Received: 21 March 2022 | Revised: 12 April 2022 | Accepted: 12 April 2022

DOI: 10.1002/glr2.12010

REVIEW ARTICLE

Grassland Research Open Access

Use, calibration and verification of agroecological models for boreal environments: A review

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Handling Editor: Bernhard Schmid

Funding information
Milk and Beef Production in Finland - Progressing Pathways Carbon-neutrality by 2035, Grant/Award Number: VN/28562/2020-MMM-2; Mechanisms for nitrous oxide uptake in cropping systems in different climate zones (NSINK), Grant/Award Number: 334422

Abstract

Past assessments report negative impacts of the climate crisis in boreal areas; but milder and shorter winters and elevated atmospheric CO_2 may provide opportunities for agricultural productivity potentially playing a significant role in future food security. Arable cropping systems are expanding in boreal areas, but the regional mainstay will likely continue to be livestock production. Agroecological models can when appropriately calibrated and evaluated, facilitate improved productivity while minimising environmental impacts by identifying system interactions, and quantifying greenhouse gas emissions, soil carbon stocks and fertiliser use. While models designed for temperate and tropical zones abound, few are developed specifically for boreal zones, and there is uncertainty around the performance of existing models in boreal areas. We reviewed model performance across boreal environments and management systems. We identified a dearth of modelling studies in boreal regions, with the publication of three or less papers per year since the year 2000, constituting a significant research gap. Models IFSM and BASGRA_N performed best in grassland production, DNDC best in predicting soil N_2O and NH_3 emissions. No model outperformed all others, strengthening the case for ensemble modelling. Existing agroecological models would be worthy of further evaluation, providing model improvements designed for boreal systems.

KEYWORDS

boreal region, carbon–nitrogen cycling, ecophysiological modelling, greenhouse gas emissions, soil carbon

INTRODUCTION

Circumboreal countries adjacent to polar regions provide significant global greenhouse gas (GHG) emissions mitigation opportunities due to their potential for increased carbon sequestration and storage. Boreal soils are known to be important carbon stores and sources and may have the potential to act as further sinks (Lind et al., 2020). As the climate warms, boreal fertile soils, previously either under permafrost or exposed to snow/thaw cycles, might release C either as CO_2 or methane and eventually become available for agriculture increasing the potential for global food production. Given the uncertainty around the risks and opportunities arising in boreal regions, agro-ecological simulation models may help elicit and contrast manifold metrics generated using management × environment scenarios (viz Christie et al., 2018, 2020). However, the vast majority of extant models have been designed for—and applied in—non-boreal areas characterised by milder temperatures falling within biological optima for plant growth and livestock performance (Harrison, Christie, et al., 2014; Harrison, Jackson, et al., 2014). As such, there is considerable uncertainty regarding the performance of these 'temperate-borne' models when applied in boreal conditions, for the accuracy in which agricultural productivity, C and N and GHG emissions are simulated.

The science underpinning ecosystems models has advanced over several decades into systems-based approaches for studying environmental processes as networks of ecophysiological interactions rather than in isolation (Jones et al., 2016). As such, models have increasingly become indispensable tools in both agricultural planning, adaptation and complementing measurements obtained from laboratory experiments or field trials. The use of models to simulate complex systems enables (1) integration and interpretation of multiple input variables, (2) prediction of the effects of climate change on whole landscapes and regions, (3) holistic quantification of GHG emissions and (4) improved mechanistic understanding of soil–plant–animal interactions, accounting for dynamic feedback loops and emergent properties (Harrison et al., 2012a, 2012b; Phelan et al., 2015). To some extent, models allow insight into interactions between processes and to make predictions and contrast alternative scenarios. Changes in soil carbon cycling due to management interventions for example can evolve over several decades (Forster et al., 2021); time horizons that are impractical and costly to measure in field experiments, and given the imminent need to reduce atmospheric GHGs (Alcock et al., 2015; Sándor et al., 2016, 2020), simulations permit assessment and exploration that would often be not otherwise possible Harrison et al. (2017).

Agro-ecological models have long been used to simulate management × environment scenarios in Europe (Lugato et al., 2015; Metzger et al., 2005), North America (Guest et al., 2017; Khalil et al., 2020; D. Kim et al., 2019), Australia (Bilotto et al., 2021; Coleman et al., 1997) and elsewhere, with applications ranging from reductionist to holistic systems with scales ranging from the paddock to the planet (Harrison et al., 2011). In contrast, the number of model studies conducted in boreal climates—defined here as climates characterised by very cold winters and short, cool summers such as those found at latitudes greater than 60°—are much more limited. While process-based agro-physiological models have demonstrated reliability for the contexts in which they have developed, the majority of these models require (1) initialization, that is, input of initial data, (2) calibration or parameterisation, where simulations are calibrated by modifying model parameters/equations such that simulations to better match measured variables and (3) evaluation, where calibrated models are compared with independently measured data and information (Harrison et al., 2019). There is limited evidence of either model calibration or evaluation for boreal environments, particularly in simulating GHG emissions. This key information gap forms a central focus of the present review.

Studies have been carried out in diverse climatic zones, for example, Jose et al. (2016) examined the accuracy and efficiency of several models in simulating livestock-derived GHG's but paid less attention to specific environments, while Harrison, Christie, et al. (2014) and Harrison, Jackson, et al. (2014) and Ho et al. (2014) modelled the productivity, profitability and GHG emissions of farms as a function of herd management, animal genotype and pasture nutritive quality on farms in Australia. An 'ensemble modelling' approach was used by both Ehrhardt et al. (2018); and Sándor et al. (2020) to integrate multiple models and multiple management scenarios, although even the performance of the ensemble was limited in Scandinavian regions. Model intercomparisons have also been carried out for Canada (e.g., Guest et al., 2017; Sansoulet et al., 2014) with moderate success, and models have been successful in simulating agriculturally relevant outputs in a range of climates from Europe (Lugato et al., 2015; Metzger et al., 2005), North America (Höglind et al., 2016), Australia (Coleman et al., 1997), but studies over Boreal Europe are much more limited (Höglind et al., 2013; Korhonen et al., 2018).

Boreal regions will experience increasing environmental and agricultural pressure in the coming decades due to agricultural land use expansion and intensification (Unc et al., 2021). This pressure will mean that ecological and socioeconomic implications of farming become ever more important; models used in boreal conditions need to be able to deal with the contrasting soil and extreme seasonal climate conditions including snowfall (Jégo et al., 2014), the subzero temperatures as low as −35°C to −45°C, as well as site-specific livestock management in boreal ecosystems (Figure 1) if they are to be fit-for-purpose.

The purpose of this paper is to review the literature for process-oriented models dealing with managed grasslands in boreal countries, with an aim of identifying process deficiencies in model-based approaches for simulating agricultural and environmental variables, particularly productivity and GHG emissions. Identification of these deficits together with an assessment of the performance of existing models will then form the basis for recommendations for improving modelling of agro-ecosystems in boreal regions. Key areas examined include the performance of models in predicting biomass production, soil C cycling and GHG emissions from soils, plants, and livestock over the range of process-based models.

