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Assessment of the agronomic potential of dual-use winter-hardy peas in Northern New England: Cold tolerance and production challenges for harvestable cover cropping peas

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Abstract

Cover crops play a significant role in improving and maintaining good soil quality. However, there are often some agronomic and cost challenges associated with successfully establishing cover crops. In Northeastern regions of the United States, abiotic stressors such as cold affect and high costs limit uptake of the practice. Using two field trials, a high tunnel study, and laboratory methods, we investigated the possibility of growing improved winter peas (*Pisum sativum* L.) as a cash cover crop in Northeastern regions of the United States. Results of the field trial showed no significant variance in winter survival between the winter pea genotypes tested. The genotypes tested include cold-hardy cultivars traditionally cultivated for forage and improved winter pea breeding lines selected for edible traits. In two field trial seasons of 2021/2022 and 2022/2023, all genotypes reached their reproductive stage in the first week of June when seeded the previous year around the end of September in Vermont. Our results show that although peas are a viable overwinter crop allowing potential double cropping. However, the mid-June maturity date for dry or fresh pea harvest conflicts with spring planting of cash crops on many Vermont and Northeastern farms, greatly limiting the potential of double cropping to increase winter cover cropping uptake. Consequently, some reported barriers to winter cover crop adoption in the far Northeast, such as high seed cost and time constraints, cannot easily be solved by double cropping.

Plain Language Summary

Cover cropping, where a crop is planted but not harvested, is an important practice for maintaining soil health because it keeps like roots in the soil for as much of the

Abbreviation: REL, relative electrolyte leakage.

year as possible. In colder temperate regions, cold-tolerant covers are available, but not widely used. We hypothesized that a cover crop that could be harvested as a valuable vegetable might increase uptake of cover cropping. We used field, high tunnel, and laboratory experiments to explore the cold tolerance and agronomic viability of overwintering peas in Vermont in the Northeastern United States. We found no difference among the pea types in their cold tolerance. We found no significant effect of planting depth on overwintering survival. Most importantly, we found that the peas matured sufficiently late in spring that they interfered with planting other crops. Although overwintering peas are cold tolerant, timing is a challenge in regions like Northern New England where spring occurs later.

1 | INTRODUCTION

Cold stress is one of the key challenges that limits winter cropping in the Northeastern United States. This abiotic stress has been reported to affect germination, flower and fruit development, yield, and in extreme cases mortality (e.g., Yadav, 2010). This makes double cropping (i.e., planting one cash crop after another within the same year) impractical in much of the Northeastern United States. As a result, cultivated land remains fallow in the fall, winter, and early spring seasons, increasing the risk levels of land degradation and erosion. Cover cropping, where a crop is planted for soil enrichment but not harvested, is a widely recommended tool for maintaining soil health between growing seasons, but the adoption rate remains low. A report on the cover crop adoption rate in the United States was 5.1% (15.4 million acreage cover over all cultivated land including orchards) for the year 2017 (Wallander et al., 2021). Losses from cold stress, combined with other factors such as higher seed costs and seed availability, timing of field operations, and lack of knowledge on cover cropping, are some of the limiting factors of cover crop adoption (Arbuckle & Roesch-McNally, 2015; Runck et al., 2020; Snapp et al., 2005).

Despite the low rate of cover crop adoption, farmers who have adopted cover cropping have realized the multitude of benefits cover crops provide in maintaining soil health and improving soil fertility (Darby et al., 2014). Cover crop species vary in functional traits, from adding value (i.e., increasing yield), providing nitrogen in the form of soil organic matter, stabilizing mineral residues to reduce leaching (Kaye et al., 2019), and/or reducing pest pressure on subsequent or companion crops (Marques et al., 2020). Legume cover crops, including winter peas (*Pisum sativum* L.), can serve an additional role of increasing fertility via nitrogen fixation through their association with rhizobia (Kocira et al., 2020).

Growers choose specific species or combinations as cover crops based on their functional traits to meet specific management objectives (Kaye et al., 2019). In much of the northern United States, growers plant either winter-kill crops or cold-hardy cover crops in the fall and terminate the latter in spring before planting summer crops (Cornelius & Bradley, 2017). A key principle of soil health is having living roots in the soil for as much of the year as possible. However, winter-kill cover types are seeded in the fall season. This is primarily done to take advantage of the frost or below-freezing temperatures as a natural termination strategy to allow for easy seeding in the spring. Soils with a history of cold-hardy crops planted as cover crops have been reported to be more productive compared to soil with a history of bare fallowing (Simon et al., 2022). Cold-hardy species like winter peas may still experience some degree of losses from winter stress (Auld et al., 1983), particularly in cold temperate regions like Vermont.

