

SPECIAL SECTION: ADVANCING RESILIENT AGRICULTURAL SYSTEMS: ADAPTING TO AND MITIGATING CLIMATE CHANGE

Perennial forages in cold-humid areas: Adaptation and resilience-building strategies toward climate change

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Abstract

In the continental cold and humid areas of northeastern North America, climate change by mid-century may increase the yield potential of perennial forage species as a result of increased temperature and atmospheric CO₂ concentration, and a longer growing season compared to the 1990–2000 period. More winter thaws and less snow cover along with more summer drought events, however, may reduce winter survival and summer regrowth, thus potentially reducing the persistence of perennial forages over time. Based on nearly two decades of research on the effects of climate change on forages in cold and humid areas of northeastern North America, through field experiments and modeling, we summarize in this review the expected effects of climate change on forage production in terms of yield, nutritive value, and winter survival. We also propose a set of 12 adaptation and resilience-building strategies for forage systems that can be implemented at the field and farm levels. Research priorities for the future, including the improvement of species, forage management practices, and modeling tools, are also identified. Implementing strategies to alleviate or take advantage of the effects of a changing climate may improve productivity and resilience of well-adapted forage systems in cold and humid areas.

1 | INTRODUCTION

Perennial forage crops cover 36% of cultivated land in eastern Canada (Statistics Canada, 2021c, 2021d) and 43% in the northeastern United States (USDA Census, 2017a, 2017b) where they are used mostly for dairy production, one of

the most important agricultural activities in these Canadian and American regions (AAFC, 2022; Cherney et al., 2020; NASS-USDA, 2022; Statistics Canada, 2021a). Perennial forage crops in these northeastern areas are almost exclusively rainfed and intensively managed, that is, they are fertilized, frequently harvested, and maintained for relatively short periods of time (3–8 years) within crop rotations including mostly corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merrill], and small grain crops (Castaño-Sánchez et al., 2020; Payant et al., 2021; Thivierge et al., 2017; Veltman et al., 2018). Most of the forage production is mechanically harvested and conserved as hay or silage. Perennial forage stands are composed mostly of cool-season grasses

Abbreviations: BMPs, beneficial management practices; CATIMO, Canadian Timothy MOdel; CP, crude protein; DM, dry matter; DNDC, DeNitrification-DeComposition (DNDC) model; dNDF, in vitro digestibility of neutral detergent fiber; EPIC, Environment Policy Integrated Climate; GDD, growing degree days; GHG, greenhouse gas; IFSM, Integrated Farm System Model; NDF, neutral detergent fiber; RCP, representative concentration pathway; TDN, total digestible nutrients.

and legumes. Alfalfa (*Medicago sativa* L.) or alfalfa-grass mixtures represent 44% of perennial forage areas in eastern Canada (Statistics Canada, 2021c) and 20% in northeastern United States (Cherney et al., 2020; USDA Census, 2017a). Timothy (*Phleum pratense* L.) is one of the main grass species and is often grown in mixture with alfalfa (Payant et al., 2021; Thivierge et al., 2016). Other important forage species include orchardgrass (*Dactylis glomerata* L.), tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort.], reed canarygrass (*Phalaris arundinacea* L.), meadow bromegrass (*Bromus biebersteinii* Roem. & Schult.), and red clover (*Trifolium pratense* L.) (Cherney et al., 2020; Goslee et al., 2013; Pomerleau-Lacasse et al., 2019).

Low summer temperatures and a short growing season are important factors limiting forage crop yields in northern areas (Baron & Bélanger, 2020; Payant et al., 2021). Even under the most optimistic scenarios, atmospheric CO₂ concentration is projected to increase until at least 2050 (IPCC, 2022), with expected increases in temperatures and length of the growing season that will affect spring growth (Jing et al., 2014; Payant et al., 2021; Rotz et al., 2016b; Thivierge et al., 2016), summer regrowth (Jing et al., 2013; Thivierge et al., 2016), and winter survival (Bélanger et al., 2002, 2006; He et al., 2019) of perennial forages. A better understanding of expected changes in forage crop production will enable the identification and implementation of adaptation and resilience-building strategies for forage systems, which are needed to alleviate the impact of climate change on forage production (Hatfield et al., 2011; Henry et al., 2018; Jing et al., 2013; Mäkinen et al., 2015; Rotz et al., 2016b; Soussana, 2015; Thivierge et al., 2022), and may even result in more productive forage systems in northeastern North America as suggested by modeling studies (Jing et al., 2014; Rotz et al., 2016b; Thivierge et al., 2016, 2017).

Climate change also may exacerbate the environmental impact of dairy farms in the cold and humid areas of eastern Canada and northeastern United States (Rotz et al., 2016b; Thivierge et al., 2017; Veltman et al., 2021). Perennial forages have a greater potential than annual crops for soil C sequestration (Gregorich et al., 2001; Liang et al., 2020). By covering the ground for a longer period of the year, they also result in a greater land surface albedo (reflectivity of solar radiation) that contributes to mitigating climate change (Liu et al., 2021; Martin et al., 2020). Therefore, maintaining perennial forages has the potential to partially offset the impact of ruminant-based farming systems on climate change along with providing numerous ecosystem services, particularly regarding biodiversity, water quality, and soil health (Cooledge et al., 2022; Glover et al., 2010; Guyader et al., 2016; Liang et al., 2020; Martin et al., 2020).

Objectives of this review were: (1) to summarize current knowledge on expected climate change in cold and humid regions of northeastern North America along with projected

Core Ideas

- Without adjusting the harvest schedule, perennial forage quality may be reduced by climate change by mid-century.
- Winter thaws and reduced snow cover may increase the risk of winter damage to perennial forages in cold areas.
- Twelve adaptation and resilience-building strategies are suggested for forage systems in cold and humid areas.
- Together, these strategies are expected to improve yield, nutritive value, and resilience of forage systems.
- Research priorities should target the improvement of species, forage management practices, and modeling tools.

effects of climate change on perennial forages including yield, nutritive value, and winter survival, (2) to propose a set of adaptation and resilience-building strategies for forage systems in cold regions that can be implemented on farms, and (3) to identify future research priorities.

2 | STUDY BOUNDARIES AND FUTURE CLIMATE SCENARIOS

As the impact of climate change varies according to the geographic area, adaptation strategies need to be region-specific (Jing et al., 2013; Rotz et al., 2016b; Veltman et al., 2021). Therefore, this review focuses on the cold and humid areas of eastern Canada and northeastern United States. Eastern Canada encompasses the provinces of Ontario, Quebec, New-Brunswick, Nova Scotia, Prince Edward Islands, and Newfoundland and Labrador, while northeastern United States encompasses the states of Connecticut, Delaware, Maine, Massachusetts, Maryland, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont. Under current climate conditions, most of these areas have a warm-summer humid continental climate (Dfb climate, Köppen-Geiger climate classification; Peel et al., 2007), although before the end of the century, they could rather be characterized by a hot-summer humid continental climate (Dfa climate; Beck et al., 2018). Areas with a Dfb climate (middle latitudes of the Northern Hemisphere, 40° to 55° North) are characterized by a cold climate with inter-annual variations in temperature, including warm summers (without dry season), little precipitation difference between seasons, and snow that remains on the ground for more than a month.

These regions are sometimes identified as having a temperate climate in the geographical sense of the term, that is, they are located between the tropics and the polar regions.

Information relative to the projected impact of climate change on forage systems comes primarily from modeling studies, using models that were developed or adapted for the continental climate of northeastern areas of North America (Table 1), but also from experiments under controlled conditions with varying temperatures and/or air CO₂ concentrations. In addition, information deemed relevant to adaptation and resilience-building strategies was extracted from both modeling and experimental studies conducted, for the vast majority, within the geographic boundaries described earlier. Studies with other climates were sometimes referenced to document strategies that are not climate-specific.

Mid-century is considered a critical period beyond which the temperature increase will limit the possibilities for adaptation strategies to counterweight the effects of climate change (Hatfield et al., 2018). Therefore, when more than one future period was projected in modeling studies, the one that encompassed the 2050–2060 period was selected (Table 1). In most studies, representative concentration pathways (RCP) 4.5 and 8.5 were used, which represent two plausible sets of projections of greenhouse gas (GHG) concentrations leading to the alteration of the radiative budget of the Earth by +4.5 and +8.5 W m⁻², respectively, in year 2100 relative to 1750 (IPCC, 2014a, 2014b). According to these projections, atmospheric CO₂ concentration of 487 μmole mol⁻¹ with RCP 4.5 and 541 μmole mol⁻¹ with RCP 8.5 may be expected by mid-century (IPCC, 2013). Climate models used to generate future scenarios differed among studies and often were numerous for a given study. Because there are large uncertainties surrounding the use of climate models and crop models (Payant et al., 2021), this review is limited to identifying common trends among these studies.

