Supporting Information for

Regional drought-induced reduction in biomass carbon sinks of Canada's boreal forests

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Materials and Methods

Data selection and analysis

For our analysis, forest plots from Canada's boreal forest region were strictly selected based on the following criteria: (1) All plots were in natural forest stands, which we defined as stands that reproduced naturally rather than regenerated by sowing or planting. (2) Because at least two different time intervals were required to compare changes in aboveground live biomass, all plots had at least three consecutive censuses. (3) We required all plots with complete tree recruitment and mortality records. In addition, every tree above a defined diameter at breast height (DBH, 1.3 m above the ground) was measured during the initial census. (4) The individual trees must have been clearly marked and repeatedly measured. (5) To detect potential long-term changes in aboveground live biomass, all plots had at least 10 years of observation between their first and last census. (6) To avoid biomass changes caused by disturbance, we chose only plots with no evidence of fire, flood, storm, or insect disturbance and no evidence of forest management such as thinning or harvesting. (7) To minimize biomass changes associated with stand development and succession, the stand age was ≥ 80 years in all plots. This age was chosen based on the mature ages of the major species in Canada's boreal forest (i.e., *S1*, *S2*). The stand ages were obtained by counting tree rings in increment cores of the largest trees or from available historical records. (8) To reduce random variation in plot-level aboveground live biomass, we only used plots with a large enough number of live trees (≥ 80) at their initial census (Table S1). (9) To obtain climatic data for each plot, the spatial location of all plots was required.

To find data that met these criteria, we selected and thoroughly reviewed data from permanent sample plots (PSPs) in Alberta (*S3*), Saskatchewan (*S4*), Manitoba (*S5*), Ontario (*S6*), and Quebec (*S7*). We did not consider PSP data from British Columbia and New Brunswick because most plots in these two provinces were not boreal forest types. The main objectives in permanent sample plot sampling are to assess stand dynamics such as succession, regeneration, ingrowth and mortality, to provide a data base that can be used to develop yield curves, to provide representative areas for study of management techniques, and to monitor provincial forest resources. The Alberta's PSPs have been established since 1960 by Forest Management

Branch of Alberta (*S3*). The PSPs are re-measured by different schedules to monitor the stand dynamics of different types of stands. The Saskatchewan's PSPs were built by the Department of Tourism and Renewable Resources Forestry Branch, Forest Inventory Section of Saskatchewan since 1960 (*S4*). Some new permanent sample plots were established from time to time in each of the surveys to replace those destroyed by fire, harvesting etc. The Manitoba's PSPs were established and measured by the Forestry Branch of Manitoba since 1970s (*S5*). The Ontario's PSPs were established and monitored by the Ministry of Natural Resources and Ontario Forest Research Institute since 1990 (*S6*). More than 4,000 PSPs in managed and natural forests were established across the Ontario province. Since 1970, approximately 12,000 permanent sample plots have been progressively established and inventoried by the ministère des Ressources naturelles et de la Faune du Québec (MRNFQ) (*S7*). Although there were many PSPs for each province (i.e., 580 plots for Alberta, 2426 plots for Saskatchewan, 368 plots for Manitoba, more than 4000 plots for Ontario, and about 12 000 plots for Quebec), most of the plots did not meet our criteria, either because they did not have three or more censuses or they were not located in undisturbed mature forest. Finally, ninety-six plots were selected (Table *S1*).

To obtain the climatic variables associated with the individual plots, we used data from the daily 10-km raster-gridded climate dataset for Canada from 1961 to 2003 (*S8*), which contains data for daily maximum temperature (°C; $T_{\max}$), minimum temperature (°C; $T_{\min}$), and precipitation (mm; *PCP*) for the Canadian landmass south of 60°N. The 10×10 km grids were interpolated from daily Environment Canada climate station observations using a thin-plate-smoothing spline-surface-fitting method implemented by the ANUSPLIN V4.3 software (*S9*). The climatic data for plots with census years after 2003 were downloaded from the nearest climate stations (Table *S3*, *S10*). We used the annual climate moisture index (*CMI*) (cm) (*S10*) to indicate the annual climatic water deficit. Monthly *CMI* values were calculated as monthly *PCP* minus *PET*, where *PET* is the potential evapotranspiration, which is estimated from $T_{\max}$, $T_{\min}$, and elevation (*S10*). Annual *CMI* was calculated by summing the monthly *CMI* values from January through December.

Positive *CMI* values indicate relatively moist conditions and negative *CMI* values indicate relatively dry conditions. In addition to the annual *CMI*, we also calculated the annual moisture index (*AMI*) (*S11*), which is defined as the ratio of the annual number of degree-days above 5 °C to the mean annual precipitation. Large values of *AMI* indicate dry conditions due to high heat (thus, high evaporative demand) relative to the available moisture, whereas low values of *AMI* represent relatively wet conditions. Therefore, the larger the value of *AMI*, the greater the probability of drought. Both *CMI* and *AMI* were used to measure climatic water deficits in this study. The annual mean temperature and annual precipitation were also calculated. To model the changes in aboveground biomass as a function of climatic parameters, we averaged the annual climatic variables across all years within each census interval for a given plot.

Estimation of Aboveground Stand Biomass

We calculated the aboveground stand biomass at each census using published Canadian national equations for aboveground tree biomass (*S12*). The biomass densities were calculated from total, plot-level biomass divided by plot area. We identified measurement errors by comparing multiple measurements of the same tree between censuses; where we found a decrease in tree diameter, we corrected the problem by interpolating between the previous and subsequent census data (*S13*). Because tree height was not available for every tree, we used DBH-based biomass equations. Based on DBH, we first calculated the total dry biomass of a living tree by summing the dry biomass components of its wood, bark, foliage, and branches (each calculated using the corresponding equation; *S12*). We then calculated plot-level biomass as the sum of the biomass of all living trees in the plot (Table *S2*). We estimated the rate of biomass change per year for the western (Alberta, Saskatchewan, and Manitoba) and eastern (Ontario and Quebec) regions as well as for Canada's southern boreal forest as a whole. We calculated the changes in plot biomass between successive census dates and then divided this by the number of calendar years between the two censuses to calculate the annual rate of change. Finally, we derived the rate of biomass change per year by averaging the change rates across all plots (Fig. 2).

Statistical analysis

To account for the variations and correlations that result from the hierarchical structure of our data (i.e., repeated measurements were nested within plots), we used a linear mixed-effect model with random effects modeled at the plot level to analyze the trends in the rate of biomass change (t ha^{-1} year^{-1}), trends in the rate of mortality biomass change, trends in the change of stand density, trends in the rate of surviving trees' biomass change, the trends in the climatic variables, and the correlations between the rate of biomass change and the explanatory variables. We applied likelihood-ratio tests to determine whether the incorporation of random effects produced a statistically significant improvement in the model fit. If the likelihood-ratio tests indicated that it was not necessary to include random effects, we refitted the models without random effects. We also used a dummy variable with values of either 0 or 1 (an indicator variable) to represent the province so we could show whether the relationships between rates of biomass change and the explanatory variables varied among the provinces.

Trends in the rate of biomass change

To estimate trends in the rate of biomass change (t ha^{-1} year^{-1}), we modeled this rate as a function of calendar year in the following form:

$$y_{ij} = \beta_0 + \beta_1 year_{ij} + \gamma_i + \varepsilon_{ij} \qquad [1]$$

where i is the plot number, j is the jth census ($j \neq 1$), y_{ij} is the rate of biomass change (t ha^{-1} year^{-1}) for the jth census (calculated as the biomass difference between the jth and (j-1)th census, divided by the number of years between the two censuses), and $year_{ij}$ represents the calendar year of the jth census. The plot random intercept γ and the random term ε_{ij} follow normal distributions. We applied this model separately for the western and eastern regions and for all plots combined. The results were showed in Table 1. The same method was used to estimate the trends of the rate of stand-age corrected biomass change (Table 4).

Trends in the rate of mortality biomass change

We used the same method as in the estimation of aboveground stand biomass to calculate the rate of mortality biomass change (t ha^{-1} year^{-1}). Thus, to estimate the trends in the rate of mortality biomass change (t ha^{-1} year^{-1}), we modeled this rate as a function of calendar year using the linear mixed model in equation [1]. We applied this model separately for western and eastern regions, and the results were showed in Table *S4*. We found that the rate of mortality biomass change (t ha^{-1} year^{-1}) was all increasing for western and eastern region.

Trends in the change of stand density

To estimate the trends in the change of stand density, we regressed the number living trees (number ha^{-1}) as a function of calendar year using the linear mixed model in equation [1]. The results were showed in Table *S5*. We found the stand density for both western and eastern regions were decreasing.

