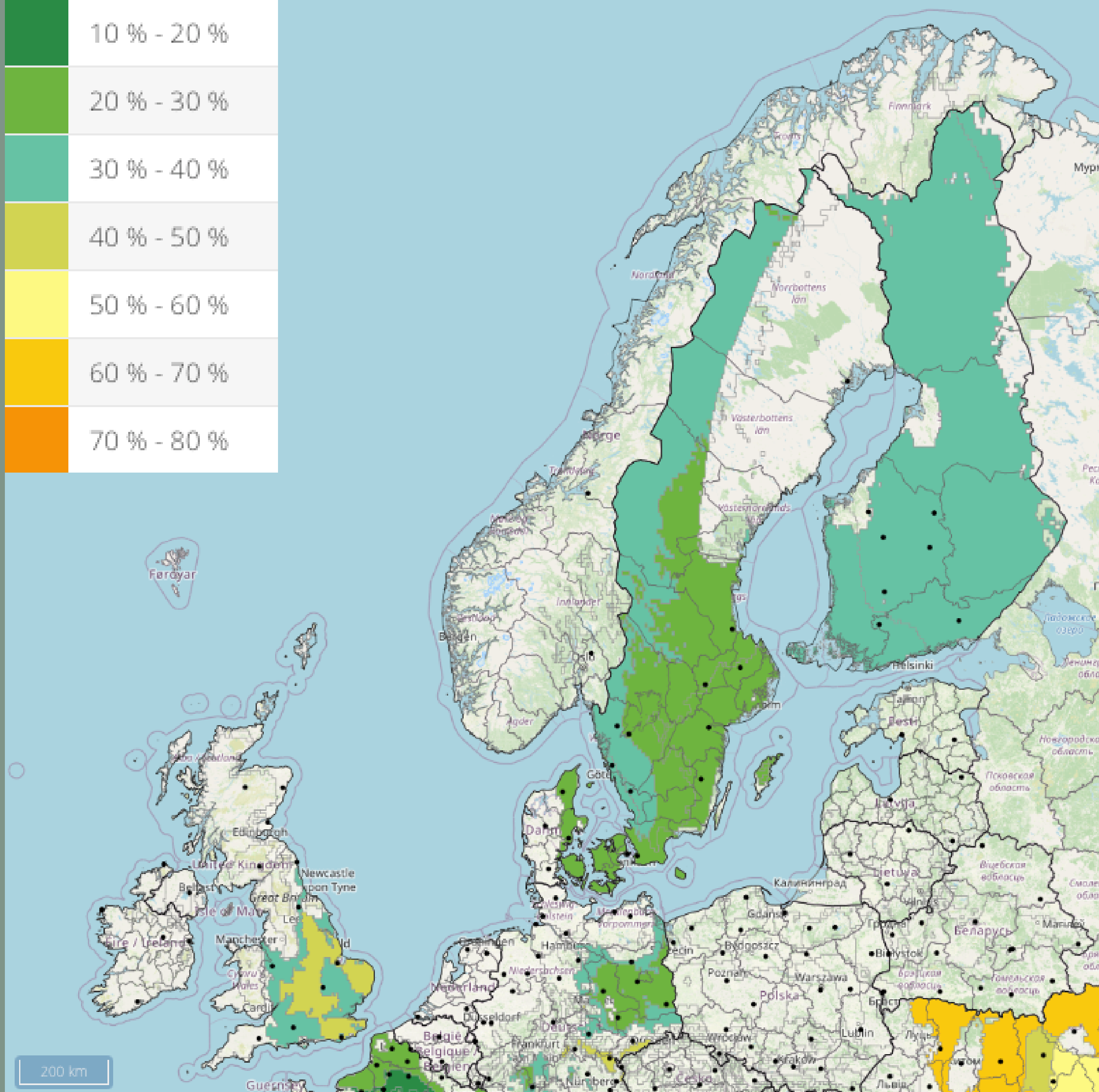

YIELD GAP ANALYSES FOR PEA IN NORTHERN EUROPE, AND IMPLICATIONS FOR CLIMATE CHANGE IMPACT AND MANAGEMENT EFFECTS

PPS Research Practice
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Abstract

Legumes, such as peas, offer numerous benefits including mitigating environmental impacts, enhancing agroecosystems, and providing essential nutrition. Despite the potential advantages, legume production in Northern European countries remains constrained. Our objectives were to assess the current yield gaps (absolute yield gap (Yg) and relative yield gap (ReYg)), explore how the water-limited potential yield (Yw) might change under projected climate scenarios, and investigate opportunities from adaptive management (i.e., straw mulching) in four Northern European countries: Denmark, Finland, Sweden, and the UK. In this study, we utilized the SSM-iCrop2 crop growth model to simulate Yw for rainfed peas and the potential yield (Yp) for irrigated peas. Actual yields retrieved from national statistics were used for yield gap calculations. Future scenarios SSP3 and SSP5 were introduced to analyze the Yw under climate change in 2050. Moreover, a simple mechanism concerning the relationship between soil coverage and evaporation was implemented in the model to assess the impacts of straw mulching. Results show highest rainfed yield gap in the UK (Yg: 2.37 t/ha, ReYg: 39%), followed by Finland (Yg: 1.23 t/ha, ReYg: 31%), Sweden (Yg: 1.13 t/ha, ReYg: 26%), and Denmark (Yg: 1.10 t/ha, ReYg: 23%). Additionally, we analyzed the yield gap for irrigated peas in Denmark, with Yg estimated at 1.37 t/ha and ReYg at 28%. Examination of Yw under climate change projections revealed significant increases across the four countries compared to the baseline scenario (1995-2014), particularly in the UK (SSP3: 17%, SSP5: 19%). Finally, we investigated the effects of straw mulching on Yw, observing improvements with increased mulching rates. Notably, the most substantial benefit of mulching was observed in Denmark, where an application rate of 6 t/ha led to a remarkable 6.1% increase in yield compared to non-mulching practice. Such mulching practices hold promise in reducing the variability of grain pea yield in potentially poor harvest years, especially for Finland and Sweden. Overall, our study quantified the yield gap for grain pea in four Northern European countries and highlighted the potential benefits of climate change on future pea cultivation. We advocate for the exploration of adaptive management strategies like straw mulching to enhance yields. Future research should consider more representative simulation mechanisms and field experiments to validate model performance and inform policy decisions.

Keywords: Yield gap analysis, pea, climate change, straw mulching

1 Introduction

Legumes have been found to be effective in mitigating environmental impacts, improving agroecosystem and providing nutrition to daily diets (Marteau-Bazouni et al., 2024). Improving food production by involving legumes has gained widespread attention in Northern European countries (Cusworth et al., 2021; Lötjönen & Ollikainen, 2017). Cultivating legumes in rotation with staple crops allows for increased nitrogen fixation in the soil, providing essential nutrients for subsequent crops (Pandey et al., 2017). Ensuring abundant production of legumes thus becomes paramount in supporting nutrient input for the entire cropping system, further enhancing overall food production.

Yet, current legume production in Northern European countries is restrained by multiple factors. One example is the short growing season. Countries in Northern Europe, such as Denmark, Sweden, Finland and the UK, are well-known for their low temperatures during long and harsh winters. The cold weather limits agricultural areas and growing seasons (Monteith & Moss, 1977; Rötter et al., 2011; Wiréhn, 2018). For instance, pea can only be cultivated in the southern regions, as in the northern region of Finland and Sweden full maturity cannot be reached (Carlson-Nilsson et al., 2021). Meanwhile, farmers would invest more on economy-benefit crops rather than legumes (Alandia et al., 2020; Juhola et al., 2017). In this context, there is still ample room for improving legume production, and there is a long way to go.

Conducting yield gap analysis would help quantify how much legume production can be improved. This approach has been applied worldwide for various legumes and other crops (GYGA, 2023a). The yield gap refers to the difference between the water-limited potential yield and the actual yield in rainfed systems, or the difference between the yield potential and the actual yield in irrigated systems (van Wart, Kersebaum, et al., 2013). By estimating the yield gaps in different regions, farmers can adopt diverse management strategies to increase grain legume production, thereby enhancing overall crop production in their limited agricultural areas.

Climate change might be both an opportunity and threat for legume production in the Northern European countries. Elevated temperatures could alleviate the coldness in the region, enabling more legumes to thrive in harsh winters, likely benefiting both the potential yield in irrigated system and the water-limited potential yield in rainfed systems (Parihar et al., 2022). On the other hand, extreme precipitation may lead to soil erosion and water logging, limiting oxygen availability for plant growth (Wiréhn, 2018). This could possibly restrict the water-limited potential yield. Moreover, prolonged drought events would reduce crop water availability, posing challenges throughout the entire growing periods and thereby restraining the water-limited potential yield.

