TRIPLEX-Mortality model for simulating drought-induced tree mortality of boreal forests: Model development and evaluation

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Introduction

Globally, increasing drought-induced tree mortality rates under climate change are projected to have far-reaching effects on forest ecosystems. Among these forest systems, the boreal forest is considered a 'tipping element' of the Earth's climate system. This forest biome plays a critical role in ecosystem services, structures and functions while being highly sensitive to drought stress. Although process-based models are important tools in ecological research, very few have yet been developed that integrate advanced physiological mechanisms to simulate drought-induced mortality in boreal forests.

A robust process-based model that provides the advanced understanding of drought-induced mortality (hydraulic failure and carbon starvation) (McDowell., 2011) [1] is highly desirable to evaluate and predict effects of drought on forest ecosystems under a warmer and drier world (Choat et al., 2018) [2].

Methods

Data

- **Observed tree mortality and forest data**

We selected 73 sites from long-term permanent sampling plots (PSPs) across Canada's boreal and hemiboreal regions (Fig. 1) including tree mortality, forest stand type, forest type, tree age and tree species for the simulation of each stand for model simulation, calibration and validation.

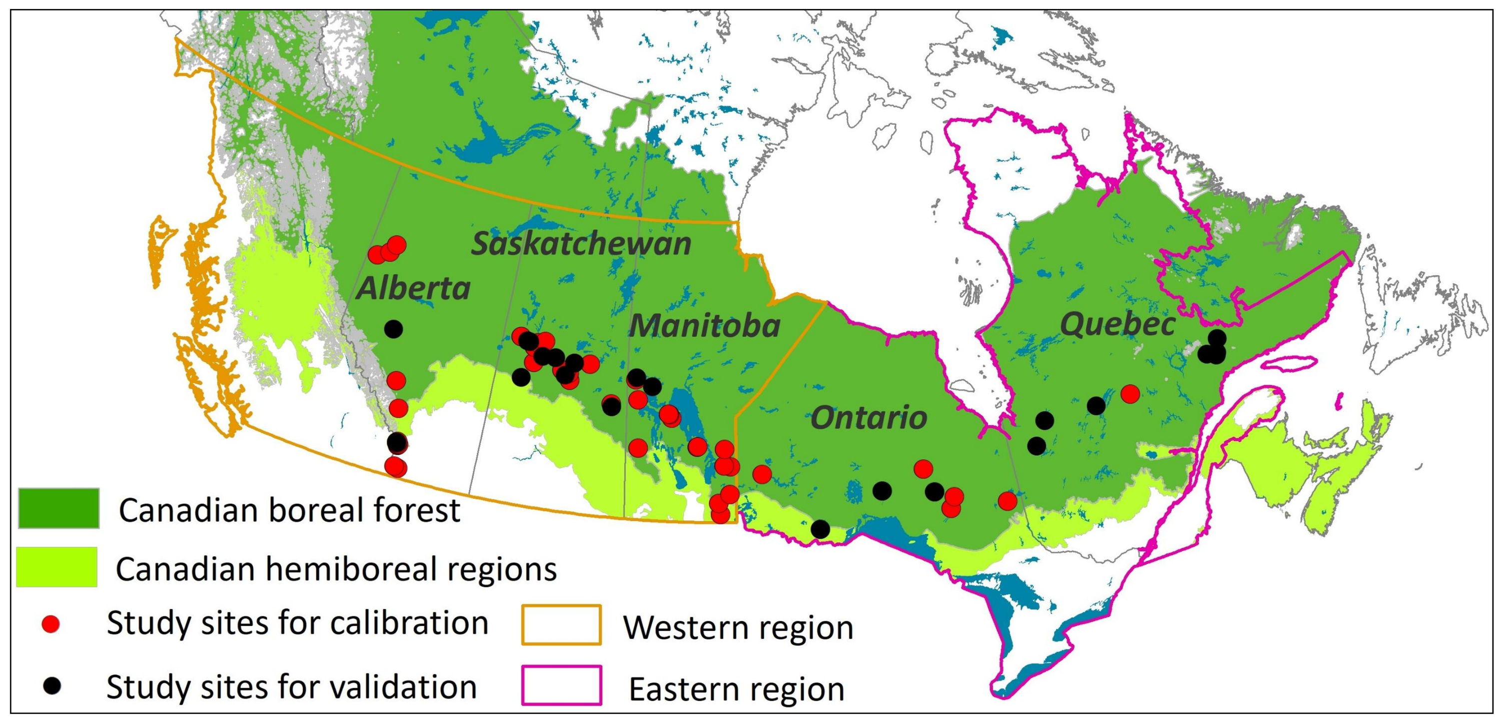

Figure 1. Locations of the 73 study sites selected across Canada's boreal forests.

- **Climate data**

As a driving force, climate variables of the TRIPLEX-Mortality model primarily include mean monthly temperature, monthly precipitation, potential evapotranspiration and monthly mean relative humidity. These climate variables were interpolated between the different sites for the years 1900–2008 (Fig. 1) using the BioSIM model.

- **Soil data**

Soil information at each site is also required for model initialization. The soil organic carbon data used in model initialization was obtained from the dataset generated by Tarnocai and Lacelle, (1996). We also used a soil property dataset generated by Batjes, (2012), which contains soil texture information (i.e., soil clay, sand and the silt fraction) to initialize the TRIPLEX-Mortality model.

TRIPLEX 1.0 model

TRIPLEX1.0 (Peng et al., 2002)[3] is a hybrid model that incorporates forest growth as well as carbon and nitrogen dynamics. TRIPLEX1.0 (Fig. 2) is based on three well-established models: 3-PG (Landsberg and Waring, 1997), TREEDYN3.0 (Bossel, 1996) and CENTURY4.0 (Parton et al., 1993) and has been successfully calibrated and validated for different forest ages (Peng et al., 2002; Zhou et al., 2006), tree species (Sun et al., 2008; Zhou et al., 2004), harvest disturbance and climate change (Wang et al., 2012b, 2011), as well as insect disturbance (Liu et al., 2019, 2018) in boreal forest ecosystems.

