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# Implementation of a dynamic rooting depth and phenology into a land surface model: Evaluation of carbon, water, and energy fluxes in the high latitude ecosystems



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# ABSTRACT

Recent studies and observations have shown that northern high latitude ecosystems (NHLE) are strongly responsive to environmental changes, particularly warming temperature. Ecosystem models are important tools that help us to understand and assess the impact of environmental changes in the NHLE. However, models lack processes that are essential for modeling ecosystem dynamics for the NHLEs. In this study, NHLE-specific dynamic phenology and dynamic rooting distribution and depth parameterizations was implemented in a land surface model, the Integrated Science Assessment Model (ISAM), to improve the estimated carbon, water, and energy fluxes in the NHLs. These parameterizations account for light, water, and nutrient stresses while allocating the assimilated carbon to leaf, stem, and root pools. The model parameters related to these processes were calibrated and evaluated using measured data from 16 sites (12 fluxnet sites and 4 non-flux net sites) representative of the dominant NHLEs. By including these dynamic processes, ISAM was able to capture the measured seasonal variability in leaf area index (LAI) and root distribution in the soil layers. The evaluation of the model results suggested that without including the dynamic processes, the modeled growing season length (GSL) in the NHLE was almost two times higher, as compared to measurements. To quantify the implication of these processes on the C, water, and energy fluxes, we compared the results of two different versions of ISAM, a dynamic version that includes dynamic processes (ISAM<sub>DYN</sub>) and a static version that does not include dynamic processes (ISAM $_{BC}$ ), with measurements from 12 eddy covariance flux sites. The results showed that ISAM<sub>DYN</sub>, unlike ISAM<sub>BC</sub>, was more capable to capture the flux site-based seasonal variability in GPP, water, and energy fluxes. Regional analysis revealed that the growing season length increased on average by about 5 days in the NHLs in the 2000s compared to 1990s.

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# 1. Introduction

The northern high latitude ecosystems (NHLEs) have experienced rapid warming over the recent decades, in response to increased air temperature, and the same trend is expected throughout this century (Hinzman et al., 2005; Serreze et al., 2000). Some of the major responses of the NHLE to warming include the changes in carbon (C) storage in vegetation and soil, mainly as a result of advancement in the onset of the NHLE growing season (Myneni et al., 1997), shifts in ecosystem composition and abundance, such as higher shrub density (Chapin et al., 2005; Rogers et al., 2013; Swann et al., 2010; Tape et al., 2006), and latitudinal advances in the tree line (Llyod et al., 2005). Given these changes, it is important to understand and quantify the response of the NHLE to changes in C, water, and energy fluxes under climate change.

While continued research on the development of more detailed Earth system models (ESMs) is essential to understand the interactions and feedbacks among vegetation, soil, and climate change in the NHLE, one of the challenges for the Land Surface Models (LSMs), a land component of the ESMs, is the treatment of the exchanges of C, water, and energy between the terrestrial ecosystems and the atmosphere and the impact of these exchanges on climate through a variety of biophysical and biogeochemical pathways over a range of spatial and temporal scales. Several inter-comparison projects have highlighted the differences between LSM simulations and observational data for the C fluxes, in particular ecosystem gross

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primary productivity (GPP) (Huntzinger et al., 2012; Keenan et al., 2012; Schaefer et al., 2012) and water and energy fluxes, in particular latent and sensible heat fluxes (Jiménez et al., 2011). The differences are even larger for the NHLE, because they are complicated to model due to the presence of snow, permafrost, peat lands, nitrogen (N) limitation, complex topography, etc.

The structural properties of vegetation, particularly the phenology and rooting depth, are important to study the exchanges of C, water, and energy between the terrestrial biosphere environment of the NHLE and the atmosphere. Additionally, changes in structural properties can also impact the global and regional climate due to their feedbacks with environmental factors, such as atmospheric CO<sub>2</sub> concentration. Modeling the vegetation structural properties is more challenging in the NHLs, because of the scarcity of observational data to evaluate the model performance. Due to these challenges, the current LSMs often simplify the vegetation and soil organic carbon (SOC) structure as a set of fixed parameters, as well as the biogeochemical and biophysical factors. For example, the seasonal evolution of leaf area index (LAI) is often prescribed, and seasonal LAI values are usually assumed constant year after year. A recent synthesis study based on various LSM results highlighted the deficiency in the phenology parameterization schemes, because of the LSMs incapability to simulate the start and the end dates of the growing seasons, resulting in the overestimation of the annual GPP by about 20%. (Richardson et al., 2012). Murray-Tortarolo et al. (2013) evaluated LSMs calculated LAI for the NHLEs and found that models overestimated, on average, the growing season length by 22 days mainly due to late dormancy. Another example is the root distribution, which controls transpiration and water uptake, is treated in LSMs as a static component (Arora and Boer, 2003), with a few exceptions (Chen and Coughenour, 1994; Eastman et al., 2001). Several local scale studies have reported the importance of deep roots for supporting the canopy greenness and higher productivity (Nepstad et al., 1994; Ichii et al., 2007, 2009) and evapotranspiration rates during the dry season (Jipp et al., 1998; Potter et al., 2001; Song et al., 2013). Other studies experimented using different static root depth in LSMs and concluded that deep roots are required for accurate calculations of the GPP seasonality (Baker et al., 2008; Ichii et al., 2007). While most of the previous modeling studies accounting for deep roots have focused on the tropical evergreen forests, there is also a need to study the impact of deep roots and dynamic roots on GPP and water uptake in the NHLs. It is also important to note that in many LSMs the allocation of assimilated vegetation C to leaves, stems, and roots is based on fixed fraction of assimilated C and can limit the models ability to predict the vegetation response to changes in key environmental variables, such as soil nitrogen (Franklin et al., 2012; Ostle et al., 2009).

Most LSMs also do not properly include a strong coupling between C-N processes with soil/snow hydrology, and energy (McGuire et al., 2006), which is another factor that impacts the vegetation structural properties and SOC in the NHL regions.

Thus, the objective of this study is to implement the dynamic vegetation structural properties in a LSM to understand how these properties are changing due to changes in environmental factors that impact the C, water, and energy fluxes. This study builds upon and extends the application of the dynamic phenology and the rooting depth and distribution in a LSM, the Integrated Science Assessment model (ISAM), by implementing a new dynamic phenology component and dynamic root parameterizations in the NHLs.

The new implemented parameterizations differ in many ways from the other LSMs. For instance, the new parameterization accounts for the impact of the soil moisture stress on leaf onset, which is not only important in NHLEs, but also is important in subtropical herbaceous ecosystems, because soil moisture demand triggers the growing season. In addition, the timing of the leaf onset and offset are determined by the temperature and day length thresholds, which are particularly important in the temperate and high latitude ecosystems where shorter and colder days induce dormancy. Unlike many other LSMs, the dynamic phenology in ISAM takes into consideration the nutrient availability, particularly N, on the dynamic N allocation to leaf, stem and roots. Furthermore, the linkage between phenology and plant water uptake are emphasized by highlighting the role of dynamic rooting depth and distribution as an essential scheme in LSMs for a better prediction of the growing season length in the NHLEs. The dynamic rooting depth and distribution allow the plant to grow its roots laterally and horizontally to maximize the access to soil moisture, altering the water stress on plant productivity and improving the model LAI and growing season length estimation.