There has not been sufficient research done to mitigate the factors that reduce the usage and adoption of cover crops. One approach to mitigating barriers to cover cropping is to increase the economic value of the crop by harvesting it. Winter pea is one of the crops that has a dual-usage potential, serving as both a cover and an edible crop. There is considerable phenotypic variation among peas. Due to this, individual cultivars may be best for specific uses, including animal feed (e.g., forage, concentrate) and human food (dry peas, sweet green peas, edible podded snap and snow peas, and pea shoots). Traditionally, winter peas have been grown for animal feed and spring peas grown for human consumption. Traits from the Austrian winter pea, a cold-hardy forage-type market class, have been successfully transferred to spring peas (Auld et al., 1983), and recent breeding efforts at the USDA plant germplasm and introduction testing research facility in Pullman, WA, are working on improving the traits of winter cultivars to be fit for human consumption (McGee et al., 2017). However, a lack of effort has been devoted to evaluating and characterizing improved winter pea cultivars in the cold and wet climates of the Northeastern United States. Improved winter peas could potentially provide a secondary benefit as pulses (grain legumes), green vegetables, or a protein-rich feed for dairy in the Northeastern United States. By harvesting immature pods instead of mature seeds, harvests may be earlier, providing more time in the summer growing season for the primary cash crop. This could increase the likelihood of farmers adopting cover cropping as a critical conservation practice.

Past studies have used several methods to evaluate cold hardiness in overwintering crops, including field trials and physiological assays (e.g., relative electrolyte leakage [REL]). The REL technique can provide a more quantitative measure of cold tolerance compared to field trials and is known to improve screening and capture more variation between tissues of the same or different plants. REL assessment is performed in the laboratory by exposing plant tissues to stepwise decreasing temperatures and quantifying solute leakage from cells damaged by freezing (Butnor et al., 2019). Studies have used REL assays to assess the feasibility of planting crop species/cultivars in specific climates along with predicting their lethal temperatures.

Here, a field trial and REL were used to investigate whether it is feasible to grow winter peas (*Pisum sativum*) as a double crop in the 2021/2022 and 2022/2023 seasons. We present the following hypotheses: 1. Winter peas with food quality traits will tolerate Northern New England winter conditions as well as winter forage types. 2. Certain agronomic management practices, including deeper planting depth, intercropping, and fencing, will decrease winter losses. 3. Double cropping is possible if certain pea cultivars with food-grade qualities are overwintered. We investigated these research hypotheses using field trials, a high tunnel study, and REL laboratory assays.

Core Ideas

- Cover crops that can be harvested as a marketable crop might increase adoption of cover cropping, an important practice for soil health.
- In Northern New England, limited cold tolerance of some autumn-planted cover crops limits choices for those adopting cover cropping.
- Peas with winter hardiness and marketable vegetable characteristics could allow double cropping in USDA Zone 4 regions.

2 | MATERIALS AND METHODS

2.1 | Experiment 1: Varietal evaluation

2.1.1 | Planting information

We evaluated 17 pea genotypes (listed in Table S1) for cold hardiness at the University of Vermont—Horticulture Research and Education Center (HREC) located in South Burlington, Vermont (44.4285 N, 73.2055 W, USDA Zone 5a) during the 2021/2022 winter season. The 17 genotypes were planted under dryland conditions (without irrigation) in a field size of 50 m × 25 m. The soil type for the trial field is Adams Windsor, a sandy loam formed on the banks of Lake Champlain when it was a Pleistocene seashore. To prepare the planting bed, the soil was tilled and packed (described in Marques et al., 2024). The peas were planted on September 30, 2021, in between rows of triticale (i.e., a cereal companion crop) following recommendations of the Cover Crop Breeding Network (https://www.covercropbreeding.com/) to reduce risks involved with late planting and poor establishment. The triticale served as a bio-insulator and windbreaks, as well as support for the peas to climb. We used a standard sowing depth of 2.54 cm and an intrarow space of 5 cm in all plots. Plots were single rows of approximately 3 m in length with row spacing of 30.5 cm. We planted 50 seeds per plot, or experimental unit, for each of the replicates. The pea seeds were not inoculated with rhizobia inoculum due to past use of the field for peas (2019–2020). No pesticides were used, nor was fertilizer applied to the plants.