This review focuses on intensively managed cultivated forage stands, which excludes pastures and grazing systems. When reported, forage yield refers to the dry matter (DM) mass of mechanically harvested forages. Similar to a previous review of forage adaptation to climate change under Nordic and Mediterranean Europe (Ergon et al., 2018), livestock production and its specific adaptation and mitigation strategies are not within the scope of this review, despite the obvious linkage between forage and livestock production within ruminant-based farming systems (Henry et al., 2018). Moreover, the effect of adaptation or resilience-building strategies on GHG budget is essentially discussed at the field scale, although this will reflect in the farm environmental footprint and sometimes induce trade-offs (e.g., positive effect of perennial forages on soil C storage vs. enhanced enteric methane [CH₄] emission intensity by ruminants; Guyader et al., 2016). Finally, future climate conditions are expected to exacerbate the pressure exerted on crops by pests, dis-

eases (including root diseases), and weeds (Dupigny-Giroux et al., 2018; Hatfield et al., 2011; Hayhoe et al., 2007; Wolfe et al., 2018), but this effect is not reviewed here as no study specifically addressed the projected impact on perennial forage species, even less in the context of northeastern North America.

3 | EXPECTED CLIMATE CHANGE IN COLD AND HUMID AREAS OF NORTHEASTERN NORTH AMERICA

Areas in northern latitudes are expected to experience the most climate change, with a greater temperature warming and precipitation increase than areas of lower latitudes (Zhang et al., 2019). By mid-century, mean annual temperatures are projected to increase by 1.5–3.3°C in the northeastern United States (Pennsylvania and New York; Rotz et al., 2016b; Veltman et al., 2021) but by 2.4–5.4°C in eastern Canada (He et al., 2019; Jing et al., 2013; Smith et al., 2013; Thivierge et al., 2017). In most studies, a greater temperature increase is projected in winter than in summer, lessening differences among seasons (Bootsma et al., 2005; Cordeiro et al., 2019; Dupigny-Giroux et al., 2018; Jing et al., 2013; Lynch et al., 2016). An earlier spring thaw (Hayhoe et al., 2007; Qian et al., 2013) and onset of forage crop growth (12–46 days earlier; Jing et al., 2013; Qian et al., 2013; Thivierge et al., 2016), along with a delayed arrival of the first frost (Wolfe et al., 2018; 14–22 days later in Qian et al., 2013 and Thivierge et al., 2017) and winter snowfall (Dupigny-Giroux et al., 2018) is expected to increase the length of the growing season by 21 to 49 days (Hayhoe et al., 2007; Payant et al., 2021; Qian et al., 2013) and the accumulation of growing degree-days (GDD) by 487 to 1029 (5°C basis; Payant et al., 2021; Thivierge et al., 2016).

Precipitation in northeastern North America is projected to slightly increase by mid-century (+28 to +196 mm; He et al., 2019; Jing et al., 2013; Rotz et al., 2016b; Smith et al., 2013; Thivierge et al., 2016; Veltman et al., 2021), even during the growing season of perennial crops (+23 to +97 mm; Payant et al., 2021; Thivierge et al., 2016). Precipitation is projected to increase during most of the year but especially in winter and spring (Hayhoe et al., 2007; Jing et al., 2013; Lynch et al., 2016; Thivierge et al., 2016). Climate models do not always agree on projected changes in late summer and early fall in the northeastern United States (Lynch et al., 2016) but point toward little change or a decline (Wolfe et al., 2018), while a decrease in precipitation is projected in eastern Canada for August, September, and possibly October (Jing et al., 2013; Thivierge et al., 2016). More episodes of intense precipitation are projected in the northeastern United States (Wolfe et al., 2018; +1 or +2 extreme rainfall events per year, with ≥25 mm day⁻¹ in Veltman et al., 2021) and eastern Canada (+0.5 to +10 abundant rainfall days per year, with ≥10 mm day⁻¹;

TABLE 1 Modeling studies including perennial forage crops and representative of eastern Canada or northeastern United States, with the regions and future periods considered, and projected attributes.

References	Models	Regions (climate ^a)	Future periods	Reference periods	RCPs	Perennial forage species	Projection with/without adaptation strategies	Projected attributes relevant to this review
Castaña-Sánchez et al. (2022)	IFSM	Central Pennsylvania (Dfa), United States	2037–2062	1980–2005	RCP 4.5, RCP 8.5	Alfalfa; orchardgrass	Without and with	Forage yield; N, P, and soil losses; NH ₃ and N ₂ O emissions; farm C footprint
Cordeiro et al. (2019)	IFSM	St. John's, NL (Dfb), Canada	2050–2079 ^b	1990–2016	RCP 2.6, RCP 4.5, RCP 8.5	Grass mixture (timothy + tall fescue); grass-legume mixture [timothy + white clover (<i>Trifolium repens</i> L.) + red clover]	Without	Forage yield
He et al. (2019)	DNDC	Elora, ON (Dfb), Ottawa, ON (Dfb), and Quebec City, QC (Dfb), Canada	2041–2070 ^b	1971–2000	RCP 4.5, RCP 8.5	Alfalfa	With	Alfalfa yield; alfalfa winterkill
Jing et al. (2013)	CATIMO	London, ON (Dfb), Charlottetown, PE (Dfb), Montreal, QC (Dfb), Normandin, QC (Dfb), and St. John's West, NL (Dfb), Canada ^b	2040–2069	1961–1990	IPCC (2007) emission scenarios A1B and A2	Timothy	Without	Timothy yield; timothy nutritive value (NDF, dNDF)
Jing et al. (2014)	CATIMO	London, ON (Dfb), Charlottetown, PE (Dfb), Montreal, QC (Dfb), Normandin, QC (Dfb), and St. John's West, NL (Dfb), Canada ^b	2040–2069	1961–1990	IPCC (2007) emission scenarios A1B and A2	Timothy	Without and with	Timothy yield; timothy nutritive value (NDF, dNDF)

(Continues)

TABLE 1 (Continued)

References	Models	Regions (climate ^a)	Future periods	Reference periods	RCPs	Perennial forage species	Projection with/without adaptation strategies	Projected attributes relevant to this review
Payant et al. (2021)	IFSM	Southwestern Quebec, QC (Dfb) and Eastern Quebec, QC (Dfb), Canada	2050–2079 ^b	1971–2000	RCP 4.5, RCP 8.5	Alfalfa in binary mixture with either: timothy; tall fescue; meadow fescue (<i>Schedonorus pratensis</i> [Huds.] P. Beauv.); meadow brome grass	With	Forage yield; forage nutritive value (NDF, CP); alfalfa proportion in mixture
Rotz et al. (2016a)	IFSM	Central New York (Dfb), United States	2037–2062	1991–2015	RCP 4.5, RCP 8.5	Alfalfa; orchardgrass	Without and with	Forage yield; N and P losses from field; NH ₃ and N ₂ O emissions; farm C and N footprints
Rotz et al. (2016b)	IFSM	Southern Pennsylvania (Dfa) and Northern New York (Dfb), United States	2037–2061 ^b	1981–2005	RCP 4.5, RCP 8.5	Alfalfa; orchardgrass; pasture ^c	Without and with	Forage yield; N and P losses from field; NH ₃ emissions; farm C and N footprints

(Continues)

TABLE 1 (Continued)

References	Models	Regions (climate ^a)	Future periods	Reference periods	RCPs	Perennial forage species	Projection with/without adaptation strategies	Projected attributes relevant to this review
Thivierge et al. (2016)	IFSM	Southwestern Quebec, QC (Dfb) and Eastern Quebec, QC (Dfb), Canada	2050–2079 ^b	1971–2000	RCP 4.5, RCP 8.5	Alfalfa; timothy; alfalfa + timothy mixture	Without and with	Forage yield; forage nutritive value (NDF, CP); alfalfa proportion in mixture; temperature stress index; water stress index
Thivierge et al. (2017)	IFSM	Southwestern Quebec, QC (Dfb) and Eastern Quebec, QC (Dfb), Canada ^b	2050–2079 ^b	1971–2000	RCP 4.5, RCP 8.5	Alfalfa + timothy mixture	With	Forage yield; N and P losses from field; NH ₃ , N ₂ O, and CO ₂ emissions; farm C and N footprints
Veltman et al. (2021)	IFSM, Manure-DNDC, EPIC	Pennsylvania (Dfa) and New York (Dfb), United States ^b	2040–2059	1990–2009	RCP 4.5, RCP 8.5	Alfalfa; orchardgrass	Without and with cropping system adaptations and farm BMPs	Forage yield; P losses from field; farm C and N footprints

Abbreviations: BMPs, beneficial management practices; CATIMO, Canadian Timothy Model; CP, crude protein; DNDC, DeNitrification-DeComposition (DNDC) model; dNDF, digestibility of the neutral detergent fiber (NDF); EPIC, Environment Policy Integrated Climate; IFSM, Integrated Farm System Model; RCPs, Representative concentration pathways. Canadian provinces abbreviated as QC, Quebec; ON, Ontario; NL, Newfoundland; PE, Prince Edward Island.

