



Recent Advances and Challenges in Monitoring and Modeling Non-Growing Season Carbon Dioxide Fluxes from the Arctic Boreal Zone

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Abstract

Purpose of Review While previously thought to be negligible, carbon emissions during the non-growing season (NGS) can be a substantial part of the annual carbon budget in the Arctic boreal zone (ABZ), which can shift the carbon balance of these ecosystems from a long-held annual carbon sink towards a net annual carbon source. The purpose of this review is to summarize NGS carbon dioxide (CO₂) flux research in the ABZ that has been published within the past 5 years.

Recent Findings We explore the processes and magnitudes of CO₂ fluxes, and the status of modeling efforts, and evaluate future directions. With technological advances, direct measurements of NGS fluxes are increasing at sites across the ABZ over the past decade, showing ecosystems in the ABZ are a large source of CO₂ in the shoulder seasons, with low, consistent, winter emissions.

Summary Ecosystem carbon cycling models are being improved with some challenges, such as modeling below ground and snow processes, which are critical to understanding NGS CO₂ fluxes. A lack of representative in situ carbon flux data and gridded environmental data are leading limiting factors preventing more accurate predictions of NGS carbon fluxes.

Keywords Carbon dioxide flux · Winter · Shoulder seasons · Arctic · Boreal · Carbon cycle modeling

Introduction

Non-growing season (NGS) carbon dioxide (CO₂) emissions from the Arctic boreal zone (ABZ) are now known to contribute a significant portion of the annual carbon budget in these ecosystems [1, 2]. These carbon emissions are vitally important given the vast stores of carbon in ABZ soils, with between 1350 and 1700 Pg of carbon stored in the top 3 m of permafrost soils [3–5]. Boreal ecosystems also store 100 Pg of carbon in biomass adding to the significant carbon store the ABZ provides [6]. These carbon stores are becoming increasingly vulnerable to loss to the atmosphere as the region warms at a rate up to four times the global average

[7] with the rate of warming happening particularly fast in the winter [8]. This rapid warming has been found to cause increased CO₂ emissions during the NGS [2, 9–11], due to the temperature control on metabolic rates [12] among many factors covered in this review.

The NGS can be defined in many ways in the ABZ, often depending on the purpose. The NGS has previously been defined by month, incoming solar radiation, temperature, snow cover, and the frozen or unfrozen status of soils. Some studies have defined it based on the absence of gross primary productivity (GPP, i.e., carbon uptake through photosynthesis), where the term NGS is derived. For Arctic ecosystems, the growing season typically starts in early–mid June after spring snowmelt, with the NGS starting after senescence in September. Boreal ecosystems, which are typically further south and warmer, have a wider range with growing seasons starting as early as April and the NGS typically starting in October. For this review, we are accepting the definitions of the NGS used in individual papers including winter and the fall and spring shoulder seasons.

Until recently, CO₂ flux data have sparsely been measured outside of the summer growing season in the ABZ due

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to measurement constraints including harsh environmental conditions [13]. But with improvements in measurement and remote power technology (e.g., wind, solar, and batteries), and increased research infrastructure (e.g., research stations), there has been an increase in sites measuring NGS CO₂ fluxes. These in situ observations of CO₂ fluxes at extremely cold temperatures build upon previous in situ and laboratory studies that have shown that microbial activity, the primary CO₂ producer in ABZ winters, may continue even at temperatures well below freezing [14, 15].

Techniques to measure and constrain carbon fluxes include chambers [16], eddy covariance [17, 18], atmospheric inversions and concentration enhancements using aircraft or tall towers [9, 19], and satellite monitoring [20], all of which have different advantages and disadvantages that support or limit their use in the ABZ. For instance, satellite monitoring in the ABZ is very difficult in the NGS due to low or no sun conditions for many months of the year and high snow and cloud cover [20]. Chambers cover only a small area and are thus good at monitoring specific land-cover types; however, snow cover can make this a difficult method to use in the winter, with moving parts freezing and burying chambers [16]. Eddy covariance can measure larger areas than chambers and the equipment operate without moving parts, making it suitable for winter conditions; however, the relatively large power draw (50–120 watts) creates challenges for measurements in remote high-latitude locations due to icing of equipment and low battery and solar capacity in the cold low-sun winters. Aircraft gas concentration measurements can be taken in the shoulder seasons, but these measurements are expensive and require flying specific aircraft and thus are temporally discontinuous. Concentration measurements at tall towers can be made more continuously but lack the spatial coverage extent of aircraft campaigns.

Overview and Synthesis

This review is laid out in the following way. We will first discuss dynamics of CO₂ fluxes in the ABZ in the NGS under seasonal cycles including the fall zero-curtain, when soil temperatures pause near 0 °C during freezing or thawing, and spring snowmelt. We will then mention impacts of disturbances such as shrubification, wildfire, and permafrost thaw and the impacts these changes can have on NGS carbon flux. We then transition to reviewing modeling methodologies and efforts and end with carbon NGS carbon budgets for the ABZ to put these efforts in context.

NGS CO₂ flux measurements across the ABZ are still sparse, with only 40% of all eddy covariance tower sites (33 out of 83 in 2019) and 28% of the chamber sites (19 out of 69 in 2016) in this region including NGS measurements [16,

21]. Even in locations where NGS CO₂ fluxes are measured, data gaps are more common than in the growing season. Severe gaps in NGS measurements exist in sparsely vegetated environments, drier shrub-dominated ecosystems, wet coastal climates, and extremely cold and continental climates dominated by larch forests [16, 21, 22]. Nevertheless, the existing sites exhibit significant regional and temporal variability in NGS CO₂ fluxes, with the boreal biome often having higher NGS CO₂ emissions than the tundra [2].