Using these new schemes, ISAM performance was evaluated through the interactions between vegetation growth and C, water, and energy fluxes with observational data in the NHLEs. Errors in the modeled fluxes were also estimated with and without including dynamic processes. In summary, our objectives were: (1) to calibrate and evaluate the dynamic rooting and the phenology schemes in ISAM; (2) to assess the impacts of these schemes on ISAM estimated LAI and growing season length (GSL); (3) to infer the implications of dynamic vegetation structure on daily and yearly C, water, and energy fluxes in the NHLs.

# 2. Methods

# 2.1. Model description

ISAM is a LSM that simulates the terrestrial C, N, water, and energy cycles at  $0.5^{\circ} \times 0.5^{\circ}$  spatial resolution and at multiple temporal resolutions ranging from half hourly to yearly time scales. ISAM soil column consists of ten hydrologically and thermally active layers, five hydrologically inactive layers, and one thermally active bedrock layer that are used to calculate soil temperature and moisture. ISAM biogeochemistry is composed of eight vegetation pools, four litter pools, and four soil organic C pools. Each model grid cell contains at least one of the twenty eight land cover classifications (primary and secondary forests, C3 and C4 croplands, pasturelands and grasslands, and urban lands), glacier and bare grounds (Meiyappan and Jain, 2012).

ISAM contains comprehensive biogeophysics (Barman et al., 2014a,b; Song et al., 2013) and biogeochemical (El-Masri et al., 2013; Yang et al., 2009) components. ISAM computes stomatal conductance and photosynthesis for sun and shaded leaves where LAI is used to scale those variables from the leaf to the canopy level (El-Masri et al., 2013; Barman et al., 2014b). The stomatal conductance model is a variant of the Ball-Berry stomatal conductance model (Ball et al., 1987; Collatz et al., 1991). ISAM utilizes C3 photosynthesis model based on Farquhar et al. (1980) as implemented by Collatz et al. (1991), and the C4 photosynthesis model based on Collatz et al. (1992). In the model the latent heat (LH) and the rate of stomatal conductance, or its inverse, stomatal resistance, is directly linked via the boundary layer resistance of the leaf and the absolute concentration gradient of water vapor from the leaf to the atmosphere. Maintenance respiration is calculated separately for leaves, stem, and root using biome specific maintenance respiration rates and a temperature dependent  $Q_{10}$  function (El-Masri et al., 2013). The growth respiration for each vegetation carbon pool is assumed to be a fixed percentage (25%) of the difference between GPP and maintenance respiration.

The model includes the following snow dynamic processes that are important to the NHLEs: (1) energy exchange between shallow and deep soils, by representing soils up to  $\sim$ 50 meters (e.g.,

Lawrence et al., 2008), (2) effect of SOC on thermal/hydrological properties (Lawrence and Slater, 2008), (3) wind compaction of snow depth (and density), and (4) depth hoar formation in snow (Anderson, 1976; Barman, 2014; Schaefer et al., 2009). Notably, the majority of analyzed CMIP5 models did not include these important processes, causing a wide range in simulated permafrost area, temperature, and C across models (Burke et al., 2012; Koven et al., 2011; Slater and Lawrence, 2013; Todd-Brown et al., 2013).

The biogeochemistry component of ISAM accounts for major N processes, such as nitrification, denitrification, immobilization, leaching, and volatilization (Yang et al., 2009; Jain et al., 2009). GPP is modified through the N feedback availability on C assimilation, and it is obtained by comparing plant N demand and supply (El-Masri et al., 2013). The initial [N] in each vegetation pool is calculated based on its C:N ratios as defined in Yang et al. (2009). Changes in the N content of aboveground and belowground litter and SOM reservoirs are calculated mainly based on Bradbury et al. (1993), Parton et al. (1987), and Moorhead et al. (1999). The nitrification and denitrification rates in ISAM are calculated based on Bradbury et al. (1993). The C dynamics for aboveground litter, belowground litter (i.e., dead roots and soil organic C dynamics), and soil pools are based on Parton et al. (1987,1994); Parton et al. (1987,1994), Moorhead et al. (1999), and Jenkinson (1990), taking into account both environmental and biological drivers of decomposition, namely temperature, soil moisture, and quality of aboveground litter. Description of the model litter fall scheme is detailed in El-Masri et al. (2013). The model estimates litter fall for leaves, stem and roots as a function of temperature, water stress, and turnover rates. The model biome specific turnover rates for leaf, stem and root range from 0.75 year for leaves to 50 years for stem (El-Masri et al., 2013). Most importantly, the changes in C and N stocks in vegetation, litter, and soils, following land cover changes and forest fire, are affected by the changes in NPP, soil respiration, and the effect of changing environmental conditions. In this way, the C-N cycle is fully coupled.

#### 2.2. New phenology and root distribution schemes

The dynamics of the vegetation structure is driven by plant phenology, C allocation, and root distribution. The original version of ISAM (ISAM<sub>BC</sub>) includes static phenology based on prescribed biome specific LAI, which is derived from MODIS LAI data (Lawrence and Chase, 2007). Also, the ISAM<sub>BC</sub> uses static root parameterization with constant root fraction in each soil layer and constant rooting depth. However, the ISAM<sub>BC</sub> uses a resource limitation based dynamic C allocation scheme (Friedlingstein et al., 1999), which assumes that the C allocated to leaves, stems, and roots are adjusted to minimize adverse effects of limited availability of light, water, and mineral nutrients. The stem C allocation is parameterized based on the pipe model (Shinozaki et al., 1964), which assumes light limitation under high LAI conditions and wood C allocation increases to compete for light (akin to structural support). According to the functional balance hypothesis, when water and nutrient limitations occur, root C allocation increases (Gleeson, 1993). Allocation to foliage is then calculated as the residual.

#### 2.2.1. Dynamic phenology

The extended version of ISAM (ISAM<sub>DYN</sub>) accounts for a C-gainbased dynamic phenology and corresponding LAI. For instance, when C assimilation is less than the leaf respiration, LAI will decrease and it can trigger a change in the phenological stage if a decrease in LAI continuous for a period of time. Similarly, when C assimilation is greater than the leaf respiration, LAI will increase and such an increase will trigger a change in the phenological stages. Thus, a change in the (C assimilation – leaf respiration) amount will modify LAI and eventually the phonological stages. This approach is based on the following two assumptions: (1) the leaf onset starts when the environmental conditions are advantageous for the plant to produce leaves and to start carbon assimilation; and (2) the leaf offset starts when the plant experiences unfavorable environmental conditions resulting in C loss, such as cold temperature, photoperiod (shorter day length), and soil moisture stress. The phenology scheme consists of four stages (Table A1): (1) The leaf onset is triggered when temperature and photoperiod threshold are reached and C is allocated only to the leaves (White et al., 1997). (2) The normal growth starts when LAI reaches half of the biome specific maximum LAI (Lawrence and Chase, 2007; Tian et al., 2004; Zeng et al., 2002) and C is allocated to leaves, stems, and roots. (3) The senescence starts when temperature, water stresses, and day length threshold are met and C is allocated to stems and roots (White et al., 1997). (4) The dormancy starts when temperature and photoperiod threshold are met and C allocation seizes. In grasses and tundra ecosystems, soil water stress threshold was also applied in the leaf onset and offset stages, because water availability was one of the main driving factors that determined the start of the growing seasons in these biomes (Kurc and Benton, 2010).