The 17 genotypes were selected to compare available forage type (Austrian winter pea) and food grade (white flowers and larger seeds with a yellow or green color) winter peas. The food-quality winter-hardy types planted were *USDA Dint*, *USDA Klondike*, and *USDA MiCa*, all developed by R. McGee of USDA ARS (Crowder et al., 2022; McGee et al., 2017). The feed pea types in the trial included *Wyowinter*, *Windham*, *Koyote*, *Granger*, and *Melrose* bred primarily for feed grain but which can also be used as forage or green manure. The *Wyowinter* forage pea was bred by the University of Wyoming and released in 2016 for its excellent cold hardiness, good seed yield, and better forage yield (Homer et al., 2019). *Windham*, which has a semi-dwarf growth habit, was developed by USDA-ARS and released in 2006 for its tolerance to severe winter conditions and high yield (McPhee et al., 2007). *Melrose* was bred from a cross of an Austrian winter pea and a spring pea with powdery mildew resistance by the University of Idaho in partnership with three other universities. This old cultivar, first evaluated in 1973 is still known for its cold hardiness and abundant root nodules (e.g., Murray et al., 1984). *Granger* was bred by USDA-ARS and released in 1996 for its excellent cold hardiness ability and resistance to lodging (e.g., McGee & McPhee, 2012).

2.1.2 | Measured traits

A germination census for the individual cultivars was recorded on October 14, 2021, 14 days after planting. We recorded flowering dates, pod set dates, and dry seed yield.

We collected other phenotypic data such as seed mass (g/100 seeds), plant height, and number of pods per plant. We scored the plants for visual damage from cold stress using a scale of 1–7 (where 1 indicates dead/most damage from cold stress and 7 indicates no damage/least damage) on March 23, 2022. We took a census count of each plot at four different times during the season. Counts were recorded on October 14, 2021, November 5, 2021, December 17, 2021, and March 23, 2022. Flowering was first observed on June 1, 2022, with pods emerging from June 6, 2022. Pods were harvested in mid-June, allowed to air-dry, and then hand-threshed to allow weighing of the per individual plant.

2.1.3 | Data analysis

The analyses were done using the Agricolea package in R (Mendiburu & Yaseen, 2020). Prior to analyzing the count data, the cultivars that had very low germination rates (PS1130240W-A and PS1130240W) and the cold-sensitive cultivars (Amigo and HMOS VNS) used as control were removed from the dataset, as they were used to confirm that it was cold enough and that there was a differential winter kill. The data from the third replicate were also removed due to rabbit damage.

To normalize the census count data, we used the proportion of overwintering plants that survived. The normalized census count was then transformed using the arcsine function built in R programming language (R version 4.1.2). We back-transformed for reporting. Counts recorded on March 23, 2022 and December 17, 2021 were used for the numerator and denominator, respectively. We then ran an analysis of variance (ANOVA) in R to determine the effect of cultivar on survival, including the block effect.

2.2 | Experiment 2: Seed depth assessment

2.2.1 | Planting information

A second field trial was conducted to test for the effect of seeding depth on overwinter survival and performance of winter peas at the University of Vermont HREC during the same season as Experiment 1. Seventeen genotypes (Table S1) were planted as treatments under a dryland condition (without irrigation) in a total field size of 50 m × 25 m. The same soil preparations as in Experiment 1 were used. The pea seeds were planted in between rows of triticale on September 30, 2021. We used different sowing depths of 2.54, 5.08, and 7.62 cm but the same intra-row spacing of 5 cm in the plots. Plots were a single row of approximately 3 m long with a row spacing of 30.5 cm. The pea seeds were not inoculated with rhizobia inoculum, and neither were any pesticide or fertilizer applications performed.

The design used for this experiment was factorial, in which "sowing depths" and "genotypes" were the treatment factors. The sowing depth factor comprises three levels (2.54, 5.08, and 7.62 cm). This experiment was a non-replicated augmented design due to a seed limitation. We planted 50 seeds per plot, or experimental unit, for all possible combinations. The cultivars and depth treatment combinations were assigned to 51 plots in a complete randomized design. Each plot was counted before the winter season and at the onset of spring to collect the count census data that would be used to infer winter survival rates.