Seasonal Trends of Carbon Fluxes in Terrestrial Ecosystems

Fall Shoulder Season Fluxes

The fall shoulder season is a period where GPP has slowed, vegetation has senesced, and temperatures are dropping to below freezing temperatures. A large, sometimes majority, portion of annual net CO₂ emissions originate from the fall shoulder season, despite its relatively short length [9, 18, 23–25]. This outsized impact has been tied to the persistence of the zero-curtain, a period when soil temperatures stay near 0 °C during freeze-up, which is often pivotal to describing the fall in the ABZ [26–28]. During the zero-curtain, liquid water still exists in the soil column and microbial activity can continue, even while air temperatures are well below freezing, which can cause a mismatch for modeled carbon flux predictions that use air temperature as the primary prediction variable [24, 29]. Soil temperatures are in general the main driver explaining NGS CO₂ emissions [2, 23], and air temperatures often have a clear link with CO₂ emissions as well due to its correlation with soil temperatures [1], which break down during shoulder seasons. In fact, studies have found NGS CO₂ respiration models improved by 70% when modeling of zero-curtain dynamics was improved [24]. It is these sustained soil temperatures that allow for higher rates of carbon fluxes during the zero-curtain than the remainder of the winter [9, 30].

In total, the fall zero-curtain can have similar total emissions to the rest of the winter. In fact, a recent data compilation showed only minimal differences between average cumulative fall and winter net CO₂ emissions (i.e., net ecosystem exchange of CO₂) [13]. In the tundra, mean fall net ecosystem exchange (NEE; or the net exchange of carbon between the ecosystem and atmosphere) was 10 g C m⁻² month⁻¹, and winter NEE was 9 g C m⁻² month⁻¹. In the boreal biome, mean fall NEE was 14 g C m⁻² month⁻¹, and winter NEE was 11 g C m⁻² month⁻¹ [12]. However, as these are net CO₂ fluxes, fall NEE may have been offset by gross primary productivity (GPP; carbon uptake by photosynthesis), such that gross emission (i.e., respiration) rates were higher during the fall shoulder season compared

to those during winter. The range of reported emissions is highly variable in the fall, however, and larger during the fall than during the winter ([13]; seasons based on climatological definition).

The zero-curtain period is also observed to be increasing in length, lasting longer into the fall and winter seasons, which in turn leads to larger carbon emissions during the NGS [9, 29, 30]. For example, respiration of CO₂ in northern Alaska from October to December over the past several decades has increased by about 73% as a result of the increased zero-curtain duration [9]. Controls of the zero-curtain length include warming winter temperatures that cool soil more slowly [9, 29], increased and earlier onset of snow that can insulate soils from colder winter air temperatures [31], and increases in moisture, which is related to a slower freeze [30]. However, drier areas have also been observed to emit CO₂ at a faster rate during the zero-curtain. Total zero-curtain emissions are a balance of the respiration rates and zero-curtain duration, both of which are impacted by soil moisture, where wetter areas may have lower carbon emissions but a longer zero-curtain [18]. Warmer falls before the zero-curtain forms have also been linked to increasing net CO₂ emissions in peatlands

due to warmer temperatures accelerating ecosystem respiration more than GPP [32].

Emissions in the fall are driven by not only current production of CO₂, but also releases of gases that have been trapped in the soil from the growing season. As the growing season progresses, CO₂ concentrations in the soil are highly elevated above atmospheric concentrations (~ 5000–8000 ppm), and as temperatures drop and respiration slows, inputs into the soil CO₂ pool slow, but gasses continue to be emitted dropping the soil CO₂ concentration (~ 1500 ppm) [33, 34]. This soil CO₂ pool can help explain the sudden shift to CO₂ source conditions in the early fall (September/October) as GPP stops and built-up CO₂ is being emitted (Fig. 1d). As soils begin to freeze from the top-down (Fig. 1a), CO₂ gets trapped in the soil, as can be seen by quickly increasing soil CO₂ concentrations (30,000–75,000 ppm) [33, 34], and may be released suddenly throughout the winter in the form of “burst” emissions as ice cracks and the gas is able to escape [34–38]. The sudden rise in soil CO₂ concentrations is likely from both current respiration of CO₂ and aqueous gas being forced out of solution during freezing [38]. Burst emissions are sporadic and short-lived (hours or days at a time), but due to their high emissions of up to ~ 500 mmol CO₂ m⁻², they can contribute