GRASSLAND AGRICULTURE IN THE BOREAL REGION

The global livestock sector is responsible for about 8.1 Gt of CO_2-e year^{-1}; about 16.5% of global anthropogenic GHG emissions (Twine, 2021) and 57% of that derived from food production (Xu et al., 2021). Livestock farming has been intensifying globally, including the conversion of natural grassland to pasture and increased CH_4 and N_2O emissions, with warming effects on global temperatures being larger than the cooling effect of increased grassland carbon sinks (Chang et al., 2021)

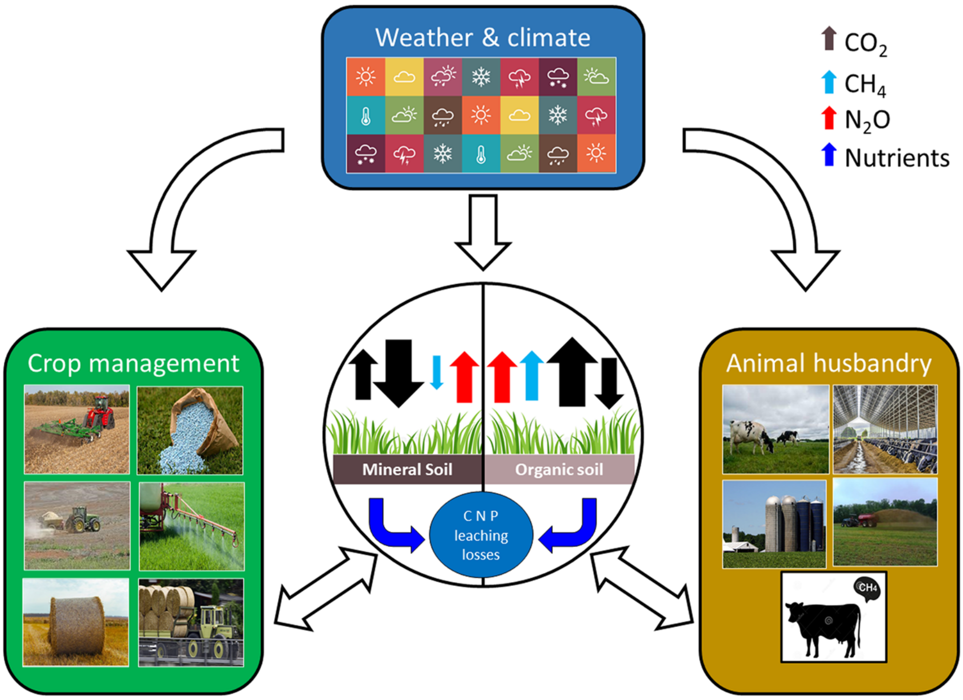

FIGURE 1 Interactions affecting soil/atmospheric fluxes of GHG's (coloured arrows) in agriculture in mineral and organic soils (central circle), including: climate inputs (blue box), crop management including sowing, fertilising, harvest, spraying, baling and transport (green box), animal husbandry including grazing, housing, feed, manure management and GHG emissions, both enteric and from subsequent manure (brown box). White arrows indicate interactions between compartments.

so that grasslands may become a net source of radiative forcing. While the growth in livestock numbers until 2050 will become increasingly underpinned by production of monogastrics (pigs and poultry), ruminant numbers through beef, sheep and dairy production systems will also continue to grow (Harrison et al., 2021).

The 26th Conference of the Parties (COP26) held in Glasgow (Glasgow Climate Pact, 2021) reaffirmed the terms agreed under Article 2 of the Paris Agreement (Paris Agreement to the United Nations Framework Convention on Climate Change, 2015), where more than 150 signatory countries pledged to make efforts to mitigate the impacts of climate change with the aim of keeping global temperatures well below 2°C above preindustrial levels. In the wake of this agreement there has been an increased interest in agricultural land use, and a recognition of the role of grasslands as potential carbon sinks (Whitehead, 2020), both in soils and in vegetation (Harrison et al., 2021). Carbon sequestration in the soil has been recognised as important for climate mitigation and enhancing food security and has led to the political target to increase soil carbon by 0.4%, or '4 per mille' per year (Minasny et al., 2017). According to the 6th Assessment Report (IPCC, 2021), the Paris Agreement targets are likely to be missed during the mid-21st century unless large reductions in GHG emissions are made in the coming decades. While there is hope that the development and application of carbon capture and storage technologies may develop in the future (Wilberforce et al., 2021), synthetic and industrial propositions for carbon capture are unlikely to provide the environmental and agricultural cobenefits offered by nature-based solutions (Harrison et al., 2021).

The need for sustained and harmonized efforts to mitigate global climate change become increasingly urgent. Opportunities arising from the poleward shift of agricultural activities, including increased cultivation and conversion from grassland to arable, and the implications for both food production and GHG emissions increases (Altdorff et al., 2021), have drawn relatively little academic attention, very likely missing opportunities for climate change mitigation and adaptation (IPCC, 2021). Circumboreal countries may have opportunities for increased sequestration efforts from increased crop-mediated CO_2 storage (Fan et al., 2019). Yet, they are also susceptible to climate change effects due to permafrost thawing (Hugelius et al., 2020). Boreal soils are known to be important carbon stores and may have the potential to act as further sinks from the enhancement of vegetation growth due to warming or as carbon sources from warming-induced decomposition of soil organic matter. In particular, peat soils—which occupy some 3.7 ± 0.5 million km^2 (Hugelius et al., 2020) of boreal regions, storing 415 ± 150 Gt C (Beaulne et al., 2021)—could become sources of carbon, including the potent CH_4, due to warming-related increased soil respiration if management is not appropriately adapted to changing environmental conditions (Roulet, 2000). Northern peat soils being cultivated have also caused large carbon losses to the atmosphere in the history (Qiu et al., 2021) and in the present period (Carlson et al., 2017).

Livestock grazing in boreal regions

In boreal areas, livestock farming on grasslands comprises a considerable part of the agricultural sector due to limitations imposed by soil and climate, with permanent pasture comprising 12% ± 8% of Scandinavian, 33% of Canadian, and 97% ± 2% of agricultural land in Greenland and Iceland (FAOSTAT, 2022), thus livestock farming has an important role to play in mitigating agricultural GHG emissions in these regions.

Boreal economies are affected by climate change in both positive and negative ways. For example, elevated atmospheric CO_2 concentrations stimulate photosynthesis of C_3 vegetation and may result in longer growing seasons and increase production (Ergon et al., 2018), while the accompanying increase in microbial activity and shorter freezing periods due to climate warming will probably increase soil enzyme activity (Miura et al., 2020) and respiration (M. K. Kim & Henry, 2013), resulting in soil carbon losses, a problem of concern in soils of high organic content dominant in many boreal landscapes. Ecosystems resilience and vulnerability may also be influenced by changes to seasonal weather patterns, including increasingly variable regional precipitation, which can impact farm activities such as preserving hay and silage on which livestock rely during predictable dry periods (Chang-Fung-Martel et al., 2017; Harrison, Christie, et al., 2014; Harrison, Jackson, et al., 2014).

