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Re-evaluating temperature thresholds for growth and nutrient uptake in winter cereals in Estonia: a review of air-soil temperature dynamics

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Abstract. This study re-evaluates the agronomic validity of temperature thresholds for cereal growth and nutrient uptake in cool-temperate agroclimates. By integrating a physiological review with a spatiotemporal analysis of Estonian air temperature records (1965–2024), we assess the potential for phenological mismatch between atmospheric warming and soil thermal readiness.
Our analysis reveals a significant advancement in the onset of the thermal growing season, particularly in South-Eastern Estonia, where spring now begins approximately 10 days earlier compared to the 1965–1990 baseline.
Synthesizing these trends with established principles of soil thermal inertia, we identify a potential increase in the risk of 'false springs', where atmospheric signals trigger vegetative growth while soil conditions remain restrictive. Published evidence indicates that nutrient uptake is kinetically constrained in cool soils: nitrogen uptake becomes effective only at soil temperatures of +8–10 °C, and phosphorus uptake is critically limited by low diffusion rates and suppressed mycorrhizal activity, whereas potassium uptake is comparatively less sensitive.
We suggest that under increasingly variable climatic conditions, relying solely on the standard +5 °C air temperature threshold may lead to premature fertilisation and nutrient losses. Therefore, agronomic decision-making in Northern Europe may need to increasingly account for the hysteresis between rapid atmospheric warming and slower soil thermal activation.

Key words: base temperature, Estonia, heat stress, nitrogen, phosphorus, potassium, soil temperature, thermal growing season, winter cereals.

INTRODUCTION

Europe is currently the fastest warming continent, with increasing climate variability posing growing risks to agricultural production systems (IEEP, 2024). Temperature strongly governs crop phenology, biomass accumulation, and yield formation in cereals. Consequently, agronomic practice and crop growth models rely on standardised temperature thresholds to describe the onset and cessation of vegetation and to parameterise development rates (Porter & Gawith, 1999; Hay & Porter, 2006). Across Europe, the thermal growing season is commonly defined using a +5 °C mean daily air

temperature threshold. Long-term analyses have demonstrated a significant lengthening of this season since the mid-20th century, particularly in northern and northeastern regions (Cornes et al., 2018). While these air-temperature-based indices serve as robust proxies for regional climate monitoring (Eitzinger & Kubu, 2010), they inherently simplify the complex thermodynamic coupling between the atmosphere and the pedosphere.

These simplifications become critical sources of error when base and optimum temperatures differ among phenological stages (Slafer & Rawson, 1995) or when atmospheric warming outpaces soil warming. In Estonia and similar cool-temperate regions, the high thermal inertia of moist mineral soils causes root zone warming to lag behind air temperature. This hysteresis creates a risk of 'false spring,' where early-season atmospheric signals trigger vegetative resumption while root activity remains thermally restricted. Such events may lead to increased vulnerability to subsequent frost damage due to premature de-hardening and advancement of phenological stages. Experimental and observational studies have shown that earlier spring warming can increase the risk of frost damage by disrupting the synchronisation between plant development and climatic conditions (Gu et al., 2008; Augspurger, 2013; Vitasse et al., 2014). In addition, temperature-driven changes in physiological processes such as carbohydrate allocation, membrane stability, and cold acclimation can further increase plant susceptibility under fluctuating spring conditions. Although extensive long-term soil temperature datasets are often less available than atmospheric records, the agronomic risks of this decoupling can be effectively assessed by juxtaposing observed trends in spring advancement against the known physiological constraints of nutrient uptake. The novelty of this study lies in integrating long-term air temperature trends with physiological constraints on root-zone processes to identify a potential mismatch between atmospheric signals and soil thermal readiness in Northern European agroecosystems. Recent reviews emphasise that climate change disrupts soil–plant–atmosphere interactions, altering nutrient cycling and plant development, and increasing the risk of phenological mismatches (Oishy et al., 2025).