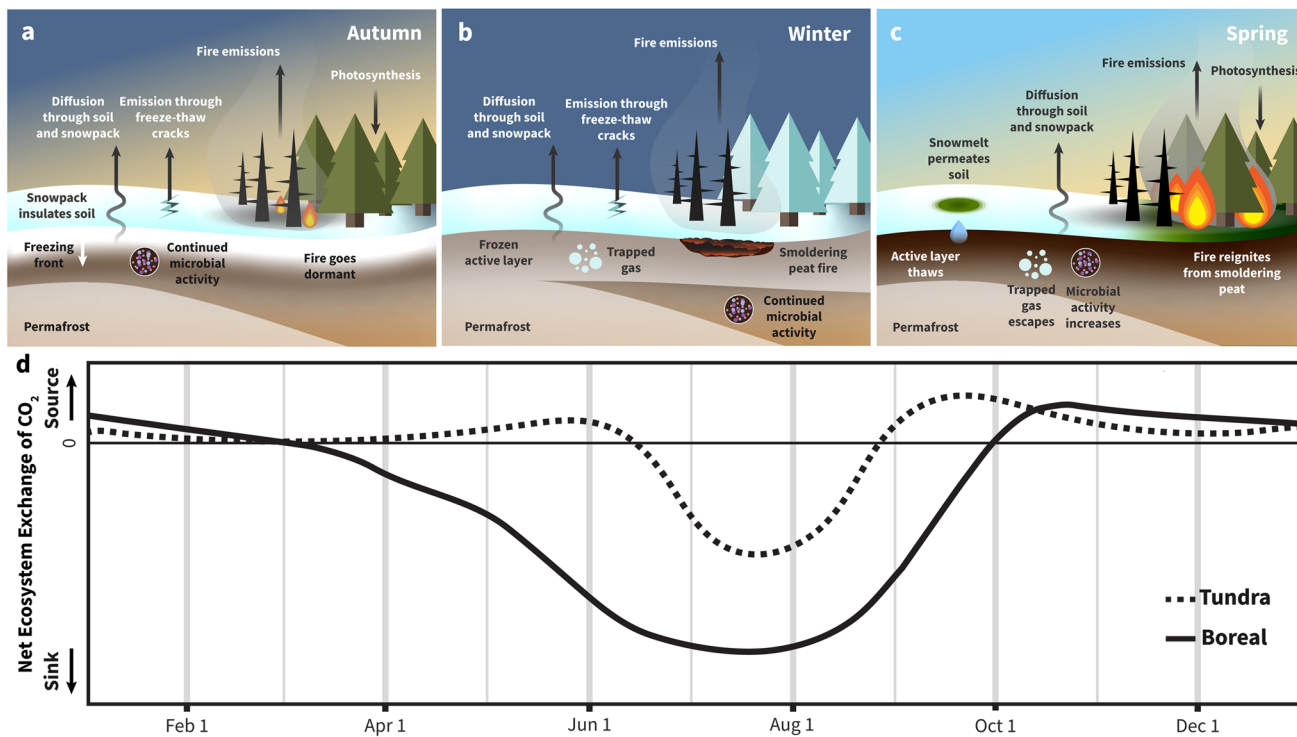


Fig. 1 Schematic diagram of CO₂ production and transport dynamics in the **a** fall, **b** winter, and **c** spring. **d** A conceptual net ecosystem exchange (NEE) comparing tundra and boreal ecosystem dynamics throughout the course of a typical year showing steady winter emissions, and shoulder season bumps in emissions. Fluxes above the 0 line denote a source to the atmosphere and below the 0 line are car-

bon sinks. Data from the FLUXNET-CH4 dataset from the RU-Che and RU-Fy2 sites used for tundra and boreal, respectively, with the smoothed average of the daily mean flux rate used. One site was chosen for each so that annual trends were not lost in temporal and inter-annual variability between sites

up to 46% of NGS carbon emissions [34]. Bursts are not always observed using eddy covariance as there is spatio-temporal variability in where and when bursts occur, and the measurement footprint of eddy covariance towers is larger and varies based on the wind conditions during the time of measurement which can average out a burst signal [33].

Winter Carbon Fluxes

Winter is typically a cold period with short daylight, if any in Arctic, and temperatures well below freezing where soils have become fully frozen as well. As temperature often plays a large role in controlling the rate of production of CO₂ [39] and with winters warming faster than other seasons in the ABZ [8], winter emissions have been estimated to increase by as much as 17–41% by 2100 [2]. The temperature response of respiration has even been found to be much stronger at below freezing temperatures than at above freezing temperatures as shown by higher Q₁₀ values for respiration from sub-zero soils [40, 41]. Other factors that control soil temperature in the winter can thus have an indirect effect on emissions from the NGS. Snowpack insulates the soil from colder air temperatures and can cause soil temperatures to stay elevated well through the winter, leading to increased CO₂ production throughout the NGS [31, 42]. However, a comprehensive understanding of snowpack-CO₂ flux relationships is still lacking, partly because the depth and density of the snowpack can be highly variable both at local and regional scales [43, 44], creating a mismatch at the scale at which snowpack and fluxes are measured.

Second to temperature, moisture also plays a large role in how much CO₂ is emitted from the ABZ in the NGS [18]. As the primary respiration pathway that creates CO₂ is an aerobic process, drier sites often have higher oxygen availability than wetter sites and thus support higher rates of respiration, even at similar temperatures. In addition, drier sites have been observed to have higher GPP in the growing season [18], which can also enhance respiration into the winter because it adds a pool of labile carbon to the soil [45, 46]. This signal is seen on a regional basis where higher NDVI has been linked to increased CO₂ anomalies in the early winter [47]. Soil carbon stocks and fine soil material content have been shown to be positively related to annual or NGS CO₂ emissions as well, related to the observed trend of carbon availability driving CO₂ emissions [2, 48]. This relationship has been shown at depth where landscapes with deeper, carbon-rich organic layers have been observed to respire larger quantities of carbon in the winter than areas with thinner organic layers [29]. However, as soils stay warmer throughout the NGS, this labile soil carbon may become a limiting factor towards respiration and may eventually lead to reduced winter CO₂ emissions [49]. This reduction in CO₂ emissions may be balanced by the respiration of older soil carbon as permafrost thaws, as evidenced

by isotope studies revealing older carbon making up a larger proportion of NGS CO₂ emissions as the NGS progresses [50].