#### 2.2.2. Dynamic LAI

The dynamic LAI approach is different from others in that LAI seasonality is not dependent on temperature through growing degree days (Richardson et al., 2012), rather it is a function of photosynthesis that is dependent on soil moisture, solar radiation, maximum leaf photosynthetic capacity, and fraction of allocated C to the leaves. Dynamic LAI was estimated using stem leaf area (SLA) and leaf biomass (See Eq. A36 of Song et al., 2013).

#### 2.2.3. Dynamic rooting depth and profile

In the ISAM<sub>BC</sub>, root fraction in each soil layer and rooting depth were constant and independent of the plant age or root biomass. The rooting depth and fraction were calculated following Schenk and Jackson (2002), which assume time invariant soil depth and biome-dependent coefficient ( $\beta$ ) to determine the rooting depth (defined as the depth containing 95% of the roots) and distribution. The disadvantage of using the static root is that both young and mature trees are treated with the same rooting depth and biomass fraction and distribution. However, in reality water fluxes should vary with root fractions, which are functions of the plant age. Thus, the assumption for fixed rooting depth and fraction in the ISAM<sub>BC</sub> limits the roots ability to grow deeper to extract water from deeper soil layers, which leads to the overestimation of water stress and hence the underestimation of plant transpiration.

Therefore, a dynamic rooting depth distribution process was implemented to simulate better the root response to soil water uptake and transpiration; and to improve the litter fall to represent better water and energy interception by the canopy during leaf senescence. The C allocated to the root was distributed horizontally and vertically, depending upon the available biomass, which will be affected through the soil water and nutrient in space and time (Fitter, 1994; Arora and Boer, 2003; Song et al., 2013). Roots grow vertically and horizontally with increased amount of root biomass under no water stress conditions. However, when water in a root zone is not enough to maintain the plant growth, roots grow more vertically toward deep and moist soil layers by increasing root density in deep soil layers. The root fraction for each soil depth was calculated by dividing the root biomass for the corresponding soil depth by the total root biomass.

# 3. Model calibration

# 3.1. Site data and method

The references of various data sets used to calibrate ISAM different processes and corresponding variables, as well as GPP, LH, and SH fluxes are provided in Tables A2 and A3. Measured LAI and data for the boreal evergreen, the boreal deciduous and the tundra sites were acquired from the Ameriflux and Big Foot project websites. Flux tower data for the calibration sites were acquired from the Ameriflux website.

The calibration of the dynamic phenology and the rooting depth and distribution was performed in three steps: (1) monthly measured LAI data were interpolated to daily time step and were used

#### 3.3. Statistical analysis

Two levels of validation and error analysis of the model results were performed. The model estimated LAI and the rooting depth were validated with the corresponding site level measured data. The mean absolute error (MAE) and the Willmott's index of agreement (*d*) were calculated to quantify the model estimated GPP, LH, and SH. The MAE was defined as the absolute difference between the observed and the simulated data sets for all samples and is given by:

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |P_i - O_i|$$
(1)

Willmott's index of agreement (*d*) (Willmott et al., 2012) is defined as:

$$d = \begin{cases} 1 - \frac{\sum_{i=1}^{n} |P_i - O_i|}{c \times \sum_{i=1}^{n} |O_i - \bar{O}|}, when \sum_{i=1}^{n} |P_i - O_i| \le c \times \sum_{i=1}^{n} |O_i - \bar{O}| \\ \frac{c \times \sum_{i=1}^{n} |O_i - \bar{O}|}{\sum_{i=1}^{n} |P_i - O_i|} - 1, when \sum_{i=1}^{n} |P_i - O_i| \ge c \times \sum_{i=1}^{n} |O_i - \bar{O}| \end{cases}$$
(2)

as input data in ISAM to calibrate the model parameters related to C allocation and plant growth for each vegetation C pool (stem, root, and leaf) by comparing simulated and measured leaf, stem and root carbon; (2) the model parameters for the dynamic phenology scheme were calibrated by comparing the model predicted daily LAI with the observed LAI data to minimize the differences between the observed and the modeled LAI (Table A1); and (3) the parameters used for the dynamic root growth and distribution calculation were calibrated by comparing the observed and the calculated root biomass distribution (Table A3).

The model calibration was optimized by using trial and error method. As a result, the calibrated biome-specific parameter values were identified and the minimum absolute difference between the observed and the model values was achieved (Table A3). The optimization for the dynamic rooting depth and distribution was performed for boreal evergreen and deciduous forests (Alberta), tundra (Bar), and grassland (Dickinson) sites. The optimization for the dynamic phenology parameters was performed for boreal evergreen (Nobs), boreal deciduous (Oas), grassland (Let), and tundra (Bar) sites (Table A2). Moreover, the maximum carboxylation rates for different biomes at the reference temperature of 25 °C (V<sub>cmax</sub>) were down regulated based on temperature, water, and nitrogen stresses (Cai and Dang, 2002; Domingues et al., 2010). V<sub>cmax</sub> for various biomes were calibrated so that the final V<sub>cmax</sub> after accounting for stresses fall in the range of reported values in the literature (Kattge et al., 2009).

#### 3.2. Model spin-up

The new version of ISAM, ISAM<sub>DYN</sub>, was initialized using site soil properties and meteorological data with fixed atmospheric  $CO_2$ levels (used the values of the start year of the simulation value and N disturbances). The model was spun up for each site by repeating the half hourly climate forcing data obtained from eddy covariance sites until the soil temperature and moisture and the C and N pools achieved a steady state. Then, the model was run for the years with available climate forcing data along with variable atmospheric  $CO_2$ concentration and N deposition data. To evaluate the performance of the dynamic allocation, the dynamic phenology, and the dynamic rooting depth and distribution, the original version of the model, the ISAM<sub>BC</sub> was run using fixed allocation factors, prescribed biome specific LAI, and static rooting depth and distribution (Table A4). where,  $P_i$  is the estimated values,  $O_i$  is the observed values,  $\overline{O}$  is the mean of the observed values, and c is a constant set to 2. Willmott's index varies from -1 to 1. A d of 1 indicates perfect agreement between model and observation, and a d of -1 indicates either lack of agreement between the model and observation or insufficient variation in observations to adequately test the model. The ability of Willmott's index of agreement to measure the model errors makes it appropriate to be used for model validation.