^aAccording to the Köppen-Geiger climate classification (Peel et al., 2007);

^bOther regions or future periods were part of the study but were not considered relevant for the present review; Species not specified.

Ouranos, 2015). An increase in flood risk remains ambiguous for the northeastern United States (Dupigny-Giroux et al., 2018) but has been identified as a clear threat for coastal regions of eastern Canada (Alberti-Dufort et al., 2022). Variability in precipitation patterns is projected to increase over time (Jing et al., 2013).

The number of days with very high temperatures (maximum temperature $\geq 28^{\circ}\text{C}$) is projected to increase by 15–42 days in eastern Canada (Thivierge et al., 2017) and the northeastern United States (Veltman et al., 2021). Higher temperatures will lead to increased evapotranspiration in summer months, and despite higher or similar precipitation during the growing season (Hayhoe et al., 2007; Jing et al., 2013; Qian et al., 2013; Thivierge et al., 2016), increased plant water stresses are projected in both the northeastern United States and eastern Canada (Hayhoe et al., 2007; Thivierge et al., 2016).

Milder winters, fewer cold extremes, and fewer frost days are expected (Dupigny-Giroux et al., 2018; Hristov et al., 2018). December and January are projected to be the months with the highest temperature increase (up to $+8.2^{\circ}\text{C}$ for the monthly average temperature; Jing et al., 2013; Thivierge et al., 2016). Consequently, because a greater proportion of winter precipitation is expected to fall in the form of rain, a shorter period during which the ground is covered with snow (Dupigny-Giroux et al., 2018) and a reduction in snow depth are projected in both the northeastern United States (Hayhoe et al., 2007) and eastern Canada (Bélanger et al., 2002).

4 | IMPACT OF CLIMATE CHANGE ON FORAGE SYSTEMS

Expected changes in temperature and precipitation, combined with increased atmospheric CO_2 concentration, will affect perennial forage systems in northeastern North America (Rotz et al., 2016b; Thivierge et al., 2016). The effects of climate change will vary by region and crop species and will be manifested primarily through changes in forage DM yield, nutritive value, and stand persistence.

4.1 | Yield and nutritive value of forage species

Most cool-season forage species with a C_3 photosynthetic pathway, which are CO_2 -limited at current atmospheric concentration (Izaurrealde et al., 2011; Morgan et al., 2004), generally respond positively to elevated CO_2 concentration in terms of photosynthesis and growth (Baslam et al., 2014; Bertrand et al., 2007b; Kettunen et al., 2007). Because plants can acclimate to rising CO_2 concentrations through photosynthetic down-regulation, short-term and long-term measured

responses may differ (Soussana & Lüscher, 2007). Response to CO_2 depends also on numerous environmental factors, including the availability of soil nutrients (Izaurrealde et al., 2011; Morgan et al., 2004; Soussana & Lüscher, 2007), and varies among species (Morgan et al., 2004), as shown by the absence of response to CO_2 for several cool-season grass species (Piva et al., 2013; Sæbø & Mortensen, 1996).

The positive response to elevated atmospheric CO_2 concentration is generally greater in legumes than in grasses ($+24\%$ vs. $+10\%$ in DM production; meta-analysis from Ainsworth & Long, 2004), due to the N-fixing ability of legumes (Lüscher et al., 2000). Indeed, the increased plant demand for N under elevated CO_2 often limits growth while biological N fixation in legumes, enhanced at elevated CO_2 as a response to low soil-N availability, provides an unlimited N supply (Lüscher et al., 2000; Soussana & Hartwig, 1995; Zanetti et al., 1996). Moreover, photosynthetic down-regulation is generally reduced in the absence of N limitation (Ainsworth & Long, 2005; Stitt & Krapp, 1999).

Elevated atmospheric CO_2 concentration also results in partial stomatal closure and the resulting reduced plant transpiration may enhance plant water-use efficiency (Ainsworth & Long, 2005; Hatfield et al., 2011; Izaurrealde et al., 2011; Morgan et al., 2004) and potentially translate into reduced plant sensitivity to water-limited conditions (Izaurrealde et al., 2011; Morgan et al., 2004; Soussana & Lüscher, 2007). Changes in precipitation and increased temperature, however, might offset the general positive effect of elevated atmospheric CO_2 concentration (Hatfield et al., 2011; Izaurrealde et al., 2011; Lee et al., 2013).

Greater forage yield variability is also expected, with changes in the seasonality of production with enhanced spring and fall growth but reduced summer growth (Hristov et al., 2018). Under future climate scenarios, forage crops are expected to reach a given phenological stage earlier due to higher temperatures and greater GDD accumulation than under current conditions (Izaurrealde et al., 2011). Without any adaptation to the harvest schedule, climate change is then expected to reduce forage nutritive value, although this effect will depend on the species (Bertrand et al., 2007b, 2008; Jing et al., 2013; Sanz-Sáez et al., 2012b).

4.1.1 | Timothy

Largely grown in northern regions of North America, but also in northern Europe (Ergon et al., 2018; Höglind et al., 2013), timothy is a perennial grass usually harvested two to three times a year under current climate conditions. By mid-century and without any adaptation to the harvest schedule, timothy annual DM yield is projected to increase ($+4\%$ to $+16\%$ in eastern Quebec, Thivierge et al., 2016; $+7\%$ to $+67\%$ across five sites in eastern Canada, Jing et al., 2014). A yield increase

is also projected for the timothy-tall fescue mixture in Newfoundland (Cordeiro et al., 2019). However, for orchardgrass, one of the main grasses in northeastern United States, yield is expected to remain stable or to decrease (−2% to −12%; Castaño-Sánchez et al., 2022; Rotz et al., 2016a).

Timothy yield at first harvest is expected to benefit from warmer spring temperatures and shorter winters (+517 kg DM ha^{−1} on average across five sites in eastern Canada; Jing et al., 2013) because of faster development of new leaves in spring and increased intercepted solar radiation (Jing et al., 2013). As a drought sensitive species (Bertrand et al., 2008; Garwood et al., 1979), timothy is expected to suffer from more frequent and intense water stress events, with reduced summer regrowth (Jing et al., 2013; Thivierge et al., 2016) and a yield decrease (212 kg DM ha^{−1}) for the second harvest of the season in eastern Canada (Jing et al., 2013). Optimum growing temperature of timothy (17°C–21°C, Bertrand et al., 2008), already exceeded in the summer, will be exceeded to a greater extent under future climate (Thivierge et al., 2016). As a result, in warmer areas of southwestern Quebec, annual timothy yield is projected to decrease by an average of 12% to 29% if no adaptation measures are implemented (Thivierge et al., 2016).

Without any adjustment to the harvest schedule of timothy, its nutritive value averaged across five sites in eastern Canada is expected to decrease through increased neutral detergent fiber (NDF) concentration (+5 and +8 g kg^{−1} DM) and decreased *in vitro* NDF digestibility (dNDF) (−7 and −15 g kg^{−1} NDF) for the first and second harvests, respectively (Jing et al., 2013). This projected negative effect on the nutritive value of timothy is in line with experimental results that showed a reduction in dNDF with increasing air temperatures (Bertrand et al., 2008).

4.1.2 | Alfalfa

In simulation studies in both eastern Canada (Thivierge et al., 2016) and northeastern United States (Castaño-Sánchez et al., 2020; Rotz et al., 2016a), alfalfa yield was improved by elevated atmospheric CO₂. Alfalfa is also expected to be less affected than timothy by water stress under future climate conditions in eastern Canada (Thivierge et al., 2016).

Because of a higher optimum growing temperature for alfalfa (approx. 28°C, Zaka et al., 2017) than timothy, a yield increase in alfalfa could be expected under future climate conditions. By mid-century, without adaptation to the harvest schedule, alfalfa yields are projected to increase by 11% in New York (Rotz et al., 2016a), by 21% to 29% in eastern Quebec (RCP 4.5 and 8.5), and by 8% in southwestern Quebec (RCP 4.5; Thivierge et al., 2016). A yield decrease, however, is projected in southwestern Quebec under RCP 8.5 (−8%;

Thivierge et al., 2016). No modeling studies have projected the effect of climate change on the nutritive value of alfalfa, but experimental results suggest a reduced *in vitro* DM digestibility with increased temperatures (Sanz-Sáez et al., 2012b) and a decreased crude protein (CP) concentration under elevated atmospheric CO₂ (Bertrand et al., 2007b).