Therefore, understanding the functional meaning and limitations of the static +5 °C threshold is essential for adapting fertiliser management to changing climatic conditions. The aim of this review is to: (i) examine spatiotemporal trends in the onset of the thermal growing season (hereafter referred to as spring onset) in Estonia (1965–2024) to explore potential regional risks of air-soil decoupling as a regional case study; (ii) synthesise physiological evidence on temperature-dependent constraints for the uptake of major nutrients (N, P, and K), highlighting the gap between the onset of growth and the onset of efficient uptake; and (iii) provide a conceptual basis for adapting agronomic thresholds, specifically addressing the risks of premature fertilisation under 'false spring' conditions.

In the context of Estonian and Northern European cropping systems, this review focuses primarily on winter wheat (*Triticum aestivum*) and winter rye (*Secale cereale*). These species represent the dominant overwintering cereals in the region, whereas winter barley cultivation has historically been limited by insufficient winter hardiness during the reference period. Overall, this study represents a synthesis combining agroclimatic trend analysis with established physiological knowledge rather than a fully data-driven experimental assessment.

MATERIALS AND METHODS

Literature search strategy and selection criteria

This study adopts a narrative review approach to synthesise knowledge at the intersection of plant physiology and agroclimatology. A targeted literature search was conducted using major scientific indexing databases, including Scopus, Web of Science, and Google Scholar. The search strategy focused on identifying studies relevant to cereal production in cool-temperate and hemiboreal climate zones (specifically Northern Europe, Scandinavia, and the Baltic region).

Key search terms included combinations of: 'cereal phenology,' 'base temperature,' 'nutrient uptake kinetics,' 'low-temperature stress,' 'soil-air temperature hysteresis,' and 'false spring.'

The selection of literature was guided by the following inclusion criteria:

1. **Relevance to mechanism:** Studies describing physiological mechanisms of N, P, and K uptake under low-temperature constraints.

2. **Climatic relevance:** Field studies conducted in pedo-climatic conditions comparable to Estonia (e.g., cool springs, dominance of Cambisols and Luvisols, seasonally wet soils) (Astover et al., 2012).

3. **Data quality:** Peer-reviewed original research and meta-analyses. The search covered literature published between 1980 and 2025, with priority given to studies from 2000 onwards to reflect modern cereal cultivars and recent climatic trends. Foundational physiological studies (e.g., from the 1980s–1990s) were retained where the fundamental biological mechanisms remain valid. Approximately 80–140 studies were screened based on title and abstract, of which 42 were included based on relevance to physiological mechanisms and climatic comparability.

Agroclimatic data analysis

To contextualise the literature within recent local conditions, we analysed long-term air temperature data provided by the Estonian Environment Agency (Keskkonnaagentuur). Daily mean air temperature from 21 observation stations across Estonia were used to calculate the spring onset (defined as the first period where mean daily air temperature persistently exceeds +5 °C).

The analysis was conducted in two stages. First, to visualise the spatial variability of phenological changes, we calculated the linear trend of spring onset for the full period (1965–2024) for all stations. The total calculated shift (in days) based on this trend was mapped to illustrate territorial differences between inland and coastal regions (Fig. 1).

Second, to quantify the magnitude of shifts between historical and modern climates, we compared two distinct reference periods: the historical baseline (1965–1990) and the modern period (1991–2024). For each station, the mean onset date was calculated for both periods, and the statistical significance of the shift was assessed using a *paired t-test* (Fig. 2).

The paired t-test assumes independence between stations and approximate normality of differences; these assumptions were evaluated visually. Missing data were minimal and handled by excluding incomplete years.

Data processing and statistical analyses were performed using the *R* software environment. Spatial visualisations and maps were generated using the *ggplot2* and *sf* packages to ensure cartographic accuracy.

RESULTS AND DISCUSSION

Agroclimatic definition and baseline trends (1965–2018)

In Estonian meteorological and agroclimatic practice, the thermal growing season is defined as the period when the daily mean air temperature rises persistently above +5 °C and ends when it falls persistently below this threshold (Jaagus, 2006; Tarand et al., 2013). This definition is widely applied in agronomy and agroclimatology across Northern Europe and provides a standardised basis for assessing vegetation activity and crop growth conditions. However, several agrometeorological syntheses emphasise that an extension of the thermal growing season does not necessarily translate into improved crop performance, as increased variability in spring temperatures and precipitation may elevate production risks (Eitzinger & Kubu, 2010; Trnka et al., 2014).