Trends in the rate of surviving trees' biomass change

In this study, we also calculated the rate of surviving trees' biomass change by using the same method showed in the estimation of aboveground stand biomass. Here, the surviving trees referred to the trees which living through all census periods. Thus, to estimate the trends in the rate of surviving trees' biomass change (t ha^{-1} year^{-1}), we modeled this rate as a function of calendar year using the linear mixed model in equation [1]. The results were showed in Table *S6*. We found the tree growth in western region was decreasing, but it was increasing in eastern region.

Relationships between the rate of biomass change and stand age

It has long been known that aboveground forest productivity declines with age (*S14*, *S15*). This age-related decline in forest growth may be caused by altered carbon allocation, an imbalance between photosynthesis and respiration, nutrient limitations, and decreased stand leaf area, among other possibilities (*S14*, *S15*). Because the declines are particularly evident in boreal and cold-temperate forests (*S15*), we regressed the rate of biomass change as a function of stand age to test whether there were noticeable trends. We used the following linear mixed model:

$$\begin{aligned} y_{ijk} &= \alpha_0 + \alpha_1 D_k + \beta_1 age_{ijk} + \beta_2 age_{ijk} D_k + \gamma_i + \varepsilon_{ijk} \\ &= (\alpha_0 + \alpha_1 D_k) + (\beta_1 + \beta_2 D_k) age_{ijk} + \gamma_i + \varepsilon_{ijk} \qquad [2] \end{aligned}$$

where i is the plot number, j is the jth census ($j \neq 1$), k is the kth province, D_k is a dummy variable (value of either 1 or 0) for the provinces, y_{ijk} is the rate of biomass change (t ha^{-1} year^{-1}) for the jth census (calculated as the biomass difference between the jth and (j-1)th census, divided by the number of years between the censuses), and age_{ijk} represents stand age. The plot random intercept γ_i and the random term ε_{ijk} follow normal distributions. In equation [2], α_0 is the overall intercept and α_1 is the intercept adjustment for the provinces, and β_1 is the overall slope of stand age and β_2 is the slope adjustment for the provinces.

The biomass decreased significantly with increasing stand age for the western region and all combined plots, but there was no significant trend for eastern region (Table *S7*, Fig. 3(a, b)). None of the estimated β_2 parameters was significant. We also tested models with polynomial terms for stand age and random slopes among plots, but found no evidence (either from fixed-effects *t*-tests or likelihood-ratio tests) to support these models.

Trends in the climatic variables

To model the trends in the climatic variables, we first extracted the time series for the climatic variables for all plots between the initial and final census years, and then regressed the extracted data sets as a function of calendar year using the linear mixed model in equation [1].

The annual mean temperatures in the western and eastern regions increased significantly (Table *S8*). The annual precipitation and *CMI* decreased significantly for western region, but increased significantly for eastern region (Table *S8*). We found that *AMI* increased significantly for western region but not for eastern region (Table *S8*).

Relationships between the rate of biomass change and climatic variables

To explore the associations between the rate of biomass change and the climatic variables, we regressed the rate of biomass change as functions of the climatic variables using a model with the following form:

$$\begin{aligned} y_{ijk} &= \alpha_0 + \alpha_1 D_k + \beta_1 x_{ijk} + \beta_2 x_{ijk} D_k + \gamma_i + \varepsilon_{ijk} \\ &= (\alpha_0 + \alpha_1 D_k) + (\beta_1 + \beta_2 D_k) x_{ijk} + \gamma_i + \varepsilon_{ijk} \qquad [3] \end{aligned}$$

where x_{ijk} represents the average annual value of climatic variable for the *j*th census of the *i*th plot of province *k*, which was obtained by averaging the annual climatic variables across all years of the census interval between the *j*th and (*j-1*)th census, and the other parameters are the same as in equation [2].

For the western region, both the average precipitation and *CMI* were significantly positively correlated with the rate of biomass change ($\beta_1 + \beta_2 D_k$; Table 2). Except for the average temperature in Manitoba, both the average temperature and *AMI* were significantly negatively correlated with the rate of biomass change for the western region ($\beta_1 + \beta_2 D_k$; Table 2). There were no significant correlations between the climatic variables and the rate of biomass change for the eastern region. We also tested models with polynomial terms for the climatic variables and random slopes among plots, but we found no evidence (either from fixed-effects *t*-tests or likelihood-ratio tests) to support these models.

To intuitively show these relationships, we prepared scatterplots between the rate of biomass change and the climatic variables for each province in the western region and a single scatterplot for eastern region (Fig. *S4* to *S7*). The trends in the scatterplots were consistent with our model results (Table 2).

Relationships between the rate of biomass change and the combined effects of climatic variables and stand age

To examine the relationships between the rate of biomass change and the combined effects of climatic variables and stand age, we regressed the rate of biomass change as a function of climatic variables and stand age simultaneously to test for the existence of a significant correlation. Furthermore, to compare the relative importance of the different variables, we applied standardized regressions rather than models using the original variables. Before fitting the regression, we standardized both the response variable and the explanatory variables by subtracting the mean from each value and then dividing the result by the standard deviation. Please note that we standardized the variables for western and eastern regions separately rather than standardized all the combined data sets. The magnitude of the estimated standardized coefficients can then be used to directly compare the effects of the explanatory variables on the response variable. We used the following form of linear mixed model:

$$\begin{aligned} y_{ijk} &= \alpha_0 + \alpha_1 D_k + \beta_1 x_{ijk} + \beta_2 x_{ijk} D_k + \beta_3 age_{ijk} + \beta_4 age_{ijk} D_k + \beta_5 x_{ijk} age_{ijk} + \gamma_i + \varepsilon_{ijk} \\ &= (\alpha_0 + \alpha_1 D_k) + (\beta_1 + \beta_2 D_k) x_{ijk} + (\beta_3 + \beta_4 D_k) age_{ijk} + \beta_5 x_{ijk} age_{ijk} + \gamma_i + \varepsilon_{ijk} \qquad [4] \end{aligned}$$

All symbols are the same as defined in equations [2] and [3]. After fitting the data using equation [4], we found that the estimated β_4 and β_5 coefficients were not significant. Therefore, we can rewrite equation [4] in the following simplified form:

$$y_{ijk} = (\alpha_0 + \alpha_1 D_k) + (\beta_1 + \beta_2 D_k) x_{ijk} + \beta_3 age_{ijk} + \gamma_i + \varepsilon_{ijk} \qquad [5]$$

The fitted results were showed in Table 3.

Table S1. Characteristics of the 96 forest plots that met the criteria for inclusion in our analysis.