2.2.2 | Data analysis

The analysis was done using the Agricolae package in R (Mendiburu & Yaseen, 2020) and PROC GLM in SAS OnDemand (Documentation.sas.com). Prior to analyzing the data, genotypes that were used as sensitive control groups (Amigo and HMOS VNS) and genotypes that had very low germination rates (PS1130240W-A and PS1130240W) were removed from the dataset.

We normalized survival rates using the same approach as in Experiment 1 and transformed the resulting values using the arcsine transformation. To analyze the data statistically, the presence of interaction effects was assessed before testing for main effects of genotype and planting depth. Due to seed limitation, this experiment was not blocked; thus, to have an error term for a valid statistical test, Tukey's 1 *df* test for non-additivity was employed (Tukey, 1949).

2.3 | Experiment 3: Assessing cold hardiness with REL assays

2.3.1 | Planting materials and acclimation

We planted 34 genotypes (Table S1), including the 17 genotypes used in Experiment 1 on September 16, 2022, in a high tunnel at the HREC, to expose the plants to winter temperatures and leave plant tissue snow-free for harvest throughout the winter. The soil in the high tunnel is Adams Windsor sandy loam. The genotypes were planted in a complete randomized design. This was a replicated design of two replicates per genotype. We planted five seeds per plot for each replicate. We used the Agricolae package in R (Mendiburu & Yaseen, 2020) to randomly assign the genotypes to 68 plots.

Hourly air temperature inside the high tunnel was recorded with an Arable Mark II weather station (Arable Labs). The unit was removed from its stand and placed at ground level. The plants were supplied with moisture through a drip irrigation system. The plots were counted after emergence (October 25, 2022) and after winter (March 27, 2023) to infer winter survival rates. The peas were scored based on visual damage using a scale of 1–9 (where 1 indicates dead/most damage and 9 indicates no damage/least damage). The tissues were harvested in the mornings of October 25, 2022, December 12, 2022, January 10, 2023, and March 27, 2023 while leaves were fully hydrated and kept in a cooler with ice packs until processing in the laboratory later that day.

2.3.2 | Cold tolerance assay

This laboratory experiment assesses tissue cold hardiness by measuring the quantity of solute that leaks from the cells when exposed to freezing and thawing, called REL (Kovaleski & Grossman., 2021). REL has been used for decades to assess cellular leakage after exposure to environmental stressors such as sub-freezing air temperatures or drought. For cold tolerance assays, replicates of tissue are placed in a chamber that is programmed to slowly lower the air temperature and hold it at specific temperatures to incubate for a period of time. After being held at a given temperature, a tissue replicate is removed, the temperature is lowered, and the process is repeated. After exposure to the temperature series, the electrical conductivity of the plant tissue in aqueous solution is measured, maximum cellular rupture is induced by heating or exposure to liquid nitrogen, and the REL at a specific temperature is expressed as a percentage of the maximum (Kovaleski & Grossman, 2021). The higher the REL, the more the cells are damaged from freezing. A sigmoid response curve is often used to describe the relationship between the REL measurements and treatment temperatures. The midpoint of the curve is identified as LT_{50}, which represents the lowest temperature where 50% of tissue has been damaged and repair is unlikely. The smaller the LT_{50} values, the higher the acclimation abilities of the tissues.

Our method and protocol were similar to Gurney et al. (2011) and Butnor et al. (2019), but included several improvements and a 4-day workflow (Butnor et al., 2024). Important improvements were related to tissue handling, application of a 2.5 h span at 95°C to rupture cells, use of a custom-made multi-electrode conductivity meter (Butnor, unpublished), and semi-automation of data interpretation with the R programming language (R Core Team, 2023).

Leaf tissue was harvested in the field, immediately put in a cooler with ice packs, returned to the laboratory, and placed in a refrigerator set to 4°C. The leaves were sectioned into 5-mm disks with a surgical biopsy punch and placed in 48-well plates (48 × 3.5 mL wells per plate). The plates were put in an environmental chamber (Espec North America Corp.) set to 4°C until the programmed stepwise exposure to the assay temperatures (−5, −10, −15, −20, −30, and −80°C) commenced. Electrical conductivity of leaf tissue in aqueous solution was measured before and after exposure to cold to

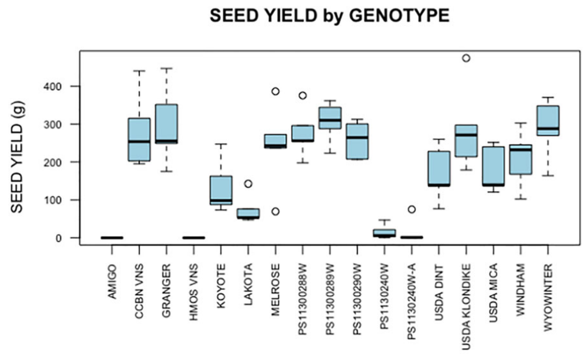

FIGURE 1 Box plot of dry seed yield by genotypes in Experiment 1.