Spring Shoulder Season Carbon Fluxes

Spring is typically a period before green-up, with snow cover still on the ground, and the soil around 0 °C as the active layer begins to thaw. Like the fall shoulder season, the spring shoulder season is also a large source of CO₂ that can offset the growing season CO₂ sink by about 45% [17, 34]. The difference that makes the emission rates higher compared to the winter is the infusion of snowmelt into the soil. Unlike the fall, the soil at this time is usually depleted in soil gas [33, 34], so most of the flux of CO₂ out of the soil is a result of a rapid increase in microbial activity due to both sudden soil warming by snowmelt and that snowmelt being oxygen rich allowing for microbial respiration [17]. Bursts observed during this period may also be from microbial respiration that occurred during the winter, or even from the previous growing season that was trapped in the soil through the frozen winter period [34]. Because the period of spring emissions is relatively short, often a month or less, synthesis efforts show net spring CO₂ emissions to be significantly smaller than fall or winter emissions or non-existent due to increasing carbon uptake offsetting microbial respiration (spring NEE values for tundra: 6 g C m⁻² month⁻¹, and boreal: -5 g C m⁻² month⁻¹) ([13]; seasons based on climatological definition). Warming in the spring also can cause earlier snow melts, creating a longer growing and snow-free season [31]. These changes can lead to a deeper thaw and active layer which in turn increases respiration for the following year, as a deeper active layer will take longer to freeze and make more carbon available for decomposition [31].

Aquatic Carbon Emissions

Open-water bodies, including lakes and ponds, across the ABZ consist of 5.6% of the landscape [51]. Despite the relatively small proportional area, Watts et al. [23] found adding open water contributions to annual CO₂ budget estimations has reduced the overall carbon sink by 21% and shifted many tundra landscapes and some boreal forests to a carbon source. Despite the contribution of open water to carbon budgets, continuous measurements of lake CO₂ fluxes are even more sparse than those from terrestrial ecosystems. However, a recent synthesis included eddy covariance data from nine Arctic boreal lakes [52]. Lakes can have fluxes between 0 and 2 (but often less than 1) g C m⁻² day⁻¹ during the ice-free NGS season [52]. During the ice period, lakes are often assumed to emit no CO₂ to the atmosphere [52] but CO₂ is likely trapped below the ice. Emissions during the ice-out period, when CO₂ that has built up over the winter

is released to the atmosphere, contribute 15–30% of the annual CO₂ emissions from lakes [53–55]. Here, again, rain events and snowmelt events in winter can introduce oxygen into the water column where oxygen availability becomes the limiting control on winter CO₂ production more than temperature, which is the control during the ice-free season [53]. Furthermore, spring periods have sometimes the highest rate of allochthonous organic matter input in lakes, which is often the primary carbon source and controlling factor of respiration rates in lakes [55].

Shrubification and Vegetation Impacts

Vegetation can have a dynamic impact on soil temperatures and snow processes and thus affects NGS ecosystem respiration. For example, it has been found that taller shrubs and boreal vegetation, which stick above snowpack, can warm soils compared to tundra vegetation by lowering albedo and through thermal conductivity transporting heat into the soil [56]. This effect is, of course, dependent on sunlight to warm woody vegetation, which is low or non-existent at times in the NGS in the ABZ. Increased snowpack can also collect in vegetated areas and insulate soil [56]. This warming of soils in the NGS has outweighed cooling effects from shading in the growing season, meaning shrubification may drive increased thaw [56], thus increasing CO₂ emissions throughout the NGS. The same thermal bridging that warms soils in the presence of sunlight, however, has been found to cause winter cooling as much as 1.21 °C as heat is lost more rapidly through woody vegetation than insulating snowpack [57]. Thermal bridging causing warming or cooling is key as largely sunless winters in the ABZ may cause cooling, with heating starting again in the spring with the return of daylight. Soil warming trends in shrub ecosystems dominate as isotope observations show carbon residence times have decreased by 13.4%, likely due to thawing permafrost [58]. It has also been found that deciduous shrub ecosystems have a mycorrhizal relationship that can further enhance soil respiration, amplifying carbon losses in shrub ecosystems compared to other tundra vegetation types [59].

Arctic and Boreal Wildfires

Wildfires are increasing in frequency and severity in the ABZ, currently emitting an estimated 142 Tg C year⁻¹, with the majority (92%) occurring in boreal forests [60]. While wildfires typically occur during the summer growing season, impacts can be seen year-round, affecting processes governing NGS CO₂ emission dynamics such as soil organic carbon content [61], vegetation composition [62], active layer thickness [63], and permafrost thaw [64]. For example, though

the effect of fire on soil organic carbon reservoirs can be highly variable depending on fire intensity and duration [61], post-fire annual CO₂ source-to-sink shifts have been driven by NGS ecosystem respiration and decreased growing season GPP [65]. Likewise, increased active layer depth, frequently associated with wildfire [63, 66], would create an elongation of the fall freeze period thereby increasing NGS CO₂ emissions. Moreover, soil warming can result in disproportionately high post-fire soil CO₂ emissions during the fall (October–November; [67]). This may cause conditions favorable for increased NGS emissions resulting from reported higher post-fire soil temperatures [64, 68] and deepening active layers that can persist for decades [64].