4.1.3 | Alfalfa–timothy mixtures

Under climate change, legume–grass mixtures can be expected to behave differently than their individual species (Thivierge et al., 2016). Without any adaptation to the harvest schedule, forage yield of an alfalfa–timothy mixture is expected to increase in eastern Quebec (+7% to +28%), but not in southwestern Quebec under RCP 8.5 (−10% to +1%, depending on the climate model) (Thivierge et al., 2016). Under an atmospheric CO₂ concentration representative of mid-century climate, Messerli (2015) measured an 18% increase in alfalfa–timothy yield using field CO₂-enriched open-top chambers in Quebec. The percentage of alfalfa in mixture is also projected to increase by 1 to 12 percentage points (Thivierge et al., 2016). Greater alfalfa winter mortality under future climate conditions might, however, offset this projected increase in forage yield and proportion of alfalfa, and was not considered in the simulation study (Thivierge et al., 2016) and the open-top chamber experiment (Messerli, 2015). In Newfoundland, where climate conditions are less suitable for alfalfa growth, Cordeiro et al. (2019) projected a yield increase by mid-century for another legume–grass mixture composed of white clover, red clover, and timothy.

Regardless of the area and climate scenario, forage yield of the alfalfa–timothy mixture is expected to increase at the first harvest (+42%, Messerli, 2015; +29% to +46%, Thivierge et al., 2016) but to decrease at the summer harvests (Thivierge et al., 2016) due to more days when the mixture will experience water stress (+13 to +32 days by mid-century in eastern Canada, Thivierge et al., 2016) and above optimum temperatures.

Without adapting the timing and number of harvests, the NDF concentration of alfalfa–timothy mixtures is projected to increase in eastern Canada (+34 to +53 g kg^{−1} DM), while the total digestible nutrient (TDN) concentration, an estimate of forage energy density, is projected to decrease (−39 to −77 g kg^{−1} DM; Thivierge et al., 2016). The CP concentration is projected to remain similar or to slightly increase (+8 to +16 g kg^{−1} DM), due to an increased alfalfa proportion in the mixture (Thivierge et al., 2016). Elevated CO₂ concentration was shown to slightly reduce forage CP concentration and digestibility and increase the fiber concentration (Messerli, 2015).

4.2 | Winter survival of perennial forage crops

In northern areas, harsh overwintering conditions affect the survival of winter-sensitive species (Bélanger et al., 2006; Castonguay et al., 2006; Höglind et al., 2013). Alfalfa, red clover, and orchardgrass are among the most challenged forage species for survival (Bélanger et al., 2006; Castonguay et al., 2006). Increasing risks of winter injuries are projected under future climate conditions in eastern Canada and the northernmost regions of northeastern United States (Bélanger et al., 2002; He et al., 2019; Hristov et al., 2018).

Cold hardiness allows plants to tolerate subfreezing temperatures (Bélanger et al., 2006). The fall cold hardening period is projected to be 4 days shorter by mid-century in eastern Canada, resulting in a reduced accumulation of cold degree-days and a lower level of cold hardiness (Bélanger et al., 2002). In alfalfa, increased atmospheric CO₂ concentration is also expected to delay the cold acclimation process and to decrease freezing tolerance (Bertrand et al., 2007a). Cold hardiness can be lost when temperature exceeds 0 °C during winter or early-spring thaws, making de-acclimated plants more susceptible to subsequent freezing temperatures (Bélanger et al., 2006). This risk is projected to increase with twice the accumulation of GDD above 0 °C during winter in eastern Canada by mid-century (Bélanger et al., 2002).

Cumulated precipitation in the form of rain in winter (1 November to 30 April) is projected to increase by an average of 83 mm across five forage-producing areas of eastern Canada, while precipitation in the form of snow is expected to decrease (−75 cm), along with the number of days with a snow cover (−39 days) (Bélanger et al., 2002). Similarly, in northeastern United States, winter precipitation is projected to increase by 6% to 16% by mid-century, while the amount of snow on the ground during winter is projected to decrease by 45% (Hayhoe et al., 2007). As a result, the number of days where crops are at risk of damage by subfreezing temperatures is expected to increase (Bélanger et al., 2002; He et al., 2019). Risk of rain forming ice at the soil surface is projected to increase (Bélanger et al., 2002), resulting in anoxic conditions toxic to plants, physical damage to the root system, and greater risk of soil heaving pushing plant crowns out of the soil (Bélanger et al., 2002; 2006; Castonguay et al., 2006).

5 | ADAPTATION AND RESILIENCE-BUILDING STRATEGIES

We are proposing 12 adaptation and resilience-building strategies for perennial forage systems, some of which also contribute to climate change mitigation (Figure 1). With a few exceptions, these strategies are easy to implement

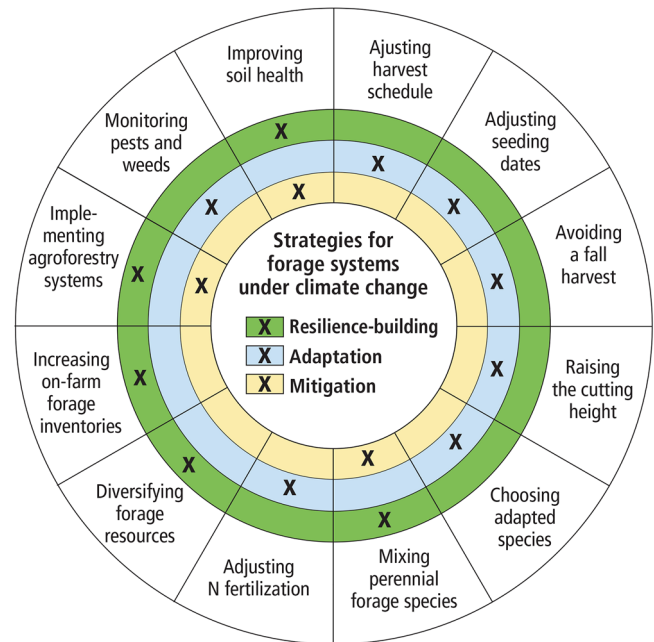


FIGURE 1 Resilience-building (green) and adaptation (blue) strategies along with their mitigation (yellow) contribution for perennial forage systems in cold and humid areas of northeastern North America in the context of climate change.

using well-known forage-, cropping system-, or soil-related management practices without important investments, and as such can be qualified as tactical or incremental strategies (Lee et al., 2013; Sautier et al., 2017).

Adaptation strategies are approaches to adjust production systems to climate change to moderate harm or even exploit opportunities (IPCC, 2014b; Lee et al., 2013). Resilience-building strategies increase the ability of the system to cope with a disturbance or a challenge, that is, to respond and reorganize to resume its key functions and maintain its capacity for adaptation (IPCC, 2014b; Meuwissen et al., 2019). Resilience applies to forage stands (Finn et al., 2018; Grange et al., 2021; Lüscher et al., 2022; Mäkinen et al., 2015; Soussana, 2015) and to farming systems or agricultural landscapes (Asbjornsen et al., 2014; Bennett et al., 2021; Meuwissen et al., 2019), so that they recover rapidly after a perturbation and sustain provision of food and non-food ecosystem services over time despite environmental shocks, stresses, or variations (Bennett et al., 2021; Mäkinen et al., 2015; Meuwissen et al., 2019). An important determinant of resilience is diversity (in functions and in response to change), at field, farm, and landscape scales, which buffers or mitigates the impact of perturbations (Cabell & Oelofse, 2012; Mäkinen et al., 2015; Martin & Magne, 2015; Meuwissen et al., 2019; Volaire et al., 2014) and decreases the vulnerability of the system (Lüscher et al., 2022; Martin & Magne, 2015). Resilience and adaptation to climate change are complementary, and they

obviously overlap: resilience improves the capacity of the system to adapt to climate change (Henry et al., 2018; IPCC, 2014b; Mottet et al., 2020) while many adaptation strategies increase resilience (Castaño-Sánchez et al., 2022; Hatfield et al., 2011; Izaurralde et al., 2011).