calculate percent REL for each temperature. The data were further analyzed in R with dose-response curve analysis (Ritz et al., 2015) to calculate the lethal temperature where 50% cellular leakage had occurred (LT_{50}), minimum leakage (Y_{MIN}), and maximum leakage (Y_{MAX}).

3 | RESULTS

3.1 | Experiment 1: Varietal screen

3.1.1 | Weather data

The coldest month during the 2021/2022 season was January, with an average minimum temperature of −15.7°C (Figure S1). There were 9 days with daily minimum temperatures above 0°C in the winter season (December–February). The lowest minimum temperature was −24.7°C recorded January 27, 2022. The total amount of precipitation recorded between September 15, 2021 and June 15, 2022 was 494.53 mm. The amount of precipitation recorded during flowering (June 1, 2022–June 15, 2022) was 36.06 mm.

3.1.2 | Germination, survival, height, and seed yield

We observed variation in the germination census among the genotypes, with five (*Amigo*, *Koyote*, *Lakota*, *Ps1130240W*, and *Ps1130240W-A*) having a germination count of less than 50% (a count below 25, Figure S2). Winter survival was generally high (excluding winter-killed control cultivars; Table S2), and one-way ANOVA revealed no significant differences among cultivars for survival rates ($F = 0.67$, p-value = 0.76). Seed yield varied among genotypes ($F = 6.867$, p-value < 0.001, Figure 1). The range of height at maturity for the tested genotypes was 30–128 cm (excluding winter-killed control cultivars) (Figure S3a). The tallest was

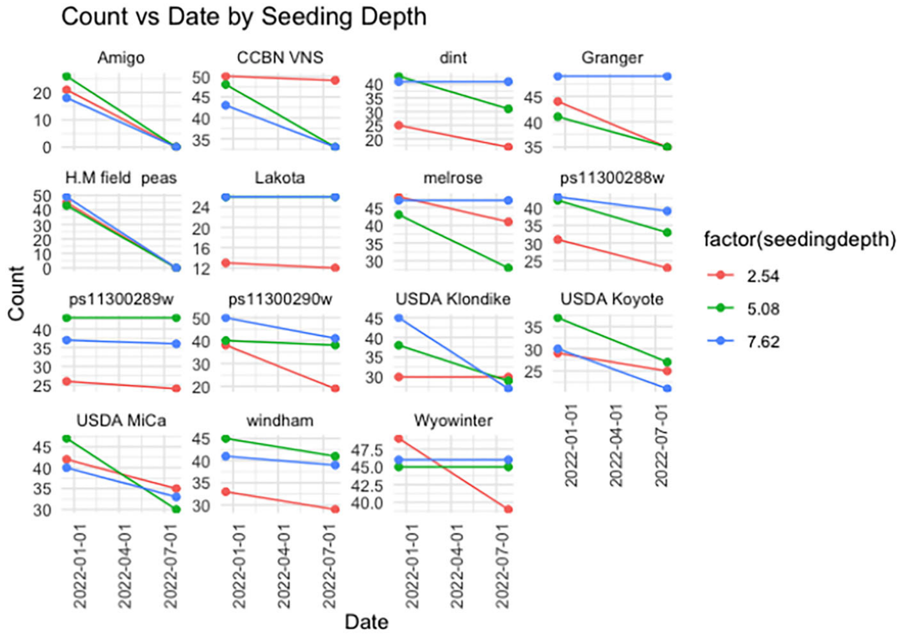

FIGURE 2 The average number of plants recorded for the individual genotypes in Experiment 2 on December 17, 2021, and July 25, 2022. Red lines indicate the shallowest planting depth (2.5 cm), green lines the intermediate (5 cm), and blue the deepest (7.6 cm).

Melrose at 128 cm and among the shortest were Windham and Ps1130240W at 30 cm. The range of hundred seed weight was 14.05–22.66 g (Figure S3b). The lowest hundred seed weight was 14.05 g for *Melrose* and the highest was 22.66 g for *USDA Klondike*. The dry seed yield for the cultivars is visualized using a bar plot (Figure 1). The distribution of the maximum number of pods per plant ranged from two pods for *Ps1130240W* to 26 pods for *Melrose* (Figure S3c). We did not observe significant variation in flowering or podding time among the genotypes.