Since the 1970s, global grasslands have been estimated to transition from an anthropogenic sink to a source of anthropogenic GHG (Chang, Ciais, et al., 2015; Chang et al., 2021) due to increased livestock numbers and conversion of natural grasslands to improved pastures, according to a global modelling assessment. Nevertheless, boreal grasslands studies have concluded to either carbon sinks (Heimsch et al., 2021; Kätterer et al., 2011; Poeplau et al., 2015) or sources (Heikkinen et al., 2013; Lind et al., 2020; Lohila, 2004). Thus, a useful avenue of research is to reduce this uncertainty and assess if boreal grasslands are collectively either a net source or sink of CO_2, both historically and in the future. There remains considerable uncertainty due to regional variability even within boreal areas, so to adequately account for interregional differences, we discuss European and Canadian regions separately.

The Nordic European region

Grasslands in the Nordic regions, which here include Iceland, Norway, Sweden and Finland (Figure 2) consist mainly of timothy (*Phleum pratense*) with red (*Trifolium pratense*) or white clover (*Trifolium repens*) (Helgadóttir et al., 2014). In Finland, 10.4% of the cultivated area (252 000 ha) is on organic soil (Myllis et al., 2012). This land may form significant sources of N_2O and CO_2 when drained for agriculture, a problem that may persist even when cultivation ceases (Maljanen et al., 2010), making their careful management and preservation of critical importance. The managed grassland area in Finland has been steadily decreasing due to reductions in livestock farming (Niemi & Minna, 2019). Conversion to arable grassland is becoming common as agricultural technologies and practices advance and global warming makes temporary pasture and crop production more tenable (Soussana et al., 2010). Arable farmland in Finland is generally thought to be a source of carbon emissions (Official Statistics of Finland, 2017). On the other hand, a study conducted in southern Finland using eddy covariance over 2 years showed that grasslands were a net sink of carbon (Heimsch et al., 2021). Contrarily, in Eastern Finland, mixed grassland of timothy and meadow fescue (*Festuca pratensis*) were found to be a large carbon source when offtakes were taken into account (Lind et al., 2020), although to date GHG emissions associated with grasslands in Finland have not been well quantified, and large-scale carbon balance estimates are not available.

In Sweden, agricultural land comprises around 3 232 039 ha, 7.9% of the surface area (Lundblad, 2015), of which 16% is pasture, and 7% (225 722 ha) is on organic soil. There is good potential to increase soil organic carbon (SOC) stocks further with the addition of ryegrass cover cropping methods (Poeplau et al., 2015). In Norway, while the bulk of carbon storage is thought to be in forests and wetland, agricultural areas have been envisioned as being carbon sources (de Wit et al., 2015). Bartlett et al. (2020) estimated grassland SOC storage in Norway to be 98 t C ha, although there is a lack of data on deeper soil C accumulation and in grasslands more generally. Grasslands in Iceland have been found to act as C sinks due to elevated N inputs both from agriculture and sea-bird manuring waiving N as a limiting factor (Leblans et al., 2017).

Canada

In Canada, timothy (*Phleum pratense*), alfalfa (*Medicago sativa*), Kentucky bluegrass (*Poa pratense*), crested wheatgrass (*Agropyron cristatum*) and tall fescue (*Festuca arundinacea*), all of which have good winter hardiness and are suited to cooler climates, are usually grown for feeding livestock. A study of the sink potential of agricultural soils (Boehm et al., 2004) indicated enhanced C sequestration associated with conversion to zero tillage, and a study in Canada using Roth-C (Fan et al., 2019) indicated that increased plant inputs made cultivated soils a sink of carbon on the whole. However, this sink is steadily decreasing since then. Moreover, forage areas are increasingly converted to cropland (Mardian et al., 2021) and may become a net source of carbon if such trends continue due to (1) soil cultivation enhancing soil carbon turnover, (2) shallower root profiles and reduced soil carbon buried deeper in the profile of annual crops relative to perennial, deep-rooted pastures and (3) increased use of nitrogen fertilizers, which may increase emissions of N_2O (Harrison et al., 2016; Shcherbak et al., 2014) while enhancing carbon sequestration.

METHODS

Independent literature searches were conducted using the Web of Science Database® and Google Scholar between May 4 to July 30, 2021. Search terms were: (a) grasslands, modelling and GHG emissions, soil carbon, methane,