Adaptive management can reduce the negative impacts induced by climate change. One practice is straw mulching (Cardinael et al., 2021; Chen et al., 2019; Nikolaou et al., 2020). When the soil is covered by the straw mulch, less water evaporates, allowing more water to be retained in the soil and become available for crop uptake (Lalljee, 2013). Moreover, such practice can prevent soil erosion and runoff, further enhancing water-limited potential yield in rainfed systems (Saucke et al., 2009; Singh & Lal, 2005).

In this study, we focused on pea cultivation across four countries in Northern Europe, namely Denmark, Finland and Sweden and United Kingdom (UK). The following three research questions were addressed throughout the study using a crop growth model:

1. What is the current yield gap of grain pea in these countries?
2. How would climate change affect the water-limited potential yield in the next decades?
3. What would be the effect of mulching on the current and future water-limited potential yield for peas?

2 Materials and methods

Potential yields simulation and yield gap analysis conducted in this study utilized a "bottom-up" approach outlined in the Global Yield Gap Atlas (GYGA, 2023b, 2023c), where estimates at each location are eventually scaled-up to regional level or even country level. This would allow for yield gap analysis for grain pea production in these Northern European countries to be transparent and reproducible. Below is the approach shortly described, and more details about all the steps of the protocol and data sources used can be retrieved from www.yieldgap.org and van Loon et al. (2023). Prior to this study, the first seven steps of the protocol (Figure 1) were performed as follows. Steps 1,2) Pea can be chosen as the target crop regardless of its growing area, given its cultivation in relatively small agricultural areas across the four countries investigated in this research. Rainfed peas are grown in Finland, Sweden and UK, while in Denmark, irrigated peas are grown in half of the areas and rainfed peas are grown in in the other half. Steps 3, 4) The identified pea-growing areas include 12 climate zones (CZs, classified based on the homogeneity in local climate variables dominating crop growth and yield (van Wart, van Bussel, et al., 2013)). In total, 20 buffer zones were selected across these CZs and each buffer zone was scaled up from a weather station. We have created a map to display the locations of these stations, which can be accessed at https://rpubs.com/Wisteria/1149402. Step 5) Daily weather data (i.e., maximum temperature, minimum temperature, total precipitation and total solar radiation) was obtained from the abovementioned weather stations. Step 6) The most dominant soil types were selected and soils with a depth shallower than 30 cm were excluded. Knowledge on the cropping systems was collected from local agronomists. Step 7) Data on the pea actual yields were collected from the statistic institutes of the four countries (Denmark, 2023; GOV.UK, 2024; Luonnonvarakeskus, 2023; Sweden, 2023). Once the simulation is completed, results in each soil were converted to the fresh weight using a water content of 14%, and then scaled up to each station with soil coverage serving as the weighing factor. To analyze yields at the country level, the simulated results, along with actual yields, were further scaled up to the climate zone and country level. The cropped area of each buffer zone and climate zone respectively served as the weighting factor in this process. At both the regional (station) and country levels, absolute and relative yield gaps were calculated as follows:

$$Yg = \begin{cases} Yw - Ya, & for\ rainfed\ pea \\ Yp - Ya, & for\ irrigated\ pea \end{cases}$$

$$ReYg = \begin{cases} (1 - \frac{Ya}{Yw}) \times 100, & for\ rainfed\ pea \\ (1 - \frac{Ya}{Yp}) \times 100, & for\ irrigated\ pea \end{cases}$$

Here, Yg denotes the absolute yield gap (t/ha), ReYg denotes the relative yield gap (%), Yw represents the water-limited potential yield for rainfed systems (t/ha), Yp represents the potential yield for irrigated systems (t/ha), and Ya represents the actual yield (t/ha).

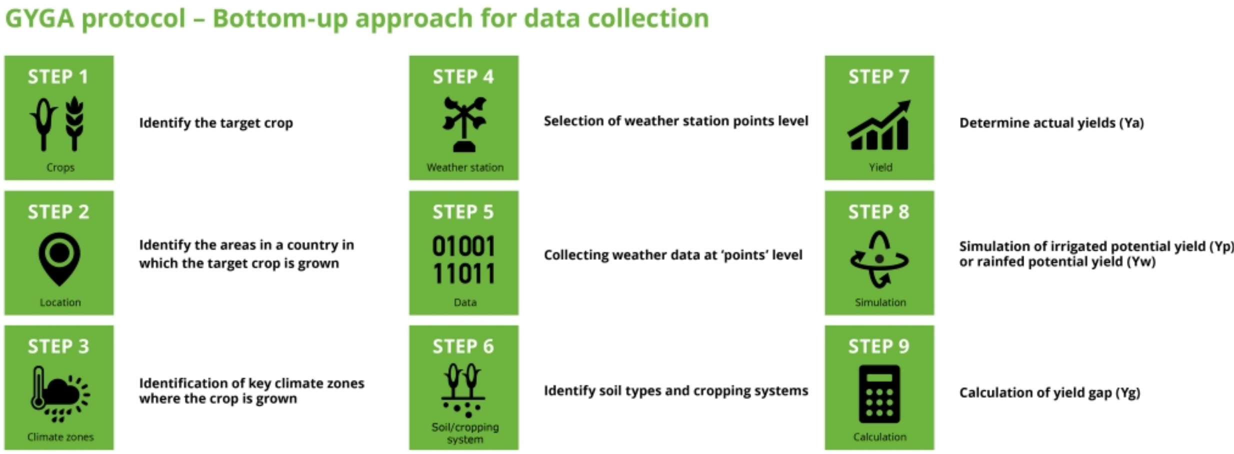

Figure 1. The nine-step protocol for data collection in GYGA (GYGA, 2023c).

2.1 SSM-iCrop2 model

In this study, we employed the SSM-iCrop2 model for water-limited potential yield and potential yield simulation (Soltani et al., 2020). This model was originally published by Soltani and Sinclair (2012), and has been further developed to include growth and yield simulation for various crop species at large scales, where the model parameters were initialized for 32 crops in Iran (Soltani et al., 2020). Therefore, prior to potential yield simulation, calibration for cultivars in the four countries was conducted using crop management and phenology information provided by local agronomists.

Specifically, sowing temperature (SowTmp) was calibrated with the averaged sowing date, and temperature unit for harvest or leaf fall (tuHAR) was calibrated using the averaged growth duration. More details can be found in S1 Figure 7. Ultimately, SowTmp values were set to 7.5°C for Denmark, 6.0°C for Finland, 8.0°C for Sweden, and 9.5°C for the UK. Similarly, tuHAR values were established at 1300 GDD for Finland and 1500 GDD for the remaining countries. Furthermore, additional crop physiology variables were calibrated based on recommendations from local agronomists, with further details provided in S1 Table 1.

Subsequent to calibration, the model underwent evaluation with growing season duration and yield data obtained from Antichi et al. (2023). Root mean square error (RMSE), coefficient of variation (CV) and correlation coefficient (r) were the three metrics used for model evaluation (S1 Figure 8).

Upon successful calibration and evaluation, the model was applied to simulate potential yield (Yp) and water-limited potential yield (Yw) using the collected soil, weather, and management data.

2.2 Current yield gap analysis

To understand how much improvement can be achieved in current grain pea production, yield gap analysis was conducted for the recent 20 years (2004 to 2023). This analysis involved simulating Yp or Yw based on soil conditions, historical weather data, and crop management practices collected prior to this study. The simulated yields were then scaled up to the station and country levels to calculate the yield gap (Yg), relative yield gap (ReYg), and water limitation index (WLI). The WLI, expressed as $(1 - Yw/Yp) \times 100$, quantifies the extent to which water availability limits potential yield if no irrigation is implemented. These results, along with actual yields (Ya) and Yp or Yw, were visualized to examine their distribution and identify key factors influencing yield variations.

2.3 Water-limited potential yield under climate change

To compare Yw under climate change, one baseline (1995 to 2014) and two climate change scenarios, SSP3-7.0 and SSP5-8.5 in 2050 (2039 to 2058), were applied. The latter featured higher temperature, increased CO_2 concentrations, and more severe extreme events (i.e., intense precipitation and prolonged drought) compared to the former. Weather data for the future scenarios were derived from the existing weather data in the baseline, with modifications guided by the projections proposed by the Intergovernmental panel on Climate Change (IPCC, 2023). Specifically, daily precipitation and temperature were modified based on monthly changes projected by the IPCC, while CO_2 concentrations for the future scenarios were set at levels projected for 2050. The projections included two situations: one predicting a global temperature increase of 2.1 °C (referred to as SSP3-7.0 or simply SSP3) relative to the baseline, and another representing a worse-case scenario with a global temperature increase of 2.4 °C (referred to as SSP5-8.5 or simply SSP5) in the medium of the 21st century (IPCC, 2023). Elevated temperatures could extend the growing season, while higher CO_2 concentrations could enhance photosynthesis, providing more favorable conditions for pea growth. However, it is crucial to note that increased frequency of intense precipitation events may lead to field flooding, submerging the peas and hindering their growth. Additionally, prolonged drought is likely to promote evapotranspiration and stress pea growth, further increasing the risk of desiccation. Therefore, all the above potential opportunities and challenges of climate change on pea growth were considered within the model.