The  $d_s$  was calculated for the monthly mean observed and modeled data. The  $d_a$  was used to examine the degree to which the model represents the annual mean variation in the observed values. The comparison between  $d_s$  and  $d_a$  allowed us to evaluate the model biases at these different time scales.

#### 4. Results

# 4.1. Model results for the calibration sites

#### 4.1.1. Root fractions

The cumulative root fractions in the NHLEs calculated based on the ISAM<sub>DYN</sub> captured well the trend in the measured root fraction with soil depth, while the root fraction on the ISAM<sub>BC</sub> showed only a fixed curve shape (Fig. 1). The ISAM<sub>DYN</sub> root depth was in close agreement with measurements (Fig. 1), because the dynamics parameterization more realistically represented the vertical root growth that was initiated in response to water or nutrient stresses, compared to the fixed root fraction in the ISAM<sub>BC</sub>. This was an indication that prescribed static roots parameters were not suitable in the NHLE, in particularly in boreal deciduous biome.

The advantage of implementation of dynamic roots in the  $ISAM_{DYN}$  was the model ability to simulate plant water uptake from deeper soil layers as compared to the static root case in the  $ISAM_{BC}$ . Most of the root density and water uptake were within the top 20 cm of the soil in the boreal evergreen and deciduous sites (Fig. 2). In comparison, the  $ISAM_{DYN}$  calculates maximal water uptake in the soil layer, at least 30 cm deeper than the  $ISAM_{BC}$ , allowing plants to access water from deeper soil layers that can retain more moisture.

#### 4.1.2. LAIs

The ISAM<sub>DYN</sub> LAIs, particularly the timing and the magnitude of the peak LAIs matched the measured seasonal variations in the NHLE, whereas the ISAM<sub>BC</sub> LAI, which is based on MODIS data, failed to capture leaf onset and senescence, and the annual vari-



**Fig. 1.** Comparison of dynamic (ISAM<sub>DYN</sub>) and static (ISAM<sub>BC</sub>) models estimated cumulative root fractions for four calibration sites: (a) tundra (Barrow, AL); (b) boreal deciduous (Alberta Aspen, Canada); (c) grassland (Dickinson, ND); and (d) boreal evergreen (Alberta Black spruce, Canada).



Fig. 2. Water uptake for each soil layer for dynamic root (ISAM<sub>DYN</sub>) vs static root (ISAM<sub>BC</sub>) for (a) tundra (Bar); (b) grassland (Dickinson), (c) boreal deciduous (Alberta), and (d)boreal evergreen (Alberta) sites.

ation of LAIs as compared to ground based measurement (Fig. 3). The ISAM<sub>DYN</sub> overestimated the peak LAI in the grassland site (Let) as compared to ground-based measurements (Table 1). The calibrated ISAM<sub>DYN</sub> LAI compared well with the measurements than the ISAM<sub>BC</sub> LAI, which overestimated the peak value of the measured LAI by more than two folds in the grassland site (Table 1).

# 4.1.3. Growing season length (GSL)

Overall, the growing season length (GSL) calculated based on the ISAM<sub>DYN</sub> were in good agreement with measured GSL for the major biomes in the NHLs, with grasslands having the longest GSL (178 days) and tundra the shortest GSL (111 days). Whereas, the ISAM<sub>BC</sub> overestimated measured GSL except in the boreal evergreen site (Nobs) (the ISAM<sub>BC</sub> underestimated GSL by about 20% compared to measurement) (Fig. 4). The dynamic phenology scheme, which was based on plant's physiological benefits, was able to initiate leaf onset and offset dates that were in close agreement with measurements (see LAI plots in Fig. 3).

# Table 1

Comparison of ISAM\_{DYN} and ISAM\_{BC} calculated peak LAI with measured LAI (  $m^2/m^2)$  for the study sites.

-				
Biome type	Site name	ISAM <sub>DYN</sub>	ISAM <sub>BC</sub>	Measured
Calibration sites				
Tundra	Bar	1.79	1.95	1.75
Boreal evergreen	Nobs	4.84	3.89	4.80
Boreal deciduous	Oas	3.98	5.08	3.67
Grassland	Let	1.63	3.02	1.22
Validation sites				
Tundra	At	1.80	2.37	1.75
Boreal evergreen	Obs	3.80	3.29	3.41
	Gro	4.29	5.08	4.30
	Ojp	2.48	3.54	2.60
	Qfo	3.64	3.80	3.70
	Нуу	3.69	3.40	3.30
	Fla	3.85	3.70	3.40
	Nor	4.53	4.00	4.50
Boreal deciduous	Sor	5.00	2.74	4.20-5.00



**Fig. 3.** Comparison of measured LAI, dynamic (ISAM<sub>DYN</sub>) model estimated LAI with MODIS LAI, which is used in the ISAM<sub>BC</sub>, for (a) tundra (Barrow, AL); (b) boreal deciduous (Oas); and (c) boreal evergreen (Nobs).

#### 4.1.4. GPP

Improvements in the root distribution, GSL, and LAI significantly improved the ISAM<sub>DYN</sub> annual total and seasonal GPPs in the NHLEs



**Fig. 4.** Comparison of dynamic (ISAM<sub>DYN</sub>) and static (ISAM<sub>BC</sub>) models estimated growing season length (GSL) with measured GSL for the calibrated sites (Oas, Nobs, Barrow, Let) in the northern high latitudes.

(Fig. 5a). The annual GPP improved the most in the tundra biome (Fig. 5a), because of the significant improvement in the ISAM<sub>DYN</sub> LAI and GSL. Also, the seasonal variability in the ISAM<sub>DYN</sub> GPP in the tundra site was in much better agreement with the site data, showing a late leaf onset and shorter GSL (Fig. 6a). The ISAM<sub>BC</sub> estimated growing season started much earlier, resulting in much longer GSL and overestimation of the annual total GPP by two folds (Fig. 6a). The calibration results were also evident by high  $d_s$  values for the ISAM<sub>DYN</sub> than for the ISAM<sub>BC</sub> (Table 2). Although, the ISAM<sub>DYN</sub> and ISAM<sub>BC</sub> annual GPPs in the grassland site (Let) were close to observations (Fig. 5a), the ISAM<sub>DYN</sub> GPP at the start of the growing season were more consistent with measurements than the ISAM<sub>BC</sub> GPP.

The ISAM<sub>DYN</sub> annual GPP in the boreal deciduous (Oas) and the boreal evergreen (Nobs) sites were in better agreement with the



**Fig. 5.** Comparison of dynamic (ISAM<sub>DYN</sub>) and static (ISAM<sub>BC</sub>) models estimated annual (a) GPP, (b) LH, and (c) SH with flux tower measurements for the calibrated sites in the northern high latitudes (Oas, Nobs, Barrow, Let). The model results were not compared with flux tower SH data for Tundra biome, as no data were available.