Plot ID*	Region	Long. (°W)	Lat. (°N)	Plot size (ha)	EL (m)	Initial stand age (years)	Initial no. live trees	Calendar year of census					Species composition§	Biomass Change (t ha^{-1} $year^{-1}$)
								Year1	Year2	Year3	Year4	Year5		
AB5	west	116.77	54.17	0.10	881	135	160	1988	1993	2002			BS 0.78 LP 0.22	-0.1462
AB6	west	111.84	55.33	0.10	661	83	100	1986	1996	2002			JP 1.00	-0.0492
AB7	west	114.39	49.38	0.10	1490	104	134	1984	1994	2003			LP 1.00	-0.0376
AB8	west	114.15	49.34	0.10	1435	86	369	1984	1994	2003			LP 1.00	-0.0805
AB9	west	114.47	50.18	0.10	1882	117	116	1984	1994	2003			LP 0.55 ES 0.34 AF 0.11	-0.2339
AB10	west	114.59	50.27	0.10	1903	98	199	1984	1994	2003			LP 0.93 ES 0.03 AF 0.03	0.0259
AB11	west	114.60	50.26	0.10	2010	120	195	1984	1994	2002			PF 0.97 WP 0.03	-0.1149
AB12	west	114.60	50.25	0.10	2010	118	257	1984	1994	2002			PF 0.91 AF 0.05 ES 0.03	-0.0491
AB13	west	114.59	50.22	0.10	2010	149	146	1984	1994	2003			LP 0.58 ES 0.25 AF 0.16	-0.1715
AB14	west	114.59	50.25	0.10	2010	111	273	1984	1994	2003			LP 0.92 AF 0.05 ES 0.02	-0.0810
AB15	west	114.57	50.29	0.10	1903	129	257	1984	1995	2007			LP 1.00	0.0140
AB16	west	115.05	51.45	0.10	1532	97	150	1984	1994	2006			LP 1.00	-0.0007
AB17	west	115.67	52.40	0.82	1501	90	958	1963	1976	1986	1998		LP 0.90 WS 0.09 BS 0.01	0.0223
AB18	west	117.62	54.51	0.40	844	125	406	1964	1977	1987	2002		WS 0.47 TA 0.24 BF 0.12 LP 0.11 BP 0.06	0.0363
AB19	west	118.59	56.79	0.32	845	136	574	1965	1979	1988	1993		LP 0.68 TA 0.30 WS 0.01 BP 0.01	-0.1581
AB20	west	119.31	56.55	0.40	815	98	533	1965	1979	1984	1990		TA 0.95 WS 0.05	-0.3962
AB21	west	118.33	57.13	0.16	747	170	447	1966	1978	1988	1993		WS 0.59 BF 0.17 LP 0.10 WB 0.08 TA 0.06	-0.4114
AB22	west	114.25	55.51	0.10	746	172	275	1983	1988	1993	2001		BS 0.97 LP 0.03	-0.0046
AB23	west	114.51	50.14	0.10	1882	176	176	1984	1989	1994	2002		AF 0.43 ES 0.39 LP 0.18	-0.0744
AB24	west	114.50	50.15	0.10	1882	203	135	1984	1989	1994	2002		ES 0.74 AF 0.15 LP 0.11	0.0064
AB25	west	114.51	50.16	0.10	1882	208	155	1984	1989	1994	2002		LP 0.92 ES 0.07 AF 0.01	0.0060
AB26	west	114.50	50.16	0.10	1882	207	297	1984	1989	1994	2002		LP 0.98 AF 0.01 ES 0.01	-0.0477
AB27	west	114.55	50.20	0.10	2448	212	114	1984	1989	1994	2002		LP 0.59 ES 0.29 AF 0.11	-0.0300
AB28	west	114.55	50.19	0.10	2448	154	154	1984	1989	1994	2002		AF 0.73 ES 0.25 LP 0.02	0.0321
AB29	west	115.25	53.03	0.32	929	123	466	1963	1976	1982	1992	1998	TA 0.44 WS 0.42 BP 0.14 LP 0.01	-0.1704
AB30	west	115.45	53.28	0.16	920	142	791	1963	1980	1986	1991	1997	BS 0.98 WS 0.02	-0.0730
AB31	west	114.82	55.14	0.32	784	158	652	1964	1978	1984	1989	1995	LP 0.75 BS 0.25	-0.0398
SK1	west	105.70	54.09	0.08	1696	92	262	1970	1979	1996			BS 0.85 WS 0.12 BP 0.03	-0.1852
SK2	west	105.38	53.80	0.08	1091	104	180	1970	1979	1996			BS 0.89 BP 0.07 WS 0.04	-0.3226
SK3	west	107.27	54.52	0.08	829	100	236	1970	1980	1992			BS 0.67 WS 0.18 TA 0.13 BP 0.02	-0.2365
SK4	west	105.95	54.12	0.08	662	84	217	1971	1979	1996			BS 0.87 BP 0.11 WS 0.02	-0.1940
SK5	west	104.27	54.48	0.08	1831	133	104	1971	1980	1996			BS 0.87 BP 0.07 JP 0.06	-0.1754
SK10	west	105.24	54.46	0.06	2025	86	175	1981	1992	1999			BS 0.88 BF 0.07 WS 0.02 TA 0.01 WB 0.01	-0.2773
SK11	west	107.73	55.97	0.08	1958	86	173	1967	1979	1996			WS 0.82 TA 0.14 BP 0.05	-0.0965

SK12	west	107.88	54.79	0.08	1700	88	139	1967	1979	1996			WS 0.97 BP 0.03	-0.1195
SK13	west	107.27	55.07	0.08	2130	97	100	1967	1979	1996			WS 0.78 TA 0.13 BS 0.07 BP 0.02	-0.1414
SK14	west	108.86	55.09	0.08	1692	108	107	1967	1979	1996			WS 0.93 TA 0.05 BP 0.02	-0.1233
SK15	west	104.92	55.36	0.08	1085	82	194	1969	1980	1991			TA 0.73 WS 0.26 BS 0.01	-0.1476
SK16	west	105.48	54.05	0.08	1353	88	123	1980	1991	1994			WS 0.54 TA 0.45 BP 0.01	-2.1428
SK17	west	105.26	54.44	0.08	790	129	202	1981	1992	1999			WS 0.51 BP 0.19 BF 0.19 BS 0.05 WB 0.04 TA 0.01	-0.0175
SK18	west	105.24	54.45	0.08	790	96	167	1981	1992	1999			WS 0.72 BF 0.13 WB 0.07 BP 0.06 BS 0.02	-0.1556
SK19	west	108.26	54.97	0.08	1518	92	140	1966	1973	1979	1998		WS 0.61 BP 0.37 BS 0.03	-0.0888
SK20	west	108.42	54.97	0.08	904	147	93	1966	1973	1979	1998		WS 0.63 TA 0.30 BP 0.07	-0.0653
SK21	west	107.88	54.79	0.08	1700	117	140	1966	1974	1979	1996		WS 0.67 TA 0.23 BP 0.10	-0.0301
SK22	west	108.86	55.09	0.08	1692	102	88	1966	1973	1979	1996		WS 0.65 TA 0.31 BS 0.05	-0.0881
SK23	west	108.35	53.62	0.08	2609	106	89	1966	1974	1979	1999		TA 0.58 BS 0.32 WS 0.11	-0.0479
SK24	west	107.07	54.48	0.08	827	98	104	1966	1974	1979	1999		TA 0.60 WS 0.36 BS 0.04	-0.0331
SK25	west	102.68	53.13	0.08	1392	127	100	1966	1974	1979	1996		WS 0.63 TA 0.29 JP 0.07 BS 0.01	0.0021
SK26	west	102.64	53.03	0.08	1626	82	158	1969	1974	1979	1998		TA 0.57 WS 0.42 BF 0.01	-0.0885
SK27	west	106.47	54.54	0.08	1582	84	121	1966	1974	1979	1998		TA 0.55 WS 0.45	-0.1122
SK28	west	106.47	54.54	0.08	1582	80	123	1969	1974	1979	1998		TA 0.68 WS 0.32	-0.0512
SK29	west	108.35	53.62	0.08	2609	95	162	1966	1974	1979	1998		WS 0.45 TA 0.43 BF 0.10 BS 0.02	-0.0667
SK30	west	107.77	54.23	0.08	1245	82	91	1966	1974	1980	1996		WS 0.65 TA 0.34 BP 0.01	-0.1052
SK31	west	105.72	53.97	0.08	1044	112	134	1968	1979	1984	1998		JP 0.89 BS 0.11	-0.0125
MB1	west	100.86	51.59	0.05	680	121	399	1994	1999	2004			BS 0.91 LP 0.09	0.0204
MB2	west	96.14	49.69	0.05	492	80	234	1986	1991	1996	2001	2006	CE 0.95 WS 0.04 LP 0.01	-0.5525
MB3	west	96.04	49.28	0.05	488	80	285	1986	1991	1996	2001	2006	BS 0.93 JP 0.06 LP 0.01	-0.0896
MB4	west	95.52	50.02	0.05	426	107	430	1989	1994	1999	2004		BS 0.71 WS 0.13 BP 0.05 TA 0.05 JP 0.04 WS 0.03	-0.5502
MB5	west	95.79	51.66	0.05	366	83	85	1988	1993	1998	2003	2008	JP 0.98 BS 0.01 BF 0.01	-0.0515
MB6	west	95.82	51.06	0.05	394	150	181	1988	1993	1998	2003	2008	BS 0.84 LP 0.11 BF 0.05	0.0403
MB7	west	95.47	51.02	0.05	397	152	258	1988	1993	1998	2003	2008	BS 0.99 LP 0.01	-0.1084
MB8	west	97.40	51.73	0.05	219	85	156	1994	1999	2004			BS 1.00	-0.0740
MB9	west	97.38	51.75	0.05	220	83	91	1994	1999	2004			BS 0.99 LP 0.01	-0.1529
MB10	west	98.96	52.77	0.05	247	80	114	1990	1995	2000	2005		TA 1.00	-0.0904
MB11	west	99.12	52.89	0.05	275	133	200	1990	1995	2000	2005		BS 0.98 LP 0.02	-0.0046
MB12	west	99.19	52.91	0.05	275	89	183	1990	1995	2000	2005		JP 0.57 BS 0.43	-0.2436
MB13	west	101.09	53.36	0.05	285	103	483	1989	1994	2002	2007		BS 0.93 BP 0.06 WS 0.01	-0.0852
MB14	west	100.27	53.88	0.05	255	97	196	1989	1994	2002	2007		BS 0.82 WS 0.14 TA 0.04	-0.1218
MB15	west	101.26	54.16	0.05	334	95	323	1989	1994	2002	2007		JP 0.69 BS 0.30 WS 0.02	-0.0115
MB16	west	101.32	54.08	0.05	273	112	534	1989	1994	2002	2007		BS 0.99 WB 0.01	-0.0216
ON1	east	93.64	50.72	0.12	349	86	132	1993	1998	2006			TA 0.72 JP 0.12 WS 0.08 BF 0.05 BS	-0.0248