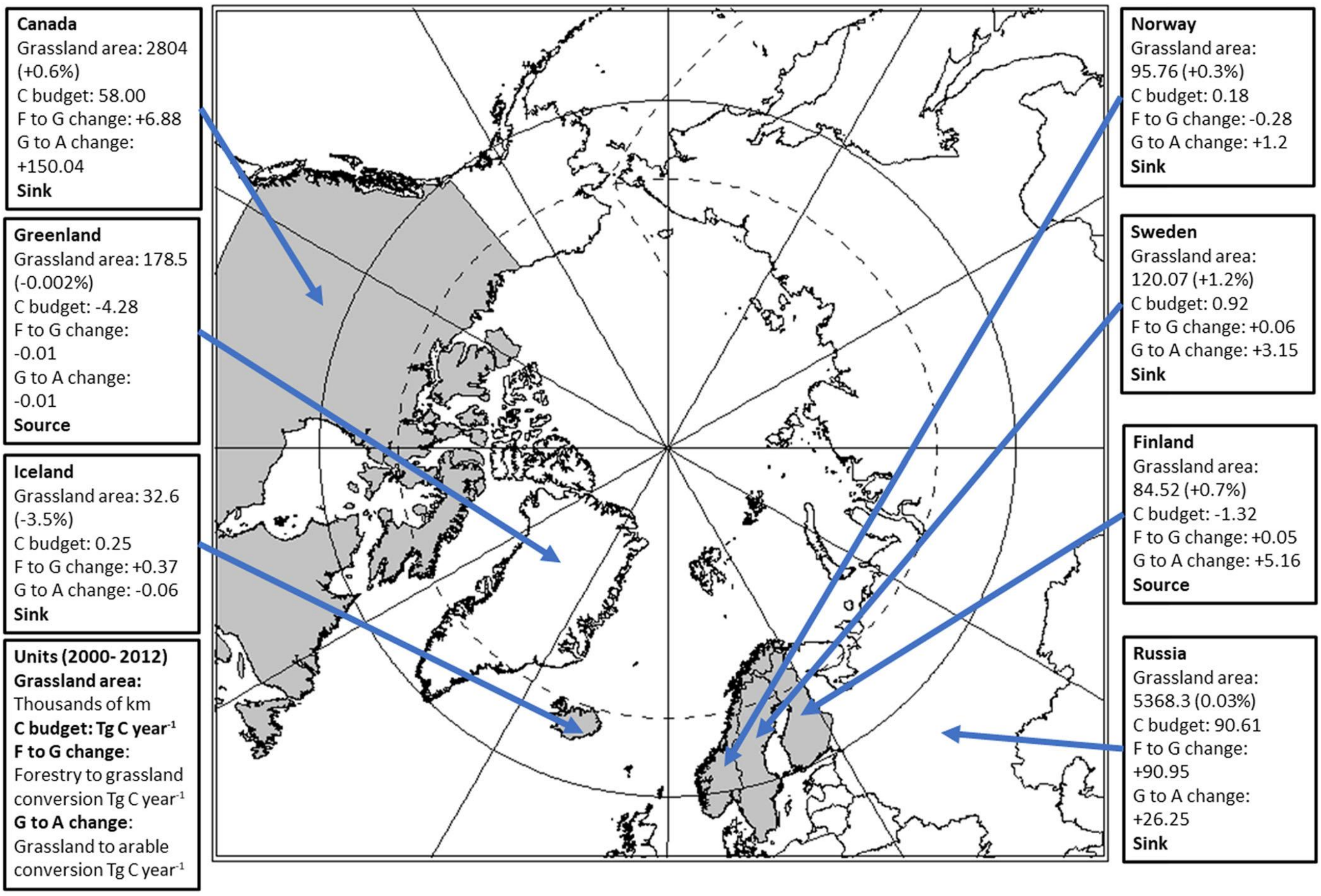

FIGURE 2 Regions examined in this study (greyed areas) and other boreal regions not included in this study (in white). Total grassland area (thousands of km) and percent change, carbon budget, and change associated with conversion from forestry to grassland (F to G change) and grassland to cropland (G to A change) in Tg C year^{-1}, for the period 2000–2012 modelled using ORCHIDEE_GM (Chang et al., 2021), and a summary carbon '**Sink**' or '**Source**', in bold.

carbon dioxide, nitrous oxide accompanied by words restricting results to boreal foci: boreal, Finland, Sweden, Norway, Denmark, Iceland, Canada and Russia. Our searches for Icelandic, Estonian and Latvian grasslands studies did not result in any literature reference identified. Only original research articles (not reviews or meta-analyses) were included. Papers were excluded if they had primary focus on statistical modelling, measurements or monitoring without modelling, if they did not represent regions within scope of the present review, for example, Scandinavia, Iceland, Canada, or those not published in English. No papers from boreal Russia, in theory a major area for this type of research, were found. Excluding duplicate hits, the searches provided an initial total of 65 papers published between 1998 and 2020, of which on inspection 21 were retained as meeting our criteria for inclusion. Publications were weighted towards recent studies as 10 were published in or after 2016, three of which were published in 2020, and no papers between 2008 and 2012 were found (Figure 3).

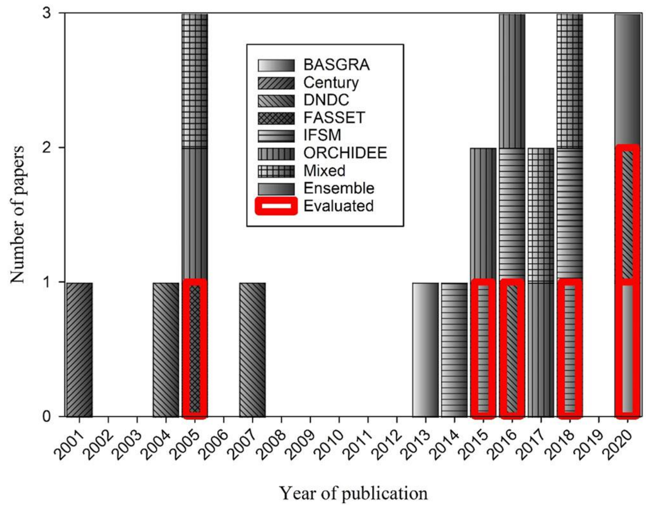

FIGURE 3 Number and type of model used in boreal modelling studies by year. Ensemble and mixed model approaches incorporate various models, but these approaches are judged sufficiently different form single model methods to be classed as models in their own right. Red highlighted papers contain model evaluations.

For an assessment of model validation results, an assessment method was adapted from Despotovic et al. (2016), He et al. (2020), and Moriasi et al. (2015): model performance was graded as 'poor', 'fair', 'good' or 'excellent'. Validation results from each article were extracted and scored from 1 to 4 on this scale (see Supporting Information material for details), and mean scores across methods were calculated. A final score was calculated as the sum of the validation scores. It is recognised that this methodology has its weaknesses, in that it attempts to compare the relative merits of a range of validation equations over a broad suite of variables, regions and timescales, using subjective interpretations of the results found, though every effort has been made to ensure our results reflect those of the original authors.

RESULTS

Overall, seven models were found, though one, CATIMO, only appeared in ensemble studies and so is treated as such. The key result in Figure 3 is the dearth of modelling studies in Boreal grasslands with three or less studies per year in the last 20 years, in contrast with a large number of publications on boreal forests. This result is investigated further in the following sections as each model in the literature search is discussed.

BASGRA and BASGRA_N

The BASGRA_N model is an advancement on the earlier BASGRA grasslands model (Höglind et al., 2013, 2016, 2020); both models are designed for cold climate growth of timothy in Scandinavia. The model is process-based and uses the source/sink concept for net exports and imports of photosynthetic assimilates between photosynthetically developed leaf tissue and source tissue, developing plant parts and roots (Persson et al., 2019) on a daily time-step with temperature and day length as driving variables. The model is also designed to account for winter conditions such as snow cover and soil freezing which are common to boreal regions and typically lead to high rates of tiller death and reduced spring season growth. BASGRA is the only model which simulates tiller death and growth dynamics in timothy, making it especially useful in northern regions where this is the primary forage grass. To date, there is a lack of comparable Scandinavian data from which to assess BASGRA_N model performance regarding tiller dynamics in response to N fertilisation (the fraction of vegetative, nonelongating and elongating generative tillers in swards and their winter survival) as well as fluxes in C and N (soil respiration, N_2O-emissions and N leaching), making this an area in need of further research.

BASGRA was designed with simulating biomass production and feed value, and accordingly included all the processes of tillering, foliar dynamics, winter death and spring regrowth of timothy. The aim of the updated BASGRA_N model (Höglind et al., 2020) was to supplement this with a number of additional features such as forage nutritive values, C and N cycling and GHG emissions, as well as accounting for N limiting conditions and the dynamics of cell wall content. Otherwise, the updated model retains many of the key features of its predecessor (Höglind et al., 2013). Model performance assessment was only assessed by Höglind et al. (2020) who reported reasonable performance in simulating dry matter production and good performance for crude proteins, but less reliable correlations between fertilisation and dry matter production (Table 1).

TABLE 1 Summary of score given for each model for variables validated

Variable	BASGRA_N	CATIMO	DNDC	DNDC v.CAN	FASSET	IFSM	STICS
Biomass							
CP (g m^{-2})	Good	-	-	-	-	-	-
DM (g m^{-2})	Good	Fair	Fair	-	-	Good	Fair
LAI	Good	Excellent	-	-	-	-	Excellent
NDF	-	-	-	-	-	Good	-
N (uptake)	-	-	-	-	-	Fair	-
P (uptake)	-	-	-	-	-	Good	-
N fertilizer DM	Poor	Poor	-	-	-	-	Fair
Gas emissions							
N_2O	-	-	Fair	-	Good	-	-
NH_3	-	-	Fair	Good	-	-	-
Soil climate							
WFPS	-	-	Fair	-	-	-	-
Soil temperature (°C)	-	-	Good	-	-	-	-
N (mineral) (kg ha^{-1})	-	-	Poor	Good	-	-	-
Number of studies	2	1	2	1	1	1	1
Overall model score	10	7	12	6	3	11	8

Note: Values represent the mean of scores given to each validation method where more than one was used to assess the variable. Validation data was extracted from five papers (Chatskikh et al., 2005; Congreves et al., 2016; He et al., 2020; Höglind et al., 2020; Jégo et al., 2015; Korhonen et al., 2018) from the initial literature search and summarised according to a system derived from Despotovic et al. (2016); He et al. (2020); and Moriasi et al. (2015).