3.2 | Experiment 2: Planting depth

3.2.1 | Stand count analysis

The stand counts taken at two different time points during the growing season are shown in Figure 2. We observed no winter losses of plants in some plots with 7.62-cm and 5.08-cm planting depth treatments on December 17, 2021 (Figure 2).

3.2.2 | Comparison of winter survival rates

Mean winter survival was consistent among the depth treatments (Table S3) and two-way ANOVA revealed no significant effect of planting depth on survival rates (F = 1.09, p-value = 0.41).

3.3 | Experiment 3: REL

3.3.1 | Temperatures during growing season

Temperature conditions in a high tunnel differ significantly from outdoor ambient conditions; hence, an Arable Mark II weather station for in-field sensing was used to capture temperature data in the high tunnel (Figure S4). Within the high tunnel, February 2023 was the coldest month with an average minimum temperature of −7.7˚C. From December 2022 through February 2023, only 11 days had an average minimum temperature >0˚C, with the lowest minimum temperature of −17˚C on February 25, 2023. These conditions were ideal for differential winter kill.

3.3.2 | Germination data

The germination rates for the genotypes tested are reported in Table S4. Nine genotypes had 100% germination rates. Amigo was the only genotype that had less than 50% germination. Most genotypes had an emergence rate of 80% or more.

3.3.3 | Field survival

One-way ANOVA revealed no significant effects of genotype on survival rates (F = 0.89, p-value = 0.61). The winter survival means for the genotype groups are reported in Table

S5. The cold-sensitive genotypes used as controls had 0% survival rates. Most of the genotypes had 50%–80% survival rates. Some genotypes, such as Lakota and Melrose, had 100% survival rates.

3.3.4 | Cold tolerance assay

Two-way ANOVA was used to analyze variation in cold tolerance (LT_{50} derived from REL assays) among dates and cultivars. ANOVA revealed a trend toward differences in cold tolerance among dates ($F = 6.0$, p-value $= 0.08$) but no significant effect of cultivar ($F = 0.62$, p-value $= 0.92$) on LT_{50}. Tukey's honestly significant difference test yielded a significant decrease in LT_{50} between October 2022 and March 2023 after removing cold-sensitive cultivars from the dataset prior to analysis (Figure S5). The average LT_{50} values for the cultivars at different dates are reported in Table S6.

4 | DISCUSSION

4.1 | Vegetable pea types have equivalent cold tolerance to Austrian field peas

The USDA plant hardiness zone map categorizes Vermont as Zone 4a–6a. Fall-seeded peas in Vermont experience both chilling (0–15°C) and freezing (<0°C) stresses in their various growth stages, from emergence to reproductive stage. The Champlain Valley of Vermont starts to have freezing temperatures toward the end of October, based on the recorded average minimum temperatures (Figure S1). Cold stress affects overwinter survival, yield, and harvest quality (Adhikari et al., 2022). The severity of low-temperature injuries on crops is related to other important variables such as the species, genetic variant, physiological age, and tissue health of plants (Yadav, 2010). Low-temperature acclimation is the most common mechanism that many plant species, including peas, have evolved for adapting to cold stress (McGee et al., 2017). Acclimation is the ability of plants to gradually develop resistance to cold stress. This happens when plants are gradually exposed to low temperatures (Yadav, 2010).

Generally, Austrian winter peas landraces are known to have better winter survival abilities compared to spring pea market classes, as well as a less palatable chemical profile (Canbolat et al., 2007; Klein et al., 2014). Recently, pea breeding programs of USDA-ARS in Pullman, WA, and Progene Plant Research in Othello, WA, have focused on breeding strategies to improve the edible traits of Austrian winter pea types by crossing them with food-quality spring peas. In the field, we observed 100% mortality rates for the control/cold-sensitive cultivars (4010 field pea, High Mowing Organic Seed's unnamed field pea, and Amigo), which indicates there was sufficient cold for non-cold-tolerant peas to be killed. There were no statistically significant differences among the winter genotypes for winter survival. The older Austrian winter peas had the same survival abilities as the newly developed food-quality winter-hardy types.