Climate change mitigation aims at reducing the concentration of GHG in the atmosphere and, therefore, the impact of agricultural practices on the environment (Hatfield et al., 2011). Mitigation addresses the cause of climate change, either by reducing GHG emissions or by increasing C sequestration in soils or vegetation (enhance sinks) (IPCC, 2014b). It is crucial to also consider mitigation when developing adaptation and resilience-building strategies (Castaño-Sánchez et al., 2022; Ghahramani et al., 2019; Lee et al., 2013).

5.1 | Adjusting the harvest schedule

Adjusting the harvest schedule of perennial species is an intuitive and essential adaptation strategy (Dumont et al., 2015; He et al., 2019) to ensure optimal forage yield, nutritive value, and persistence under a warming climate. This adjustment involves a change in the interval between harvests and potentially the number of harvests per growing season while still respecting the fall rest period (Jing et al., 2014; Payant et al., 2021; Thivierge et al., 2016).

The increased daily temperatures and the lengthening of the growing season are expected to result in one or two additional harvests during the growing season in both eastern Canada and northeastern United States (He et al., 2019; Jing et al., 2014; Payant et al., 2021; Rotz et al., 2016b; Thivierge et al., 2016). Even if growth onset is projected to occur earlier, the interval between growth onset and the first harvest is projected to remain similar (Thivierge et al., 2016) or even increase (+7 days; Jing et al., 2013). However, the intervals between other harvests are expected to decrease by 5 to 11 days in eastern Canada (Jing et al., 2013; Thivierge et al., 2016).

When compared to the reference scenario, forage yields with adaptation to the harvest schedule are expected to increase by 45% to 68% for alfalfa (He et al., 2019), by 5% to 34% for the alfalfa–timothy mixture (Thivierge et al., 2016), by 24% to 62% for diverse alfalfa–grass mixtures (Payant et al., 2021), and by 23% to 35% for timothy (Jing et al., 2014) in eastern Canada. These projected increases are higher than those estimated without adaptation of the harvest schedule by up to 9% for the alfalfa–timothy mixture (Thivierge et al., 2016) and by 17% to 32% for timothy (Jing et al., 2014). However, in the northeastern United States, one additional harvest (from four to five harvests per year) is not projected to improve alfalfa yield, compared to a non-adapted system (Rotz et al., 2016a).

Adjusting the forage harvest schedule is mostly projected to limit or even cancel the loss in nutritive value expected under climate change (Dumont et al., 2015; Jing et al., 2013, 2014; Thivierge et al., 2016). While the annual forage NDF concentration was expected to increase without adaptation of the harvest schedule, it is expected to decrease or to slightly increase (less than without adaptation) when one or two additional harvests are taken during the growing season (−36 to +13 g NDF kg^{−1} DM compared to the reference scenario; Jing et al., 2014; Payant et al., 2021; Thivierge et al., 2016). The annual NDF digestibility of timothy, however, is expected to decrease by an additional 2 to 7 g kg^{−1} NDF when a third harvest is included as an adaptation measure, compared to no adaptation (Jing et al., 2014). With additional harvests, the annual forage TDN concentration for the alfalfa–timothy mixture is projected to slightly decrease or to remain similar compared to the reference period (−19 to +6 g kg^{−1} DM), but to be greater than without adjusting the harvest schedule in all areas and climate scenarios (+20 to +83 g kg^{−1} DM) (Thivierge et al., 2016). Finally, the annual CP concentration of the alfalfa–timothy mixture is not projected to be much affected by this adaptation strategy, similarly to the proportion of alfalfa in the mixture (Thivierge et al., 2016). When compared to the reference period, however, both the proportion of alfalfa in mixture and the CP concentration under future conditions with adaptation are projected to be greater for many alfalfa–grass binary mixtures, and even more so when the initial proportion of alfalfa in mixture was low (Payant et al., 2021; Thivierge et al., 2016).

5.2 | Adjusting seeding dates

Seeding dates will have to be adjusted under future climate conditions (He et al., 2019; Jing et al., 2013; Thivierge et al., 2016, 2017; Veltman et al., 2021) and seeding is projected to occur 6 to 18 days earlier for alfalfa by mid-century in Ontario and Quebec (He et al., 2019). Despite a much earlier spring thaw under future conditions (Hayhoe et al., 2007; Qian et al., 2013), spring climate conditions with increased rainfall and heavy rainfall events (Dupigny-Giroux et al., 2018; Hristov et al., 2018; Wolfe et al., 2018) could make soils unsuitable some years for early tillage and seeding. Indeed, with a higher soil moisture content in spring (wet or flooded soils) resulting in greater risks of soil compaction when using heavy equipment (Hatfield et al., 2011; Wolfe et al., 2008, 2018), the number of days suitable for field work is expected to decrease (Dupigny-Giroux et al., 2018; Hristov et al., 2018; Thivierge et al., 2017). Seeding could be delayed (Hatfield et al., 2011; Wolfe et al., 2018), preventing the full advantage of the extended growing season in the establishment year

(Cordeiro et al., 2019; Dupigny-Giroux et al., 2018; Wolfe et al., 2018).

5.3 | Avoiding a fall harvest

Accumulation of non-structural carbohydrates and N reserves in the fall is essential for winter survival and spring regrowth of perennial forage species (Bélanger et al., 2006; Castonguay et al., 2006). The projected shorter cold hardening period for perennial species, along with more challenging conditions for winter survival, reinforces the need for a conservative harvest management of perennial forages in cold and humid areas (Bélanger et al., 2020).

Taking a fall harvest of alfalfa increases risks of winter damage in eastern Canada (Bélanger et al., 1999a; Dhont et al., 2004) and, even though one more harvest is taken, forage yield over four post-seeding years is not improved while the alfalfa proportion in alfalfa–grass mixtures decreases (Bélanger et al., 2020). Even if maintaining a minimum regrowth interval of 500 GDD above 5°C between the fall harvest and the preceding one helps in reducing risks of winter damage (Bélanger et al., 1999a), avoiding a fall harvest could be a valuable strategy to decrease the risks of winter damage to alfalfa under the more challenging projected winter conditions. Persistence and spring regrowth of other winter-sensitive perennial species, like orchardgrass, could also be negatively affected by a fall harvest, although this has not been extensively assessed under the conditions of northeastern North America (Bélanger et al., 2006).

5.4 | Raising the cutting height

Raising the cutting height could help reduce the risks of winter damage and water stress during the growing season under future climate conditions. Although lowering the cutting height increases forage yield at a given harvest, it decreases the nutritive value (Lajeunesse & Bélanger, 2022; Sheaffer et al., 1988) and adversely affects plant regrowth (Jones & Tracy, 2018, 2019) because of less photosynthetic tissues left after cutting and a greater dependence on root reserves (Harrison & Hodgson, 1939). Ultimately, repeatedly cutting at a low height decreases forage stand yield, ground cover, and persistence (Griffith & Teel, 1965; Harrison & Hodgson, 1939; Jones & Tracy, 2018, 2019). Forage species will be affected differently by the cutting height, depending on their morphology and the location of their C and N reserves either above or below the soil surface (Harrison & Hodgson, 1939; Jones & Tracy, 2018). Regardless of the species, however, the remaining vegetation after cutting will affect the surface microenvironmental conditions by shading the soil, thus reducing soil surface temperature (Stringer et al., 1981)

and promoting the resumption of plant growth after cutting, especially in dry conditions (Jones & Tracy, 2015). Considering the increasing risks of temperature and water stresses under future climate conditions, a cutting height of at least 10 cm is suggested for summer harvests (Jones & Tracy, 2018; Thivierge et al., 2022).

A higher stubble in the fall also holds more snow on the ground, providing better cold protection for plants over winter (Baron & Bélanger, 2020; Bélanger et al., 2006; Sheaffer et al., 1988), which is especially important for winter-sensitive species like alfalfa, red clover, and orchardgrass (Bélanger et al., 2006; Castonguay et al., 2006). With no fall harvest, more snow accumulates with a remaining vegetation before winter of 20 to 25 cm (Howley & Wright, 1991; Lajeunesse & Bélanger, 2022; Sheaffer et al., 1988). If a fall harvest is necessary, a cutting height of at least 15 cm is suggested (Sheaffer et al., 1988; Undersander et al., 2011).

5.5 | Choosing adapted species and cultivars

Timothy may be the cool-season grass that will benefit the least from climate change. With its low optimum growth temperature and low drought tolerance (Bertrand et al., 2008; Garwood et al., 1979), it is poorly adapted to the projected future summer conditions in northeastern North America, which will especially affect its summer regrowth (Payant et al., 2021; Thivierge et al., 2016). Timothy is, however, one of the most winter-hardy and persistent perennial grasses (Jing et al., 2014; Pomerleau-Lacasse et al., 2019; Rapacz et al., 2014), withstanding cold temperatures and surviving long periods under ice without winter damage (Bélanger et al., 2006), which could be advantageous under the more challenging projected winter conditions (Bertrand et al., 2008). Its low optimum growth temperature also offers a clear advantage for an early and strong spring regrowth, even under future projected conditions (Payant et al., 2021). Thus, in terms of climate change adaptation and especially for eastern Canada, farms would benefit from using other grasses in addition to, rather than in replacement of timothy.