CENTURY and DayCent

The CENTURY model is used to assess SOM processes involving C, N, P and S, and the effects of changes in management to soil processes. The model consists of a variety of submodels which can simulate grasslands, agricultural crop systems, forest systems and savannahs and works on a monthly time-step and is useful for modelling long-term changes to SOM of over 10–100 years. DayCent is a daily timestep version of CENTURY (Del Grosso et al., 2001) developed to link atmospheric models to better estimate trace gas fluxes from different environments (Parton et al., 1998). For boreal regions, Smith et al. (2001) simulated the effects of management changes resulting in increases of sequestered C of 0.62 and 0.44 Mg C ha $year^{-1}$, respectively for conversion of arable to grassland and the inclusion of forage in crop rotations in western Canada using DayCent.

DeNitrification-DeComposition (DNDC) and variants

The field-based DNDC model was designed as a process-based model which computes a range of descriptors related to soil carbon storage such as estimated soil-atmosphere fluxes, soil organic matter (SOM) storage and C and N related biogeochemistry in agricultural systems by tracking groups of microbes active under different environmental conditions as well as predicting crop and livestock yields (EOS, 2017). DNDC has been used with some success in a range of boreal grassland situations, although the main model was primarily used in arable systems. DNDC has produced a suite of models adapted to different region and management practices identified by a prefix. For example, NZ-DNDC is a New Zealand-specific model, and the Manure DNDC model specialises in manure emissions from livestock farms. Unless specified with a prefix we refer to the main crop model in this review.

Grant et al. (2004) used DNDC to estimate the impact of change in management practices on N_2O emissions for seven major soil regions in Canada from 1970 to 2029. They estimated significant reduction of N_2O emissions by converting from arable to managed permanent grassland and adopting no-tillage (Table 2). However, other factors such as soil type and regional differences influenced the general trend, like the adoption of no-tillage in eastern Canada, which would increase N_2O emissions as soils are wetter than in the semi-arid zone of the Prairies. However, the conversion of cropland to grassland in eastern Canada would strongly reduce N_2O emissions because of depleted organic matter of the mineral soils and reduced N fertilisation. This overall decrease was attributed to the slower decomposition of SOM in no-till compared to conventional tillage. Increasing N-fertilizer application rates by 50% would increase average emissions by 32%, while decreasing them by 50% would decrease emissions by 16%.

He et al. (2020) calibrated and validated DNDC to simulate the impacts of manure management practices, including slurry application rates and seasonal timing, on N_2O emissions, using N_2O flux data, soil moisture, soil inorganic N, biomass and soil temperature measured from managed grasslands in contrasting climates of Canada (Table 2). The performance of DNDC was evaluated using NRMSE and NARE (See Supporting Information material), statistics, and was found 'fair' (<20%) to 'excellent' (≤10%) for predicting biomass, 'good' (<10% to ≤20%) for predicting soil temperature, but only 'acceptable' (<20%) in estimating soil water and inorganic N contents (see Table S2). The latter result could be associated with the limitations of a cascade water transfer sub-model and inaccuracies in simulating root development/uptake. The DNDC model demonstrated 'fair' (NRMSE <20% to <30%) performance in predicting daily N_2O fluxes, capturing the impact of the timing and rate of slurry application and soil texture on total N_2O emissions. Finally, the authors recommended improvements to DNDC simulation of soil freeze-thaw cycles, manure decomposition dynamics, soil water storage, rainfall canopy interception, and microbial denitrification and nitrification activities in grasslands. A modified version called DNDC v.CAN was used by Congreves et al. (2016) in Quebec, Canada, to simulate the effects of swine slurry distribution on grasslands and bare soil, improving the models capacity to predict NH_3 losses from soils, and also provided reasonable model validation results (Table S2). Levy et al. (2007) conducted a study for all of Europe in which grasslands in a range of biogeographical regions were assessed, including arctic and boreal regions. Their study did not attempt to model changes in atmospheric CO_2 or temperature resulting from climate change and concluded that mitigating livestock-based GHG emissions rather than attempts to increase C sinks was more likely to be beneficial in terms of limiting global temperature change.

FASSET

FASSET is a whole farm soil–plant–atmosphere model developed by the Danish Institute of Agricultural and Fisheries Economics to deal with all major N flows at the farm level (Jacobsen et al., 1998). FASSET dynamically simulates the soil-plant-climate system at the field level on a daily time-step (Olesen et al., 2002). This was further developed by Chatskikh et al. (2005), who developed and added an algorithm for N_2O production and emission from agricultural soils. The model of Chatskikh et al. (2005) simulated carbon and nitrogen turnover on a daily basis. Both nitrification and denitrification were included in their model as sources for N_2O production with N_2O emissions influenced by soil microbial and physical conditions. Their model was tested on experimental data of N_2O emissions from grasslands in Finland, Denmark and UK, thus at sites that differed in their climatic conditions, soil properties and management. The simulated N_2O emissions showed a nonlinear response to increasing N rates with increasing emission factors at higher N rates. This result aligns with trends reported in