4.2 | Impacts of companion cereals and planting depth on winter survival

In Experiment 2, there was no significant effect of planting depth on survival rates. However, we observed a trend toward deeper depths having higher survival than a more widely practiced 2.54-cm seeding depth, which may suggest some insulating effect of deeper planting, which may be useful in colder conditions than our field study.

4.3 | The need for physiological measures of cold tolerance

One limitation with screening peas for cold tolerance in the field is the limited variability observed in results of field trials (e.g., Liu et al., 2017). Field trials only assess the plant's ability to tolerate how cold it gets in that specific trial season, which is another limitation because there is evidence of temperature fluctuations between seasons. Hence, it was important for us to carry out Experiment 3, a laboratory method that complements field methods to assess the acclimation abilities in peas.

Acclimation abilities in crops can be quantified using REL assays (Butnor et al., 2019; Deans et al., 1995; Lindén et al., 2000; Lim et al., 1998). A previous REL study (Swensen & Murray, 1983) reported that winter peas will acclimate at temperatures between 10°C and freezing, attaining a maximum freezing tolerance after 2–6 weeks of acclimation. We performed our REL experiment (Experiment 5) in a high tunnel to be able to access leaf tissue in the middle of winter but found that temperatures were sufficiently warm inside that full acclimation may not have occurred. In Experiment 3, REL for leaf tissues from 34 pea cultivars was assessed in October, December, January, and March. The LT_{50} values were informative in giving us insight about the acclimation states of plant tissues and risk of exposure under freezing temperatures. The average LT_{50} values of the different experiment runs were October 2022 (−10.61°C), December 2022 (−12.45°C), January 2023 (−11.53°C), and March 2023 (−13.79°C). The average LT_{50}s in this study were lower than the minimum mean lethal temperature of −8.5°C attained in previous REL study for peas (Swensen & Murray, 1983). There was a significant difference between the October 2022 and March 2023 run. The reason for not identifying significant differences between the LT_{50}'s in comparisons between other months may be explained by insufficient sample size. Another reason for not detecting differences may be explained by similar acclimation states between the months. The pea tissues may have already acclimated to cold in October when the first REL assay was done and maintained their acclimation abilities through December and January. This is supported by the chilling temperatures (between 10 and 0˚C) experienced by the pea tissues in the field prior to the first run on October 18, 2022. The LT_{50} values for some cultivars did not follow the predicted trends. The average LT_{50} values of Lakota, one of the cultivars with highest field survival rates in the study, were −9, −12.44, −11.71, 0.44 for October, December, January, and March, respectively. The lethal temperatures for some genotypes were not consistent with mortalities in the field. Despite estimating −11.71˚C to be the lethal temperature for Lakota tissues/plants on January 11, the tissues survived −15 and −14˚C on February 3 and 4, respectively. On the other hand, the LT_{50} values over the course of the REL study for P1448, field pea 4010, and P1485 supported the observed mortalities in the field. The LT_{50} values for P1485 were −11.35, −10.38, and −10.79˚C for October 18, 2022, December 13, 2022, and January 11, 2023, respectively. The 100% tissue death of P1485 observed on March 6, 2023 may be due to preceding lower temperatures of −15 and −17˚C recorded on February 1, 2023 and February 25, 2023, respectively, as compared to the prior lethal temperature of −10.79˚C predicted on January 11, 2023. The variability of LT_{50} values across the months may be due to some tissues acclimating and de-acclimating as the environmental condition changes, or to new growth in March leading to unacclimated young leaves.

4.4 | Feasibility of double-cropping winter peas with summer crops in the Northeast

Emergence for the cultivars in all the experiments was generally high, ranging from 17% to 87% in Experiment 1 and 38% to 94% in Experiment 2. Recording 100% emergence in a few plots indicates that conditions for pea germination were adequate in the autumn. The daily maximum temperatures in the first 3 weeks of October ranged from 11 to 23.7˚C. Findings from pea germination studies also imply conditions were adequate for pea emergence in the autumn; a pea germination study assessing various temperatures (5–40˚C) reported the germination base temperature to be −1.1˚C (Raveneau et al., 2011) with the highest emergence at 10˚C (Sincik et al., 2004).