												0.04	
ON2	east	86.96	49.75	0.12	347	122	198	1993	2000	2004		JP 0.58 BS 0.41 TA 0.01	0.6531
ON3	east	84.08	49.42	0.12	275	111	100	1993	1997	2004		JP 0.70 BS 0.22 BF 0.05 WS 0.03	-0.0351
ON4	east	83.07	49.11	0.12	267	92	135	1993	2000	2006		TA 0.36 BP 0.33 WS 0.13 WB 0.11 BF 0.07	1.1679
ON5	east	80.28	48.53	0.12	316	85	109	1994	1999	2006		TA 0.59 BP 0.41	-0.6913
ON6	east	90.49	50.31	0.12	101	153	278	1993	1998	2004		JP 0.61 BS 0.35 TA 0.02 WB 0.02	0.4342
ON7	east	89.37	48.72	0.12	306	96	179	1992	1997	2006		BS 0.79 TA 0.17 BF 0.03 BP 0.01	0.0349
ON8	east	89.89	48.17	0.12	426	81	202	1992	1997	2004		JP 0.90 BF 0.09 BS 0.01	0.0398
ON9	east	90.61	48.61	0.12	395	97	191	1992	2001	2004		JP 0.85 WB 0.09 TA 0.06 BS 0.01	-0.8195
ON10	east	81.27	48.46	0.12	305	88	234	1993	1998	2004		JP 0.79 BS 0.10 BF 0.05 WB 0.04 TA 0.02	0.1699
QC1	east	78.34	50.24	0.04	266	173	90	1974	1980	1991	1998	BS 0.53 BF 0.41 WB 0.06	-0.1072
QC2	east	77.11	51.02	0.04	255	101	85	1972	1979	1990	1999	BS 0.99 BF 0.01	-0.0442
QC3	east	77.88	50.66	0.04	247	113	89	1972	1979	1990	1999	BS 0.98 BF 0.02	-0.0633
QC4	east	77.95	50.21	0.04	244	113	89	1972	1979	1990	1999	BS 0.98 BF 0.02	0.0288
QC5	east	74.01	50.96	0.04	394	90	85	1971	1979	1990	1999	BS 0.91 WB 0.09	0.0536
QC6	east	73.38	50.04	0.04	394	103	93	1971	1979	1992		BS 1.00	0.0274
QC7	east	73.96	49.03	0.04	427	92	89	1971	1979	1992		BS 1.00	0.1101
QC9	east	75.10	48.83	0.04	452	87	84	1973	1980	1992		BS 1.00	0.0811
QC10	east	71.96	50.93	0.04	590	120	83	1975	1980	1995		BS 0.99 BF 0.01	0.0726
QC11	east	69.80	49.63	0.04	543	96	99	1976	1987	1998		BS 0.99 BF 0.01	-0.0533
QC12	east	66.03	51.53	0.04	667	218	80	1977	1989	2001		BS 0.59 BF 0.41	0.1103
QC13	east	66.38	52.06	0.04	646	164	81	1977	1989	2001		BS 0.75 BF 0.25	-0.0418
QC14	east	66.98	51.19	0.04	487	166	84	1977	1989	2001		BS 0.97 BF 0.03	0.0156
QC15	east	65.94	50.33	0.04	59	98	92	1977	1989	1999		BF 0.66 WB 0.29 WS 0.03 BS 0.01	-0.0297
QC16	east	66.50	51.01	0.04	675	143	91	1977	1989	2001		BF 0.58 BS 0.42	-0.1048
QC17	east	66.41	51.09	0.04	562	143	89	1977	1989	2001		BS 0.69 BF 0.31	-0.0088

* AB = Alberta, SK = Saskatchewan, MB = Manitoba, ON = Ontario, and QC = Quebec.

§ Species composition of the stand at the time of the initial census. Values represent the proportion of the basal areas of each species and may not add to 1 due to rounding. AF = alpine fir (*Abies lasiocarpa*), BF = balsam fir (*Abies balsamifera*), BP = balsam poplar (*Populus balsamifera*), BS = black spruce (*Picea mariana*), CE=cedars *(Genus cedrus)*, ES = Engelmann spruce (*Picea engelmanni*), JP = jack pine (*Pinus banksiana*), LP = lodgepole pine (*Pinus contorta*), PF = limber pine (*Pinus flexilis*), TA = trembling aspen (*Populus tremuloides*), WB = white birch (*Betula papyrifera*), WP=eastern white pine (*Pinus strobus*), WS = white spruce (*Picea glauca*).

Table S2. Aboveground biomass (t/ha) for the 96 forest plots in our analysis.

Plot ID*	Region	Long. (°W)	Lat. (°N)	Aboveground biomass(t/ha) of calendar year of census				
				Year1	Year2	Year3	Year4	Year5
AB5	west	116.77	54.17	155.06	153.28	138.22		
AB6	west	111.84	55.33	119.06	125.2	127.11		
AB7	west	114.39	49.38	68.14	80.82	88.55		
AB8	west	114.15	49.34	196.64	192.85	182.92		
AB9	west	114.47	50.18	154.75	163.65	152.72		
AB10	west	114.59	50.27	123.00	131.52	141.29		
AB11	west	114.60	50.26	123.61	130.15	128.03		
AB12	west	114.60	50.25	105.58	115.82	120.86		
AB13	west	114.59	50.22	204.17	216.52	213.74		
AB14	west	114.59	50.25	106.24	117.22	120.54		
AB15	west	114.57	50.29	79.89	97.63	119.02		
AB16	west	115.05	51.45	129.07	140.49	154.1		
AB17	west	115.67	52.40	73.85	76.81	86.85	95.87	
AB18	west	117.62	54.51	248.81	245.21	207.95	210.25	
AB19	west	118.59	56.79	182.12	183.61	186.22	182.22	
AB20	west	119.31	56.55	112.59	145.89	145.57	131.41	
AB21	west	118.33	57.13	179.63	197.83	198.34	171.75	
AB22	west	114.25	55.51	141.03	140.85	128.84	125.4	
AB23	west	114.51	50.14	175.3	185.41	171.92	175.39	
AB24	west	114.50	50.15	165.76	167.2	166.41	168.83	
AB25	west	114.51	50.16	167.06	166.33	168.55	168.66	
AB26	west	114.50	50.16	148.27	153.36	156.17	159.11	
AB27	west	114.55	50.20	184.1	187.57	166.29	163.25	
AB28	west	114.55	50.19	172.39	178.63	188.01	201.87	
AB29	west	115.25	53.03	242.19	268.93	267.63	230.16	224.99
AB30	west	115.45	53.28	141.16	167.78	171.82	165.16	170.00
AB31	west	114.82	55.14	216.82	222.63	222.17	207.45	210.59
SK1	west	105.70	54.09	148.25	180.57	188.08		
SK2	west	105.38	53.80	74.39	124.75	126.66		
SK3	west	107.27	54.52	147.52	184.75	195.37		
SK4	west	105.95	54.12	42.62	77.30	94.93		
SK5	west	104.27	54.48	41.47	73.40	85.26		
SK10	west	105.24	54.46	126.88	131.16	120.29		
SK11	west	107.73	55.97	141.64	169.41	180.86		
SK12	west	107.88	54.79	114.77	149.94	165.22		
SK13	west	107.27	55.07	141.09	170.45	171.17		
SK14	west	108.86	55.09	155.99	175.94	168.58		
SK15	west	104.92	55.36	136.18	154.17	154.29		
SK16	west	105.48	54.05	200.13	211.83	195.73		
SK17	west	105.26	54.44	176.50	182.32	185.16		
SK18	west	105.24	54.45	165.47	174.96	173.37		
SK19	west	108.26	54.97	143.87	163.58	173.99	182.23	
SK20	west	108.42	54.97	167.49	184.84	193.88	206.72	
SK21	west	107.88	54.79	148.34	147.67	150.55	142.09	
SK22	west	108.86	55.09	162.33	178.4	189.22	193.96	
SK23	west	108.35	53.62	162.12	179.85	194.35	220.87	
SK24	west	107.07	54.48	155.62	161.14	179.12	196.86	
SK25	west	102.68	53.13	166.99	177.35	177.91	194.06	