Fig. 6. Seasonal variability of daily tower fluxes and model simulated GPP, latent energy (LH), and sensible energy (SH) for the calibrated sites.

flux tower annual GPP than the ISAM<sub>BC</sub> GPP (Fig. 5a). The ISAM<sub>BC</sub> GPP was overestimated at the start and end of the growing season, which was consistent with the LAI and GSL overestimation, as discussed above. Although, the ISAM<sub>DYN</sub> GPP was also overestimated at the start of the growing season, the phenological timing of the growing season was consistent with the site observation (Fig. 6g). On daily scale, the trend and magnitude of the ISAM<sub>DYN</sub> GPP was consistent with the site data in the boreal evergreen site (Nobs), unlike the ISAM<sub>BC</sub> GPP. The  $d_s$  was higher for the ISAM<sub>DYN</sub> GPP in the boreal deciduous and boreal evergreen sites than for the ISAM<sub>BC</sub> GPP, suggesting that the dynamic processes improved GPP estimates on a monthly time scale (Table 2).

# 4.1.5. Latent (LH) and sensible (SH) heat fluxes

The statistical analysis and the direct model-data comparison results suggested that the implementation of the dynamic rooting depth and phenology schemes improved GPP, LH, and SH fluxes for the ISAM<sub>DYN</sub> in most of the NHLE, except for SH in the grassland site (Fig. 6e). Both models, ISAM<sub>DYN</sub> and ISAM<sub>BC</sub>, overestimated SH in the grassland site (Let) during the dormant season, but a slight overestimation was observed for the ISAM<sub>DYN</sub> (Fig. 6f) resulting in 4% drop in the ISAM<sub>DYN</sub>  $d_a$  (Table 2). This drop was attributed to the difference in LAI during the dormant season, where the ISAM<sub>BC</sub> LAI was about  $0.25 \text{ m}^2/\text{m}^2$  compared to the ISAM<sub>DYN</sub> LAI, which was 0. Thus, higher ISAM<sub>DYN</sub> LAI tended to lower the soil heat flux, because less solar radiation was available to warm the ground and eventually would have led to a lower SH. The relatively higher  $d_s$ and  $d_a$  values were estimated for the ISAM<sub>DYN</sub> LH and SH as compared to the ISAM<sub>BC</sub> LH and SH, suggesting that the implementation of the dynamic LAI and the rooting depth improved the annual and monthly mean estimated LH and SH.

#### 4.2. Model results for the validation sites

The sources of various data sets used to evaluate the  $ISAM_{DYN}$  modeled biome specific LAI, GPP, LH and SH are provided in Table A2. Measured LAI and flux tower data for the validation sites were acquired from the Ameriflux websites. Marconi gap filled

tower flux data were acquired for the European sites (Falge et al., 2005). The validation of the model parameters for the dynamic phenology were performed for one tundra site (Atq), 7 boreal evergreen sites (Obs, Gro, Qfo, Ojp, Hyy, Nor, Fla), and one boreal deciduous site (Sor). The model estimated GPP, LH, and SH were evaluated and compared with site flux tower data. Finally, we were not able to validate the modeled rooting depth and root distribution due to lack of measured data available in the literature.

The ISAM<sub>DYN</sub> estimated seasonal and peak LAIs in most of the NHLE were similar to the measurements (Table 1). The model slightly overestimated the peak LAI in the boreal evergreen sites (Obs, Hyy, Fla) (Table 1). Overall, these results indicated that the model calibrated parameters for the dynamic phenology and rooting depth successfully captured the seasonal and peak LAIs at the validation sites.

The ISAM<sub>DYN</sub> GPP, LH, and SH tracked the measured seasonal variability in the boreal deciduous and evergreen biomes, suggesting that dynamic processes improved the model estimates (Fig. 7, shown as the mean for all the boreal evergreen and the boreal deciduous validation sites, respectively). This was also supported by higher estimated  $d_s$  for the ISAM<sub>DYN</sub> GPP, LH and SH in the boreal deciduous and evergreen biomes when compared to  $d_s$  values for the ISAM<sub>BC</sub> (Table 2).

In the boreal evergreen biome, the underestimation of the ISAM<sub>DYN</sub> GPP after day 210 (Fig. 7d.) could have been related to the fact that the ISAM<sub>DYN</sub> underestimated peak LAI in the European validation sites (Hyy, Fla, Nor) (Table 1) and the seasonality of the modeled LAI in these sites was not verified due to the lack of seasonal LAI data. Moreover, measured precipitation in some of the European sites varied between 313 mm/yr and 610 mm/yr,. With such low precipitation values, the water stress on stomatal conductance could have increased, resulting in a decrease in the modeled GPP. In all but three European sites, the ISAM<sub>DYN</sub> SH was in better agreement with flux tower data than the ISAM<sub>BC</sub> as indicated by higher  $d_s$  and  $d_a$  values in case of the ISAM<sub>DYN</sub> (Table 2). However, this consistency was not observed for the ISAM<sub>DYN</sub> SH in the Hyy, Nor, and Fla sites. This could have been caused by errors in the model prescribed parameters for the rooting depth or errors in

#### Table 2

Statistical summary to quantify the degree the observed GPP and energy fluxes are captured by the dynamic (ISAM<sub>DYN</sub>) and static (ISAM<sub>BC</sub>) model versions in the study sites. *d<sub>s</sub>*: Willmott's index of agreement for monthly mean observed data and model results; and *d<sub>a</sub>*, for annual mean observed data and model results.

Data	Biome Type	Site name	ISAM <sub>DYN</sub>		ISAM <sub>BC</sub>	
			ds	da	ds	da
Calibration sites						
GPP	Tundra	Bar	0.83	0.90	0.27	0.58
	Boreal evergreen	Nobs	0.83	0.90	0.72	0.85
	Boreal deciduous	Oas	0.88	0.92	0.82	0.89
	Grassland	Let	0.88	0.92	0.88	0.92
LH	Tundra	Bar	0.82	0.74	0.61	0.64
	Boreal evergreen	Nobs	0.80	0.86	0.52	0.72
	Boreal deciduous	Oas	0.84	0.88	0.73	0.83
	Grassland	Let	0.77	0.83	0.72	0.83
SH	Tundra	Bar				
	Boreal evergreen	Nobs	0.68	0.74	0.45	0.68
	Boreal deciduous	Oas	0.76	0.73	0.68	0.74
	Grassland	Leth	0.74	0.74	0.57	0.77
CPP	Poroal avergroop	Obs	0.86	0.01	0.68	0.82
GFF	boleal evelgieeli	Cro	0.80	0.91	0.08	0.02
		Oin	0.88	0.91	0.30	0.91
		Ofe	0.88	0.92	0.75	0.85
		Hvaz	0.78	0.86	0.75	0.05
		Fla	0.74	0.83	0.73	0.83
		Nor	0.74	0.85	0.75	0.65
		Average for all sites	0.82	0.88	0.42	0.05
	Boreal deciduous	Sor	0.81	0.86	0.62	0.79
TH	Boreal evergreen	Obs	0.82	0.89	0.81	0.82
	borear evergreen	Gro	0.75	0.82	0.73	0.77
		Oin	0.79	0.83	0.78	0.78
		Ofo	0.81	0.83	0.76	0.77
		Hvv	0.82	0.86	0.71	0.69
		Fla	0.71	0.77	0.67	0.77
		Nor	0.77	0.85	0.68	0.81
		Average for all sites	0.78	0.84	0.71	0.77
	Boreal deciduous	Sor	0.73	0.75	0.31	0.59
SH	Boreal evergreen	Obs	0.82	0.85	0.65	0.78
	C	Gro	0.67	0.70	0.41	0.66
		Ojp	0.82	0.86	0.76	0.84
		Qfo	0.76	0.78	0.54	0.70
		Нуу	0.15	0.28	0.24	0.35
		Fla	0.52	0.49	0.57	0.54
		Nor	0.63	0.73	0.85	0.83
		Average for all sites	0.63	0.68	0.56	0.67
	Boreal deciduous	Sor	0.64	0.58	0.25	0.50

the calibration of these parameters, and/or errors in the modeled soil heat flux.