Winter peas are one of the few economic grain crops that can be overwintered due to their cold-hardy traits (Thakur et al., 2010). They are known to have better survival ability than most legume grains, which makes them a good cover crop choice. Whether growing food-quality types can additionally generate sale revenue without interfering with summer cash crop operations is an open question. Our trial findings of flowering, pod formation, and grain maturity dates suggest it may be impractical for some farm settings to adopt this cropping system. By May 25, only a few flowers were observed in each genotype. However, by June 1, nearly all genotypes that had survived the winter had almost 100% bloom. The flowering dates of the peas were later than the beginning of April (i.e., the general recommendation date for planting most frost-tolerant vegetables in spring) when the peas were planted September 30. As an example of how the late May flowering is problematic for farmers in the far northeastern United States, a collaborative field trial we conducted at Philo Ridge Farm (Charlotte VT) in the 2022/2023 season was terminated by the host farm before reaching the reproductive stage due to interference with spring operations. The late maturity date of June for dry seed harvest may work in some farming systems depending on the growing plan for that year but will often be problematic for farmers who want to have their summer crops in the ground by the last frost-free day (May 3 according to past years' data recorded at the Patrick Leahy Burlington International Airport weather station, although in 2023 we had a frost in Burlington on May 17). Scenarios where a farmer staggers planting so that not all acres are to be planted at once in the early season of spring may favor the maturity time of fall-sown peas as double-crops or alternative scenarios where fall-sown peas can replace early spring-planted peas. Another promising scenario where it could also work is in greenhouse systems. Some of the pea cultivars planted in the high tunnel without heating systems for the REL assay in Experiment 3 had flowers and pods as early as May 9, suggesting the insulating effect of the high tunnel provided enough warmth to speed up flowering. But even in this case, many Vermont high tunnels are filled with tomatoes or other crops by mid-March. Fresh snap or snow peas are simply not sufficiently valuable to delay the planting of most summer crops. Finally, instead of growing winter peas as vegetables, farmers could harvest existing Austrian winter pea cultivars as winter forage suitable for ruminants before planting summer crops.

Flowering in peas is a complex trait controlled by several genes and photoperiod (Weller & Ortega, 2015). Numerous studies on flowering of peas have focused on identifying signaling pathways that control flowering time. Weller and Ortega (2015) tabulated over 20 loci that have been reported in past studies to be related to flowering time. Variation in flowering times is a result of interactions between the SN (sterile nodes), LF (late flowering), E (early), and HR (high response to photoperiod) loci (Murfet, 1973; Weller & Ortega, 2015). Weller and Ortega (2015) again reported that genotypes with recessive alleles at the LF and SN loci are not sensitive to daylight length allowing them to flower as early as node 7. With environmental cues, the HR locus also influences freezing tolerance by delaying the vegetative-to-floral transition during winter freezing events. The dominant HR locus was found in forage pea cultivars to delay floral initiation until day length of 13 h 30 mins is reached (Weller & Ortega, 2015). It is important that winter peas flower reasonably late to avoid late winter frosts but also early to escape moisture and heat stresses in late spring (Wenden et al., 2009). A promising breeding strategy to achieve desired flowering dates may then be to combine the HR allele with an appropriate allele of LF (Wenden et al., 2009) to achieve earlier flowering with increased freezing tolerance. Burlington, VT, gets 13.5 h of daylight on April 15th.

5 | CONCLUSIONS

In temperate regions with winters including several months of temperatures below 0˚C, winter-hardy peas have the potential to provide the dual benefits of a leguminous cover crop and a double crop (McGee et al., 2017). However, in USDA Zone 5, the June maturity of overwintered peas will not work for most vegetable farmers: by comparison, the third week of May is considered as the last week of planting cucurbit and nightshade crops due to the short summer growing season in Vermont. Cold tolerance studies in peas are cultivating progress in understanding the agronomic constraints in growing winter peas in colder climates. Varietal development goals that focus on making crops adaptable to seasonal stresses and profitable will make all-year cropping practice attractive to many farmers. There is also potential for improving the cold tolerance traits of many spring green cultivars to reduce the risk of late frost damage at the beginning of the season.

AUTHOR CONTRIBUTIONS

Emmanuel Brefo: Formal analysis; investigation; writing—original draft; writing—review and editing. **Rebecca McGee**: Resources; writing—review and editing. **John R. Butnor**: Conceptualization; formal analysis; funding acquisition; writing—review and editing. **Melike Bakır**: Conceptualization; investigation; methodology; writing—review and editing. **Tucker Andrews**: Conceptualization; funding acquisition; resources. **Heather Darby**: Conceptualization; funding acquisition; writing—review and editing. **Stephen Keller**: Conceptualization; funding acquisition; methodology; writing—review and editing. **Eric von Wettberg**: Conceptualization; data curation; funding acquisition; methodology; project administration; supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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