Under current conditions in eastern Canada, meadow brome grass, meadow fescue [*Schedonorus pratensis* (Huds.) P. Beauv.], and tall fescue have proven to perform as well as timothy when grown in binary mixture with alfalfa, with comparable yield, nutritive value, and summer regrowth (Pomerleau-Lacasse et al., 2019), and very similar profit and environmental performance when simulated at the dairy farm level (Ouellet et al., 2021). Under projected future conditions, however, the greatest yield increase is expected from the alfalfa-tall fescue mixture and the least from the alfalfa-timothy mixture (Payant et al., 2021). Tall fescue has a higher optimum growth temperature (25°C; Robson, 1972; Volenec et al., 1984) than timothy and is also known for its large root

biomass and deep root system (Bolinder et al., 2002; Cougnon et al., 2017; Garwood & Sinclair, 1979), giving it access to wet, deep soil layers under dry conditions (Garwood & Sinclair, 1979). In eastern Canada, tall fescue root biomass was more evenly distributed in the soil profile and more abundant at depth than that of timothy (67–168 vs. 28–49 g ash-free DM m⁻² in the 30–45 cm soil layer; Bolinder et al., 2002). Root depth distribution is a key feature in explaining root C stability in soils (Poirier et al., 2018), and in that sense, tall fescue may sequester more C (Cougnon et al., 2017) and thus help mitigate climate change.

Alfalfa is a productive perennial legume species adapted to northeastern North America climate conditions but it is sensitive to harsh winter conditions. Although risks of winter damage are expected to increase, replacement of this species is not considered an adaptation strategy, while using an improved cultivar is possible (e.g., freezing-, drought-, or flood-tolerant) (Feyissa et al., 2021; Thivierge et al., 2017). Current cold-tolerant alfalfa cultivars usually have a high fall dormancy, oftentimes at the expense of annual DM yield. According to simulations by He et al. (2019) for low-, moderate-, and high-cold tolerant alfalfa cultivars with low, moderate, and high dormancy, alfalfa yields are projected to be greater when using a more cold-tolerant/dormant cultivar, both under current and future projected conditions, and especially for sites with colder conditions (Ottawa and Quebec, Canada). Using winter hardy alfalfa cultivars is a beneficial adaptation strategy that will be even more necessary under future climate conditions (He et al., 2019).

5.6 | Mixing perennial forage species

Increasing diversity within forage stands is almost systematically mentioned in literature reviews on adaptation of forages or ruminant-based farming systems to climate change. Forage mixtures can take full advantage of the longer growing season, combining species that grow earlier in spring or later in fall (Goslee et al., 2013; Skinner et al., 2006). Complementarity mechanisms and positive interactions among species as well as the portfolio effect (variations in the abundance of species in mixture over time) are still present under perturbations (e.g., drought, Bakker et al., 2019; Grange et al., 2021; Lüscher et al., 2022; Volaire et al., 2014) and could become even more important under increased weather variability associated with climate change (Mäkinen et al., 2015).

Under continental cold and humid conditions of northeastern North America, a moderate level of species diversity (about two to seven species) in intensively managed perennial forage stands generally benefits or at least maintains forage yield and reduces weeds (Bélanger et al., 2014, 2020; Deak et al., 2007, 2010; McElroy et al., 2012; Papadopoulos et al., 2012; Sanderson et al., 2005, 2012; Skinner & Dell, 2016;

Tracy & Sanderson, 2004) compared to monocultures and/or to less diverse mixtures. In a multi-criteria optimization study, Goslee et al. (2013) found that “ideal” mixtures for pastures in northeastern United States would mostly include an intermediate level of species richness of between three and six species.

In recent European studies, the demonstration of benefits of intensively managed multispecies mixtures was extended to multifunctionality and to forage stand resistance and resilience to harmful climate events associated with climate change. Indeed, multispecies mixtures (four to six species) were shown to improve spatial or temporal stability of forage yield and/or to mitigate the impact of extreme weather conditions like drought (Finn et al., 2018; Grange et al., 2021; Haughey et al., 2018; Hofer et al., 2016; Suter et al., 2021). Most of these studies were conducted with clover-based forage mixtures.

There is some evidence, although currently limited, that this relationship between species diversity and resilience is also valid for alfalfa-based mixtures typical of northeastern North America. In eastern Canada, year-to-year stability of forage yield in alfalfa-grass mixtures (with one or two grasses) was greater than in pure alfalfa over four post-seeding years (Bélanger et al., 2020). In Pennsylvania, lower year-to-year variability in forage yield with complex (five or seven species) rather than simple (two or three species) mixtures including alfalfa was shown using the IFSM model (Deak et al., 2010). Complex mixtures including alfalfa sometimes with other legume species were also projected to perform the best under unusually dry years (Deak et al., 2010), which is in line with experimental field results (Sanderson et al., 2005; Skinner et al., 2006). Overall, dairy farm net returns are projected to be less affected by climate perturbations when growing complex rather than simple mixtures including alfalfa (Deak et al., 2010), which indicates a greater resilience.

A larger proportion of roots are distributed in deeper soil layers under more diverse pasture mixtures in northeastern United States (Skinner & Dell, 2016; Skinner et al., 2004, 2006). This access to soil moisture at depth could contribute to alleviating drought stress. In addition, deep-rooted forage species, like alfalfa, smooth brome (*Bromus inermis* Leyss.), and tall fescue are known to redistribute water from subsurface to surface soil layers, to the benefit of neighboring shallow-rooted plant species in mixture, a process termed hydraulic lift (Alagele et al., 2021; Corak et al., 1987; Sekiya et al., 2011).

Species mixtures with deeper root distribution could contribute to mitigation of climate change by sequestering more (and deeper) C in the soil (Skinner & Dell, 2016), although many factors affect soil C sequestration potential (Poyda et al., 2021). In northeastern United States, Skinner and Dell (2016) measured a greater accumulation of soil C under 5- than 2-species mixtures for the 10–30 cm soil depth, over a period of

9 years. The effect of mixtures on root biomass might depend on species identity and combinations, as much or even more than on the number of species.

Maintaining legumes in mixtures, where both the legume and the non-legume components benefit in terms of N yield (Nyfeler et al., 2011; Suter et al., 2015), is considered a mitigation strategy for present and future climates (Ghahramani et al., 2019) as it leads to reduced use of N fertilizer and associated GHG emissions, and to limited N losses from forage systems (Lüscher et al., 2014). Biologically fixed N is not exempt from the risk of being lost, but this risk is reduced in legume-grass or legume-grass-forb mixtures (Castaño-Sánchez et al., 2020; Cummins et al., 2021; Jensen et al., 2012; Lüscher et al., 2014; Sanz-Sáez et al., 2012a). A meta-analysis by Conant et al. (2017) revealed that seeding legumes into grasslands increased soil C stock by an average of 0.66 Mg C ha⁻¹ year⁻¹. Studies are lacking to document the soil C sequestration potential for alfalfa-based forage mixtures in cold and humid areas. Moreover, consideration should be given to the destruction of legume or legume-based forage stands to limit N₂O emissions resulting from a large amount of available N with low N demand (Jensen et al., 2012), especially under wet fall and spring periods, and winter and spring freeze–thaw events in northeastern North America (Chantigny et al., 2013; MacDonald et al., 2011; Wagner-Riddle & Thurtell, 1998).

5.7 | Adjusting N fertilization

The potential increase in crop yields under climate change in cold and humid areas will likely require greater N applications to compensate for the additional N export through harvest, except for perennial legume crops or legume-based mixtures (Brassard & Singh, 2008; Rotz et al., 2016b; Smith et al., 2013; Thivierge et al., 2017; Veltman et al., 2021). Adjustments, mostly increases, of N fertilizer/manure applications were considered for future scenarios in many modeling studies, specifically on perennial grasses (Rotz et al., 2016b; Veltman et al., 2021) or forage corn (Payant et al., 2021; Thivierge et al., 2017; Veltman et al., 2021). Although the sole effect of increasing N fertilization was not assessed per se, projections under future climate conditions suggest higher N₂O emissions in both eastern Canada and northeastern United States (Rotz et al., 2016b; Smith et al., 2013; Thivierge et al., 2017; Veltman et al., 2021), and greater nitrate (NO₃⁻) losses through leaching (Dayyani et al., 2012; Veltman et al., 2021, without adaptation) and runoff (Rotz et al., 2016b; Thivierge et al., 2017), losses that were partly attributed to increased N fertilization. Adjustments for other nutrients (P, K, S) might also be needed (Lee et al., 2013). Potassium could be of particular importance under future cli-

mate conditions given its key role in cold tolerance (Baron & Bélanger, 2020).

