3	–51.2	7.7	–42.4	–61.3
Land expectation value—randomized length mill (CAN$K/ha)	3.1	1.2	–21.5	10.1	–33	–48
Duration of optimal site occupancy (% of rotation)	28	–14.3	0.0	16	–25.0	0.0
Mean height/diameter ratio (m/m)	88.9	0.6	0.8	86.4	1.9	1.3
Mean wood density (g/cm^3)	0.4556	–0.2	0.2	0.4461	–0.7	–0.6
Mean maximum branch diameter (cm)	2.86	–0.7	–0.3	2.80	–1.1	–1.8
Time to operability status (yr)	44	0.0	2.3	38	5.3	15.8
Time of initial crown closure (yr)	13	23.1	23.1	9	22.2	11.1

[a] Predicted values; [b] Poor-to-medium and good-to-excellent site qualities correspond to site indices of 8 and 12 m at a breast-height age of 25 yrs, respectively (Sharma et al., 2012). [c] As defined in the text.

(b)

Index[a] (Unit)	Site quality[b]					
	Poor-to-medium			Good-to-excellent		
	Emission scenario[c]			Emission scenario[c]		
	NC	B1 vs NC (% Δ)	A2 vs NC (% Δ)	NC	B1 vs NC (% Δ)	A2 vs NC (% Δ)
Mean annual merchantable volume increment (m^3/ha/yr)	3.3	12.1	6.1	5.8	–8.6	–12.1
Mean annual biomass increment (t/ha/yr)	2.6	7.7	3.8	4.2	–9.5	–9.5
Mean annual carbon increment (t/ha/yr)	1.3	7.7	7.7	2.1	–9.5	–9.5
Percentage of sawlogs produced	4.7	29.8	17.0	38.4	–20.8	–32.6
Lumber volume recovered—stud mill (%)	51.5	2.1	1.4	62.8	–4.0	–4.9
Lumber volume recovered—randomized length mill (%)	70.2	0.7	0.4	75.9	–1.8	–2.2
Land expectation value—stud mill (CAN$K/ha)	0.3	137.1	84.3	6.4	–37.1	–38.8
Land expectation value—randomized length mill (CAN$K/ha)	2.2	28.6	18.2	8.8	–28.1	–28.9
Duration of optimal site occupancy (% of rotation)	32	–12.5	–12.5	16	–25.0	0.0
Mean height/diameter ratio (m/m)	89.1	–1.0	–0.4	86.9	0.2	0.5
Mean wood density (g/cm^3)	0.4577	–0.4	–0.3	0.4460	–0.7	–0.6
Mean maximum branch diameter (cm)	2.87	–1.0	–0.7	2.80	–1.4	–1.4
Time to operability status (yr)	46	–4.3	–4.3	39	5.1	7.7
Time of initial crown closure (yr)	12	25.0	25.0	8	25.0	25.0

[a,b,c]As defined in **Table 4(a)**.