TABLE 2 Summary of papers examined in this review

Serial	Model	Reference	Location	Simulated period	Management	Intervention	Outcome
1	BASGRA	Höglind et al., 2013	Northern Europe, Russia	1960–1990 and 2040–2065	Permanent pasture	Irrigated and non-irrigated pasture	Increased DM yields: 14% irrigated and 11% non-irrigated.
2	BASGRA_N	Höglind et al., 2020	Norway	1985–1988	Permanent pasture	Model validation for dry matter, crude protein, NDF and soil N under different fertiliser regimes	Yield and CP responses to N modelled satisfactorily.
3	CENTURY	Smith et al., 2001	Canada	2000–2010	Arable and pasture	Conversion of arable to pasture, crop rotations and variable fertiliser applications	Conversion of arable to pasture, conversion to forage and conversion to no-till and reduction of summer fallow period may sequester 0.62, 0.44, 0.13 and 0.15 Mg C ha^{-1} $year^{-1}$ respectively.
4	DNDC	Grant et al., 2004	Canada	1970–2029	Land-use conversion	Conversion of arable to pasture and conversion to no-tillage	60% and 33% reduced N_2O emissions from conversion to grass, and conversion to no-tillage respectively.
5	DNDC	He et al., 2020	Canada	2001–2003	Grassland	Manure application rate (zero, spring, autumn, split between spring and fall) and timing (early spring, late spring, split)	Daily soil N 2.2–45.8 kg N ha^{-1}, cumulative soil N 44.4–1327.3 kg N ha^{-1}.
6	DNDC	Levy et al., 2007	Europe-wide	20 years	Grasslands	Business as usual over 20 years	Most grasslands estimated as net sources of GHG's, N_2O and CH_4 (23 Tg C $year^{-1}$). Suggested enteric CH_4 reduction more effective overall than sequestration attempts.
7	DNDC v.CAN	Congreves et al., 2016	Quebec, Canada	1999–2005	Grassland and bare soil.	Swine slurry applied to grassland and bare soil	Reduced errors for DNDC v.CAN compared to DNDC for mineral N loss.
8	Ensemble	Sándor et al., 2020	Canada, France, India, UK	2002–2012	Permanent pasture	Grazed long-term grasslands	GPP: 1763 g C m^{-2} $year^{-1}$, RECO: 1561 g C m^{-2} $year^{-1}$, NEE: 610 to 66 g C m^{-2} $year^{-1}$
9	FASSET	Chatskikh et al., 2005	Denmark, Finland, UK	1981, 2000–2002 and Feb–Nov 2002	Grassland	Lawn with control, N fertiliser and slurry treatments, annual N at 200-250 kg N ha^{-1}, and conventional vs organic pasture with different fertiliser applications	N_2O emissions model was able to predict seasonal patterns and temporal variability on N_2O patterns in the three sites. Non-linear relationships between N inputs and N_2O emissions and sensitivity to fertiliser type and soil texture found.
10	IFSM	Alemu et al., 2016	Canada	2004–2006	Dairy pasture	Control, single application (49.2 ± 8.0) and split application [2 × (48.7 ± 4.3)] of hog manure	Annual CH_4 emissions for control, single and split applications were 18.1, 25.9 and 26.5 kg CO_2-e per kg liveweight of stock.
11	IFSM	Cordeiro et al., 2019	Canada	1990–2016 and 2020–2079	Dairy pasture	Three time periods: reference (1990–2016), near future (2020–2049) and distant future (2050–2079)	Expansions of cropland resulted in increased grass-legume production of 8% to 52% and total production increase of 11% to 105%.
12	IFSM	Duchemin et al., 2019	Quebec, Canada	1986–2015	Pasture, switchgrass	NA	Average DM yields were between 9.6 and 11 t ha^{-1}.
13	IFSM	Jégo et al., 2015	Canada	1991–2011	Pasture	Dry matter yields across contrasting climate zones	DM simulated (2.94 ± 0.74) vs. simulated (2.77 ± 0.52) t ha^{-1}, and NDF simulated (0.42 ± 0.04) vs simulated (0.43 ± 0.02) g g^{-1} DM.

(Continues)

TABLE 2 (Continued)

Serial	Model	Reference	Location	Simulated period	Management	Intervention	Outcome
14	IFSM	Thivierge et al., 2017	Canada	1971–2000 and 2020–2049	Dairy production systems	Impact of climate change on range of agroeconomic parameters	Increased NH_3 (+18% to +54%), increased manure stored methane (+26% to +120%). Variable projected N footprint (−15% to +46%) and C footprint (−5% to +9%).
15	ORCHIDEE	Ciais et al., 2005	Europe-wide	2003	Various grassland, forestry, arable	Drought and ordinary year comparison	GPP reduced 30% and increased CO_2 emissions (0.5 Pg C year^{-1}) under drought conditions.
16	ORCHI-DEE_GM	Chang, Ciais, et al., 2015	Europe-wide	1961–2010	Fertilised grassland soils	Intensive and extensive grasslands	Net C balance at the continental scale was estimated to be a net sink of 15 ± 7 g m^{-2} year^{-1}.
17	ORCHI-DEE_GM	Chang et al., 2016	Europe-wide	1991–2010	Grasslands	Intensive and extensive grasslands	Net biome production increased by 24%–31% resulting from increased atmospheric CO_2 and reduced management intensity.
18	ORCHI-DEE_GM	Chang et al., 2017	Europe-wide	1901–2100	Grasslands	Intensive and extensive grasslands	Net NPP increase projected and attributed to rising CO_2.
19	Mixed model	Korhonen et al., 2018	Northern Europe, Canada	1991–2007	Pasture, Timothy	Two & three N application rates, early vs late cutting	Models tended to underestimate yield of first cut (BASGRA_N, STICS, CATIMO).
20	Mixed model	Desjardins et al., 2005	Canada	1980–2030	Pasture, arable	Converting cropland to rangeland	Potential 6% increase in soil C after conversion to rangeland. 200 Mg CO_2e ha^{-1} reduction.
21	Mixed model	Guest et al., 2017	Canada	1993–2007	Spring wheat	Model comparison	10% underestimation of soil N for DayCent, 22% for STICS, 1% for DNDC.

a global meta-analysis by Shcherbak et al. (2014). Increased soil clay content increased the simulated emissions, which were further increased at higher temperatures but generally decreased by increasing annual rainfall. Slightly higher emissions from grazed grasslands, compared with cut grasslands at similar rates of total N input (fertiliser and animal excreta) were evident. Validation results for N_2O emission simulations were good for Pearson's correlation and reasonable, though model efficiency was less satisfactory (Table S3). The authors concluded that there was greater potential for reducing N_2O emissions for intensively grazed grasslands on fine-textured soils, compared with the N_2O mitigation potential of extensively mown grasslands on sandy soils.

IFSM

The Integrated Farm System Model (IFSM) was designed to simulate all components of dairy or beef production at the whole farm level (Rotz et al., 2018) and uses discrete sub-models to simulate inputs and forecast costs and outputs. The model can simulate production of grass, small grain, soybean, alfalfa, and corn cropping systems, including growth, harvest and storage, as well as dairy outputs. It also has a beef component to simulate beef production systems. IFSM simulates environmental metrics including soil and animal-derived GHG emissions, NH_3 volatilisation and NO_3 and P leaching and runoff, and so has the potential to identify management approaches to mitigate GHG emissions and determine reductions in the C footprint of farm products. Most studies using IFSM have been carried out in the United States and Canada, with the bulk of these being carried out in temperate or maritime climate conditions. This suggests that some agricultural GHG emissions models may not be well used outside their region of development, similar to the finding by Ara et al. (2021) regarding development and use of agricultural decision-support systems.

A study on switchgrass (*Panicum virgatum*) in southern Quebec was carried out by Duchemin et al. (2019) where biomass production was predicted reasonably well despite not being designed to work with this type of grass. A larger study in Canada (Thivierge et al., 2017) used the IFSM model in conjunction with climate models (CanESM2, CanRCM4 and HadGEM2) to project the impacts of climate change on agronomic and environmental performance. Projected climate effects resulted in increased production of grasses but also increased NH_3 and CH_4 emissions from manure storage, although there were limited reductions of CH_4 emissions from enteric and field applied manure.

IFSM has also been used in Newfoundland (Canada) to model climate change impacts on dairy farm production until 2079 (Cordeiro et al., 2019). Projected climate tended to increase production, particularly in grass and legumes (Table 2), but reduced farming operation opportunities due to increased rainfall during the growing season. This study focussed on production and did not examine GHG emissions or other environmental effects. A study by Jégo et al. (2015) explored this aspect using data on timothy and alfalfa grown in Canada, for sites in New Brunswick, Quebec and Alberta. The IFSM successfully represented forage production and neutral detergent fibre (NDF) concentrations under these conditions, although N uptake required larger sample sizes to reduce uncertainty.