Based on long-term station observations covering the reference period 1965–2018, the thermal growing season in Estonia typically began in the third decade of April and ended in late October, resulting in an average duration of approximately six months (Saue, 2020). Previous studies have documented a clear spatial gradient: spring onset generally occurs earliest in southeastern Estonia and latest in western and northern coastal regions, as well as in the Lake Peipus area, where the thermal inertia of large water bodies delays atmospheric warming (Tarand et al., 2013). In contrast, regional differences are more pronounced in autumn – often exceeding three weeks – with coastal and island regions experiencing a later cessation of the growing season due to prolonged heat release from the Baltic Sea, while inland areas enter autumn earlier (Estonian Crop Research Institute, 2014; Jaagus, 2006; Saue, 2020). Consequently, the total length of the thermal growing season increases both from north to south and from inland areas towards the coast. Similar north–south and maritime–continental gradients have been documented across Northern and Central Europe, indicating that the spatial patterns observed in Estonia are consistent with broader continental-scale climatic controls (Linderholm et al., 2007; Cornes et al., 2018).

Trends and recent shifts

Long-term trend analyses demonstrate a clear lengthening of the thermal growing season in Estonia during the second half of the 20th century and the early 21st century. During the 1965–2018 reference period, Saue (2020) reported that the spring onset advanced on average by approximately two weeks across meteorological stations. More recent analyses provide a refined picture of these long-term trends. Based on growing degree day indices, the duration of the GDD5 period has increased by approximately 2.2 days per decade, reflecting a long-term warming-driven extension of thermally suitable conditions for plant growth (Kollo et al., 2023). In parallel, Kollo et al. (2023) note that the onset of the +5 °C threshold has advanced by an additional 4–7 days compared with the long-term mean, particularly in inland regions. Interestingly, they also report that during the most recent 10–12 years the increase in thermal growing season length has slowed, highlighting the importance of interannual variability and non-linear responses in agroclimatic indicators.

These trends are consistent with European-scale analyses documenting widespread lengthening of the growing season since the mid-20th century (Menzel & Fabian, 1999; Luterbacher et al., 2004; Cornes et al., 2018). However, international climate assessments

indicate that this continued lengthening in Northern Europe is likely to be accompanied by increased variability in temperature and precipitation regimes. This variability may pose new challenges for cereal production systems (IPCC, 2021; IPCC, 2023).

Updated spatiotemporal analysis (1965–2024)

To provide an up-to-date assessment of these shifts, we extended the analysis to include the most recent climatic data (1965–2024). Our updated dataset confirms that the trends identified in earlier decades have continued (Fig. 1). The lengthening of the growing season has been driven primarily by an earlier spring onset and, to a lesser extent, by a slightly later autumn cessation. At the beginning of the calculation period, the spring onset in southern Estonia typically occurred in the second half of April, whereas in recent decades it has frequently begun in the first half of April and, in some years, already at the end of March.