SK26	west	102.64	53.03	149.51	163.62	176.03	189.93	
SK27	west	106.47	54.54	177.13	206.65	214.38	223.53	
SK28	west	106.47	54.54	156.46	168.73	166.26	172.88	
SK29	west	108.35	53.62	172.73	194.01	200.02	213.06	
SK30	west	107.77	54.23	117.30	131.66	126.82	110.21	
SK31	west	105.72	53.97	163.11	168.74	176.42	184.41	
MB1	west	100.86	51.59	82.40	86.33	90.78		
MB2	west	96.14	49.69	150.17	172.37	203.52	225.34	204.62
MB3	west	96.04	49.28	138.87	143.39	156.64	166.44	164.64
MB4	west	95.52	50.02	188.00	202.31	214.41	201.20	
MB5	west	95.79	51.66	91.56	100.74	103.21	107.95	105.24
MB6	west	95.82	51.06	68.66	68.75	70.82	70.34	74.64
MB7	west	95.47	51.02	124.58	126.92	129.48	127.31	122.2
MB8	west	97.40	51.73	126.62	131.53	134.59		
MB9	west	97.38	51.75	125.73	136.60	143.64		
MB10	west	98.96	52.77	152.52	153.46	165.97	162.39	
MB11	west	99.12	52.89	64.30	65.13	67.92	68.53	
MB12	west	99.19	52.91	75.74	78.32	84.70	75.10	
MB13	west	101.09	53.36	109.21	111.69	120.9	116.73	
MB14	west	100.27	53.88	151.63	157.33	164.67	161.83	
MB15	west	101.26	54.16	60.95	61.69	63.76	63.58	
MB16	west	101.32	54.08	64.4	61.10	54.72	49.99	
ON1	east	93.64	50.72	104.08	113.95	128.16		
ON2	east	86.96	49.75	152.39	138.52	141.04		
ON3	east	84.08	49.42	93.51	97.11	101.71		
ON4	east	83.07	49.11	180.84	146.23	158.61		
ON5	east	80.28	48.53	118.77	129.65	111.00		
ON6	east	90.49	50.31	148.97	141.30	147.73		
ON7	east	89.37	48.72	73.04	71.05	70.31		
ON8	east	89.89	48.17	99.81	101.50	105.81		
ON9	east	90.61	48.61	140.36	134.22	124.8		
ON10	east	81.27	48.46	164.59	163.36	167.99		
QC1	east	78.34	50.24	152.32	187.25	161.90	156.59	
QC2	east	77.11	51.02	101.22	106.57	120.07	127.54	
QC3	east	77.88	50.66	127.06	123.24	124.37	107.24	
QC4	east	77.95	50.21	118.77	109.56	117.21	109.50	
QC5	east	74.01	50.96	94.52	86.23	95.92	95.40	
QC6	east	73.38	50.04	112.62	115.10	123.77		
QC7	east	73.96	49.03	145.29	141.53	154.02		
QC9	east	75.10	48.83	160.18	155.62	159.49		
QC10	east	71.96	50.93	115.44	112.89	121.58		
QC11	east	69.80	49.63	171.04	186.02	194.54		
QC12	east	66.03	51.53	102.74	99.62	112.39		
QC13	east	66.38	52.06	82.93	96.78	104.62		
QC14	east	66.98	51.19	119.58	119.40	121.45		
QC15	east	65.94	50.33	131.08	138.71	141.51		
QC16	east	66.50	51.01	154.75	178.26	186.67		
QC17	east	66.41	51.09	114.94	124.84	133.47		

* AB = Alberta, SK = Saskatchewan, MB = Manitoba, ON = Ontario, and QC = Quebec.

Table S3. The downloaded climatic variables for plots with census years after 2003.

Plot	Year	Climate station name	Climate station locations	
			Longitude	Latitude
AB15	2004-2007	LOST CREEK SOUTH	114.70	50.17
AB16	2004-2006	BLUEHILL LO	115.13	51.70
MB1	2004	PINE RIVER	100.57	51.80
MB2	2004-2006	OSTENFELD	96.48	49.82
MB3	2004-2006	PINEY	96.01	49.03
MB4	2004	RENNIE	95.53	49.85
MB5	2004-2008	GREAT FALLS CLIMATE	95.98	50.52
MB6	2004-2008	GREAT FALLS CLIMATE	95.98	50.52
MB7	2004-2008	GREAT FALLS CLIMATE	95.98	50.52
MB8	2004	HODGSON 2	97.47	51.19
MB9	2004	HODGSON 2	97.47	51.19
MB10	2004-2005	GRAND RAPIDS HYDRO	99.28	53.16
MB11	2004-2005	GRAND RAPIDS HYDRO	99.28	53.16
MB12	2004-2005	GRAND RAPIDS HYDRO	99.28	53.16
MB13	2004-2007	THE PAS A	101.10	53.97
MB14	2004-2007	THE PAS A	101.10	53.97
MB15	2004-2007	THE PAS A	101.10	53.97
MB16	2004-2007	THE PAS A	101.10	53.97
ON1	2004-2006	EAR FALLS (AUT)	93.22	50.63
ON2	2004	GERALDTON A	86.93	49.78
ON3	2004	NAGAGAMI (AUT)	84.16	49.75
ON4	2004-2006	KAPUSKASING A	82.47	49.41
ON5	2004-2006	KIRKLAND LAKE CS	80.00	48.15
ON6	2004	SIOUX LOOKOUT A	91.90	50.12
ON7	2004-2006	THUNDER BAY A	89.33	48.37
ON8	2004	WHITEFISH LAKE	89.92	48.28
ON9	2004	UPSALA (AUT)	90.47	49.03
ON10	2004	TIMMINS VICTOR POWER A	81.38	48.57

Table S4. Fixed effects of the linear mixed models describing trends in the rate of mortality biomass change (*t* ha^{-1} year^{-1}). β is the slope and represents the annual rate of change in morality biomass, n is the number of forest plots used in the model, and *P* is the significance level for the model's fixed effects based on a t-test.

Data	**Parameter**	**β**	**Std. error**	***P***	***n***
Western	Year	0.0289	0.0095	0.0028	70
Eastern	Year	0.0588	0.0274	0.0406	26

Table S5. Fixed effects of the linear mixed models describing trends in the density change (number ha^{-1}). β is the slope and represents the annual rate of change in density, n is the number of forest plots used in the model, and *P* is the significance level for the model's fixed effects based on a t-test.

Data	**Parameter**	**β**	**Std. error**	***P***	**n**
Western	Year	-25.624	5.1950	<0.0001	70
Eastern	Year	-7.571	2.8100	<0.0001	26

Table S6. Fixed effects of the linear mixed models describing trends in the rate of surviving trees' biomass change (*t* ha^{-1} year^{-1}). β is the slope and represents the annual rate of change in surviving biomass, n is the number of forest plots used in the model, and *P* is the significance level for the model's fixed effects based on a t-test.

Data	**Parameter**	**β**	**Std. error**	***P***	**n**
Western	Year	-0.0116	0.0056	<0.0394	70
Eastern	Year	0.0441	0.0098	<0.0001	26

Table S7. Fixed effects of linear mixed models (equation 2) describing the relationships between the rate of biomass change and stand age. β is the estimated slope of the model and reflects the rate of biomass change as a function of stand age, *n* is the number of forest plots used in the model, and *P* is the significance level for the model's fixed effects based on a *t*-test. To simplify, we have only shown the estimated β_1 parameters and the significant β_2 parameters, but none of β_2 parameters were significant.

Data	**Parameter**	**β**	**Std. error**	***P***	***n***
All plots	Stand age	-0.0091	0.0027	0.0018	96
Western region	Stand age	-0.0120	0.0039	0.0005	70
Eastern region	Stand age	0.0009	0.0052	0.8465	26

Table S8. Fixed effects of the linear mixed models (equation 1) describing trends in the climatic variables. β is the slope and represents the annual change in the climatic variable, *n* is the number of forest plots used in the model, and *P* is the significance level for the model's fixed effects based on a *t*-test. According to the results, the mean cumulative changes in temperature and precipitation are 2.0205 (˚C) and -46.51 mm for western region from 1963 to 2008, respectively. The mean cumulative changes in temperature and precipitation are 1.4140 (˚C) and 84.70 mm for eastern region from 1971 to 2006, respectively.