2.4 Current and future water-limited potential yield with mulching practices

The SSM-iCrop2 model does not account for mulching practices, therefore an algorithm was integrated into the model to account for this. The algorithm incorporates a simple mechanism based on the relationship between soil coverage and evaporation, which is expressed as:

$$CovFac = \begin{cases} \frac{ResAm}{5}, & ResAm < 5\ t/ha \\ 1, & ResAm \geq 5\ t/ha \end{cases}$$

$$EvapRedFac = CovFac * 0.6$$

$$DailyEvap_d = SEVP_d * (1 - EvapRedFac)$$

CovFac is a factor that converts the amount of straw (ResAm) at the field to the amount of soil coverage. Soil coverage steadily increases with residue amounts ranging from 0 to 5 t/ha, reaching full coverage at 5 t/ha (Chen et al., 2023; Mupangwa et al., 2007).

EvapRedFac is a conversion factor for reducing soil evaporation based on soil coverage amount. When the soil is completely covered, evaporation decreases by 60% and there is a direct correlation between soil coverage and evaporation when coverage ranges from 0% to 100% (Gava & Faria, 2014).

$DailyEvap_d$ is the daily evaporation from soil on day d (mm/day).

$SEVP_d$ represents the daily evaporation without any soil coverage by residue on day d (mm/day).

The study assessed the effects of four mulching levels — 0, 2, 4, and 6 t/ha — commonly applied in agricultural fields (Børresen, 1999; Ram et al., 2013; Saucke & Döring, 2004). Simulations were conducted for two standard timelines regarding climate change: one from 1995 to 2014 and another from 2039 to 2058. With an increase in the level of mulching, more water would be conserved in the soil. This retained water could then be absorbed by the peas during periods when precipitation alone might be insufficient for their growth. Consequently, Yw for rainfed systems would be less negatively affected with an increased level of mulching practice. The various mulching levels considered in this study could provide insights into optimizing straw mulching for enhancing grain pea yield.

3 Results

3.1 Yield gap analysis

3.1.1 Yield gap at country level

The major results of fresh grain pea yield gap analysis at country level have been summarized in Table 1. In general, the highest yield gaps (Yg: 2.37 t/ha, ReYg: 39%) for rainfed pea were found in the UK, followed by Finland (Yg: 1.33 t/ha, ReYg: 34%), Sweden (Yg: 1.13 t/ha, ReYg: 26%) and Denmark (Yg: 1.10 t/ha, ReYg: 23%). Besides, yield gaps for irrigated pea in Denmark were also investigated, with Yg estimated at 1.37 t/ha and ReYg at 28%. It seems that Denmark and Sweden have almost reached the best attainable yield (70% to 80% of the potential yield (Yuan et al., 2024)), while there is still room for Finland and the UK to narrow the yield gap and obtain a better yield.

The highest Ya (3.54 t/ha) was found in the UK, with the Ya in Denmark (3.45 t/ha for rainfed pea), Sweden (2.93 t/ha) and Finland (2.34 t/ha) following. A similar pattern was observed in Yw across these countries, where the Yw (5.91 t/ha) was highest in the UK, followed by Denmark (4.55 t/ha), Sweden (4.06 t/ha) and Finland (3.67 t/ha). It could be deduced that both Ya and Yw were driven by the growing season duration. With a longer-lasting growing season, higher Ya and Yw can be expected. Additionally, water limitation also seems to play a role in negatively affecting both Ya and Yw. The WLI of Finland and Sweden are relatively larger than the other two countries, while both Ya and Yw in these two countries are relatively low.

Interestingly, despite larger yield gaps found in irrigated peas compared to the rainfed ones, Ya in both irrigated and rainfed (3.48 t/ha) regimes were similar in Denmark.

Table 1. Summary of yield gap analysis for grain pea in four Northern European countries (Ya: actual yield in fresh weight; CV of Ya: coefficient of variation of Ya, calculated as sd(Ya)/mean(Ya)*100; Yw: water-limited potential yield in fresh weight; Yp: potential yield in fresh weight; CV of Yw or Yp: coefficient of variation of Yw or Yp, calculated as sd(Yw)/mean(Yw)*100 or sd(Yp)/mean(Yp)*100; Yg: absolute yield gap calculated as Yw -Ya or Yp – Ya; ReYg: relative yield gap calculated as (1 – Ya/Yw)*100 or (1 – Ya/Yp)*100; WLI: water limitation index calculated as (1 – Yw/Yp)*100).

Country	Water regimes	Cropped area (ha)	Ya (t/ha)	CV of Ya (%)	Yw or Yp (t/ha)	CV of Yw or Yp (%)	Yg (t/ha)	ReYg (%)	WLI (%)	Growing season duration (days)
Denmark	irrigated	3422	3.48	14.07	4.85	5.84	1.37	28	-	149
	rainfed	5358	3.45	14.57	4.55	14.38	1.10	23	9	143
Finland	rainfed	18400	2.34	12.24	3.67	18.57	1.33	34	13	116
UK	rainfed	44520	3.54	13.56	5.91	13.19	2.37	39	9	145
Sweden	rainfed	21432	2.94	15.79	4.06	17.79	1.13	26	18	136

3.1.1 Yield gap at regional level

On the regional level the variation of Ya is small among the buffer zones within each country, while the variation of Yw (or Yp), ReYg and WLI are relatively larger (Figure 2). Note, the results of the UK were not presented here, as the selected stations are in close proximity to each other, and information on both management and actual yield is consistent across the buffer zones.

In Finland, Yw ranged from 3.53 t/ha to 3.76 t/ha, while ReYg ranged from 30% to 39%, and WLI ranged from 1% to 16%. Pea growth was particularly outstanding in the buffer zone in the southwest, where the lowest Yw and ReYg, and the highest WLI, were consistently observed.

The variations of Yw, ReYg and WLI are all large across the west to the east in Sweden. The largest Yw (4.64 t/ha) and ReYg (38%), as well as the smallest WLI (3%), were always found in the western regions, while the smallest Yw (3.60 t/ha) and ReYg (16%), as well as the largest WLI (25%) were always observed in the eastern part.

Interesting patterns can also be found in Denmark, despite half of the buffer zones are rainfed and the other half are irrigated. Yw, Yp and ReYg were presented to decrease from the south to the north, while WLI was presented to increase. Specifically, Yw for rainfed pea decreased from 4.80 t/ha to 4.36 t/ha, Yp for irrigated pea decreased from 5.10 t/ha to 4.77 t/ha, ReYg decreased from 31% to 19%, and WLI increased from 7% to 10%. Such pattern, particularly for Yw and Yp, could be explained by the differences in local temperature. As the buffer zone moves further north, temperatures decrease. Consequently, temperature appears to act as a limiting factor for simulated Yw and Yp, subsequently impacting Yg and WLI.