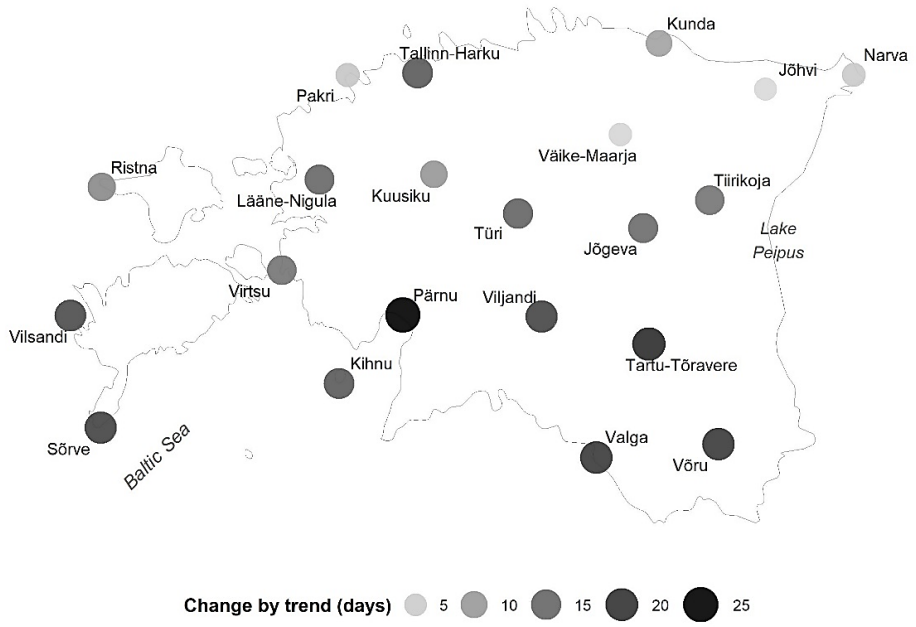


Figure 1. Spatial variability of the advancement in the spring onset in Estonia (1965–2024). The size and colour intensity of the circles are proportional to the magnitude of the calculated trend in days (circles in the legend indicate reference values). The change towards earlier spring is most pronounced in southeastern, southern, and western regions, while the northern coast exhibits more moderate changes.

To quantify these shifts, we compared the onset of spring between the historical baseline (1965–1990) and the modern period (1991–2024) across Estonian monitoring stations (Fig. 2). The updated analysis confirms a statistically significant advancement in the onset of spring ($p < 0.001$). On average, the climatic spring has advanced by 7.7 days, with the most pronounced changes observed in southern inland stations (e.g., Tartu-Tõravere, Võru), where spring now arrives up to 11–12 days earlier. In contrast,

northern coastal stations (e.g., Narva, Jõhvi) exhibit more moderate shifts of approximately 3 days. This spatial heterogeneity underscores the maritime–continental gradient discussed earlier.