Data	**Model**	**β**	**Std. Error**	***P***	***n***
Western region	Temperature trend	0.0449	0.0034	<0.0001	70
	Precipitation trend	-1.0337	0.2757	0.0002	70
	CMI trend	-0.1791	0.0331	<0.0001	70
	AMI trend	4.5310	0.5946	<0.0001	70
Eastern region	Temperature trend	0.0404	0.0067	<0.0001	26
	Precipitation trend	2.4201	0.5743	<0.0001	26
	CMI trend	0.1435	0.0613	0.0197	26
	AMI trend	0.6725	0.4019	0.0949	26

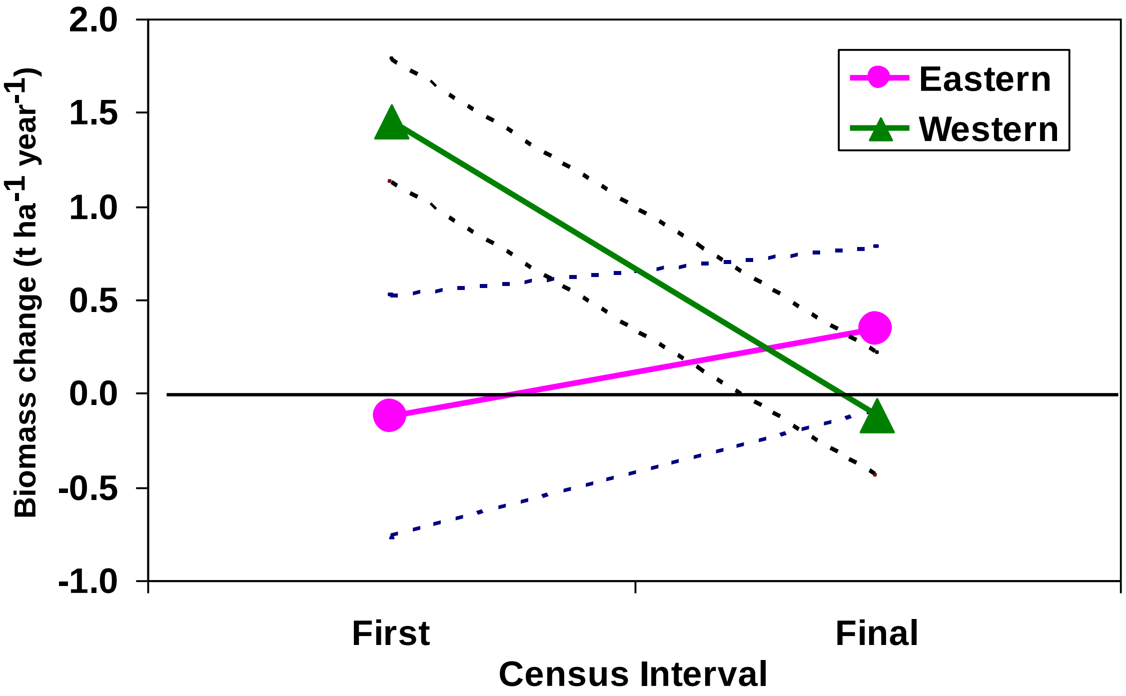

Figure S1. Average rate of biomass change (plus dashed lines representing the 95% confidence intervals) for the first and final census periods for plots in the western and eastern regions. For the western region, the biomass trend changed significantly from increasing during the first census to decreasing during the last census ($P < 0.0001$, paired two-sample *T*-test); for eastern region, there was no significant change ($P = 0.1339$, paired two-sample *t*-test). Note that the first and final intervals on the *x*-axis only represent the initial and last censuses for each plot, and thus do not reflect the length of the census intervals. The the mean census time between the initial and final census for the western region was 22.8 years, and 19.2 years for the eastern region.

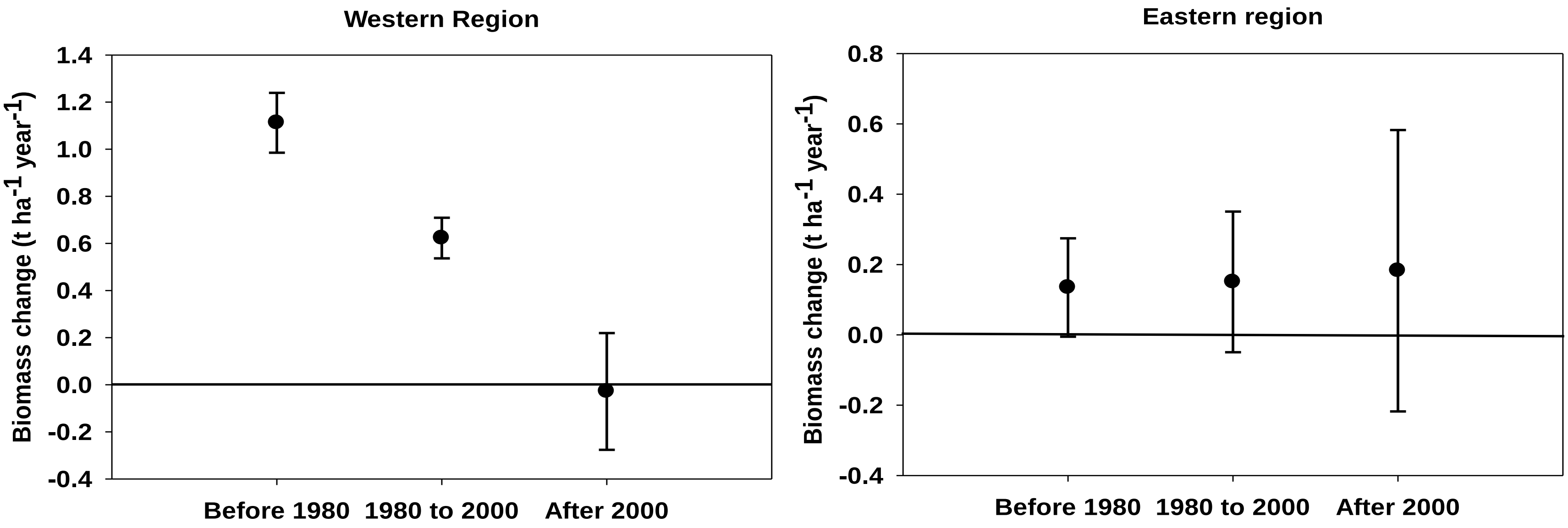

Figure S2. Rate of biomass change for the western and eastern regions during three time intervals. The black dots represent the average rate of biomass change and the range bars is defined as the 95% confidence intervals.

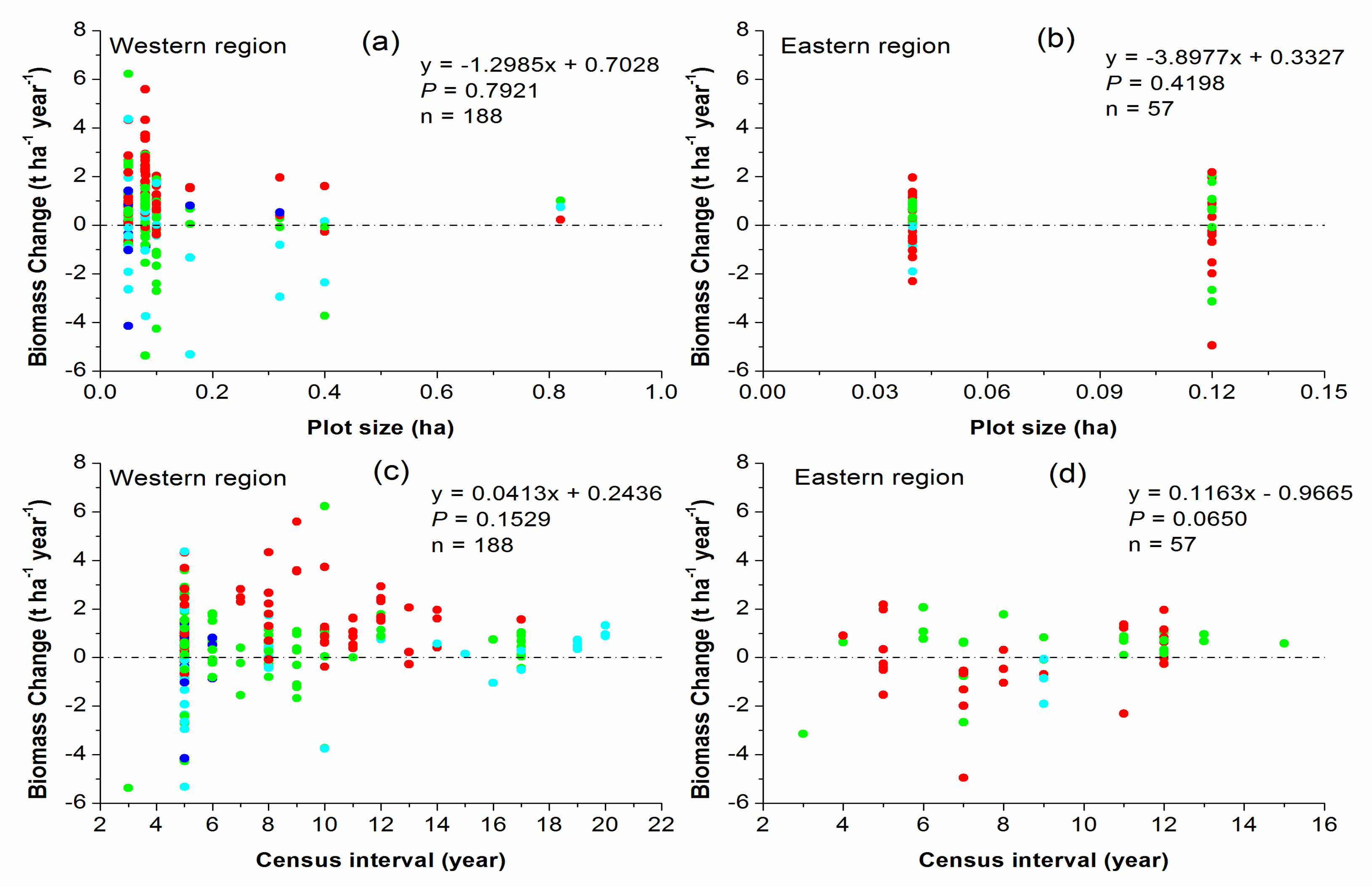

Figure S3. Plots of the rate of biomass change as a function of plot size and census interval for the western and eastern regions. The red, green, light blue and blue dots represent the first, second, third and fourth census respectively.