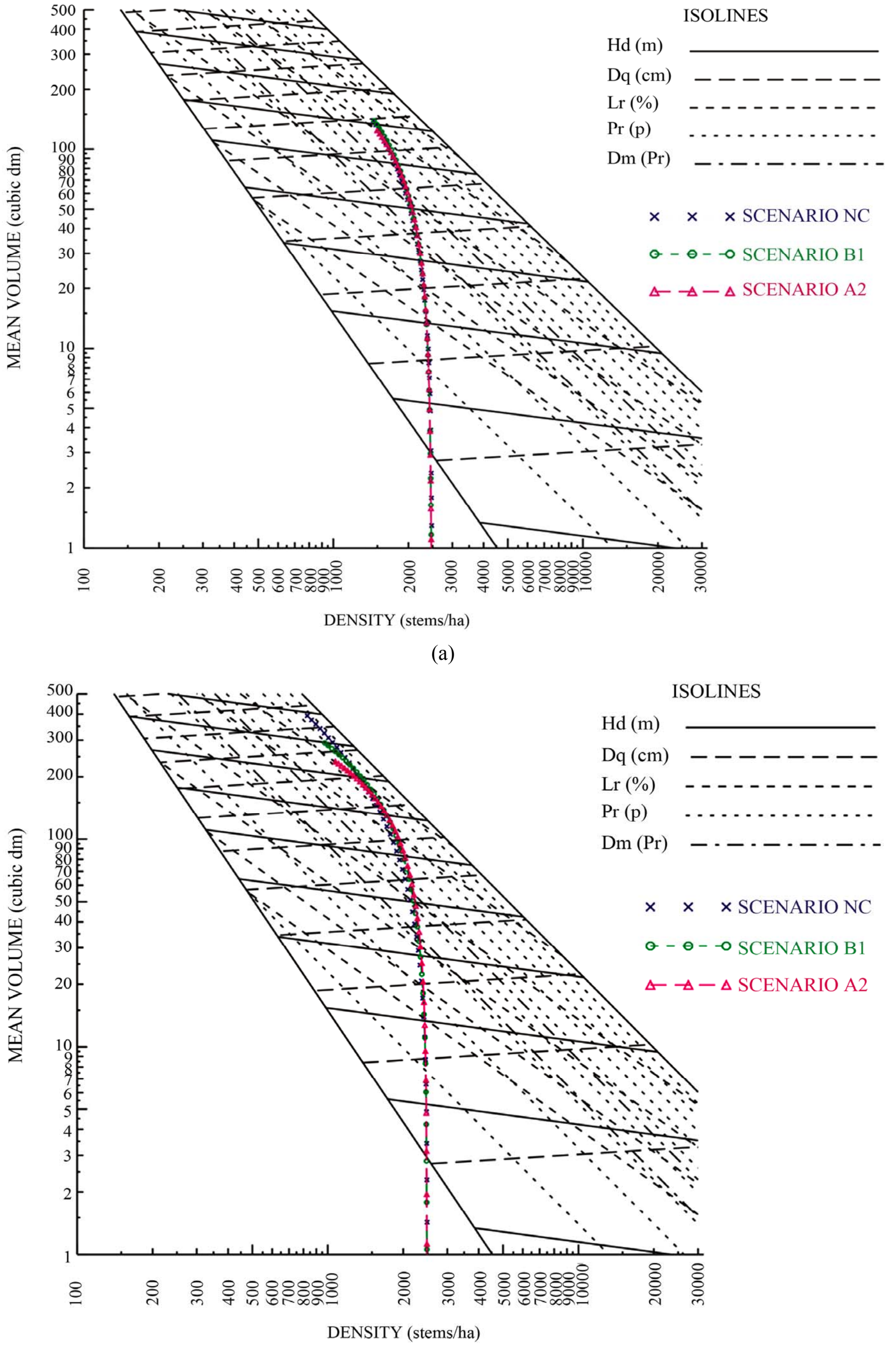
Higher Site Qualities

The effects of climate change were clearly evident for the stands managed on the good-to-excellent site qualities irrespective of locale. The size-density trajectories of the stands grown under the NC scenario incurred greater mortality during the middle of the rotation whereas the stands grown under the B1 and A2 exhibited greater rates of mortality later in the rotation (**Figures 1(b)** and **2(b)**). The stands grown under the B1 and A2 scenarios illustrated a continuous decline in the rate of their stand development as measured by their size-density trajectories and dominant height status during the later stages of the rotation (**Figures 1(b)** and **2(b)**). Relative to the NC scenario, rotational mean volumes were approximately 33% smaller within the northeastern stands grown under the B1 and A2 scenarios (**Table 3(a)**). Similarly, for the northwestern stands, mean volumes were on average 20% smaller relative to the NC scenario (**Table 3(b)**). In terms of development, the dominant height of the northeastern stands grown under the B1 and A2 scenarios were on average 11% smaller at rotation than that obtained within the stand grown under the NC scenario (**Table 3(a)**). Likewise, for the northwestern stands, the dominant heights at rotation were on average 13% smaller within the stands grown under the B1 and A2 scenarios, relative to the stand grown under the NC scenario (**Table 3(b)**).