Arctic warming, most pronounced during the NGS, has caused a lengthening of the fire season in the ABZ, with fires increasingly carrying into the shoulder seasons. Earlier snowmelt and enhanced evapotranspiration during late winter are exposing and drying ground surfaces earlier in the year, promoting increased fuel availability and subsequent fire development [69, 70]. These changes are not only increasing the fire season duration, but also priming the environment for more frequent and higher intensity fires [69, 70]. High-intensity fires can even persist through the NGS. These holdover fires (also known as overwintering or zombie fires) occur when a wildfire continues to smolder through the winter, after surface flames are extinguished, reigniting during the following spring, near the original burn scar (Fig. 1a–c) [71, 72]. Conditions for holdover fires have become more favorable in recent decades because of rising temperatures and dry summers creating ideal conditions in deep organic soils [70]. Fueled by peat soils and insulated by snowpack, holdover fires can burn deep in the soil column, releasing carbon formerly locked in soil reservoirs [73], contributing directly to CO₂ emissions [70]. While direct emissions of holdover fires have been estimated to contribute around 0.5% of fire emissions [70], recent findings indicate emissions from the smoldering phase may be underestimated [74] and that relative contributions can be significantly larger for a given year (> 5%; [70]). These phenomena are still understudied despite their importance to landscape scale change and greenhouse gas budget estimates due to the difficulty in detecting fire events in remote regions and low-light conditions.

Permafrost Thaw

The occurrence of thawing processes such as thermokarst, wet landscapes that form as a result of ice-rich permafrost thaw, has been a growing concern in the ABZ. Thermokarst landscape development and expansion occurs in response to increasing temperatures and can be exacerbated by wildfire disturbance [75, 76]. Like wildfires, thermokarst affects CO₂

emission dynamics throughout the entire year even though these features largely develop during the summer. This can result in ecosystem state transitions by creating wetland-like features or ponds with variable carbon emission magnitudes, CO₂:CH₄ emission ratios [77], and increased NGS respiration [78].

Abrupt thaw commonly results in thermokarst lakes and wetlands in areas with little drainage or hillslope thermokarst landscapes in upland areas [77, 79]. Thermokarst wetlands and lakes are the most common type of abrupt thaw landscapes [79] and develop as ice-rich permafrost thaws to create depressions filled with meltwater. Deep thermokarst lakes have the potential to remain unfrozen and microbially active throughout the NGS, resulting in the accumulation of greenhouse gases under the top layer of ice that can then exhaust upon ice break-up during spring [80, 81]. Recent analyses have shown that the highest CO₂ emissions from thermokarst lakes can occur during the NGS, with spring and fall being two times higher than summer rates [82]. Emission seasonality is largely explained by ice accretion facilitating CH₄ oxidation as 50% of below-ice CO₂ in thermokarst lakes has been found to be formed from CH₄ oxidation [80].

Hillslope thermokarst landscapes include retrogressive thaw slumps, erosion gullies, and detachment slides [83] and have increased 60-fold over previous decades [84]. These features, though not as common as thermokarst lakes and wetlands, have the potential to emit a disproportionately large amount of abrupt thaw carbon emissions due to aerobic soil conditions stimulating CO₂ production along with relatively low offsets through vegetation recovery [77]. CO₂ emissions during all NGS periods (fall, winter, and spring) can be significantly higher than summer emissions in upland areas of extensive thermokarst disturbance [78]. Furthermore, varying rates and areas of subsidence can create surface relief patterns exhibiting areas above the surrounding snowpack with a lowered albedo [85]. This increases light absorption and soil temperature during NGS periods with the potential to increase respiration. Little recent research has been published reflecting greenhouse gas dynamics of these features during the NGS. The paucity of NGS data highlights the need for in situ measurements representing the full suite of thermokarst landscape features, crucial for understanding emission patterns during this time.

Abrupt thaw events have been receiving increased attention [77, 86–90], though causes of such events are multifaceted and somewhat spatially stochastic in nature. Recent simulations indicate that abrupt thaw may not occur over larger areas because increased surface runoff leads to drier landscapes [91]. However, this may still lead to increased NGS CO₂ emissions as drier regions are also linked to substantially higher NGS CO₂ emissions [18]. As a result, abrupt thaw processes are not represented in Earth system

models and therefore remain sources of uncertainty, particularly during the NGS.

Current Modeling Efforts and Advances

In recent years, various numerical modeling approaches, informed by observations, have continued to be developed to improve accuracy in quantifying NGS carbon fluxes in the ABZ from site-level to regional and global scales. Statistical upscaling uses regression algorithms to determine the dominant drivers of observed CO₂ flux variability and then applies any derived relationships between the drivers and CO₂ fluxes over space and time. Process-based models incorporate mechanistic and empirical relationships to explicitly represent carbon storage, transformation, and movement throughout an ecosystem. These models can also be used prognostically to calculate the carbon flux balance under future climate warming scenarios. Atmospheric inversions are also being applied to both determine optimized CO₂ fluxes and improve flux model processes by better understanding the impact of fluxes on the atmospheric concentrations.