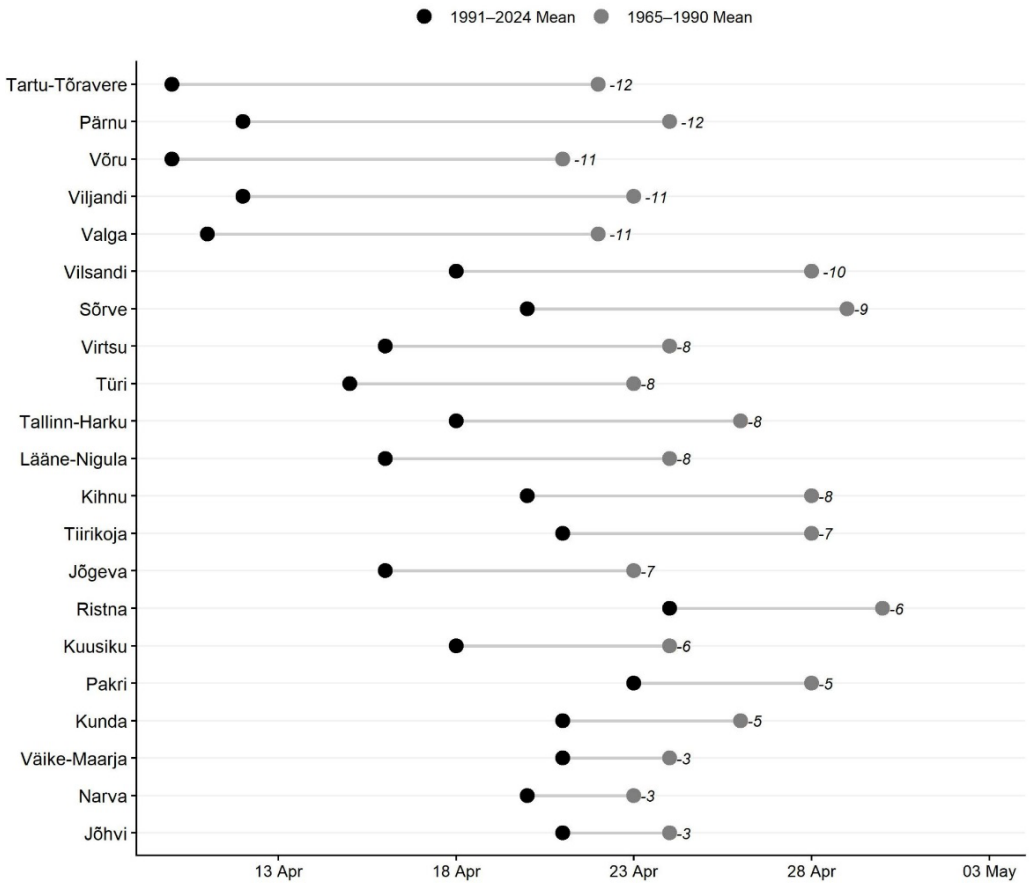


Figure 2. Phenological shift in the onset of spring in Estonia, comparing mean start dates between the periods 1965–1990 and 1991–2024. Stations are ordered by the magnitude of the shift. Difference is statistically significant (paired t-test, $p < 0.001$).

From an agronomic perspective, it is important to recognise that early-spring exceedance of the +5 °C air temperature threshold does not necessarily coincide with sufficient warming of the soil profile in the root zone. During rapid spring warming, air temperature thresholds may be met several days before soil temperatures stabilise at levels that support active root metabolism and nutrient uptake. Although soil temperature is generally closely linked to air temperature, the relationship is not instantaneous and is influenced by soil properties, moisture conditions, and heat transfer processes. Soil temperature typically responds with a temporal lag that increases with soil depth, reflecting the thermal inertia of the soil system (Zheng et al., 1993; Jin & Mullens, 2014).

As a result, rapid increases in early spring air temperature may not be immediately reflected in root-zone soil temperatures, leading to short-term decoupling between atmospheric and soil thermal regimes during transitional periods. This temporary mismatch may contribute to conditions associated with 'false springs" in Northern European cropping systems, where early atmospheric warming precedes full physiological readiness of crops and soils (Gu et al., 2008; Trnka et al., 2014). The agronomic and physiological consequences of this decoupling between air and soil dynamics are further explored in subsequent sections.

Physiological basis of the +5 °C threshold

Winter cereals typically overwinter at the tillering stage (BBCH 21–25), with a fully developed crown and an established root system, which enables rapid physiological reactivation in spring once temperature thresholds are exceeded.

From a biological perspective, +5 °C approximates the base temperature for measurable development in many temperate cereal crops. Above this threshold, developmental processes such as leaf appearance, tillering, and stem elongation proceed at rates that are agronomically meaningful (Slafer & Rawson, 1995; Porter & Gawith, 1999; Hay & Porter, 2006). Nevertheless, experimental evidence shows that base and optimum temperatures vary with phenological stage and genotype, indicating that +5 °C should be regarded as a standardised practical threshold rather than a universal physiological boundary.

It should be noted that while the +5 °C threshold is a useful general-purpose tool, winter rye (*Secale cereale* L.) is widely recognised as exhibiting earlier physiological reactivation and measurable growth at lower temperatures than winter wheat, reflecting a lower effective temperature requirement for early-season metabolic and meristematic activity (Fowler & Gusta, 1979).

Collectively, these studies indicate that while +5 °C is a convenient and widely adopted agronomic threshold, its physiological relevance is context-dependent. Caution is therefore required when applying this threshold in crop models and management decisions without considering phenological stage and environmental interactions.