Regression analysis revealed that the ISAM<sub>DYN</sub> GPP and LH showed a better correlation with flux tower data compared to the ISAM<sub>BC</sub> GPP and LH (Fig. 8a). The implementation of the dynamic phenology and the rooting depth and distribution increased the GPP R<sup>2</sup> from 0.36 to 0.86 and the LH R<sup>2</sup> from 0.37 to 0.51, and decreased the GPP MAE from 245 gCm<sup>-2</sup>yr<sup>-1</sup> to 107 gCm<sup>-2</sup>yr<sup>-1</sup> and LH MAE from 2.92 Wm<sup>-2</sup> to 2.43 Wm<sup>-2</sup> (Fig. 8b). The SH R<sup>2</sup> improved slightly from 0.25 to 0.28 for the ISAM<sub>DYN</sub>, but the MAE decreased significantly from 7.28 Wm<sup>-2</sup> to 4.26 Wm<sup>-2</sup> (Fig. 8c). Errors in the partitioning of surface energy and in the modeled ground heat flux could have caused the low improvement in the ISAM<sub>DYN</sub> SH.

#### 4.3. Evaluation of the model results in the NHLs

In the previous sections the model estimated fluxes for GPP, LH and SH in NHLE were evaluated at the site level. In this section, the ISAM<sub>DYN</sub> and ISAM<sub>BC</sub> fluxes in the entire NHLs (45-90 °N) were evaluated and compared with FLUXNET-MTE (Jung et al., 2011). In the following, first we describe the model experiment set-up and input data followed by the comparison of the model results for GPP, LH and SH with FLUXNET-MTE data.

#### 4.3.1. Model spin-up in the NHLs

Focusing on the NHLs poleward of 45°N, both version of the models, ISAM<sub>DYN</sub> and ISAM<sub>BC</sub>, were spun up using CRU-NCEP meteorology data (Wei et al., 2013) for 1970-2010, fixed HYDE land cover data for year 1970 (Klein Goldewijk et al., 2010), and fixed atmospheric CO<sub>2</sub> concentration for year 1970 (www.esrl.noaa.gov/gmd/ ccgg/trends) in three phases: (1) the ISAM biogeophysics was run for 120 model years to achieve a steady state in the soil temperature, soil moisture, and vegetation carbon by recycling the climate forcing data three times; (2) the model biogeophysical outputs, such as the soil temperature, soil moisture, and vegetation litter were used as inputs to run ISAM biogeochemistry for 20,000 model years to achieve a steady state in the soil C and soil N; (3) the biogeochemistry and biogeophysics initial states were used to run the coupled ISAM biogeophysics and biogeochemistry schemes for 120 years. This step was done to insure that GPP and vegetation C reached a steady state with the N cycle activated. For the ISAM<sub>BC</sub> run, the parameters listed in Table A4 were used.

Also, two transient experiments were performed. In the first experiment, the  $ISAM_{BC}$  was run from 1970 to 2010 using variable atmospheric CO<sub>2</sub> concentration (www.esrl.noaa.gov/gmd/ccgg/trends) and N deposition (Galloway et al., 2004). In the second transient experiment the  $ISAM_{DYN}$  was run from 1970 to 2010 with variable atmospheric CO<sub>2</sub> concentration and N deposition.



Fig. 7. Seasonal variability of daily flux measurement and model simulated GPP (a, d), latent energy (LH)(b,e), and sensible energy (SH)(c,f) for all the boreal deciduous and evergreen biomes sites.

# 4.3.2. Comparison of the modeled vs. measured GPP, LH, and SH in the NHLs

To assess the implications of the dynamic phenology and rooting depth and distribution in the NHLE, the ISAM<sub>DYN</sub> and ISAM<sub>BC</sub> calculated average monthly GPP, LH, and SH for the time period 2001-2010 in the entire NHLs were compared with FLUXNET-MTE data (Fig. 9). Most importantly, the ISAM<sub>DYN</sub> seasonal peak GPP in all four NHLE were significantly similar to FLUXNET-MTE GPP, while the  $\text{ISAM}_{\text{BC}}$  estimated GPP overestimated FLUXNET-MTE GPP by about 20% (Fig. 9). However, the estimated monthly mean LH based on both model versions showed no differences and both tracked successfully the seasonality in FLUXNET-MTE LH data, except the LH peak that was underestimated in the tundra biome (Fig. 9e). For the SH, the  $\text{ISAM}_{\text{DYN}}$  and  $\text{ISAM}_{\text{BC}}$  underestimated the FLUXNET-MTE SH at the start of the growing season in all the biomes (Fig. 9i, j, k, l). In general, the implementation of the dynamic processes increased the modeled seasonal GPP agreement with FLUXNET-MTE data in the ISAM<sub>DYN</sub>, while the energy and water fluxes estimates showed slight changes at the regional scale.

#### 4.3.3. The ISAM<sub>DYN</sub> model application

To assess the impact of the ISAM<sub>DYN</sub> ability to predict ecosystem dynamics, decadal changes in the GSL and GPP were calculated in the NHLs poleward of 45  $^{\circ}$ N (Fig. 10). The model results showed that the GSL increased in all the major NHLEs with the largest increase of 14 days in the boreal evergreen forest and smallest increase of 3

days in the boreal deciduous forest between the decades of 1990s and 2000s (Fig 10a–d). The increase in GSL also caused an increase in the GPP for all the major NHLEs. The GPP increased in the 2000s was about 6% compared to the 1990s (Fig. 10e–h). It is important to note that the GSL for the herbaceous and boreal deciduous biomes was overestimated in the ISAM<sub>BC</sub> and was constant with time, thus limiting the ISAM<sub>BC</sub> ability to predict the ecosystem dynamic in the NHLs.

# 5. Discussion

Overall, the ISAM<sub>DYN</sub> estimated rooting depth and LAI in the calibration study sites were similar to the measurements (Figs. 1 and 3). ISAM<sub>DYN</sub> GSL showed significant improvements and successfully detected the magnitude of the observed GSL compared to the ISAM<sub>BC</sub> GSL (Fig. 4).