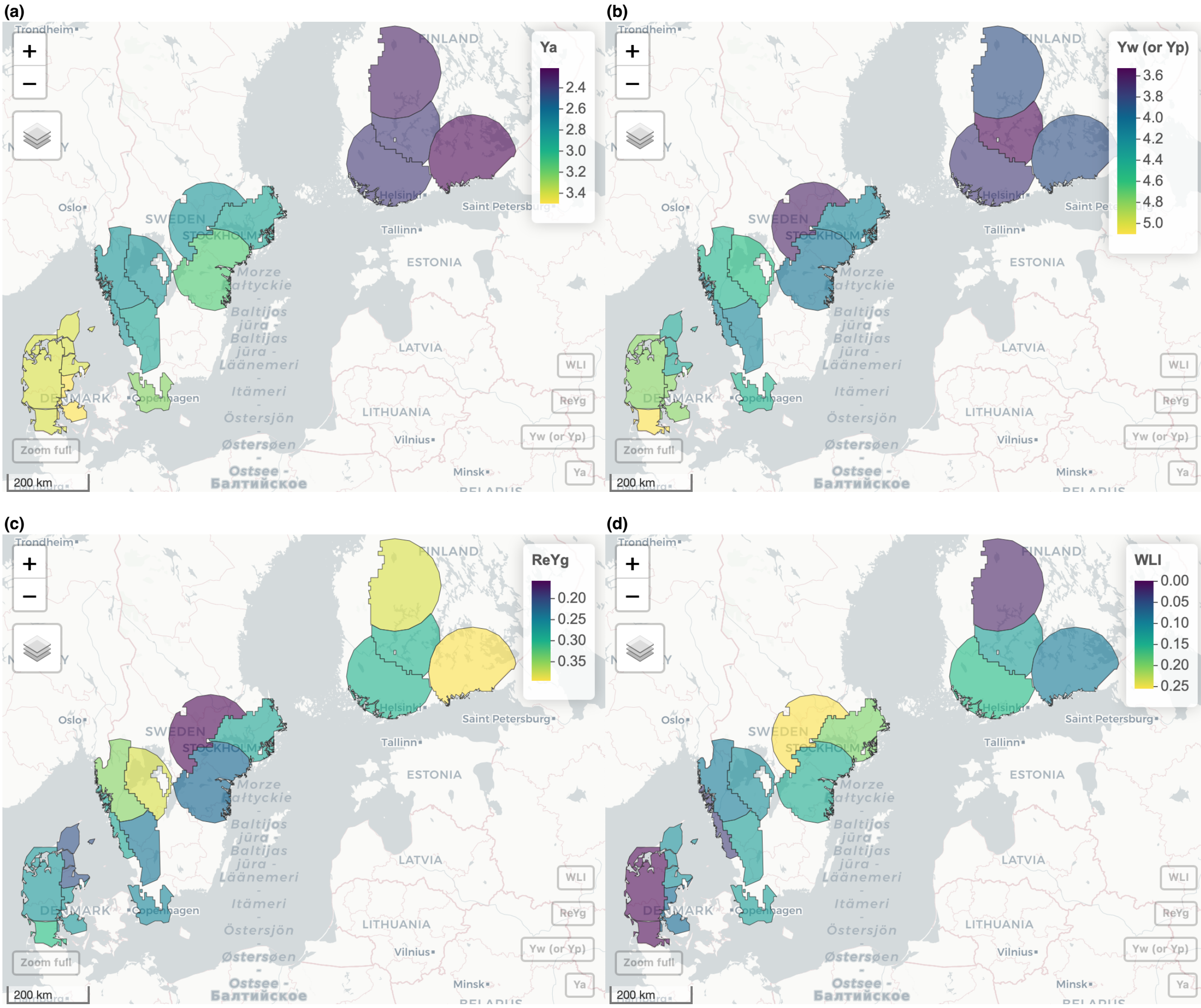

Figure 2. Actual yield (a, Ya in t/ha), water-limited potential yield (Yw, in t/ha) for rainfed areas and potential yield (Yp, in t/ha) for irrigated areas (b), relative yield gap (c, ReYg calculated as (1 – Ya/Yw)*100 or (1 – Ya/Yp)*100) and water limitation index (d, WLI calculated as (1 – Yw/Yp)*100)) plotted at regional level for the three Nordic countries.

3.2 Water-limited potential yield under climate change

Yet, potential yields, especially water-limited yields can be largely influenced by climate change in the future. SSP3 and SSP5 both represent future scenarios characterized by higher CO_2 concentration, temperature and variability in rainfall (S1 Figure 1-6), with the latter being more severe than the former. The simulation indicates that in 2050 the water-limited potential yield for fresh grain pea would increase (Figure 3a). The highest increase (SSP3: 1.05 t/ha, 17%; SSP5: 1.12 t/ha, 19%) in Yw was found in the UK, followed by Denmark (SSP3: 0.70 t/ha, 15%; SSP5: 0.74 t/ha, 16%), Sweden (SSP3: 0.65 t/ha, 15%; SSP5: 0.68 t/ha, 16%) and Finland (SSP3: 0.44 t/ha, 12%; SSP5: 0.48 t/ha, 13%). Such increase could be a co-benefit arising from both higher atmospheric carbon input and increased temperature during the growing season.

Such effects can also be reflected from the shorter growing seasons in the two future scenarios (Figure 3b). The largest decrease in growth duration was observed in Finland (SSP3: -13%, SSP5:

-15%) with Sweden (SSP3: -8%, SSP5: -10%), Denmark (SSP3: -6%, SSP5: -8%) and the UK (SSP3: -3%, SSP5: -4%) following. Greater accessibility to photosynthesis sources (i.e., CO_2, water) would not only enhance the yield but lead to a prematurity for grain pea.

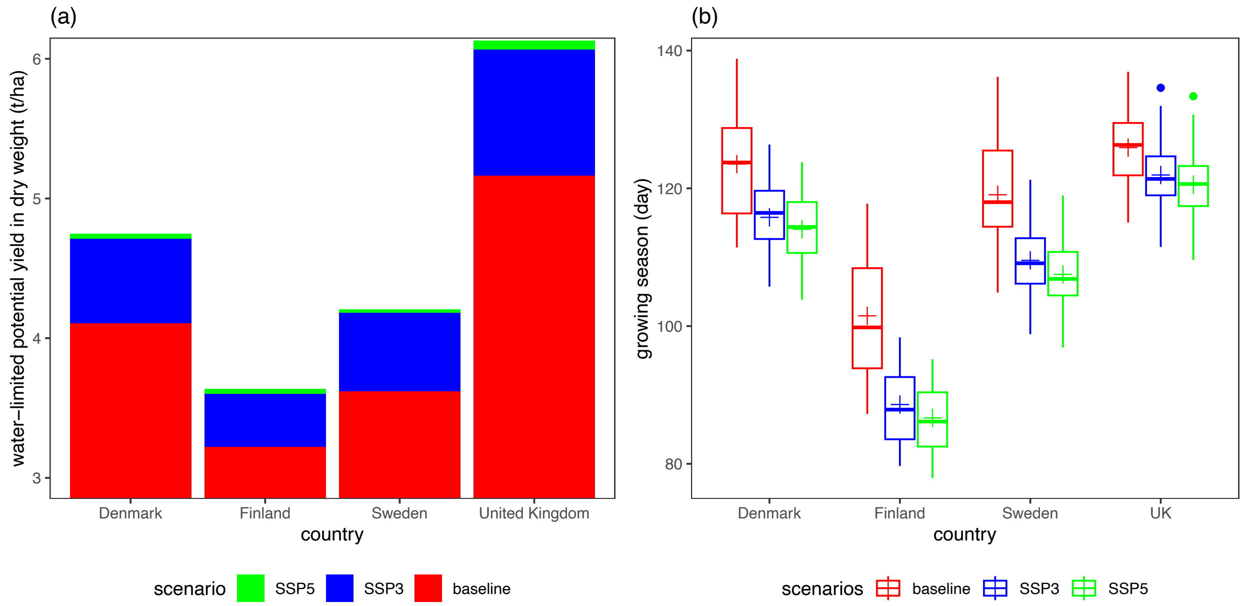

Figure 3. Water-limited potential yields (a) and growing season (b) among the baseline (1995 to 2014) and two future scenarios (SSP3 and SSP5 in 2039 to 2058). Cross marks the average value for each case.

3.3 Water-limited potential yield with mulching practices

The simulated application of straw mulching of either 2, 4 or 6 t/ha resulted in increased potential grain yield for rainfed pea across all three scenarios: baseline, SSP3, and SSP5 (Figure 4a). Notably, the most significant effect of mulching was observed at an application rate of 6 t/ha in Denmark, showing a 6.1% increase in yield compared to non-mulching practice. The least effect was observed at an application rate of 2 t/ha in the UK, resulting in a 0.9% increase in yield. While increasing the application rate of straw mulching, there was a consistent pattern of increasing yield in the Nordic countries. The pattern in the UK was also similar, despite a slight decrease in median yield from a mulching application rate of 4 t/ha to 6 t/ha. Such yield decrease could be attributed to the case that the plant was heavily submerged by the rainfall, due to less evaporation caused by excess straw mulching.

As the mulching rate increased, there was a slight increase in growing season duration (Figure 4b). This implies that higher levels of straw mulching allowed for less evaporation from the soil surface and greater water retention in the soil, thus less water stress could prolong the growing season duration by regulating the physiology process of pea. More radiation thus became potentially accessed by the plant to produce more biomass.