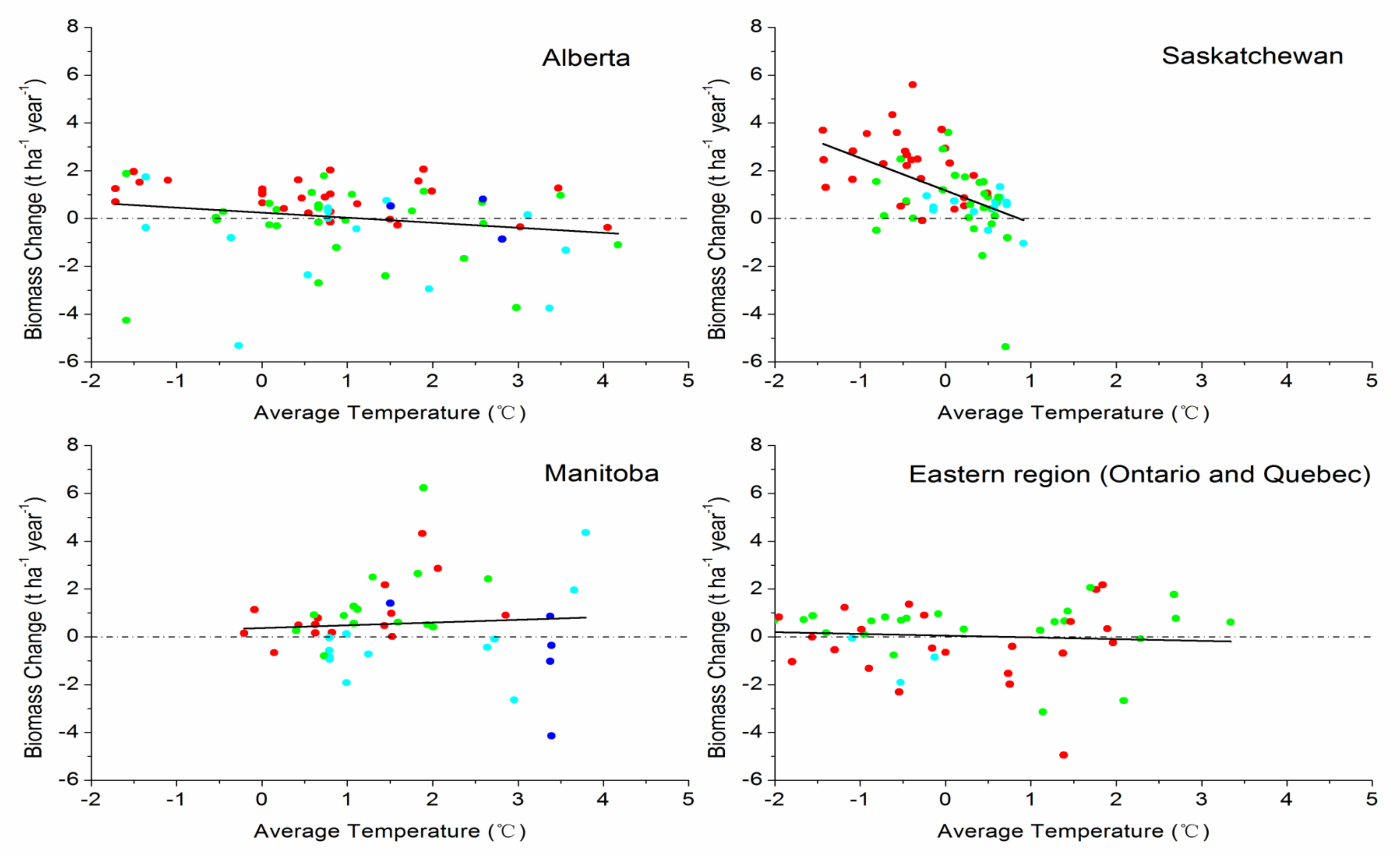

Figure S4. Plots of the biomass change as a function of the average temperature. The average temperature was obtained by averaging temperature observations across all years within each census interval for a given plot. The lines represent the modeled trends from the ordinary least squares regression models. The red, green, light blue and blue dots represent the first, second, third and fourth census respectively.

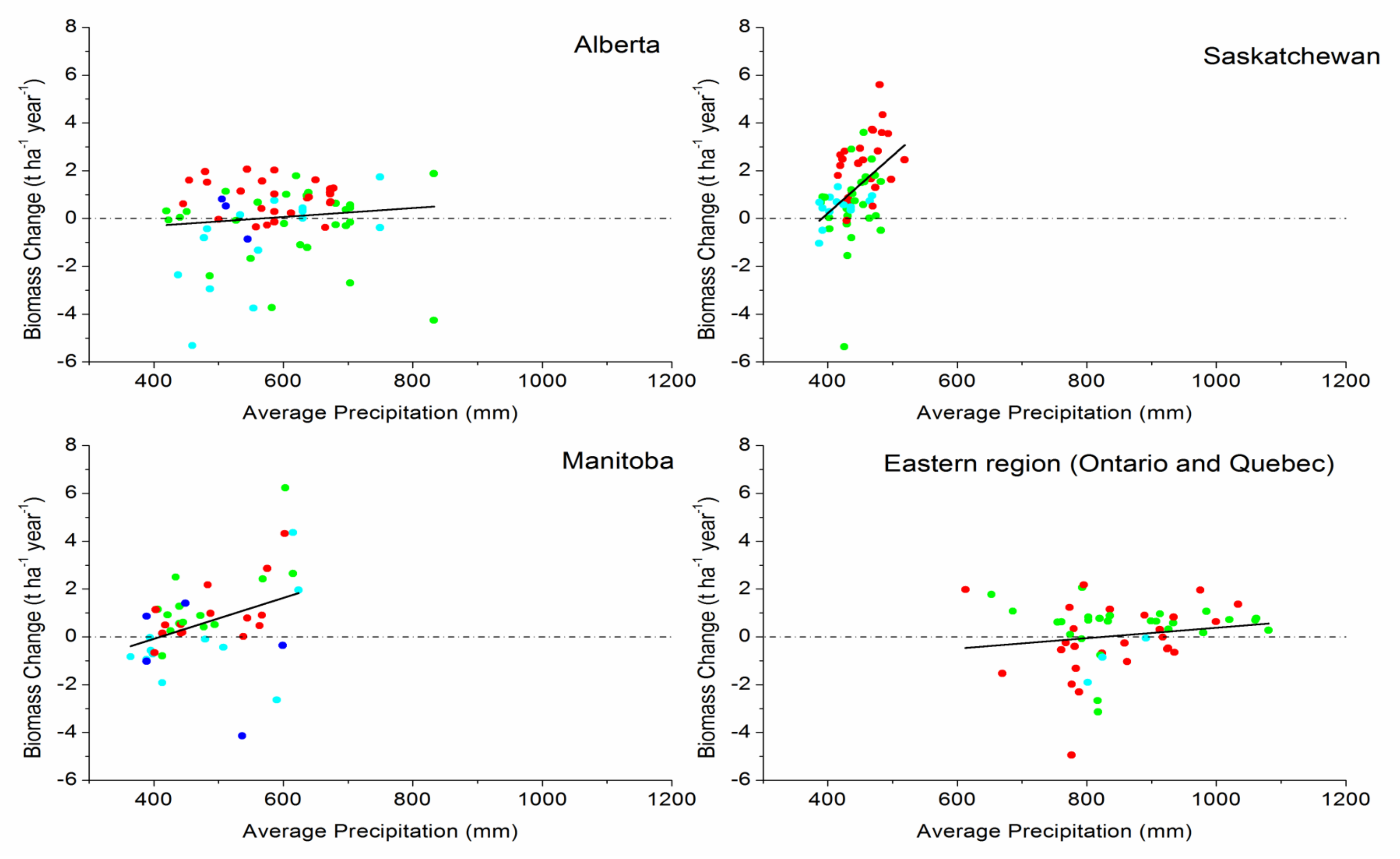

Figure S5. Plots of the biomass change as a function of the average precipitation. The average precipitation was obtained by averaging precipitation observations across all years within each census interval for a given plot. The lines represent the modeled trends from the ordinary least squares regression models. The red, green, light blue and blue dots represent the first, second, third and fourth census respectively.