Statistical Upscaling

Statistical and machine learning models are increasingly being used in ABZ CO₂ flux studies to understand flux patterns and budgets (e.g., 92–94), but they are still rarely used to upscale fluxes across larger regions, particularly during the NGS. The first study to explore NGS CO₂ flux upscaling was led by Natali and Watts et al. [2] with the result that upscaling-based current NGS CO₂ budget estimates were significantly higher than those derived from process models. The NGS has now been integrated into many other upscaling efforts focusing on year-round flux dynamics (e.g., 48, 95, 96). The predictive performance of the models is generally weaker for the NGS period compared to the growing season, likely due to lower data coverage and weaker relationships with typical flux controls like air temperature (e.g., zero-curtain becomes non-correlated with air temperature) due to gas storage causing latency of fluxes. However, given the lower magnitude at this time, it may not affect total budgets significantly.

Process-Based Models

An accurate process-based model representation of NGS carbon dynamics in Arctic tundra and boreal ecosystems is important for quantifying the global carbon budget and projecting future climate warming. The dynamic representation of respiration from permafrost during the NGS in these models, rather than assuming no respiration occurs below freezing, is of particular importance [97]. Recent efforts to

improve process-based models largely parallel incorporation of advances in seasonal process understanding. These model improvement efforts focus on reducing uncertainty in the shoulder season carbon balance (e.g., 98), representing freezing and thawing processes (zero-curtain periods) (e.g., 29), and determining magnitudes of the NGS flux while the surface and subsurface are frozen (e.g., 24). Incorporating in situ carbon flux data is key to improving these models, either for updating existing parameterizations and/or evaluating improved process-based schemes (e.g., 10, 29, 98–100). Statistically upscaled models also have the potential to inform improvements in process-based models through benchmark intercomparisons; however, recent work has been focused more broadly on the annual mean and growing season processes with little attention on the ABZ NGS [101, 102].

Many model algorithms employed for lower latitudes are not appropriate for ABZ ecosystems due to the unique plant communities, phenology, light conditions, and permafrost soils of the ABZ, but the lower latitude algorithms are being adapted as needed as part of model development and improvement efforts. For example, applying Arctic-specific plant functional types that include shrubs and other vascular plants along with a modified evaporation rate can improve overall model performance by improving soil moisture estimates, although these changes may also lead to an overestimation of late-winter CO₂ emissions [100]. Simulation of vegetation hardening, or tolerance to freezing, with the use of explicit representation of plant hydraulics is also useful to introduce reductions in plant water loss to prevent unrealistic winter desiccation in northern regions [103]. Furthermore, the global application of model factors controlling maximum electron transport and carboxylation and thus photosynthesis rates in winter may be incorrect, biasing with too high values for the ABZ [98]. These photosynthetic constants can instead be better initialized from the previous growing season for tundra areas rather than using global constants [98], creating lower and more realistic spring GPP values.

Permafrost soils and their freeze-thaw dynamics are especially challenging for models to represent. It is important to consider both soil properties, such as temperature and water content and phase, and microbial activity, as well as gas movement, storage, and exchange with the atmosphere to simulate an instantaneous carbon flux and project future changes. Recently, Tao et al. [24] implemented model improvements to the soil water phase-change scheme, decomposition rate, and cold-season emissions pathways through ice cracks and plant tissues to improve the NGS soil temperature, duration of the zero-curtain period, and the carbon emissions of simulated tundra ecosystems. Meanwhile, Larson et al. [29] sacrificed spatial variability for a more detailed vertically resolved permafrost soil scheme, which accounts for changes in soil texture and thermal and

hydraulic conductivity while soil accumulates. The resulting soil column accurately simulates soil temperatures and heterotrophic respiration during the fall zero-curtain.

Snow cover and its properties are changing rapidly but highly heterogeneously across the ABZ [104]. Accounting for snow and ice cover extent and depth is also critical for simulating NGS carbon emissions via soil temperature-dependent and physical emission processes. High-resolution snow depth rasters informed by satellite data account for local topography and accurately determine soil temperatures in a multi-layer permafrost soil model [105]. When coupled to a permafrost carbon model, these snow products can be applied over the satellite record to determine the sensitivity of heterotrophic respiration to seasonal and long-term snow cover changes [31]. In models that independently simulate snow accumulation, single-layer snow schemes may underestimate the insulation effect of snow, leading to a cold bias in soil temperature. Instead, a dynamic multilayer scheme improves permafrost extent and produces doubled winter respiration and higher vegetation carbon content [106]. The timing of ice-off is important for simulating NGS emissions from aquatic ecosystems, which can be substantial with improved lake circulation representation [54].

After incorporating additional site-level observations, higher-resolution remote sensing inputs, and new process knowledge, these carbon flux models are often compared to each other. Braghieri et al. [107] show that for the North American ABZ the most recent generation of global coupled earth system models has a narrower spread, improves simulation of photosynthesis and respiration metrics against observations, and projects a stronger future net sink compared to their previous iteration during the entire annual cycle. However, no separate comparison is made for the NGS. Similar model ensembles are also used to evaluate new models and products. For example, the carbon flux product produced by Liu et al. [10] that incorporates soil moisture observations is overall more responsive to abnormal temperature conditions during the shoulder seasons than previous models.

Atmospheric Constraints to Flux Models

Recent work has used atmospheric concentration measurements from towers, aircraft, and satellites to evaluate carbon flux models. The availability of each of these data sources has substantial spatial and temporal variation. As with site-level carbon flux data, atmospheric concentration data during the NGS are limited and under-sampled compared to during the growing season. Evaluations by atmospheric concentration measurements use atmospheric transport models, which are subject to their own uncertainties [108]. An additional limitation in assessing the performance of carbon flux models using atmospheric models is that the atmospheric model can only incorporate the integrated changes in the atmosphere and thus the net flux.