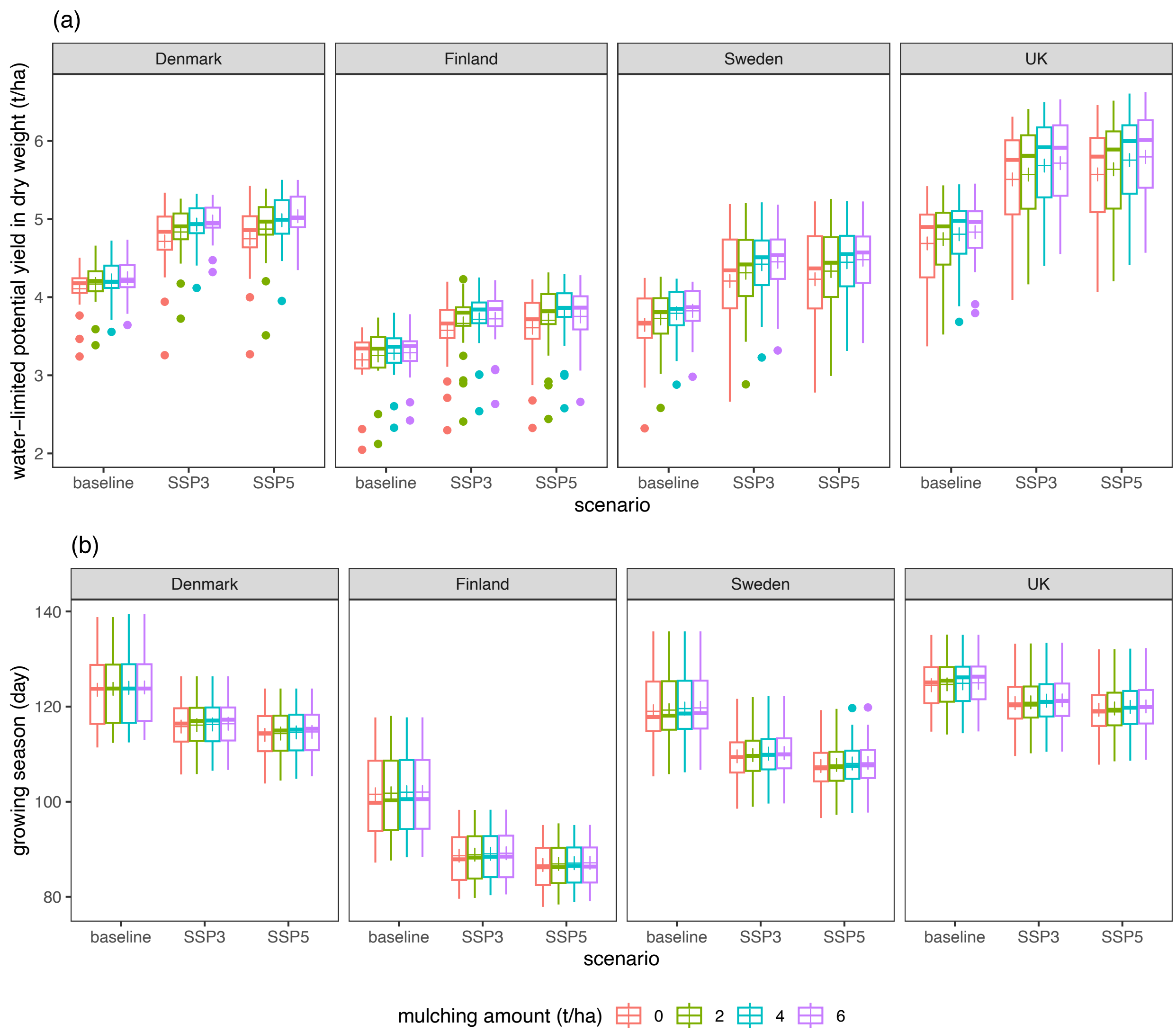

Figure 4. Boxplot of the mulching effects on the water-limited potential yields (a) and growing season (b) among the baseline (1995 to 2014) and two future scenarios (SSP3 and SSP5 in 2039 to 2058). Cross marks the average value for each case.

Upon examining the five lowest potential yields among these three scenarios, it becomes evident that the lowest yield also increased with higher application rates of straw mulching (Figure 5). This trend mirrors the overall yield pattern, suggesting that the effects of straw mulching on grain pea potential yield remain consistent as application rates increase. Specifically, in Finland and Sweden, the increasing rate of straw mulching application appears to decrease the variability of potentially poor harvests in future scenarios.

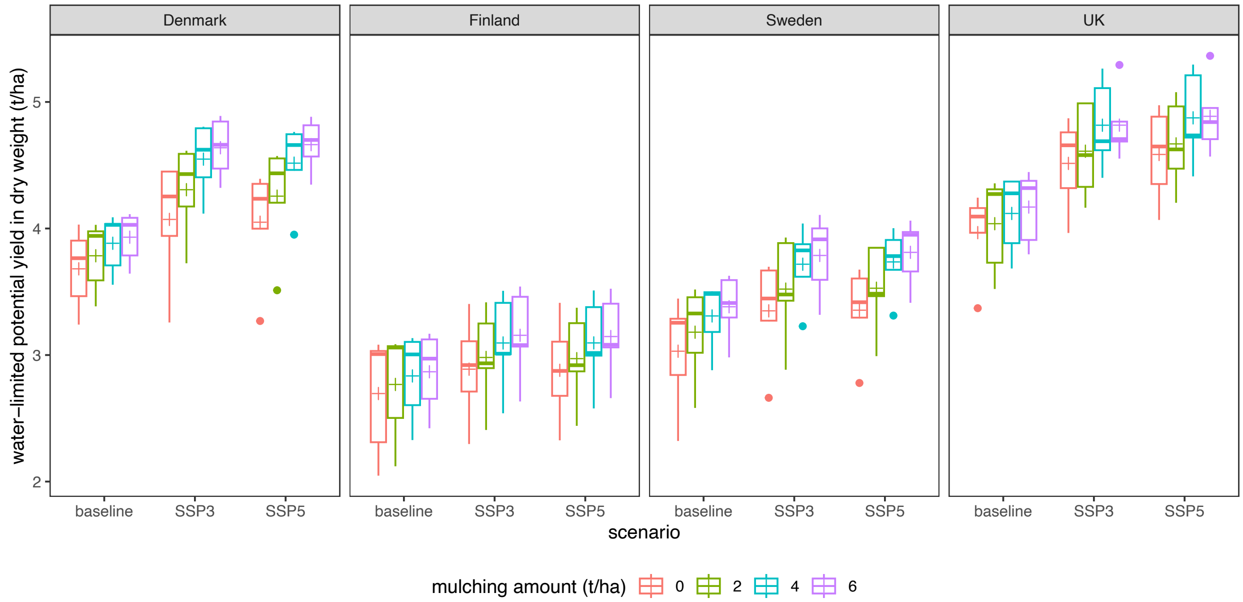

Figure 5. Boxplot of the mulching effects on the lowest 5 water-limited potential yields among the baseline (1995 to 2014) and two future scenarios (SSP3 and SSP5 in 2039 to 2058). Cross marks the average value for each case.

4 Discussion

4.1 Future prospects for pea cultivation

4.1.1 Pea cultivation in Northern European countries

Compared to other European nations, yield gaps for grain pea are relatively low in our studied countries (GYGA, 2023a). Yet, pea has not been extensively cultivated in Northern European countries, despite such legume often offering significant benefits to the environment, agriculture, and nutrition (Marteau-Bazouni et al., 2024; Reckling et al., 2016). Shifting focus towards pea cultivation could be beneficial. Incorporating legumes into mono-cropping systems could enhance biodiversity in fields, making the agroecosystem more resilient to pest invasion and virus infestation. Intercropping cereals with legumes like pea can also increase the crude protein content in cereals (Pozdíšek et al., 2011). Moreover, peas typically possess higher protein content compared to cereals, making them an excellent substitute (Bachmann et al., 2019; Lee et al., 2010). Notably, yield gaps for both pea and cereals in Northern European countries are similar, indicating that growing peas would not necessarily result in less profit (GYGA, 2023a; van Loon et al., 2023).

4.1.2 Pea cultivation under climate change

Improving pea cultivation also emerges as a strategy to adapt food production systems to climate change. As depicted in the results, climate change would result in increased potential yields for grain pea in the Northern European countries. Such positive effects were also observed with pasture yields in these areas (Dellar et al., 2018). In contrast, some research revealed decreased yields in maize under climate change (Faye et al., 2023). Therefore, advocating grain pea cultivation seems to be a sensible approach for constructing a more climate-resilient agroecosystem in the future, given the anticipated benefits of pea growth compared to maize.

Besides, replacing maize with pea has been shown to be feasible in many applications. For instance, when replacing 15% of maize by pea in cows' diet, milk yield or milk composition would still not be impacted (Pol et al., 2008). However, further support from policy and market initiatives is needed to create more opportunities in grain pea production (Magrini et al., 2016), in pursuit of making the food systems more climate resilient.

4.1.3 Straw mulching practice as adaptive management to climate change

As demonstrated in the results, straw mulching can enhance the grain pea yield, an effect that becomes more pronounced with increasing rates of application. Nevertheless, such practices have not been widely adopted in Northern European countries despite all the benefits. Currently, straw in these countries is primarily utilized for animal feed, bedding, and as biofuel production (Lötjönen & Joutsjoki, 2015). Consequently, there is limited straw available for mulching purposes in the fields. Another contributing factor could be the perceived effectiveness and affordability of plastic mulching. Plastic films have been found to effectively enhance crop yield through weed control, soil temperature regulation, and water conservation, and they are generally inexpensive (Birkeland et al., 2002; Nes et al., 2017; Svensson, 2002). Yet, numerous studies have indicated that plastic mulching may result in microplastic pollution on-site, further deteriorating soil health and hampering crop growth (Pflugmacher et al., 2021; Zhou et al., 2021). Therefore, it is still worthwhile to explore organic mulching techniques to enhance crop yield while avoiding subsequent contamination in the fields.