Methods

TRIPLEX-mortality model

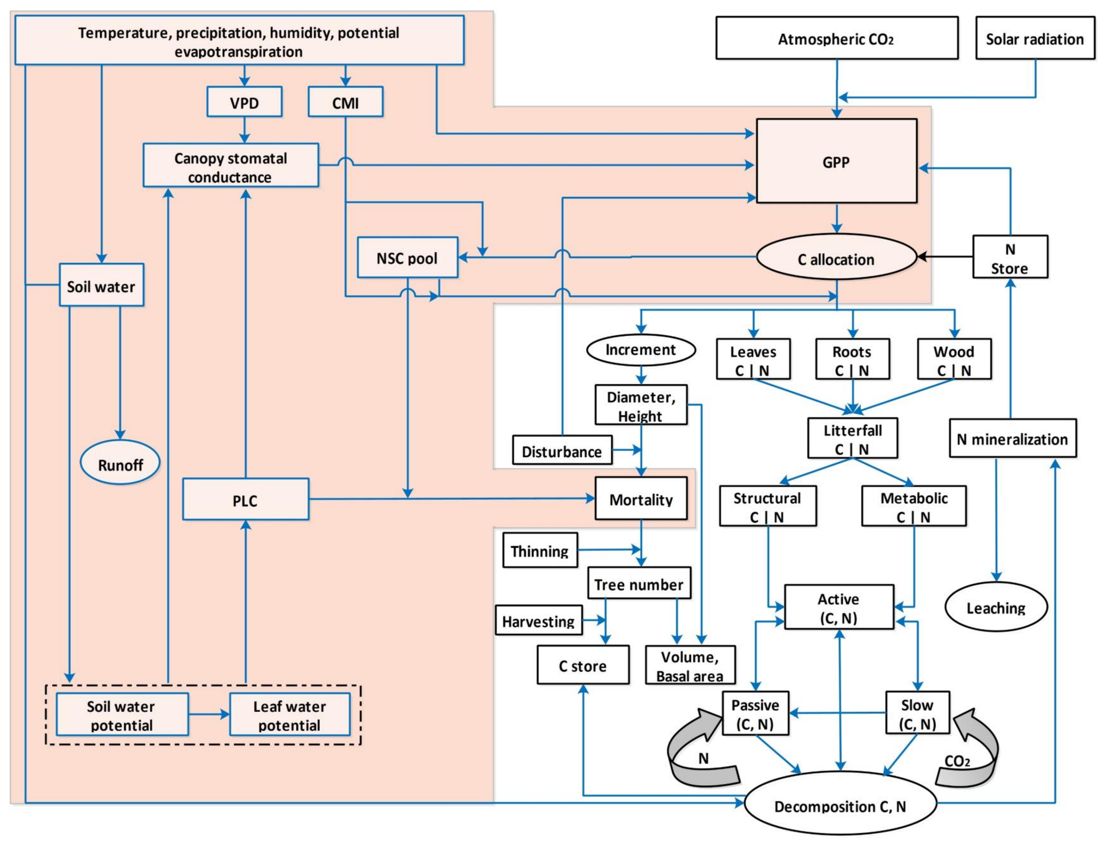

Figure. 2 Basic structural concept of the TRIPLEX-Mortality model (modified from Peng et al., (2002)). Shaded areas show the related processes involved in drought-induced mortality. CMI, PLC, NSC and GPP represent the climate moisture index, the percentage loss of conductivity, non-structural carbohydrate, and the gross primary production, respectively.

Major mechanisms of TRIPLEX-mortality model

- **Hydraulic failure (HF)**

.Tree mortality by HF is due to partial or complete loss of xylem function caused by embolisms that inhibit water transport through the vessels or tracheids. To date, the assessment of HF is generally conducted by the percentage loss of conductivity (PLC).

$$SWP = swps * vs^{-\lambda} \qquad PLC = 100\left(1 - e^{\left(\frac{-swp}{b}\right)^{c}}\right)$$

SWP is calculated using the reference soil water potential of saturated soil (*swps*, in MPa), the volumetric saturation (*vs*) in soil pores and the soil attribution parameter (λ) as follows (Oleson et al., 2010). Where *b* is the critical SWP that results in a 63% reduction in conductivity, and *c* is a shape parameter.