Nutrient uptake in relation to temperature

Agroclimatic constraints related to spring soil moisture and temperature dynamics have also been highlighted in Estonian agrometeorological analyses, particularly with respect to fertiliser application timing (Estonian Crop Research Institute, 2014). In organic and peat-influenced soils, high water content and organic matter confer pronounced thermal inertia (Kõlli et al., 2016), thereby delaying spring soil warming and prolonging low-temperature constraints on root activity (Jury & Horton, 2004). Within this context, efficient nutrient uptake by cereals requires physiologically active roots and adequate soil moisture. In addition, soil temperature must be sufficiently high to support root respiration, membrane transport, and enzymatic activity.

Agrometeorological modelling studies further demonstrate that during spring, air temperature thresholds may be decoupled from root-zone soil temperature dynamics, particularly under conditions of snow cover, wet soils, and freeze-thaw processes (Grabenweger et al., 2021). As a result, in cold soils, active ion transport and root growth are strongly reduced, creating situations in early spring where nutrients are present in the soil but cannot be rapidly absorbed by plants (Mengel & Kirkby, 2001; Marschner, 2012).

In Estonian agroclimatic conditions, low soil temperature is frequently compounded by high soil moisture content following snowmelt. This interaction creates a dual constraint on nutrient acquisition. While wet soils exhibit high thermal inertia, delaying warming, the primary physiological limitation arises from soil hypoxia. Active uptake of major nutrients (particularly NO_3 and H_2PO_4) is an energy-demanding process reliant on root respiration and ATP generation. Under waterlogged conditions, oxygen diffusion to the root zone is restricted, inhibiting oxidative phosphorylation. Consequently, the combination of cold and wet soil suppresses nutrient uptake more severely than low temperature alone. Under such conditions, roots lack both sufficient metabolic activity (due to low temperature) and energy currency (due to hypoxia) required for active ion transport (Lambers et al., 2008; Marschner, 2012).

The magnitude of this lag is strongly influenced by soil texture and moisture content. These factors determine soil heat capacity. Lighter-textured mineral soils generally warm more rapidly in spring than heavier clay soils due to lower heat capacity and improved drainage, often reducing the soil-air temperature lag by several days under comparable weather conditions, whereas organic and fine-textured soils tend to exhibit slower warming and greater thermal inertia (Jury & Horton, 2004; Grabenweger et al., 2021). In Estonian mineral soils, root-zone temperatures (10–20 cm) can lag behind air temperature by 5–10 days during rapid spring warming. This lag is often even more pronounced in organic and water-saturated soils due to their high water content and thermal inertia. Under such conditions, even when the +5 °C air temperature threshold is met, the root zone may remain functionally constrained near 0–2 °C, effectively limiting the uptake of immobile nutrients such as phosphorus (Mengel & Kirkby, 2001; Jury & Horton, 2004; Grabenweger et al., 2021).

Although nutrient-absorbing roots are present in the upper 0–10 cm soil layer, this zone is especially prone to low and highly variable temperatures in early spring, thereby limiting nutrient uptake despite apparent root activity.

Empirical field evidence, supported by physiological syntheses, indicates that during early spring, air temperature thresholds may be exceeded several days before soil temperature in the root zone rises sufficiently to support efficient nitrogen uptake. This creates a temporary physiological ‘uptake gap’ (e.g. Pregitzer & King, 2005; Peltonen-Sainio & Jauhiainen, 2014). This concept highlights the decoupling between aboveground phenological signals and belowground physiological constraints during early spring.

Nitrogen (N). Nitrogen uptake can begin at relatively low soil temperatures, but effective uptake and assimilation typically increase as soil temperature rises beyond approximately +8–10 °C (Mengel & Kirkby, 2001; Marschner, 2012). Under cool conditions, microbial processes such as mineralisation and nitrification are also slowed, further constraining nitrogen availability. The metabolic cost of nitrogen assimilation is strongly temperature-dependent, as root respiration and active ion transport generally follow a Q10-type relationship, increasing approximately twofold with each 10 °C rise in temperature within the biologically relevant range, although the exact response depends on species, developmental stage, and environmental conditions (Lambers et al., 2008; Marschner, 2012). Consequently, nitrogen applications made before root-zone temperatures stabilise above approximately +8 °C may be utilised inefficiently due to limited physiological uptake capacity.