Alemu et al. (2016) evaluated the impact of time and amount of hog manure application on farm productivity and GHG emissions from a Canadian cow-calf production system using the CCM (Coupled Components Model) and IFSM. They found that around 75% of the total farm GHG emissions were from enteric CH_4 production, similar to other livestock production systems (Christie et al., 2014; Harrison et al., 2016; Rawnsley et al., 2018; Taylor et al., 2016). Moreover, application of hog manure on grassland showed a mean GHG emission increase, mainly from enteric CH_4 and soil N_2O emissions for waste management scenarios. The authors concluded with the need of further component and whole-farm assessments to better understand the impact of the amount and timing of livestock manure application on GHG emissions from beef production systems. Validation results for dry matter and NDF has shown adequate model performance, although N uptake simulation was only 'fair' (Table S4). This result aligns with other model intercomparison studies on the ability of systems models to simulate N cycling under field conditions (Bilotto et al., 2021).

ORCHIDEE_GM

In a study spanning the entire Western European region, Chang, Viovy, et al. (2015) estimated the GHG balance (CO_2, CH_4 and N_2O). They used the process-based biogeochemical model, ORCHIDEE-GM over the period 1961–2010 (Table 2). This model (Chang, Ciais, et al., 2015; Chang et al., 2013) is an evolution of the ORCHIDEE land surface model (Ciais et al., 2005; Krinner et al., 2005; Piao et al., 2007) that includes a better representation of grassland phenology as well as of management, from the PaSim grassland model (Riedo et al., 2002). The management module includes grazing during a suitable season, and cutting for forage production, assuming that production of grass production is high enough, farmers will use a fraction of each grid cell for grazing and the other for forage production to feed animals in winter. The model can be forced by spatially explicit animal density and weight maps or calculate the maximum capacity to use all the production. CH_4 and N_2O emissions are represented by emission factors, not by mechanistic equations.

At the farm scale in Europe, the net C balance was roughly halved down to a small sink or nearly neutral flux of 8 g C m^{-2} $year^{-1}$ in ORCHIDEE_GM simulations from 1961 to 2010. At the continental scale, adding CH_4 and N_2O emissions to determine net ecosystem exchange, grasslands remained a net GHG sink as the CO_2 sink offset N_2O and grazing animal CH_4 emissions, however, at the farm scale these additions resulted in a net source of −50 g C-CO_2e m^{-2} $year^{-1}$. The largest net GHG sink by grassland was found in the British Isles. However, here too the GHG balance shifted to a net source when considered at the farm scale. The authors concluded that enhanced GHG balance reflects the combination of a positive trend of net primary production due to CO_2, climate and nitrogen fertilization and the diminishing requirement for grass forage due to the Europe-wide reduction in livestock numbers. Another study by Chang, Viovy, et al. (2015) estimated changes in potential productivity and potential grass-fed ruminant livestock density across European grasslands including boreal areas over the period 1961–2010. When compared with agricultural statistics (Eurostat and FAOstat), ORCHIDEE-GM gave a good reproduction of the regional gradients of annual grassland productivity and ruminant livestock density, although the model tended to systematically overestimate the absolute values of productivity in most regions, suggesting that most grid cells remained below their potential grassland productivity due to possible nutrient and biotic limitations on plant growth. Another work showed that net biome production (NBP) in the Nordic region increased between 1991 and 2010, mainly in response to changes in climate and atmospheric CO_2 concentration but also partly as a result of reduced management intensity and livestock numbers (Chang et al., 2016). And another study projected increased net primary productivity (NPP) and earlier and longer grazing periods under higher warming levels (Chang et al., 2017).

Model intercomparisons and ensemble modelling

Desjardins et al. (2005) investigated the role of agriculture in influencing the GHG budget and examined the opportunities from management practices for increasing soil C sequestration in Canada (see Table 2). Simulations of C and N cycling by CENTURY and DNDC models were carried out for five locations across Canada over a 30-year period to outline the potential trade-offs between C sequestration and increased N_2O emissions. Simulations suggested that conversion of cropland to grassland would result in the largest reduction in net GHG emissions. Moreover, nutrient additions, that is, by fertilizers would result in a small increase in GHG emissions. Finally, improved growing conditions would increase the soil C by 6% over the more recent 15-year period, as demonstrated for one of their sites in Alberta. The DNDC model was compared with DayCent, and the soil-atmosphere-crop model STICS (Brisson et al., 2003) in field studies in eastern Canada (Guest et al., 2017), and was the most reliable of the three at predicting soil N (−1%), although all three performed better predicting soil moisture and evapotranspiration than other output variables. STICS exhibited the largest underestimation (22%) for predicting soil N. The STICS model was recently adapted to eastern Canada conditions, by calibrating relevant cultivars and adding a snow module (Jégo et al., 2014) as it was mostly developed and used in temperate and more tropical regions than in northern ones.

Korhonen et al. (2018) used BASGRA to study the production of timothy across Finland, Sweden, Norway and Canada alongside two other models, STICS and the timothy biomass production model CATIMO (CAnadian TImothy MOdel) (Bonesmo & Bélanger, 2002), although these two did not appear anywhere else in the literature search. All three models performed similarly, none produced accurate simulations of grass growth. STICS simulated aboveground spring growth better than the other two models, though BASGRA was better for summer growth (Tables S1, S5 and S6), and was the most accurate overall, but would benefit from additional soil descriptive data input.

Combined with previous estimates of CO_2 emissions by Smith et al. (2001) who used the CENTURY model, Grant et al. (2004) postulated that the most beneficial management practices for reducing both N_2O and CO_2 emissions is the conversion from conventional tillage of croplands to permanent grassland, the implementation of reduced tillage, and the reduction of summer fallow. A trade-off in GHG flux with greater N_2O emissions and a comparable increase in C storage would be reached when 50% more N-fertilizer was added.

Ensemble modelling approaches have also been used in recent years to reduce the generalised error of predictions, for example, Ehrhardt et al. (2018); Farina et al. (2021); Sándor et al. (2020, 2018). Sándor et al. (2018) focussed on grassland sites in central and northern Europe, Scotland and the United States. Using a multi-model approach, they concluded that grasslands can be exploited for GHG mitigation in milk and beef production, following C and N sequestrations, at least under certain circumstances, to offset GHG emissions. Sándor et al. (2020) was more limited in scope to European, Canadian as well as Indian grasslands and concluded that while GPP (gross primary production) and RECO (ecosystem respiration) tended to be underestimated, NEE (net ecosystem exchange) tended to be overestimated, so ensemble modelling was a useful approach to address model uncertainties.

Model validation

While model evaluations have been conducted in other climates, those focussed on boreal regions are more scares. The use of model validation methods varied between authors, some were extensive, for example He et al. (2020), though others used only a few methods over limited variables, for example (Chatskikh et al., 2005). The following main methods used in the various research papers reviewed describe validation results for studies carried out in boreal regions only. For BASGRA, three methods over three variables were used in two papers (Höglind et al., 2020; Korhonen et al., 2018). For DNDC, 12 methods over six variables (DNDC v.CAN was compared with DNDC for N leaching) were obtained from two papers (Congreves et al., 2016; He et al., 2020), for FASSET four methods for one variable from a single paper (Chatskikh et al., 2005), and for IFSM five methods over four variables from one paper (Jégo et al., 2015). A single paper (Korhonen et al., 2018) tested forage production models STICS and CATIMO alongside BASGRA, giving four methods over three biomass variables (Tables S1, S5 and S6).