- **Carbon starvation (CS)**

Mortality by CS is caused by partial or complete depletion of nonstructural carbon content in the plant resulting in an inability to meet growth, metabolic and defensive carbon needs, due to an imbalance between carbohydrate demand and supply from photosynthesis. CS is mostly quantified by the dynamics of non-structural carbohydrate (NSC) concentrations.

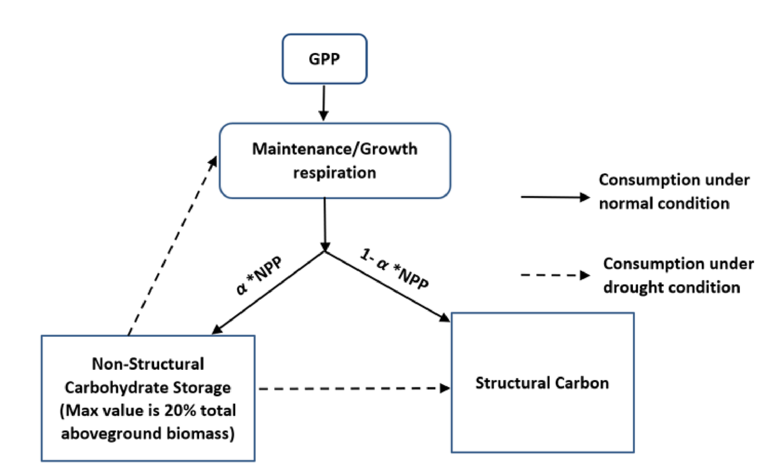

Fig. 3 The new carbon allocation mechanisms provided in the TRIPLEX-Mortality model

$$G_s = (1 - PLC)/(VPD * p)(SWP - \Psi_l)$$

where Ψ_l (MPa) is the leaf water potential, *VPD* (mb) is the vapor pressure deficit of the canopy and *p* is a coefficient

$$NSC = NPP * \alpha - C_m - C_s$$

where C_m represents the carbohydrate consumption from NSC to support basic metabolism, and C_s is the carbohydrate consumption from NSC that is transferred to structural carbon.