Greater N applications from manure or mineral fertilizer could promote soil C accumulation through enhanced productivity and, thereby, increased root-derived material and non-harvested biomass in addition to the C from manure itself (Kätterer et al., 2012; Maillard et al., 2016). Several meta-analyses indicated that fertilization from manures leads to a larger increase in soil C stock (0.29 to 0.52 Mg C ha⁻¹ year⁻¹; Bolinder et al., 2020; Maillard & Angers, 2014; Tiefenbacher et al., 2021) than fertilization with mineral N (−0.02 to +0.23 Mg C ha⁻¹ year⁻¹; Bolinder et al., 2020; Tiefenbacher et al., 2021). Manure led to an even larger increase in soil C stock when applied in a crop rotation dominated by perennial forages rather than on annual crops in eastern Canada (Maillard et al., 2016). For grasslands, Conant et al. (2017) concluded that manure application leads to greater rates of increase in soil C stocks than mineral fertilizer application (0.82 vs. 0.54 Mg C ha⁻¹ year⁻¹).

The effect of fertilization (mineral or manure) on soil C content, however, is site-specific and depends on sward age, site conditions, C allocated to roots, harvested aboveground biomass, soil texture and pH, historical land use, and initial level of soil C concentration (Bélanger et al., 1999b; Poyda et al., 2021). Despite a large positive effect of fertilization on forage yield, Bélanger et al. (1999b) found no relationships between soil C concentration and mineral fertilization (N, P, and K) of timothy in a long-term field trial (35 years) in eastern Canada. In northeastern United States, Skinner and Dell (2015) reported no change in soil C content over 9 years despite greater forage yields due to increased N fertilization. Considering the greater projected N₂O emissions related to N fertilization and the uncertainties regarding C sequestration under future climate conditions, the potential of this adaptation strategy to mitigate climate change in cold and humid areas remains unclear.

5.8 | Diversifying forage resources

Perennial forage cropping systems will be more prone to weather-related shortages under future than under current climate conditions, forcing farmers to buy forages, sometimes at great distances from their farms and at high costs (Sautier et al., 2017). Diversifying forage resources should increase farm resilience by decreasing its vulnerability to climate-related perturbations compromising the farm forage supply.

There is no species or mixture of species that is always ideal (Goslee et al., 2013) and performs well under all critical weather conditions or stress (Mäkinen et al., 2015), an issue that diversification of forage resources can address. It

can be achieved by growing a diversity of perennial species or cultivars (Ergon et al., 2018), in separated fields or in mixtures within a field (Mäkinen et al., 2015), or even different forage mixtures in different fields on the farm (Lüscher et al., 2022; Sanderson et al., 2007). Another option is the inclusion of annual forage species to the cropping system, like spring or winter small grain crops for silage (Veltman et al., 2021), forage corn or other C₄ warm-season annual crops (Rotz et al., 2016b; St-Pierre-Lepage, 2021) like forage sorghum, sudangrass, or sorghum × sudangrass hybrids [all varieties or hybrids from *Sorghum bicolor* (L.) Moench], or annual cover crops that can be harvested or grazed if needed.

Forage corn is an important forage crop on dairy farms in both eastern Canada (Statistics Canada, 2021b) and north-eastern United States (Castaño-Sánchez et al., 2020; Cherney et al., 2020). As a C₄ crop well adapted to warm temperatures, forage corn will take advantage of higher temperatures and longer growing seasons under future climate conditions (Hristov et al., 2018; Thivierge et al., 2017), and its cultivation area could expand northward (Cordeiro et al., 2019). Corn, however, is expected to experience 9 to 25 more days of water stress by mid-century (Payant et al., 2021). Forage corn yields are projected to increase more in colder (+44% to +84%) than in warmer areas (+15% to +22%) in eastern Canada (Cordeiro et al., 2019; Payant et al., 2021; Thivierge et al., 2017). In northeastern United States, forage corn yields are also expected to increase (Rotz et al., 2016b; +22% in Rotz et al., 2016a). This yield increase in forage corn is projected to be accompanied by a decrease in CP and NDF concentrations (Payant et al., 2021; Thivierge et al., 2017). With its high energy content, forage corn is a good complement to high protein forages (Ergon et al., 2018), like alfalfa and alfalfa-based mixtures.

Perennial forage crops are often seeded simultaneously with a small grain crop in northeastern North America (Jing et al., 2014), which can be harvested as silage during the establishment phase of the perennial species. Forage yields of small grain crops have not been extensively simulated under future climate conditions, but winter rye (*Secale cereale* L.) yields are projected to increase by 16% to 31% by mid-century in Pennsylvania (Veltman et al., 2021). Grain yields of wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.), however, are projected to change only slightly in eastern Canada and northeastern United States (−14% to +10%; Payant et al., 2021; Rotz et al., 2016a; Thivierge et al., 2017). A longer growing season could promote double cropping as an adaptation strategy (Hristov et al., 2018; Seifert & Lobell, 2015; Wolfe et al., 2018), that is, sequential harvests of a winter small grain silage crop and forage corn the same year in the same field. This practice is projected to increase and stabilize forage production, increase nutrient uptake, and reduce N₂O emissions (Castaño-Sánchez et al., 2022; Rotz et al., 2016b; Veltman et al., 2018); the potential decrease in forage corn

yield would be more than offset by winter cereal silage yield. Double cropping is projected to increase notably by mid-century in the northern United States (Hristov et al., 2018; Seifert & Lobell, 2015) and might increase in southern areas of Canada, provided that suitable cultivars are used (Page et al., 2019). Winter survival of some winter cereal species, however, might be compromised by overwintering conditions under future climate conditions (Hristov et al., 2018).

5.9 | Increasing on-farm forage inventories

Forage conservation is essential in northern North America due to the constraints imposed by long winters. Increasing forage inventories (stocks) following short-term feed surplus and ensuring their appropriate conservation as hay or silage in anticipation of forage shortage is an easy-to-implement adaptation strategy (Finn et al., 2018; Lee et al., 2013). It limits off-farm purchase of forage stock and animal feeding costs (Martin & Magne, 2015), although it may require an additional storage structure and therefore new capital investments (Wolfe et al., 2008). Forage reserves will buffer variations between years and within a season regarding self-sufficiency for forages, and make the farm system less vulnerable and more resilient to supply disruptions (Finn et al., 2018; Martin & Magne, 2015; Meuwissen et al., 2019) that are likely to occur more often in the future in northeastern North America. Economic studies would be beneficial to estimate the adequate proportion of forage to keep in inventory to balance resilience and profitability.

5.10 | Implementing windbreaks and tree-based intercropping systems

Agroforestry systems are often suggested as an adaptation strategy to climate change in ruminant-based farming systems (Ghahramani et al., 2019; Rivest et al., 2022; Rojas-Downing et al., 2017). Both tree-based alley-cropping systems and windbreaks have been investigated for their effect on perennial forage crops in North America (Carrier et al., 2019; McGraw et al., 2008; Rivest et al., 2022). Trees have been found to alter micro-climate conditions in-between rows by reducing wind speed, increasing air humidity and temperature, decreasing evapotranspiration, and increasing soil snow cover (Carrier et al., 2019; Rivest et al., 2022), conditions that could partially mitigate expected effects of climate change on forage production.

Alfalfa-based forage mixtures under cold and humid conditions of northeastern North America were found to be more tolerant than annual crops to light and moisture competition (Carrier et al., 2019; Rivest et al., 2022), which makes them particularly suitable for agroforestry systems. Indeed, many

perennial forage species were found to be tolerant to moderate shade (45% of full sun) in artificial shading experiments (e.g., timothy, alfalfa, smooth brome grass, Kentucky bluegrass (*Poa pratensis* L.), orchardgrass; Pang et al., 2017). Moreover, it was demonstrated in eastern Canada and in the United States that most perennial species do not suffer from competition, provided that the tree rows are widely spaced (25 to 90 m apart, Carrier et al., 2019; 24 m apart, McGraw et al., 2008; 40 m apart, Rivest et al., 2022). These widely spaced tree rows contributed to increased (Rivest et al., 2022) or similar forage yields of alfalfa or alfalfa-based mixtures (Carrier et al., 2019; McGraw et al., 2008) when compared to open plots without trees.