Phosphorus (P). Phosphorus uptake is particularly constrained at low soil temperatures because phosphate mobility is limited and the activity of root phosphate transporters and arbuscular mycorrhizal fungi (AMF) is strongly reduced. While direct evidence on temperature thresholds is limited, general physiological studies indicate that AMF colonisation and function are suppressed under abiotic stress conditions, including low temperature, thereby exacerbating cold-induced phosphorus deficiency even in soils with adequate P status (Smith & Read, 2008; Marschner, 2012; Malhotra et al., 2018; Begum et al., 2019).

Potassium (K). Potassium is more mobile in soil than phosphorus and can be absorbed under comparatively cooler conditions. Potassium plays a key role in stomatal regulation and stress tolerance, and insufficient K supply may increase sensitivity to both cold and heat stress (Mengel & Kirkby, 2001; Zörb et al., 2014).

Overall, nutrient uptake responses to temperature are element-specific, with phosphorus being most sensitive to low soil temperatures, whereas potassium uptake is less constrained. This differentiation has important implications for fertiliser timing in cool spring conditions typical of Estonia.

Cessation of vegetation and short-term frosts

When daily mean air temperature falls persistently below +5 °C, vegetation is considered agronomically inactive: growth and biomass accumulation slow markedly and nutrient uptake declines. Winter cereals are cold tolerant but not actively growing at low temperatures; they survive freezing conditions but do not sustain efficient growth or nutrient uptake (Porter & Gawith, 1999; Hay & Porter, 2006). Short-term night frosts (approximately −2 to −4 °C) usually do not kill winter cereals but temporarily halt growth.

Table 1. Generalised functional interpretation of air and soil temperature ranges for winter cereals, synthesised from published literature

Temperature, °C	Physiological status	Nutrient uptake limitation	References
0…+2	Dormancy/ minimal photosynthetic activity	Negligible uptake; root membranes are rigid and exhibit low permeability	Marschner, 2012
+2…+5	Transition phase / slow metabolism	Minimal N/K uptake; P uptake effectively inhibited by low diffusion	Mengel & Kirkby, 2001
+5…+8	Active vegetative growth	Increasing N and K uptake; P remains a bottleneck due to low AMF activity	Smith & Read, 2008; Begum et al., 2019
+8…+12	Efficient biomass accumulation	Enhanced N mineralisation; P uptake begins to normalise as soil temperature increases	Malhotra et al., 2018
+15…+25	Optimal growth range	Peak uptake rates; maximum enzymatic activity supporting nutrient assimilation	Porter & Gawith, 1999

Note: The temperature ranges shown represent generalised physiological responses reported in the literature. Actual thresholds may vary with species, cultivar, phenological stage, soil type, and moisture conditions.

High temperature effects and yield potential

Optimal temperatures for vegetative growth of cereals typically range between +15 and +25 °C, depending on developmental stage (Porter & Gawith, 1999; Hatfield & Prueger, 2015). Growth often slows at temperatures above +25–28 °C, and the risk of heat stress increases markedly at ≥ +30 °C (Porter & Gawith, 1999; Asseng et al., 2015). Heat stress reduces photosynthesis, accelerates phenological development, and shortens the grain-filling period, thereby reducing yield potential. Flowering and grain-filling stages are particularly sensitive (Asseng et al., 2015).

In addition to low-temperature constraints, increasing temperatures during later growth stages may also pose significant risks for cereal production in Northern Europe. Elevated temperatures during grain filling have been associated with reduced grain weight, accelerated phenological development, and decreased yield potential due to shortened growth duration and increased respiratory losses (Trnka et al., 2014; Asseng et al., 2015). Furthermore, the frequency of heat stress events is projected to increase under future climate scenarios, even in regions historically considered temperature-limited, potentially offsetting some of the benefits of earlier spring onset (IPCC, 2021; IPCC, 2023). These contrasting effects highlight the need to consider both early-season thermal limitations and late-season heat stress within an integrated framework of air–soil temperature dynamics.