Sensitivity analysis

- **Parameter sensitivity analysis**

Seven parameters were selected for sensitivity analysis. We used the sensitivity index (SI) (Lenhart et al., 2002) to quantify parameter sensitivity, where higher absolute SI values indicate higher parameter sensitivity.

$$SI = \frac{1}{n}\sum_{j=1}^{n}\left\{\frac{(y_{2j} - y_{1j})/y_{0j}}{2 * \Delta x / x_0}\right\}$$

y_0 is the modelling output; x_0 is an initial parameter value; y_2 and y_1 are corresponding values of the output based on + Δx (+20%) and - Δx (-20%), respectively; n is the number of sites used in the sensitivity analysis.

- **Sensitivity to climate inputs**

The sensitivity scenarios used in the analysis of climate input sensitivity involved applying a uniform 10%, 8%, 6%, 4% and 2% increase or decrease in each climate input variable.

Results & Discussion

Calibration

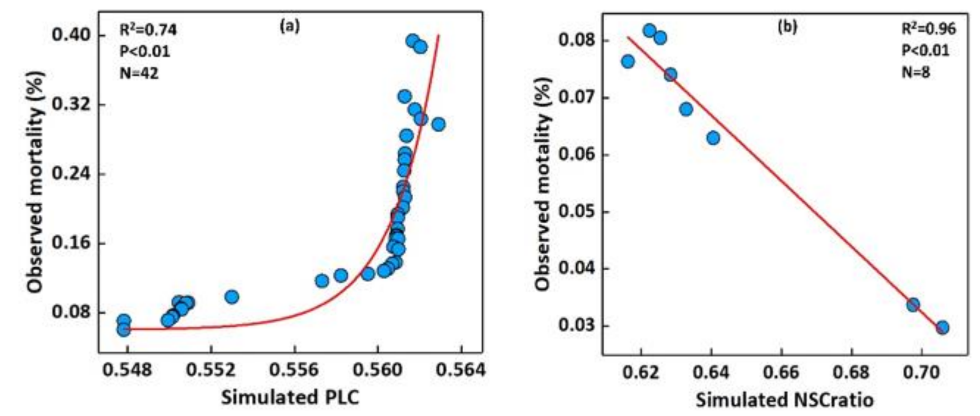

Figure. 4 Relationships between the simulated PLC (a), NSC and observed mortality rates.

We calibrated the relationship between simulated PLC, NSC and mortality observation respectively, to calculate mortality caused by HF and CS pathways.

$$Mort = 0.0606 + 6.72363 * 10^{-5} * e^{\frac{PLC - 0.54562}{0.00227}} + 9.71743 * 10^{-5} * e^{\frac{PLC - 0.54562}{0.00226}} \quad if\,PLC \geq 0.54$$

where *Mort* is tree mortality caused by HF.

$$Mortc = -0.57566 * NSC_{ratio} + 0.43536 \qquad if\,NSC_{ratio} \leq 0.7$$

where *Mort* is tree mortality caused by CS.