Volumetric productivity declined by 14% and 24% within the northeastern stands grown under the B1 and A2 scenarios, respectively, compared to the stand grown under the NC scenario (**Table 4(a)**). The corresponding values for the northwestern stands were 9% and 12% for the B1 and A2 scenarios, respecttively (**Table 4(b)**). Biomass production and carbon yields exhibited similar levels of decline for both the B1 and A2 scenarios, in both regions (**Tables 4(a)** and **(b)**). Relative to the stands grown under the NC scenario, the proportion of preferred end-products (number of sawlogs and volume of dimensional lumber) and associated economic values at the time of harvest (land expectation value), declined within the stands grown under the B1 and A2 scenarios, irrespective of locale (**Tables 4(a)** and **(b)**). Similar to the results from the low quality sites, differences in the duration of optimal site occupancy, structural stability (height/-diameter ratio), wood quality metrics, and time to crown closure, were minimal among all three scenarios (**Tables 4(a)** and **(b)**). In terms of operability, however, the northeastern stands grown under the B1 and A2 scenarios required an additional 2 and 6 years, respectively, to attain operability status. Corresponding values for the northwestern stands were 2 and 3 years, respectively.

Discussion

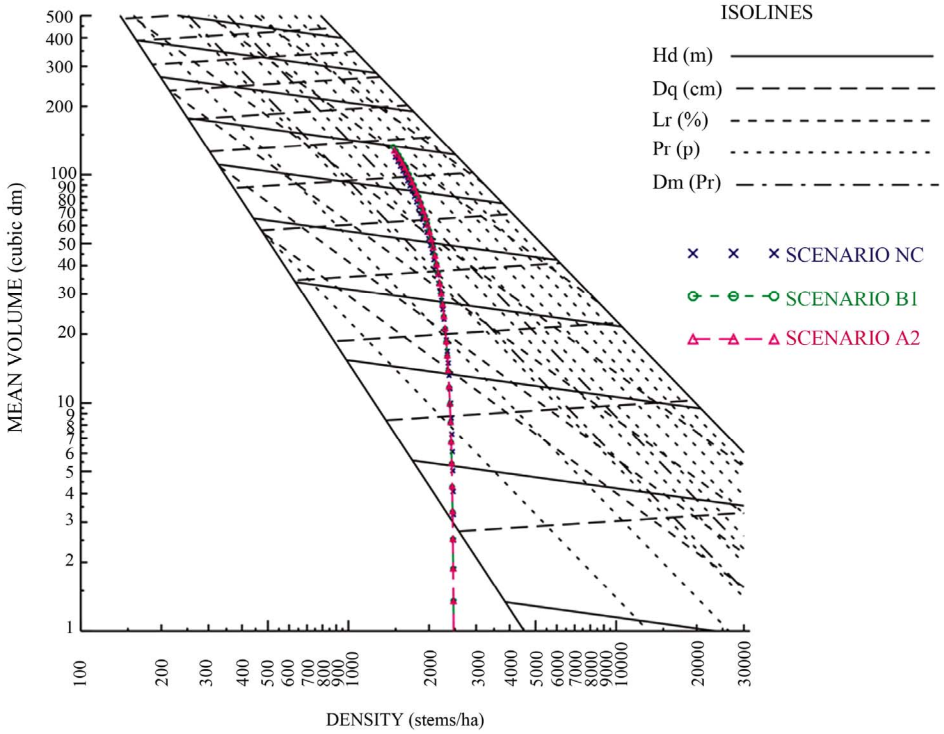
The results of this study suggest that the predicted warmer temperatures and wetter growing seasons arising from increases in the emission of greenhouse gases and aerosols will negatively affect jack pine productivity on good-to-excellent site qualities over the next 50 years (2011-2061). Specifically, stands managed employing a basic silvicultural intensity (Bell et al., 2008) and grown on such sites under either a B1 or A2 scenario will experience declines in their rate of development. By the end of the rotation, these declines will result in reductions in rotational mean sizes (11% for quadratic mean diameter and 27% for mean volume) and per unit area yields (14% for total volume and merchantable volumetric yields, and 13% for biomass production and carbon outcomes), recoverable end-product volumes (13% for the volume of recoverable chip and 23% for lumber volumes), economic worth (40% for land expectation value), and operability status (8% longer to attain the threshold operability targets), relative to comparable stands grown under the NC scenario. Contrary to expectation, these results suggest that the warmer temperatures combined with increases in precipitation forecasted under the B1 and A2 scenarios may actually degrade the productivity of jack pine plantations. Although speculative, one plausible explanation is that this additional moisture will not be made available due to the low moisture retention