The ISAM<sub>DYN</sub> C, water, and energy fluxes in the evaluation sites were similar to the site flux tower data, except for the SH in the evergreen forest sites (Hyy, Fla, Nor). The  $d_s$  values for the SH in these sites were low, suggesting that the ISAM<sub>DYN</sub> SH were underestimated, perhaps due to the overestimation of LAI that impacted the energy partitioning between the canopy and the ground. Meanwhile, this behavior happened only in these sites suggesting that limitations in the model parameters or schemes, such as the soil physical properties, leaf optical properties, and soil conductivity might have contributed to this bias and resulted in the lower  $d_s$ values for the ISAM<sub>DYN</sub> SH (Table 2). Also, the ISAM<sub>DYN</sub> underesti-



**Fig. 8.** Relationship between measured and ISAM<sub>DVN</sub> (star) and ISAM<sub>BC</sub> (open triangle) estimated (a) GPP; (b) latent energy (LH); and (c) sensible energy (LH). Here  $R^2$  is the adjusted coefficient of determination. The dark and light black lines are the regression lines for ISAM<sub>DVN</sub> and ISAM<sub>BC</sub>.

mated the observed GPP after day 200 in the Hyy evergreen site and between days 210 and 250 in the Nor evergreen site (Data not shown). One explanation in the Hyy site could be related to a negative relationship between GPP and photosynthetic active radiation (PAR), indicating that GPP was increasing due to diffuse light (Lagergren et al., 2008). The ISAM<sub>DYN</sub> did not simulate the diffuse light changes causing a decrease in the incoming solar radiation, which could have led to a decrease in the photosynthesis capacity and hence the GPP underestimation during that time period. On the contrary, the ISAM<sub>DYN</sub> LH in these two sites tracked the seasonal variability in the flux tower LH, even for the days where the ISAM<sub>DYN</sub> GPP was underestimated as compared to the observed GPP (Data not shown). This indicated a decoupling between the flux tower GPP and LH that might have led to an increase in the water use efficiency with the stomata partially closed to maintain a near constant leaf CO<sub>2</sub> concentration (Battipaglia et al., 2013; Keneen et al., 2013) in these two sites under elevated  $CO_2$  concentration. In the

ISAM<sub>DYN</sub>, a decrease in the stomatal conductance could have led to a decrease in GPP and LH, explaining the model GPP underestimation in the Hyy and Nor sites.

Similar to the site analysis, the ISAM<sub>DYN</sub> GPP outperformed the ISAM<sub>BC</sub> GPP in the NHLs poleward of 45 °N indicating that the implementation of the dynamic LAI and rooting depth not only improved the results in the sites, but also in the NHLs. The peak SH for the ISAM<sub>DYN</sub> and ISAM<sub>BC</sub> estimates in the NHLs was close to FUXNET-MTE SH, but both versions of the model underestimated the SH at the start of the growing season (Fig. 9). This could be explained by: (1) limitations in the model processes mentioned above, such as the incapability to resolve diffuse radiation and eventually, causing underestimation in the modeled SH; (2) simplified canopy radiative transfer scheme that might not have represented accurately the complexity in the NHLE, which might have led to inaccuracies in the partitioning of energy fluxes between the canopy and the ground; and (3) errors in the FLUXNET-MTE data



**Fig. 9.** Comparison of dynamic (ISAM<sub>DYN</sub>) and static (ISAM<sub>BC</sub>) models estimated monthly mean averaged over the period 2001–2008 for GPP (a, b, c, d), latent energy (LH) (e, f, g, h), and sensible energy (SH) (i, j, k, l) with FLUXNET-MTE estimated monthly mean values for the NHL biomes.



**Fig. 10.** Box and whisker plots for the 1990s (average for the period 1990–1999) and 2000s (average for the period 2000–2009) growing season length (GSL) and GPP in the NHLEs poleward of 45 °N for (a and e) boreal evergreen forest; (b and f) boreal deciduous forest; (c and g) grassland; (d and h) tundra. Boxes represent the first and third quartiles. Whiskers represent maximum and minimum range values. The bold line in the box represents the mean value.

due to limited spatial distribution of flux towers in the NHLs and errors in the empirical methods used to upscale flux tower data (Jung et al., 2011). Nevertheless, this illustrated that the dynamic processes implemented in the ISAM<sub>DYN</sub> improved the model results and lowered the modeled GPP overestimation during the start of the growing season.

The ISAM<sub>DYN</sub> estimated GSL in the NHLs has increased on average by about 5 days in the last two decades that was due mainly to the warming climate and rising atmospheric  $CO_2$  concentrations. The results showed a drastic increase in the GSL and GPP in the 2000s compared to 1990s (Data not shown). Whether, the increase in the GPP was due to an increase in the carbon uptake period or strictly due to an increase in the GSL is beyond the scope of this study and will remain a question to be addressed in the future studies.

Based on the site and regional level simulations, a number of model processes that needed to be improved in future work were identified. For instance, the leaf litter calculations might have estimated accurately the annual leaf litter fall, but might not have captured accurately the leaf litter seasonality. This was one of the reasons for the model LAI overestimation in the boreal evergreen forests at the end of the growing season (Fig 3c). Modifications

in the soil temperature and soil heat flux schemes to include the above ground organic litter layer that provides insulation to the soil, thus decreasing the transfer of heat from the air to the colder soil and eventually, increasing the modeled SH to better simulate the measurements.

# 6. Conclusions

The dynamic phenology and dynamic rooting depth and distribution were implemented and calibrated into a LSM, ISAM, in four NHLEs that are representative of the major biomes in the NHLs poleward of 45 °N. Also, the new model ISAM<sub>DYN</sub> was validated at multiple boreal evergreen, one boreal deciduous and one tundra sites. Results showed the ISAM<sub>DYN</sub> captured the seasonal variability in the GPP, LH, and SH fluxes through both direct and statistical comparisons to site measurements. The ISAM<sub>DYN</sub> for the carbon assimilation and energy fluxes showed *d* values closer to 1, thus validating our calibration approach.

Overall, the ISAM<sub>DYN</sub> GPP and LH were in better agreement with site flux tower data compared to the ISAM<sub>DYN</sub> SH. Our site data analysis suggested that these sites have energy balance closure errors (Table A5). This might have been one of the reasons that the model results in some cases might not have been consistent with the flux tower data. Further analysis into the model biases in the partitioning of energy fluxes is needed to assess the biases in the modeled SH.

The relevance of this experiment is the linkage between the dynamic vegetation structure processes (dynamic phenology and dynamic rooting depth and distribution) and how that linkage improves LAI simulations. Moreover, the results demonstrated how vegetation structure processes alongside the dynamic C allocation impacted the model simulated C and energy fluxes. Model exper-

iments performed in this study indicated that excluding any of these dynamic processes resulted in higher biases in the C and energy fluxes for most of the study sites. Therefore, the importance of including these dynamic processes in LSMs is emphasized, and more importantly for the LSMs that calculate LAI, not only to improve the modeled C and energy fluxes, but also to capture the observed vegetation seasonality and GSL. Because most LSMs are capable to estimate annual GPP that is consistent with flux tower data, but fail to simulate the observed GPP seasonality. This study is a step toward advancing model predicted seasonality.