4.2 Model performance

The SSM-iCrop2 model has already been calibrated for pea for other European countries and has been applied to simulate the potential yields of other crops (e.g., rainfed faba bean) cultivated in Denmark, Sweden, Finland and the UK. The spatial distribution of the simulated water-limited potential yield for rainfed pea aligns with the pattern for rainfed faba bean, suggesting the model can accurately represent the growth and development of pea as well (van Loon et al., 2023).

In this research, the SSM-iCrop2 model specifically calibrated for field pea demonstrated generally good performance (S1 Figure 7). Additionally, the model underwent evaluation using growing season duration and actual yields obtained from experiments (Antichi et al., 2023) (S1 Figure 8), where the simulated potential yields from our model closely matched these measured yields. These collectively support the reliability of the results and conclusions of our study. However, future research could benefit from conducting its own field experiments to further evaluate the model's performance and enhance the persuasiveness of the findings.

4.3 Uncertainty in methodology

4.3.1 Climate change simulation

We employed the projections from the IPCC to generate the future weather data for our study. This strategy has also been documented in other studies (Amiri et al., 2021; Harkness et al., 2020; Peltonen-Sainio et al., 2009). Yet, the occurrence of extreme events can be largely influenced by the real-time human activities (Margariti et al., 2019). Thus, the simulated water-limited potential yields in future scenarios would only imply a general trend under climate change, rather than estimating the yield for any individual year.

4.3.2 Mechanism of straw mulching

In this study, a simple mechanism was implemented into the model to assess the effects of straw mulching on the water-limited potential yield. Overall, the yields were shown to be enhanced with an increasing amount of the straw, since less water was evaporated from the soil surface. Yet, this mechanism cannot fully represent all the effects of straw mulching in the fields, as mentioned earlier — it is a simplified mechanism. For instance, when the application rate of straw mulching is greater than 4.5t/ha, there would be effective benefits in run-off and erosion mitigation (Chen et al., 2023). If the straw residues are left on site for the long term, nutrients mobilized by the soil microbes in the early stages may become a long-lasting nutrient source for plants (Truong et al., 2019). In both cases, straw mulching would allow for more nutrients to be retained in the soil for plant uptake, leading to better yields. On the other hand, research has shown that excessive straw mulching (13.5 t/ha) can even reduce yield (Qin et al., 2021). Unfortunately, such effects were not accounted for in the model.

5 Conclusions

This study firstly analyzed the yield gap for grain pea in Northern European countries, including Denmark, Finland, Sweden, and the UK. Variability in the yield gap of rainfed pea was observed across these countries. The highest yield gap was observed in the UK (Yg: 2.37 t/ha, ReYg: 39%), followed by Finland (Yg: 1.33 t/ha, ReYg: 34%), Sweden (Yg: 1.13 t/ha, ReYg: 26%), and Denmark (Yg: 1.10 t/ha, ReYg: 23%). The yield gap for irrigated pea was also analyzed, with Yg estimated at 1.37 t/ha and ReYg at 28%. Water-limited potential yield for grain pea under climate change was examined and suggested to be significantly increased in the future, with the highest increase (SSP3: 17%, SSP5: 19%) found in the UK. Lastly, we simulated the effects of straw mulching on the water-limited potential yield to better understand the benefits of adaptive management under climate change. With an increasing rate of straw mulching application, the potential yield appeared to improve. The greatest effect of mulching was observed in Denmark, where an 6.1% increase in yield was resulted by an application rate of 6 t/ha, compared to non-mulching practices. Such mulching practices also could also help mitigating the variability of grain pea yield in potentially poor harvest years, particularly for Finland and Sweden.

In summary, our study provided insights into the yield gap for grain pea across four Northern European countries and underscored the potential benefits of climate change for future pea cultivation. We advocate for further exploration of adaptive management strategies like straw mulching to enhance yields. Future research should also consider employing more representative simulation mechanisms and conducting field experiments to validate model performance and inform policy decisions.

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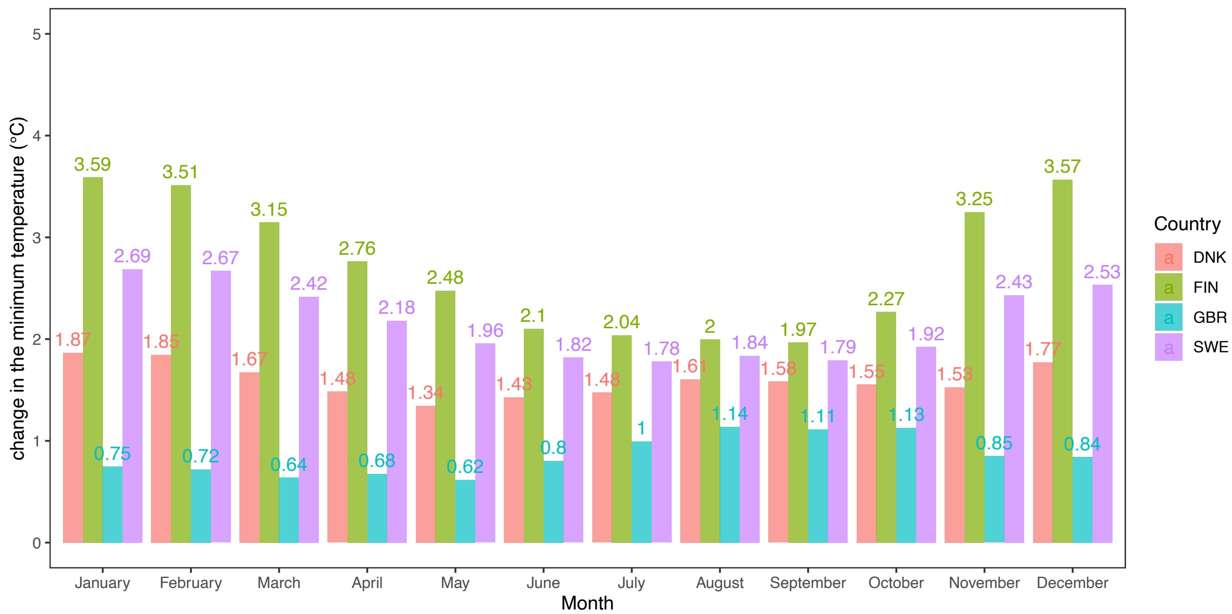
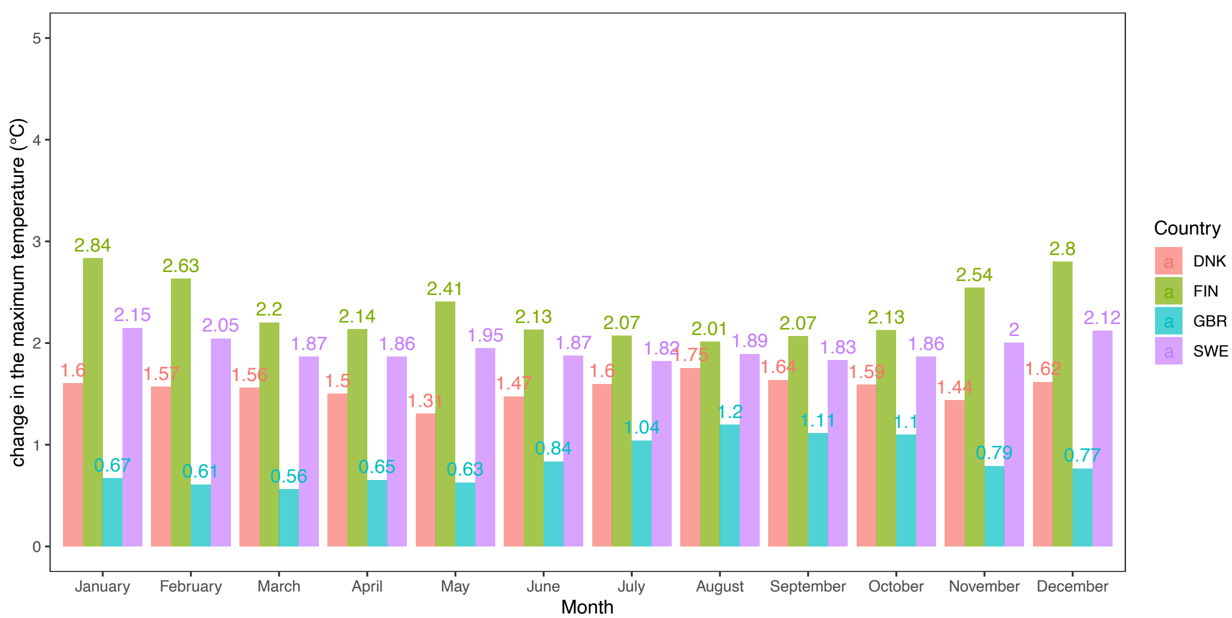
Supplementary materials

S1 Table 1. Physiological information on the calibrated cultivars.