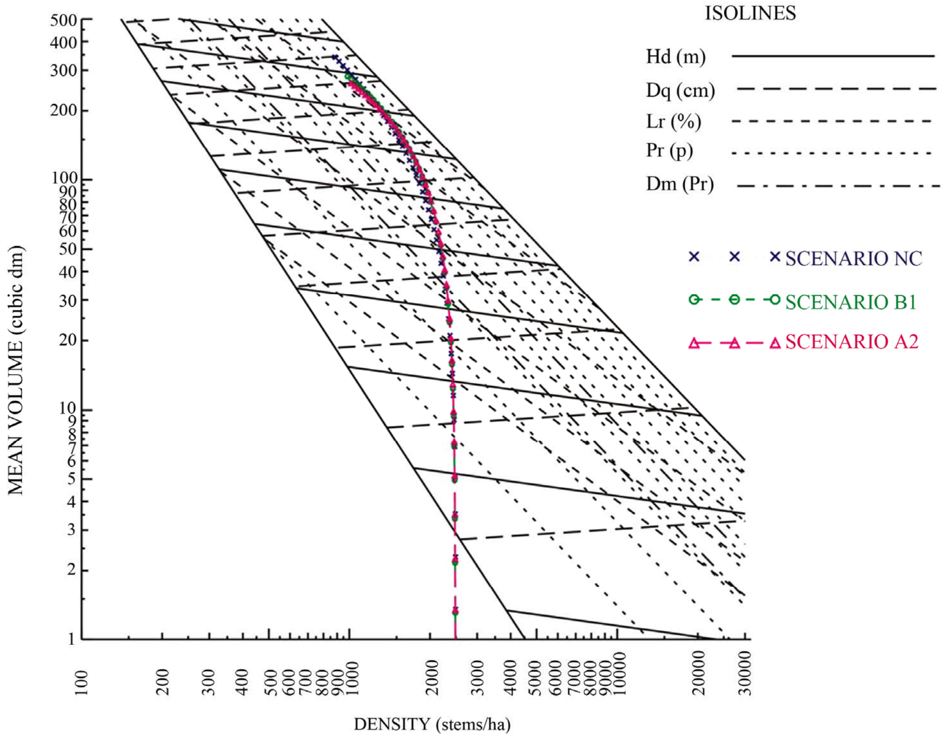
(a)

(b)