Atmospheric inversion studies use atmospheric concentration data and iterative numerical processes to determine an optimized carbon flux at the surface. The optimization process allows the atmospheric inversion to calculate the carbon flux that best matches the atmospheric concentrations observed without being constrained to the processes of the model that produced the initial estimate. Byrne et al. [109] found that their satellite-optimized NGS respiration emission estimates make up a larger portion of the annual total than the data-driven emission estimates from an ensemble of global process-based models, suggesting that process-based models might be underestimating NGS emissions. This difference is likely due to the lag in peak fall respiration driven by warmer subsurface soil temperatures during the zero-curtain and the timing of soil-insulating snowfall that are not captured by the other models. Randazzo et al. [110] performed a geostatistical inversion using aircraft concentration data to get optimized fluxes that revealed contrasting responses to fall heating between boreal (increased uptake) and tundra (increased respiration) ecosystems in Alaska. Inversion results can also provide a metric for comparison with non-optimized flux products, such as the ensemble of inversions used by Liu et al. [10] and Watts and Farina et al. [96]. Additionally, optimized fluxes were used as input to the atmospheric transport simulations of Lin et al. [111] to attribute changes in CO₂ seasonal cycle amplitude to enhanced seasonal carbon exchange in Siberian ecosystems.

Atmospheric concentration data can also be used in carbon flux evaluation frameworks without performing an inversion. In these cases, the atmospheric data are used to evaluate a flux product [23] or as a guide to inform which of several formulation options (parameterizations, scaling assumptions, etc.) are most consistent with carbon changes in the atmosphere [96, 112]. With these data, Schiferl et al. [112] also determined that additional carbon emissions observed during the fall are likely driven by physical processes, exhibited as bursts, not directly related to soil temperature. Furthermore, they found previous estimates of NGS flux by studies over larger domains [2, 9] were overestimated for the Alaska North Slope, which highlights and supports the usefulness of aircraft atmospheric observations to evaluate individual regions [113].

Trends in Total Carbon Budgets

Because of the high variability as well as lack of NGS CO₂ flux data, biomes-wide NGS CO₂ flux budget estimates remain highly uncertain. Aquatic ecosystems are net CO₂ emitters during the NGS and most of the growing season [52, 114]. It remains unclear whether terrestrial NGS CO₂ emissions can exceed net growing season CO₂ uptake at regional scales, especially in the northern parts of the ABZ. The average in situ and model-based terrestrial net NGS CO₂ emissions estimated for the past two decades in the northern permafrost

region or Arctic-boreal domain range somewhere between 500 and 1600 Tg C year⁻¹, while growing season net CO₂ uptake is often 1000 Tg C year⁻¹ or more [2, 48, 96]. With the highest NGS CO₂ emission estimates, the region is an annual CO₂ source, and the net CO₂ emissions can be as high as 10% of anthropogenic carbon emissions [115]. However, comparing these NGS and growing season estimates is challenging as the time periods and regions considered differ across the studies. The majority of in situ-based synthesis and upscaling (i.e., data-driven empirical modeling) studies still suggest the terrestrial boreal region to be a relatively strong annual CO₂ sink and tundra a small CO₂ sink or CO₂ neutral [48, 96, 116], which is also true for process-based models [117]. Some studies find an increase in the seasonal amplitude of carbon emissions (difference between winter emissions and GS uptake) and find that much of the increase is due to an increasing boreal sink and increasing fall emissions [118]. The boreal sink is moving earlier in the year but the total growing season not changing in length showing limitations to the growing season sink.

Based on a synthesis of process, inversion, and statistical model outputs produced in Watts and Farina et al. [96] and in situ data in ABCflux (13; see Table 1), the mean seasonal flux during the NGS (September–May) varies between 36 and 81 g C m⁻² season⁻¹, while during the growing season (June–August) the average flux is –72 to –108 g C m⁻² season⁻¹ (positive represents net emission and negative net uptake), with in situ-based average estimates tending to suggest higher growing season sink and NGS source compared to model estimates. However, recent studies have indicated that in some parts of the Arctic, such as in Alaska or some parts of northwestern Canada [23, 65], or in drier tundra ecosystems in general [1, 48], NGS CO₂ emissions are exceeding growing season uptake. However, syntheses may currently overestimate

Table 1 Terrestrial average cumulative non-growing season (NGS; September–May) and growing season (GS; June–August) fluxes of net ecosystem exchange (g C m⁻² season⁻¹) based on models included in Watts and Farina et al. [94] and year-round Arctic-boreal sites included in ABCflux [13]. Most of the models considered here covered the full annual cycle during 2003–2015 except for one inversion (2015), one statistical model (2003–2010; one model did not include April–May period). Positive values represent net CO₂ emissions and negative values net CO₂ uptake. A NGS:GS ratio below 1 is still a net sink and above 1 would be a net source

	NGS (g C m ⁻² season ⁻¹)	GS (g C m ⁻² season ⁻¹)	NGS:GS
Inversions	69	–103	0.67
Process models	49	–77	0.64
Statistical models	67	–81	0.83
Model range	36 to 81	–72 to –97	0.37 to 0.85
In situ	80	–108	0.74

NGS carbon fluxes and underestimate growing season sinks based on a bias in a commonly used gap-filling technique [119]. Still, the dominance of NGS net CO₂ emissions over growing season uptake may increase in the future [58] as plant carbon uptake may reach a maximum and warmer temperatures favor higher respiration, all while NGS CO₂ emissions can continue to increase if the environmental conditions are favorable (i.e., soils are unfrozen and organic matter for decomposition exists) [2, 117]. Some of these trends may already be starting with studies finding tundra emissions have outpaced even the uptake from boreal forests in Alaska making Alaska a net carbon source from 2012 to 2014 [9]. However, models disagree on the fate of the net carbon balance with some models predicting vegetation biomass and uptake outweighing soil carbon and permafrost loss [117]. Most important to this review, the models underestimate NGS emissions when these emissions may already offset the growing season sink [2, 58].