The implementation of the dynamic phenology and rooting distribution allowed the ISAM<sub>DYN</sub> to better quantify the feedbacks between climate change and C and energy fluxes. These processes helped to simulate the vegetation adaptation to changing climate, because of adjustments in the plant phenology and structure. For instance, the implementation of these dynamic processes resulted in significant improvement in the tundra simulated C and energy fluxes. Thus, the lack of these processes in LSMs may lead to the NHL C and energy fluxes overestimation, causing errors in LSMs response to climate change.

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### Appendix 1.

#### Table A1

Threshold values for root temperature, day length, and soil water stress for different biomes used in ISAM phonology scheme (Un-cal: Un-calibrated; Cal: Calibrated).

Biome Type Root temperature threshold (°C)					Soil wate	r stress (	%) Day leng	th thresh	old (hr)					
	Onset		Senescen	ice	Dormano	cy			Onset		Senescence		Dormanc	y
	Un-cal	Cal	Un-cal	Cal	Un-cal	Cal	Un-cal	Cal	Un-cal	Cal	Un-cal	Cal	Un-cal	Cal
Tundra	8	4	8	4	8	2	-	50	12	11	12	11	11	10
Boreal Evergreen	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Boreal Deciduous	8	5	10	10	8	5	-	40	12	11	11	11	11	10
Grassland	8	5	8	2	8	2	-	50	12	12	12	12	11	10

#### Table A2

Information about the sites used for calibration and validation of the dynamic processes.

Biome type	Site name	Country	Lat	Calibrated processes	Reference
Calibration Sites					
Tundra	Barrow (Bar)	USA	71.32 N	LAI, GPP, LH, SH	Huemmrich et al. (2010)
				Dynamic rooting	Dennis (1977)
Boreal evergreen	Alberta	Canada	55.28 N	Dynamic rooting	Strong and La Roi (1983)
-	Northern Old Black Spruce (Nobs)	Canada	55.88 N	LAI, GPP, LH, SH	Griffis et al. (2003)
Boreal deciduous	Alberta	Canada	55.28 N	Dynamic rooting	Strong and La Roi (1983)
	Southern Old Aspen (Oas)	Canada	53.63 N	LAI, GPP, LH, SH	Barr et al. (2007)
Grassland	Dickinson	USA	46.9 N	Dynamic rooting	Sims and Singh (1978)
	Lethbridge (Let)	Canada	49.7 N	GPP, LH, SH	Flanagan and Adkinson (2011)
Validation Sites					
Tundra	Atqasuk (Atq)	USA	70.47 N	LAI, GPP, LH, SH	Oechel et al. (2000)
Boreal evergreen	Southern Old black Spruce (Obs)	Canada	53.99 N	LAI, GPP, LH, SH	Krishnan et al. (2008)
	Groundhog River (Gro)	Canada	48.22 N	LAI, GPP, LH, SH	McCaughey et al. (2006)
	Old Jack Pine (Ojp)	Canada	53.92 N	LAI, GPP, LH, SH	Kljun et al. (2006)
	Mature Old black Spruce (Qfo)	Canada	49.69 N	LAI, GPP, LH, SH	Bergeron et al. (2007)
	Hyytiala (Hyy)	Finland	61.85 N	LAI, GPP, LH, SH	Suni et al. (2003)
	Flakaliden (Fla)	Sweden	64.11 N	LAI, GPP, LH, SH	Lindroth et al. (1998)
	Norunda (Nor)	Sweden	70.47 N	LAI, GPP, LH, SH	Lindroth et al. (1998)
Boreal deciduous	Soroe (Sor)	Denmark	55.49 N	LAI, GPP, LH, SH	Pilegaard et al. (2003)

#### Table A3

Calibrated processes and parameters and their original and calibrated values.

Calibrated Processes	Biome type	Parameter values <sup>a</sup>			
		$\epsilon_{\text{stem,}} \epsilon_{\text{root,}} \epsilon_{\text{leaf,}}$			
		Un-calibrated	Calibrated		
Carbon allocation to stem ( $\epsilon_{\text{stem}}$ ), root( $\epsilon_{\text{root}}$ ) and leaf( $\epsilon_{\text{leaf}}$ ) <sup>a</sup>	Tundra	0.00, 0.60, 0.40	0.00, 0.60, 0.40		
,	Boreal evergreen	0.05, 0.89, 0.06	0.20, 0.40, 0.40		
	Boreal deciduous	0.20, 0.40, 0.20	0.05, 0.50, 0.45		
	Grassland	0.00, 0.60, 0.40	0, 0.6, 0.4		
Root growth and		Parameter values <sup>b</sup>			
distribution <sup>b</sup>		$\alpha$ , bb			
		Un-calibrated	Calibrated		
	Tundra	0.70, 10.40	0.60, 8.40		
	Boreal evergreen	0.70, 13.73	0.60, 8.23		
	Boreal deciduous	0.70, 13.73	0.60, 8.23		
	Grassland	0.70, 7.67	0.40, 6.27		

<sup>a</sup> Carbon allocation values are adopted from Gower et al. (1997), and Steele et al. (1997).

<sup>b</sup> Carbon allocation values are adopted from Nouvellon et al. (2000).

#### Table A4

Parameters used in the static model experiment (ISAM<sub>BC</sub>).

Biome Type	Carbon allocation	Static roots <sup>c</sup>	Static LAI
Boreal Evergreen	Leaves <sup>a</sup> : 25%Stem <sup>a</sup> : 30%Roots <sup>a</sup> : 45%	d50: 10.0beta: -1.880	MODIS LAI
Boreal Decidious	Leaves <sup>a</sup> : 25%Stem <sup>a</sup> : 30%Roots <sup>a</sup> : 45%	d50: 5.0 beta: -1.880	MODIS LAI
Grassland	Leaves: 40% Roots <sup>b</sup> : 60%	d50: 9.3 beta: -1.314	MODIS LAI
Tundra	Leaves: 40% Roots <sup>b</sup> : 60%	d50: 9.0 beta: -2.621	MODIS LAI

<sup>c</sup> Root distribution equation (Rootdepth =  $d50 \times (\frac{1}{10S^{-1}})^{\frac{1}{beta}}$ ) and the beta parameter are based on Schenk and Jackson (2002).

#### Table A5

Energy balance ratio (EBR =  $\frac{\Sigma(LE+LH)}{\Sigma R_{\rm B}}$  for the study sites. Here LE, SH and Rn are the latent energy, sensible energy and total radiation fluxes measured at the top of the canopy.

Site name	Energy balance ratio (EBR)
Old aspen	0.84
Southern old black Spruce	0.85
Groundhog river	0.96
Old jack pine	0.87
Mature old black spruce	0.85
Northern old black Spruce	0.94
Lethbridge	0.67
Soroe	_
Hyytiala	0.34
Flakaliden	0.70
Norunda	0.88
Barrow	0.82

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