Figure 1.
(a) Temporal size-density trajectories by scenario for jack pine plantations managed under a basic silvicultural intensity as presented within the traditional stand density management diagram (SDMD) graphic for a low-to-medium quality site ($S_I = 8$) situated in northeastern Ontario. Graphically illustrating: 1) isolines for mean dominant height (Hd; 4 - 22 m by 2 m intervals proceeding vertically upwards), quadratic mean diameter (Dq; 4 - 26 cm by 2 cm intervals proceeding vertically upwards), mean live crown ratio (Lr; 35%, 40%, 50%,···, 80% proceeding from left-to-right horizontally), relative density index (Pr; 0.1 - 1.0 by 0.1 intervals proceeding left-to-right horizontally); 2) crown closure line (lower diagonal solid line) and self-thinning rule at a Pr = 1.0 (upper diagonal solid line); 3) lower and upper Pr values delineating the optimal density management window (Dm; 0.32 ≤ Pr ≤ 0.45); and 4) expected 50 year size-density trajectories with 1 year intervals denoted for each scenario. (b) Temporal size-density trajectories by scenario for jack pine plantations managed under a basic silvicultural intensity as presented within the SDMD graphic for a good-to-excellent quality site ($S_I = 12$) situated within northeastern Ontario. Graphical denotations as defined in **Figure 1(a)**.



(a)



(b)

Figure 2.
(a) Temporal size-density trajectories by scenario for jack pine plantations managed under a basic silvicultural intensity as presented within the SDMD graphic for a low-to-medium quality site ($S_I = 8$) situated within northwestern Ontario. Graphical denotations as defined in **Figure 1(a)**; (b) Temporal size-density trajectories by scenario for jack pine plantations managed under a basic silvicultural intensity as presented within the SDMD graphic for a good-to-excellent quality site ($S_I = 12$) situated within northwestern Ontario. Graphical denotations as defined in **Figure 1(a)**.

ability of the sites that jack pine traditionally occupies. Additionally, temperature-induced increases in the rates of evapotranspiration and tree respiration (Boisvenue & Running, 2006) during the growing season may divert some of the photosynthate resources away from the production of new plant tissue.

Conversely, the productivity of jack pine plantations established on poor-to-medium site qualities may be somewhat invariant to the forecasted changes in climate, depending on a stand's specific geographical location. Mensurational-based yield and performance metrics for the northeastern stands grown under the NC and B1 scenarios were approximately equivalent to that of the stand grown under the A2 scenario. The northwestern stands grown under the B1 and A2 scenarios actually benefitted from the increase in temperature and precipitation as evident by the slightly improved mean tree size and per unit area yield outcomes. Ecologically, this may indicate that jack pine plantations situated on poor-to-medium quality sites at the northwestern locale may be moisture deficient. Thus these stands may be able to gain from a more maritime-like climate in the future. Notably, across both site quality classes assessed and irrespective of locale, effects arising from either the B1 or A2 scenario did not appreciatively affect the duration of optimal site occupancy, stand stability or wood quality metrics.

The site-specific patterns observed in this study suggest that jack pine productivity will be affected to a much greater degree on the higher site qualities than on the lower site qualities. Similar general trends were reported by Loustau et al. (2005) who found that climate change effects on the productivity of forests in western Europe were greatest on high fertility sites.

The importance of scaling global climate change effects to the local level is increasingly being acknowledged within the climate change literature (e.g., Malone & Engle, 2011). Combining site-specific future estimates of climatic variables under various emission scenarios with a forest productivity model, as shown in this study, readily facilitates the evaluation of climate change effects at the local level. The two regions selected for assessment in this study reflected representative examples within two of the most important areas for jack pine management in Ontario. These areas were geographically separated and inherently different in terms of their biophysical characteristics. Consequently, the results reported in this study represent a plausible range of outcomes for this particular species within the central portion of its range.