Trends in NGS CO₂ fluxes over the past two decades remain uncertain, and no circumpolar statistically significant changes in in situ or upscaled NGS CO₂ fluxes in the tundra or permafrost regions have been detected [2, 40]. However, the trends are known to vary in different regions and ecosystems with, for example, Alaska showing increases in NGS CO₂ emissions during the past decade both based on in situ terrestrial and atmospheric measurements [1, 9, 25, 120], linked to the extended zero-curtain.

Table 2 Summary table of challenges and remedies suggested for improving the understanding and modeling of NGS CO₂ fluxes from the ABZ. Key challenge areas are the same discussed in “Conclusions” and are summarized here: (1) incorporate new understand-

Although freezing degree days were found to be one of the most important predictors for annual NEE [48], other conditions characterizing the winter climate, particularly snow cover, have been less important when upscaling NGS CO₂ emissions. This may be a result of high uncertainty in regional snow products or because snow presence alone is not as strongly linked to ground temperatures and carbon cycling as, for example, snow depth and density. Remotely sensed microwave radiometer observations seem promising in mapping snow depth and density as well as landscape freeze-thaw status (e.g., [104]); however, these products currently have a relatively low spatial resolution (25 km) that might not accurately represent the heterogeneous and patchy ABZ snow conditions.

Conclusions

NGS carbon fluxes in the ABZ are dynamic and quickly changing. As warming is likely to continue at an accelerated rate, increased NGS carbon losses can be expected from the ABZ. NGS CO₂ emissions are largely controlled by belowground processes and factors controlling temperature, oxygen availability, and carbon substrates. We list the most important knowledge gaps reviewed and provide suggestions on how to improve those in Table 2. Key challenges include the following: (1) Ongoing efforts

ings and changing permafrost dynamics; (2) data shortages in critical areas; (3) improved gridded data products needed; and (4) long-term data collection is needed to understand changes

Key challenge area(s)	Problem	Remedy
1, 2, 3, 4	NGS CO ₂ emission responses to disturbances (e.g., abrupt thaw, fire, vegetation regime)	Incorporate feedbacks and empirical studies on ecosystem interactions. Better maps of disturbance areas. Long-term data coverage in disturbed areas
1, 3, 4	NGS CO ₂ flux relationship with snow conditions (cover, depth, density, rain-on-snow events)	Improve representation and understanding of snow conditions on carbon fluxes and representation in gridded products
1	Microbial communities active and responsible for CO ₂ production during the NGS	Incorporate microbial diversity and functional traits into models and study the impact on carbon fluxes
1, 2	Large variety in outputs between statistical, process, and inversion/concentration-based modeling	Comparison of statistical, process, and inversion model outputs during the NGS. Improve data coverage in under sampled areas
2, 4	Lack of comprehensive NGS CO ₂ fluxes	Strategically increase flux monitoring both spatially and temporally, i.e., more sites and longer-term data. May require specific funding mechanisms
2	Improved protocols for flux data processing during NGS	Empirical studies on best practices for flux data in the ABZ including gap-filling, filtering, and partitioning flux data which may need special considerations
1, 3, 4	Carbon flux magnitudes in a changing climate	Incorporate long-term data in changing areas to better understand fluxes in future scenarios and conduct field and laboratory experiments simulating these changes
3	Poor representation of NGS conditions	Better gridded data products characterizing NGS conditions. Considerations for below-ground processes and microbial properties during the NGS

to model changes in the ABZ lag the improving process-level understanding being gained on the ground. As newer models provide more reliable results, permafrost processes should continue to be incorporated into Earth system models [90]. (2) In order to improve models, additional data in underrepresented areas is also greatly needed [21, 121]. (3) Improved coverage in gridded data products needed for modeling emissions is also necessary, both in spatial and temporal scales as well as data quality [122]. (4) While carbon flux estimates are improving, long-term data collection for model calibration and innovative numerical approaches are still needed to improve model processes influenced by winter dynamics [123]. Improving these aspects would significantly reduce uncertainties related to ABZ carbon processes and budgets in current and future climates.

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Availability of Data and Materials Data used for calculating carbon budgets can be obtained from a series of sources compiled by Watts and Farina [94]. Fluxes can be found in the following sources: European Fluxes Database (<http://www.europe-fluxdata.eu/home>); Ameriflux (<http://ameriflux.lbl.gov/>); AsiaFlux (<https://www.asiaflux.net/>); <https://data.g-e-m.dk>, ABCFlux database (https://daac.ornl.gov/ABOVE/guides/Arctic_Boreal_CO2_Flux.html); <https://doi.org/10.3334/ORNLDAAAC/2121>; <https://doi.org/10.3334/ORNLDAAAC/1692>.

Data for creating Fig. 1 can be found in the FLUXNET-CH4 Community product: <https://doi.org/10.5194/essd-13-3607-2021>.

Declarations

Ethical Approval Not applicable as no human or animal subjects were used.

Competing Interests The authors declare no competing interests.

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