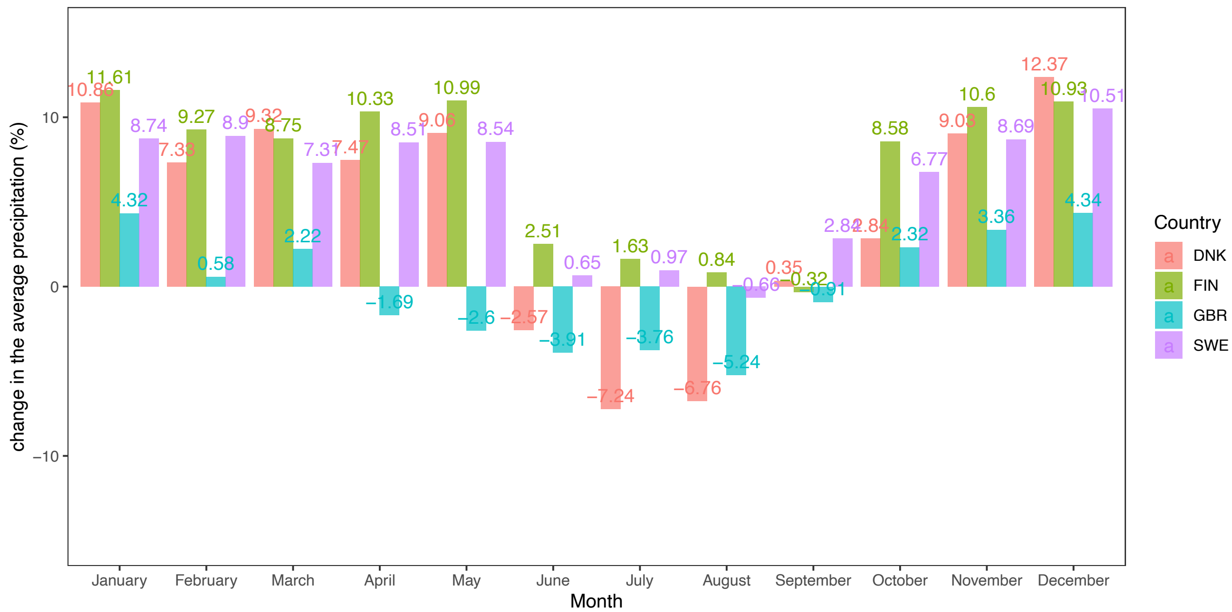
Crop	tuHAR	LAIMX	SRATE	IRUE	HImax
cultivar for Denmark and Sweden	1500	4	0.8	1.85	0.5
cultivar for Finland	1300	4	0.8	1.85	0.5
cultivar for UK	1500	5	0.7	2	0.6



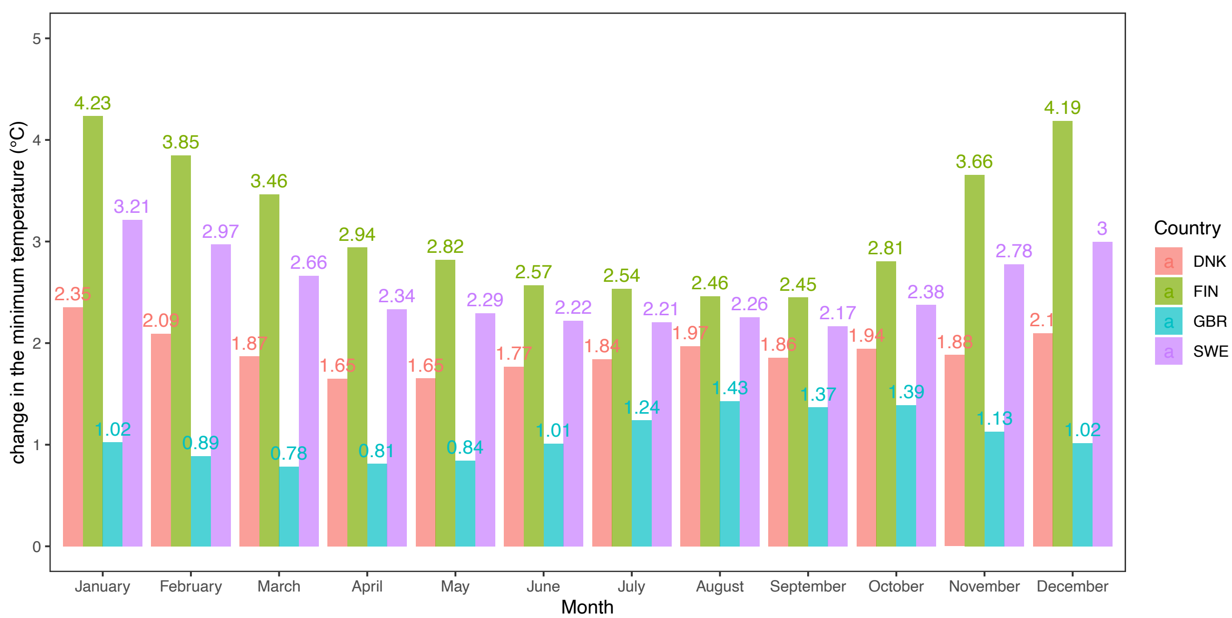
S1 Figure 1. Monthly change in the minimum temperature (°C) under climate change scenario SSP3



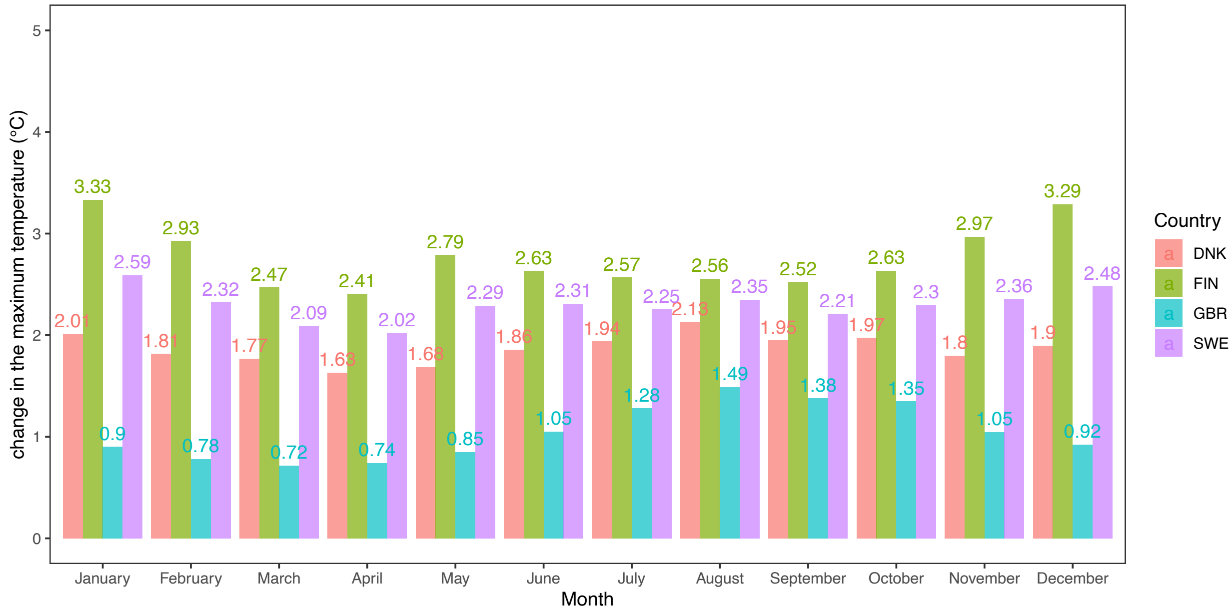
S1 Figure 2. Monthly change in the maximum temperature (°C) under climate change scenario SSP3.