Equations and validation assessment tables are given in supplementary material. Our results are drawn from the few research articles found which include validation data for models in boreal climates. While limited in scope they highlight the scarcity of such studies. Some models, such as DNDC, BASGRA_N and IFSM appear to perform within the range of 'fair' to 'good', though DNDC modelled soil chemistry poorly and BASGRA_N also performed poorly at simulating biomass growth responses to N fertiliser. What can be seen from this table in addition to performance quality, is the lack of validation in a range of areas. This is partially a limitation of the models themselves as part of their design, for example, BASGRA_N and CATIMO are both biomass focussed models, and DNDC and its extension model DNDC v.CAN are both nitrogen cycle-based models with gas exchange as a key area of focus (less so on production), though the models can certainly estimate these parameters, their accuracy remains uncertain.

SYNTHESIS AND OUTLOOK

The objective of this review was to examine the use of models in grassland settings to assess potential for use in boreal grasslands. Overall, the use of relevant models in these regions was sparce, being mainly confined to a few models with variable results and degrees of applicability. We identified significant scope for model development and evaluation in boreal regions, particularly with respect to model intercomparison using datasets collected from boreal environments. We also identified a lack of information on (and to a lesser extent models equipped for) modelling land-use change, for example, conversion forestry, wetlands and so forth, to agricultural usages. Simulation of land-use change is important, as changes in land-use can lead to large effluxes of GHG emissions, partly due to carbon loss, for example, Laine et al. (2019). Although there is some literature documenting modelled changes from arable land use to grassland using DNDC and Century (Grant et al., 2004; Smith et al., 2001), and changes in grassland extent using ORCHIDEE_GM (Chang et al., 2016) some of the models examined here only simulate elements of land use change (e.g., loss in soil carbon; APSIM, DNDC) while others may not be designed for substantive land use change at all. This may be because models tend to be designed for steady-state and prevailing conditions, rather than for abrupt transitions from one dominant land use (e.g., forestry) to another (e.g., cropping or pasture grazing).

The BASGRA_N model was primarily designed for simulating biomass production, tillering dynamics and pasture persistence but can also simulate GHG balance and is specifically designed with cold climate growth including winter conditions such as freezing soil and snow cover. However, the primary focus of BASGRA_N has been on biomass production, especially its unique capacity to simulate root death, a key route for OM into the soil substrate, while a potential weakness in simulating fertiliser effects may indicate the need to calibrate the simulation components related to N cycling. The DayCent model has the potential to link atmospheric and soil models for boreal conditions, although it has not seen much use in these regions. It has performed well for modelling Canadian grassland in an ensemble modelling study.

The DNDC model is the most widely used and tested model in boreal regions and predicted N_2O emissions, soil temperature and biomass production quite well. Simulations appear to be less reliable when estimating other key variables such as soil N leaching, and SOC and CO_2 fluxes, although the evaluation of the last two was not found in the papers reviewed. The DNDC v.CAN model has shown improvements in modelling both N leaching and NH_3 fluxes compared to the standard DNDC model and may be a preferable alternative for comparable soils in Finland.

The FASSET model, while potentially useful may be sensitive to soil structure and overestimate SOC and thus related N in undisturbed soils. Performance assessments have been limited to N_2O emissions, where assessments were moderately satisfactory. The lack of studies in boreal areas for this model also needs to be addressed as far too little has been done to make a definitive assessment.

IFSM has been used successfully throughout North America to model multiple farm processes from runoff effects to biomass production and GHG emissions on a whole-farm basis and has also been used to predict the effects of climate change. IFSM provides a tool for similar studies within Finland, and although little work in this area has been carried out to date, existing results show fair performance in a comparable climate and so should warrant further exploration.

The ORCHIDEE_GM model has shown good larger spatial-scale results including those for Scandinavia and so would be a good candidate model to investigate. ORCHIDEE_GM has not been evaluated against site scale data in boreal regions, but was recently compared with detailed grassland production from multiple sites in Mongolia with good performance (Nandintsetseg et al., 2021).

Of the models examined here (Table 1), DNDC, IFSM and BASGRA_N show the highest potential for simulating grassland and livestock productivity in boreal regions. The two models examined as part of the assessment of Korhonen et al. (2018), STICS and CATIMO also performed adequately, but being only part of a single study show only limited results. In terms of GHG simulations, DNDC again shows promise, and FASSET also has good potential although again data is limited. As yet no model provided CO_2 or CH_4 emission data validations, a key area of interest in climate change mitigation, so further work is required here.

Recommendations for future research

With a burgeoning global population, the need for both food security and increased agri-food production under a changing global climate is becoming more pressing. Intensification of global food supply and climate crisis adaptation must however occur without degrading natural capital, losing biodiversity, increasing GHG emissions or stimulating other adverse economic, environmental or social trade-offs. Process-based models have already proven as invaluable tools in a wide range of agroecological regions and at a range of scales, though such models remain underutilised in boreal regions. There is significant opportunity for future studies to identify models that have superior performance in the circumpolar regions (Roulet, 2000). This review has built a solid foundation for future research by identifying some of the more well-known models as candidates for further study as well as pointing out some of their weaknesses and areas of uncertainty. Model comparison studies have already been carried out in more general settings, such as the work of Ehrhardt et al. (2018) and Sándor et al. (2020), who have laid early foundations for this kind of research. It remains to expand this study into areas with harsher climates but great agricultural potential. Prime opportunities for future research include (1) evaluation of individual models using field data measured for grassland production, soil C and N cycling, and GHG emissions for multiple boreal environments, (2) evaluation of multiple models using the same datasets within boreal zones (i.e., a model intercomparison), (3) identification of sub-model processes underpinning superior model performance (e.g., soil C and N cycling, plant growth and senescence, simulation of soil water and reliability of holistic systems simulations, that is, the climate–soil–plant–livestock continuum) and (4) opportunities for parsimonisation to the proper level while keeping the model coherent.

AUTHOR CONTRIBUTIONS

Daniel Forster: Conceptualization; data curation; methodology; project administration; visualization; writing – original draft; writing – review and editing. **Samuli Helama**: Data curation; writing – original draft; writing – review and editing. **Matthew Harrison**: Writing – review and editing. **Jinfeng Chang**: Data curation; writing – review and editing. **Elizabeth Pattey**: Writing – review and editing. **Perttu Virkajärvi**: Writing – review and editing. **Narasinha Shurpali**: Project administration; supervision; writing – review and editing.

ACKNOWLEDGEMENTS

This study was supported by funding from the Ministry of Agriculture and Forestry Finland (Helsinki, FI) (Project: Clover for biogas, Project NC-GRASS: VN/28562/2020-MMM-2). We also acknowledge the support from the Academy of Finland funded ENSINK project (Decision number 334422).

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Forster, D., Helama, S., Harrison, M. T., Rotz, C. A., Chang, J., Ciais, P., Pattey, E., Virkajärvi, P., & Shurpali, N. (2022). Use, calibration and verification of agroecological models for boreal environments: A review. *Grassland Research*, *1*(1), 14–30. https://doi.org/10.1002/glr2.12010