As demonstrated in eastern Canada, trees promote biodiversity by providing refuge for birds and a variety of insects, many of which are natural enemies of pests in field crops, thus probably exerting a natural control (Gibbs et al., 2016; Thevathasan & Gordon, 2004; Udawatta et al., 2019). This could increase farm resilience to the increasing threat of pest pressure under future climate conditions; this is in addition to income diversification related to timber, nut, or fruit harvesting, which also benefits resilience at the farm level.

Tree-based intercropping systems represent an opportunity to contribute significantly to climate change mitigation by sequestering C in both tree biomass and soils, with a potential estimated at 3.4 Mg C ha⁻¹ year⁻¹ from six experiments in temperate North America, including sites in eastern Canada (Udawatta & Jose, 2012).

5.11 | Monitoring pests, diseases, and weeds

Despite the threat of increased pest, disease, and weed pressure under future climate conditions for crops in northeastern North America (Alberti-Dufort et al., 2022; Boucher et al., 2017; Wolfe et al., 2018), few adaptation strategies have been suggested. Acute vigilance (Wolfe et al., 2018) and monitoring of fields for a timely assessment of new insect pests, diseases, and herbicide-resistant weeds, at the farm (Thivierge et al., 2022) and regional levels (Boucher et al., 2017; Hatfield et al., 2011), will be essential to provide early warnings to forage producers. Improved and accessible decision support tools along with other adapted tools for integrated pest management, including improved cultivars, are also requested by farmers and advisers (Boucher et al., 2017). Crop diversification at the farm level is seen as a buffer against the increasing threat of pests and weeds (Wolfe et al., 2008).

5.12 | Improving soil health

Soil health is defined by Janzen et al. (2021) as “the vitality of a soil in sustaining the socio-ecological functions of its enfold-

ing land.” With the changing climate, soils now fulfill new or enhanced functions like climate regulation through C sequestration (Janzen et al., 2021) and buffering of climate-related perturbations (e.g., efficient drainage after intense rainfalls and storage of large amounts of water to mitigate the effect of drought events; Hatfield et al., 2011, 2017) and therefore contributes to the resilience of the farm system (Hristov et al., 2018). Soil organic matter concentration is a key indicator of those functions and of resilience (Hatfield et al., 2017; Hristov et al., 2018) as it reflects the potential for C sequestration along with optimal soil water holding capacity and water infiltration rate (Wolfe et al., 2018).

Perennial forages are known to increase the soil organic matter content and structural stability compared to annual crops (Angers, 1992; Gregorich et al., 2001; Perfect et al., 1990). Species with deep taproots, such as alfalfa, improve soil penetrability, aeration (Rasse & Smucker, 1998), water infiltration (Meek et al., 1990), and root penetration for succeeding crops (Gaiser et al., 2012). Perennial species also improve soil biodiversity (Nunes et al., 2020) and, therefore, must be preserved as much as possible within forage cropping systems to improve and maintain soil health.

One important threat to soil health in perennial cropping systems under the cold and humid climate of northeastern North America is the expected increased risk of soil compaction under future climate conditions due to increased precipitation in winter and spring (Dupigny-Giroux et al., 2018; Hatfield et al., 2011; Wolfe et al., 2008, 2018). Multiple machinery passes for harvesting operations, liquid manure application with heavy tanks, and trampling by grazing animals all pose additional risks regarding soil compaction in forage systems. Reduced crop productivity under compacted soils is primarily related to reduced root growth and development that limits the plant's access to soil resources (Colombi & Keller, 2019; Hatfield et al., 2017), including water under drought conditions (Gaiser et al., 2012), an ability that is likely to become increasingly important under future summer climate conditions.

6 | RESEARCH NEEDS/PRIORITIES

Several avenues for research should be considered to facilitate adaptation to climate change and to build resilience of perennial forage cropping systems in the cold and humid continental climate of northeastern North America. Crop water and heat stresses have not been major research topics for this region until recently and major research efforts through breeding (heat- and drought-tolerant cultivars for C₃ forage species, e.g., timothy; Jing et al., 2013, 2014) and forage management are required. Indeed, several practices like forage cutting height and harvest schedule, choice of species and mixtures (e.g., inclusion of non-leguminous forbs and C₄ species), and

agroforestry systems have not yet revealed their full potential to alleviate crop water stresses.

Winter survival is expected to be even more challenging under climate change in northeastern North America, and research efforts undertaken over the past 30 years (Bélanger et al., 2002, 2006; Castonguay et al., 2006) must be continued. Research aiming at improving cultivars for winter hardiness (e.g., alfalfa, orchardgrass; Bélanger et al., 2002, 2006; He et al., 2019) and resistance to plant, root, and crown diseases (Bélanger et al., 2006) should be pursued while keeping in mind the need to not impair and perhaps also improve forage yield and nutritive value. Winter survival of alfalfa and other winter-sensitive species is affected by several management practices (e.g., fall harvest and cutting height, fertilization, tree-based intercropping systems), and research is required to adapt or develop improved practices.

To refine the projections of the effects of climate change on forage production in northeastern North America and assess the effects of adaptation strategies, simulation models must be improved to take into account winter survival in a more comprehensive way, including winter-related factors such as cold tolerance, ice encasement, frost heaving, and root diseases. Because most existing simulation models are for single forage species, model improvements are required for simulating the growth of multispecies forage mixtures, at least for a moderate level of diversity (three–six species).

Resilience decreases the vulnerability of forage systems and is often associated with species diversity, which buffers climate perturbations (Voltaire et al., 2014). Multispecies forage mixtures and agroforestry systems both offer the potential to increase resilience and deserve more extensive studies, especially within alfalfa-based forage systems. The effects of numerous management practices (choice of species, number and proportion of species in mixtures, seeding rates, fertilization, forage harvest schedule, tree species, and timber management) on forage production remain to be clarified, as well as potential trade-offs between forage yield, nutritive value, persistence, resilience, and other ecosystem services (e.g., biodiversity, natural pest control, and C sequestration).

Implementing adaptation and mitigation strategies requires new knowledge and skills for farmers (Lee et al., 2013). Support from agronomists is necessary (Hatfield et al., 2011), but more decision support tools are required (Boucher et al., 2017), like improved short-term weather forecast and its impact on forage production (Reeves et al., 2015; Soussana, 2015), for example, AgWeather Quebec website (https://www.agrometeo.org/indices/category/plantes_fourageres). Involving farmers in discussions on climate change adaptation and in research initiatives at the farm level increases the adoption potential of improved practices (Harrison et al., 2017; Kalaugher et al., 2017; Kröbel et al., 2021; Rojas-Downing et al., 2017). Participatory methods involving farmers should therefore be promoted

(Martin, 2015; Mottet et al., 2020; Sautier et al., 2017), not only to develop, but also to adopt resilient forage cropping systems adapted to climate change. Finally, the proposed strategies, when contemplated for integrated crop-livestock farm systems, must be subjected to a whole-farm integrated assessment, including the farm environmental impact, productivity, and profitability, in order to make informed decisions (Veltman et al., 2018).

7 | CONCLUSION

Perennial forages are an essential component of dairy production, one of the most important agricultural activities in northeastern North America. In these continental cold and humid areas, climate change by mid-century may increase the yield potential of perennial forage species as a result of increased temperature and atmospheric CO₂ concentration and a longer growing season. More winter thaws and less snow cover along with more summer drought events, however, may reduce winter survival and summer regrowth, thus potentially reducing the persistence of perennial forages over time.

Twelve strategies are proposed for moderating harm and exploiting opportunities associated with climate change (adaptation strategies) or for decreasing the vulnerability of forage systems by improving their capacity to reorganize and cope with disturbance (resilience-building strategies). Several of these strategies are easy to implement using well-known forage-, cropping system-, or soil-related management practices, and are currently being implemented to some extent by farmers as they build on the array of already promoted beneficial agronomic practices. Research priorities should include further improvement of species, forage management practices, and modeling tools. A concerted effort from all stakeholders including scientists, crop advisors, and farmers is required to face the challenges of developing and implementing resilient forage cropping systems adapted to climate change.

AUTHOR CONTRIBUTIONS

Marie-Noëlle Thivierge: Conceptualization; investigation; writing—original draft; writing—review and editing. **Gilles Bélanger:** Conceptualization; investigation; writing—original draft; writing—review and editing. **Guillaume Jégo:** Investigation; writing—review and editing. **Sylvestre Delmotte:** Investigation; writing—review and editing. **C. Alan Rotz:** Investigation; writing—review and editing. **Édith Carbonneau:** Investigation; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT


The authors declare no conflicts of interest.

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