Validation

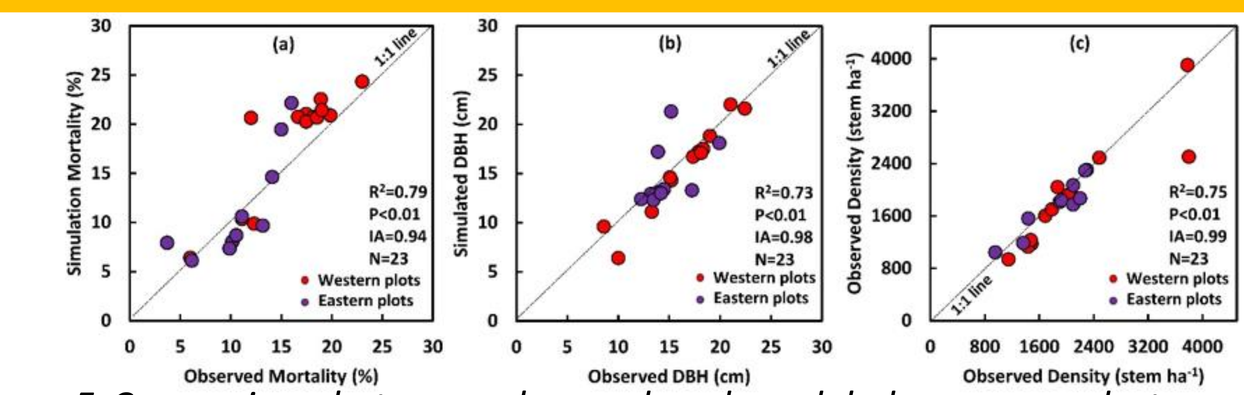

Figure. 5 Comparison between observed and modeled mean quadrat mortality (a), diameter at breast height (DBH in cm, b) and density (c).

Simulated mortality, DBH (diameter at breast height) and density results showed good agreement with observations. (mortality: R^2 = 0.79 and IA = 0.94; DBH: R^2 = 0.73 and IA = 0.98; tree density: R^2 = 0.75 and IA = 0.99)

Sensitivity analysis

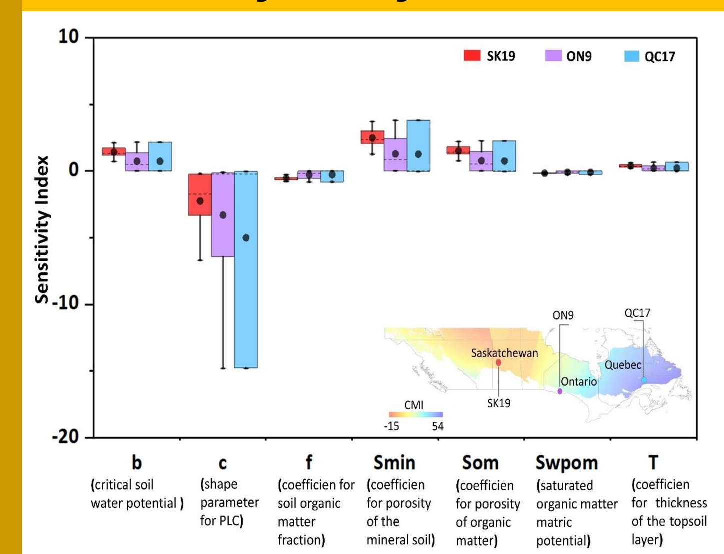

Figure. 6 Sensitivity index (SI) of the different parameters in the selected sites

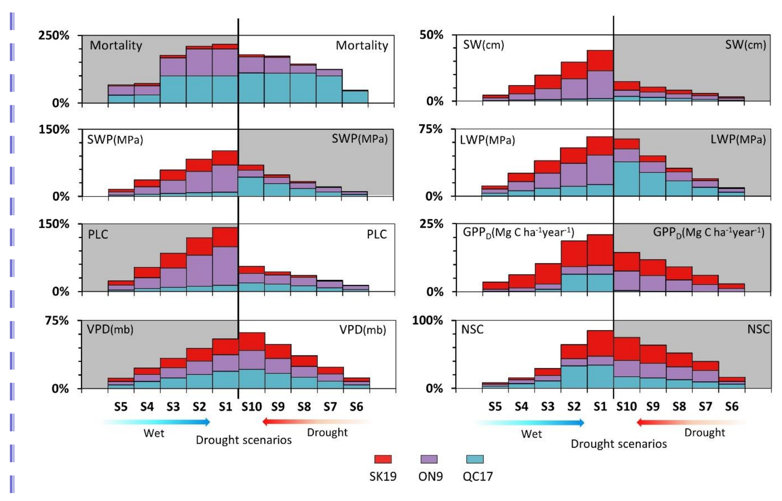

Figure. 7 Changes in simulated values of the major variables under the different drought scenarios.

Parameter c (average SI = -3.5) was the most sensitive of these parameters. TRIPLEX-Mortality model can capture changes in tree mortality under both intensified and alleviated droughts .

Acknowledgment & References

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