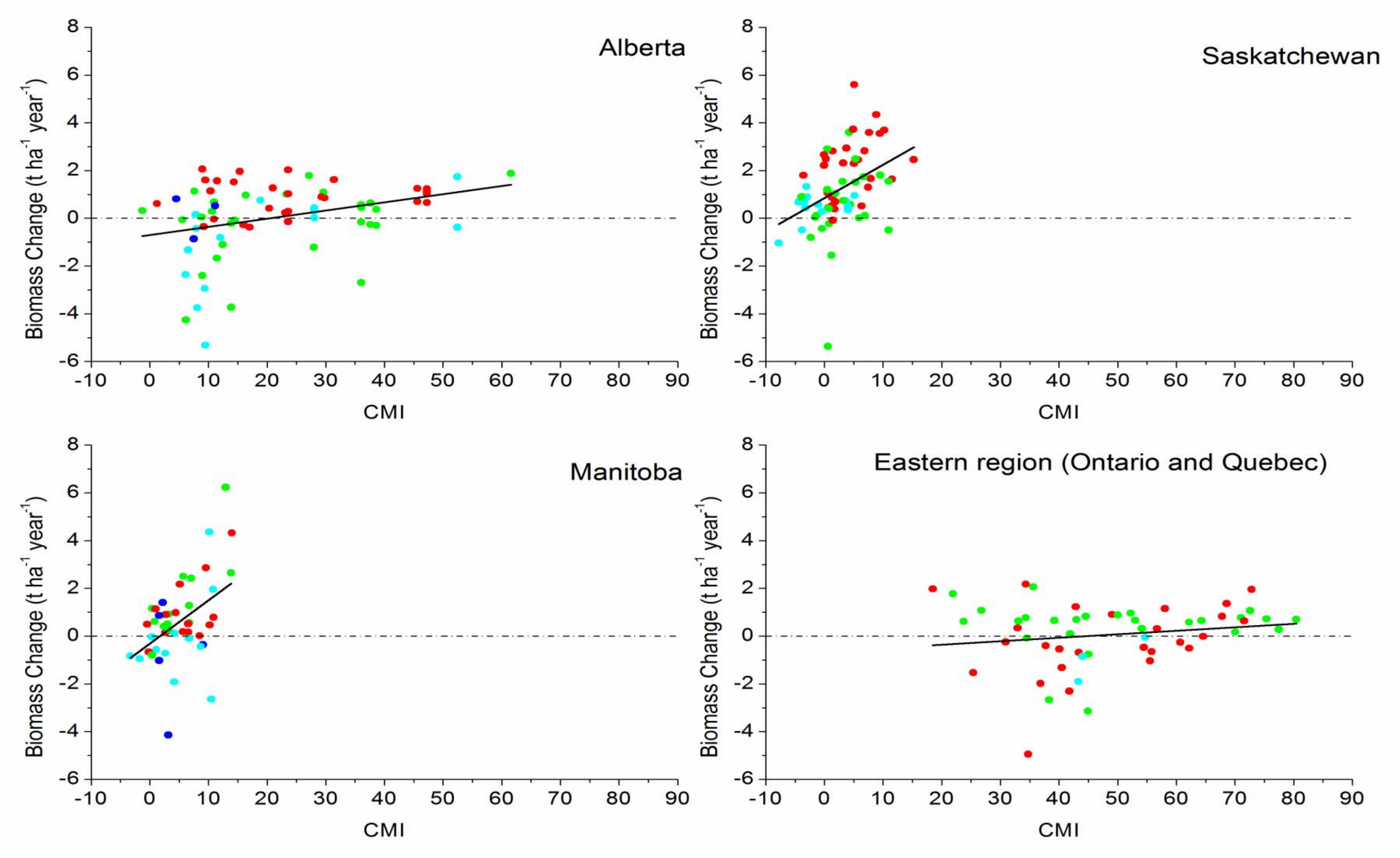

Figure S6. Plots of the biomass change as a function of the average climate moisture index (*CMI*). The average *CMI* was obtained by averaging *CMI* observations across all years within each census interval for a given plot. The lines represent the modeled trends from the ordinary least squares regression models. The red, green, light blue and blue dots represent the first, second, third and fourth census respectively.

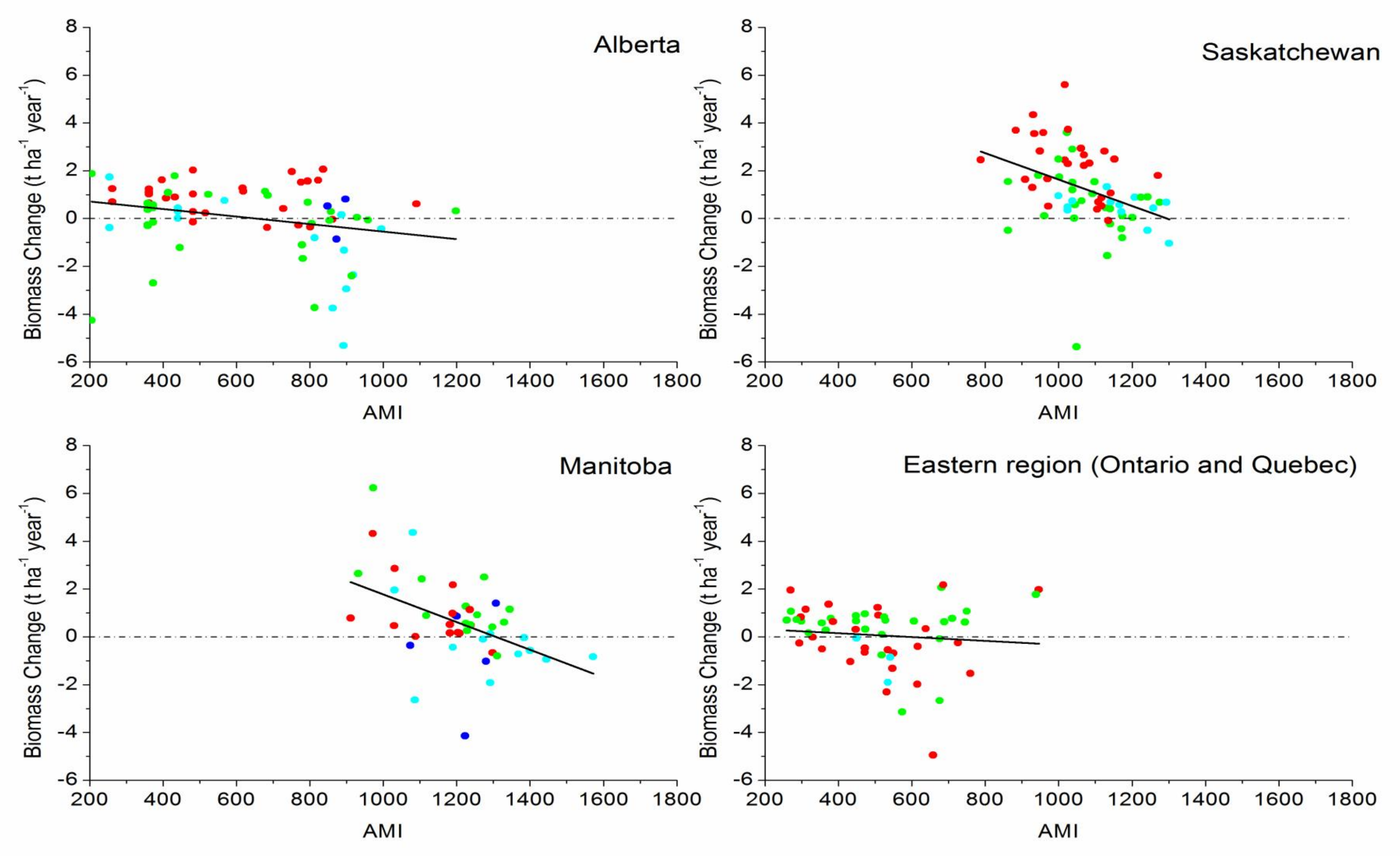

Figure S7. Plots of the biomass change as a function of the average annual moisture index (*AMI*). The average *AMI* was obtained by averaging *AMI* observations across all years within each census interval for a given plot. The lines represent the modeled trends from the ordinary least squares regression models. The red, green, light blue and blue dots represent the first, second, third and fourth census respectively.

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