IMPORTANCE OF RECENT SHIFTS IN SOIL THERMAL DYNAMICS ON GROWING SEASON LENGTH, PRODUCTIVITY, AND CARBON SEQUESTRATION IN TERRESTRIAL HIGH-LATITUDE ECOSYSTEMS

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ABSTRACT
In terrestrial high-latitude regions, observations indicate recent changes in snow cover, permafrost, and soil freeze-thaw transitions due to climate change. These modifications may result in temporal shifts in the growing season and the associated rates of terrestrial productivity. Changes in productivity will influence the ability of these ecosystems to sequester atmospheric CO_2. We use the Terrestrial Ecosystem Model (TEM), which simulates the soil thermal regime, in addition to terrestrial carbon, nitrogen and water dynamics, to explore these issues over the years 1960-2100 in extratropical regions (30˚-90˚ N). Our results reveal noteworthy changes in snow, permafrost, growing season length, productivity, and net carbon uptake, indicating that prediction of terrestrial carbon dynamics from one decade to the next will require that large-scale models adequately take into account the corresponding changes in soil thermal regimes.

METHODOLOGY
We evaluated how changes in atmospheric CO_2 concentrations and climate may alter net carbon uptake in terrestrial high-latitude regions using the Terrestrial Ecosystem Model (TEM, version 5.1). Following model calibration, we performed two types of model simulations that took into account: (1) retrospective transient climate and increases in CO_2 concentrations for the years 1960-2000, and (2) prognostic transient climate and increases in CO_2 concentrations for the years 2001-2100. We then calculated changes in snow cover, soil freeze-thaw, growing season length, permafrost distribution, and carbon dynamics over this 1960-2100 time period, and, when possible, validated our results with remotely sensed data.

RESULTS AND DISCUSSION
Our model simulations show decreases in snow cover and permafrost stability from 1960 to 2100. Decreases in snow cover agree well with NOAA satellite observations collected between the years 1972-2000, with Pearson rank correlation coefficients between 0.58-0.65. Model analyses also indicate a trend towards an earlier thaw date of frozen soils and the onset of the growing season in the spring by approximately 2-4 days from 1988-2000. Between 1988 and 2000, satellite records yield a slightly stronger trend in thaw and the onset of the growing season, averaging between 5-8 days earlier. In both the TEM simulations and satellite records, trends in day of freeze in the autumn are weaker, such that overall increases in growing season length are due primarily to earlier thaw. Although regions with the longest snow cover duration displayed the greatest increase in growing season length, these regions

maintained smaller increases in productivity and heterotrophic respiration than those regions with shorter duration of snow cover and less of an increase in growing season length. Based on analysis over the years 1960-2000, we found that for each day that the length of the growing season increased, NEP increased by 5.26 g C m^{-2} yr^{-1}, vegetation C by 8.87 g C m^{-2} yr^{-1}, and soil C decreased by 8.06 g C m^{-2} yr^{-1} (Fig. 1). Simulations also suggested that the loss of soil carbon could reverse in the future (Fig. 1).

A positive feedback between spring snow-cover disappearance and radiative balance can result in warmer spring air temperatures. These warmer spring air temperatures will then likely exacerbate the continued early thaw and growing season onset, leading to further modifications in productivity and net C uptake. Even small changes in global temperatures could result in imbalanced responses in arctic and boreal regions, with positive feedbacks that may enhance such processes as photosynthesis and respiration. Our analyses imply that the relative strength of these feedbacks affect the future trajectory of carbon storage in high latitude regions. Therefore, it is important to improve our understanding of the relative responses of photosynthesis and respiration to changes in atmospheric CO_2 and climate.

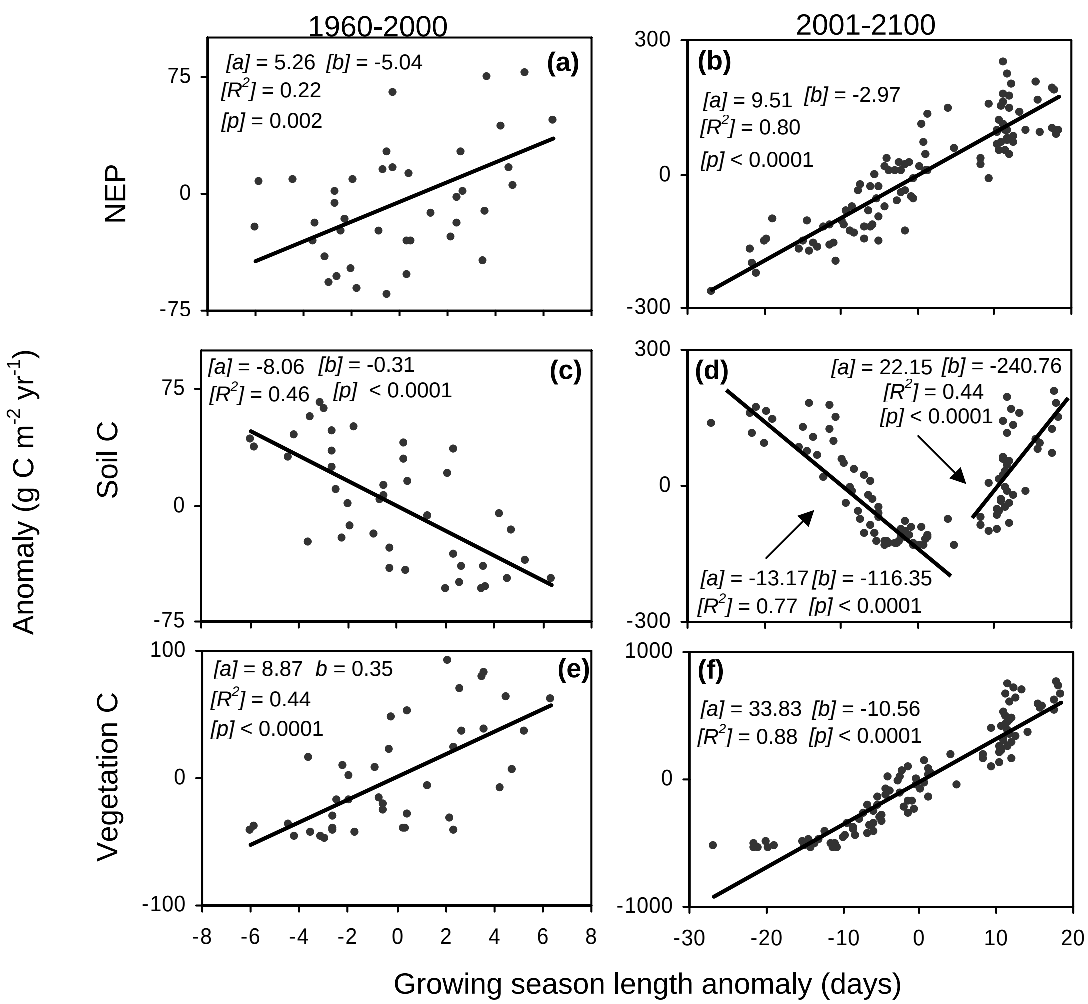

Fig. 1. Anomalies of growing season length versus anomalies in net ecosystem productivity (NEP; a-b), soil carbon (Soil C; c-d), and vegetation carbon (Vegetation C; e-f) across the high-latitude regions. Lines in each graph represent the linear least squares regression, with [a] = slope, [b] = intercept, [R^2] = coefficient of determination, and [p] = p-value.