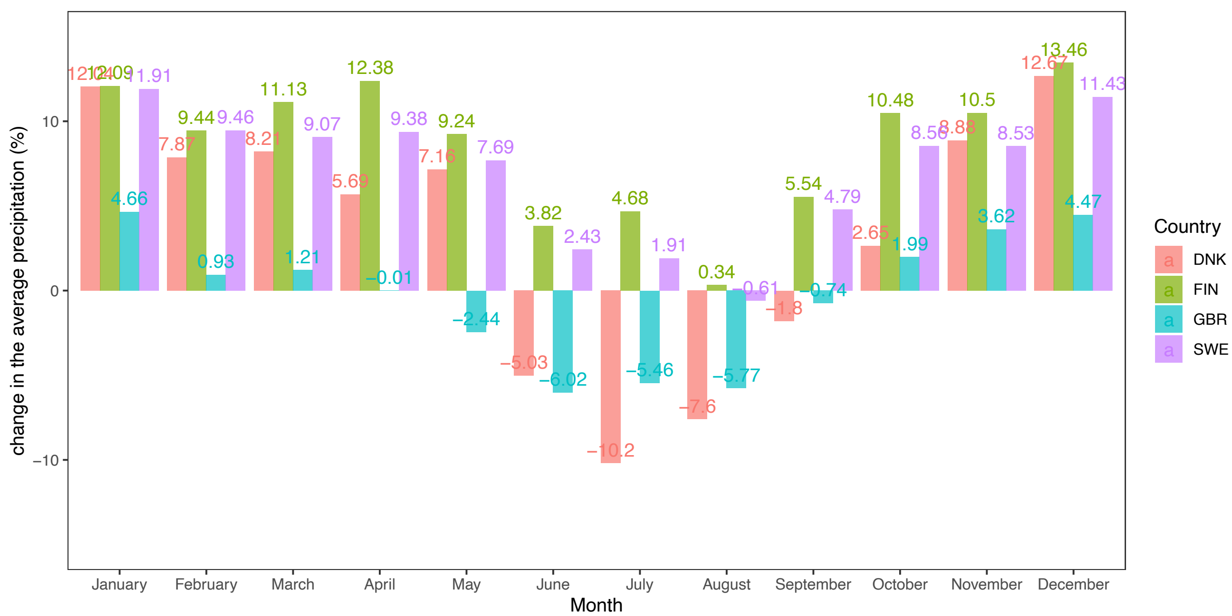
S1 Figure 3. Monthly change in the average precipitation (%) under climate change scenario SSP3.



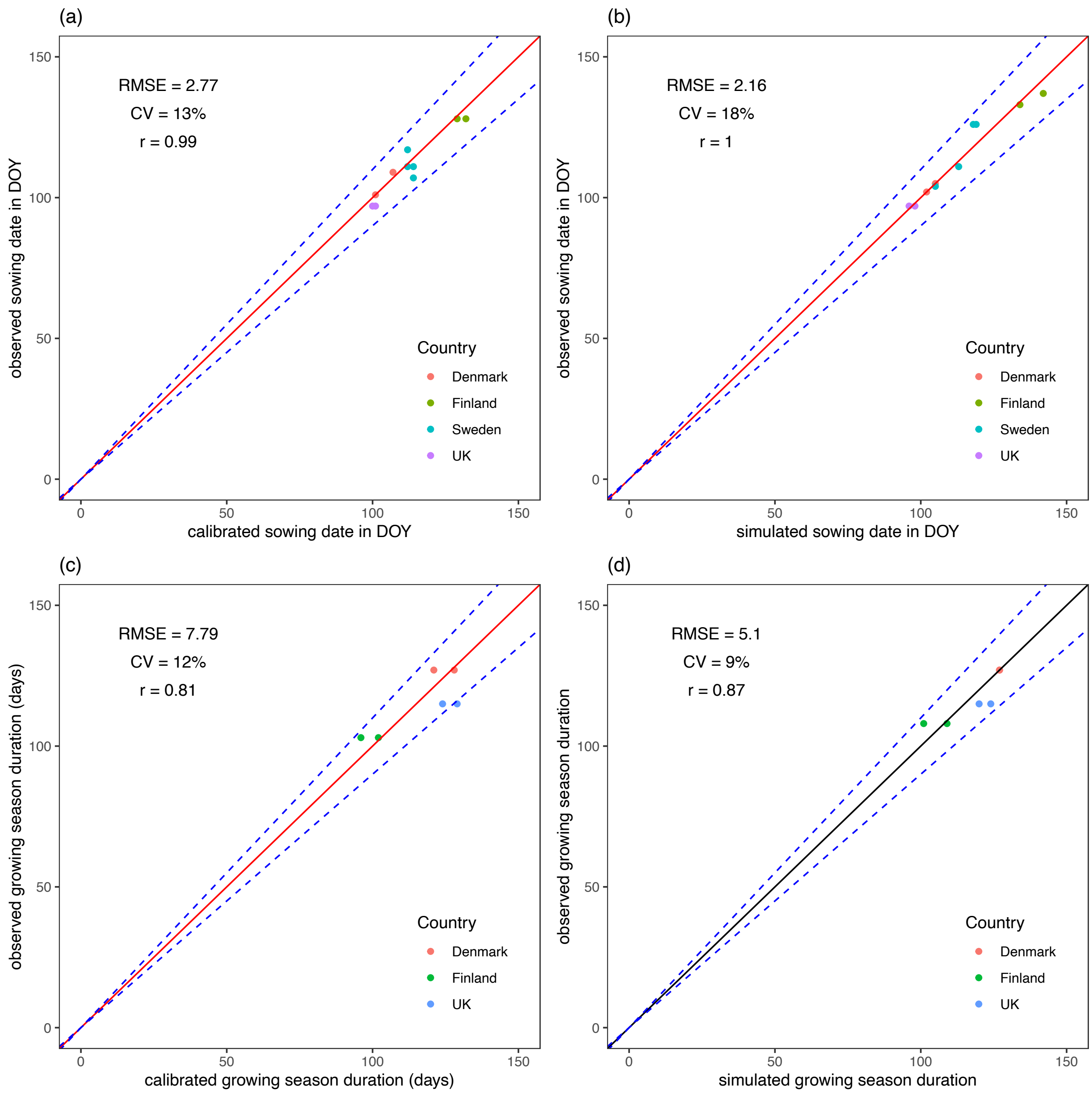
S1 Figure 4. Monthly change in the minimum temperature (°C) under climate change scenario SSP5.



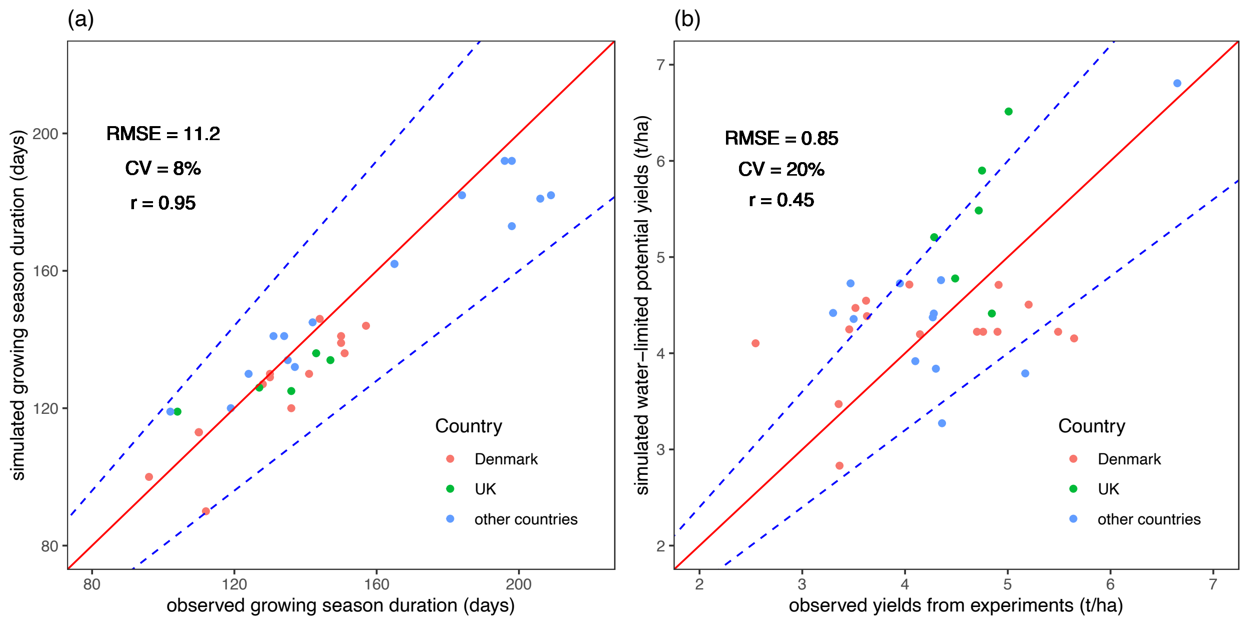
S1 Figure 5. Monthly change in the maximum temperature (°C) under climate change scenario SSP5.



S1 Figure 6. Monthly change in the average precipitation (%) under climate change scenario SSP5.



S1 Figure 7. Comparison between observed and simulated values for field pea sowing date (a, b) and growth duration (c, d, not applicable for Sweden due to the lack of observed values). The 1:1 line is plotted in solid, with 10% ranges of discrepancy between simulated and observed values indicated by the dashed lines (RMSE: root mean square error; CV: coefficient of variation; r: correlation coefficient).



S1 Figure 8. Comparison between observed and simulated values for field pea growing season duration (a) and yield (b). The 1:1 line is plotted in solid, with 20% ranges of discrepancy between simulated and observed values indicated by the dashed lines (RMSE: root mean square error; CV: coefficient of variation; r: correlation coefficient).