Modeling Approach and Associated Limitations

The objective of this study was to evaluate the potential effect of projected future climate conditions on the productivity of jack pine plantations over the next 50 years (2011-2061). Analytically, climatic parameters as predicted by a global climate model in association with a regional spatial climatic model, under 3 plausible emissions scenarios, were used as input values to a biophysical-based site-specific height-age function. The resultant function when integrated within the CROPLANNER simulation model enabled the estimation of climate change effects on a broad array of stand-level productivity measures. A similar approach was used to predict the effects of climate change on lodgepole pine (*Pinus contorta* Douglas ex Louden) in British Columbia (O'Neill & Nigh, 2011). In this case, the site-height equation within the Tree and Stand Simulator (TASS) was modified in order to account for changing climatic conditions for specific genotypes and locales. Ninety-year simulations for three disparate provenances growing under three emission scenarios suggested that volumetric yields would decline by 7% - 13%. Although acknowledging differences in species, scenarios, locale, site qualities and models between the studies, the trend of decrease productivity with future climate change is projected for both of these pine species. However, similar to most attempts to model the effects of climate change, the validity of future longterm forecasts is unknown and hence caution must be exercised when interpreting the projected consequences, irrespective of the modeling approach utilized.

The approach utilized in this study reinforces the utility of modifying existing empirical-based model structures in order to account for climate change effects on yield outcomes. However, the approach assumes that the wide array of biological changes arising from climate change can be expressed through the site-based height-age equation. Although height growth is the uni- versally accepted driver of forest productivity (O'Neill & Nigh, 2011), this is nevertheless a simplifying assumption which requires further verification. For example, a warmer and wetter climate may increase growth losses due to biotic (insect and disease) and abiotic (wind) agents (e.g., Fleming, 2000). The effects of increased decomposition rates and the CO_2 fertilization effect will also affect productivity (e.g., Girardin et al., 2011). Consequently, the effects on the insect and disease vectors and changes in the hydrological and biochemical cycles are not directly addressed using this approach. Hence until these effects of climate change are better understood, the results of this study should be considered tentative. Nevertheless, the initial projections and associated inferences suggest that jack pine may respond in site specific manner with higher site qualities experiencing the largest declines. Therefore, current yield projections derived from models that do not account for climate change effects are likely over-estimating future productivity on the better site qualities.

The scenarios evaluated in this study consisted of a static scenario which was composed of climatic variables not changing from their historical norms, the conceptual B1 emission scenario based on convergent greener world characterized by collective approaches to solving economic, social, and environmental problems, and the A2 scenario which arises from a decentralized and heterogeneous organized world where collective initiatives for addressing global environmental problems are minimal. However, the consequences of these scenarios were only assessed for the 2011-2061 period and thus included only 2 of the 3 projection periods normally considered under long-term climate change modeling (i.e., 2011-2040, 2041-2070 and 2071-2100). Consequently, the scope of the simulations did not include the most severe period of predicted climate change and hence the results do not reflect the full potential of the negative ramifications arising from extreme changes in climate on jack pine productivity. Forest managers and policy makers will need to account for these more severe climate change effects when forecasting the future development of plantations managed under a 50 yr rotation that are established after 2020.

Conclusion

The simulation results from the CROPLANNER model indicated that future yields for stands situated on low-to-medium quality sites were largely unaffected by the predicted increased temperature and precipitation rates during the 2011-2061 period. Conversely, however, stands situated on good-to-excellent quality sites grown under the B1 and A2 scenarios experienced consequential declines in stand development: reductions of 6.6% and 12.0% in mean dominant height at rotation for the B1 and A2 scenarios, respectively, relative to the NC scenario. These declines translated into decreases in merchantable volume productivity (mean annual merchantable volume increment) in the order of 19% for the northeastern stands and 10% for the northwestern stands grown under the B1 and A2 scenarios. Similar declining trends were evident for rotational mean sizes (quadratic mean diameter and mean stem volume), biomass yields (component-specific biomass production and carbon outcomes), recoverable end-product volumes (volume of recoverable chip and lumber volumes), and economic worth (land expectation value). In addition to providing plausible site-specific climate change outcomes on jack pine productivity within the central portion of the species range, the results suggest that future predictions made under the no change emission scenario may overestimate merchantable volume productivity on the higher site qualities by as much as 15%. Consequently, forest managers should exercise caution when interpreting future long-term yield forecasts derived from models that have yet to account for climate change effects.

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