Phenological risks: false springs and de-hardening

A critical challenge in the Estonian climate is the increasing risk of so-called 'false springs' – periods in March or early April when air temperatures exceed +5 °C for several consecutive days, triggering de-hardening and loss of cold tolerance in winter wheat and rye. If such periods are followed by a return to sub-zero temperatures, the advanced phenological state of the crop increases susceptibility to frost injury compared with situations where the +5 °C threshold is reached later and more gradually (Gu et al., 2008; Trnka et al., 2014).

In contrast, autumn conditions in Northern Europe are characterised by declining air temperatures while soil temperatures remain relatively high, allowing continued root growth and carbohydrate allocation in winter cereals. These processes are primarily associated with cold acclimation rather than active nutrient uptake and therefore fall outside the main focus of this review.

Management implications and future perspectives

Given the thermal lag between air and soil warming, nitrogen applications may be more efficient when timed closer to soil temperatures of approximately +8–10 °C, although this requires validation under Estonian field conditions. Applying N too early on cold, wet mineral or peat soils increases the risk of leaching and denitrification before roots become sufficiently physiologically active for efficient uptake. In addition to nitrogen, phosphorus management should consider reduced early-season availability due to limited diffusion and suppressed mycorrhizal activity in cold soils. Potassium may play a role in improving stress tolerance under both low- and high-temperature conditions and should therefore be maintained at adequate levels. Recent studies in Central and Northern Europe highlight that adaptive nutrient management, particularly nitrogen and phosphorus optimisation, is increasingly critical under climate variability (Wójcik-Gront et al., 2024).

It should be noted that this study does not include direct soil temperature measurements; therefore, conclusions regarding soil thermal dynamics are inferred from established literature and should be interpreted as conceptual rather than empirically validated for Estonia.

Finally, it must be emphasised that much of the foundational physiological literature cited in this review (e.g. studies from the 1990s and early 2000s) was conducted on cereal genotypes that have since been superseded by modern, high-yield cultivars. These contemporary varieties have been predominantly bred for yield potential and disease resistance, potentially at the expense of root system plasticity or early-season cold tolerance. Under Estonian conditions, it remains unclear how the root architectures of modern cultivars – often characterised by different branching patterns and nutrient acquisition strategies – interact with the identified soil–air thermal lags. As the frequency of 'false springs' increases, future research should prioritise quantifying the phenological stage-specific temperature thresholds of these modern genotypes. Field-based studies integrating high-resolution soil temperature monitoring with root-zone activity assessments are essential to refine fertiliser recommendations and to ensure that breeding programmes account for the specific agroclimatic constraints of the Northern European spring transition.

In addition, root system architecture and effective rooting depth vary among cereal species and cultivars, particularly between winter wheat, rye, and barley. Quantifying species- and genotype-specific root distribution across soil layers, and its interaction with early-season soil temperature dynamics, represents an important research need for refining nutrient management recommendations under cool spring conditions. Recent studies increasingly emphasise the importance of soil-plant-atmosphere interactions in determining crop responses to climate variability. Climate change has been shown to alter soil processes, nutrient cycling, and plant physiological responses, potentially leading to phenological mismatches between environmental signals and plant functioning (Oishy et al., 2025). Empirical evidence from European cereal systems further demonstrates that soil properties, particularly soil organic carbon, and nutrient management play a critical role in determining crop performance under changing climatic conditions (Campos-Cáliz et al., 2024; Wójcik-Gront et al., 2024;). In addition, recent field- and remote-sensing-based studies confirm that soil conditions significantly influence winter wheat growth dynamics, highlighting the importance of integrating soil factors into agroclimatic assessments (Sjulgård et al., 2024).

CONCLUSIONS

In Estonia, the +5 °C air temperature threshold serves as a robust indicator for the thermal growing season. During the 1965–2018 period, this season extended on average from late April to late October, with significant maritime–continental gradients causing longer durations in coastal regions compared to inland areas. Observations from the last decade (2014–2024) indicate an acceleration of spring warming, with the +5 °C threshold occurring 4–7 days earlier than the long-term mean. This trend increases the risk of 'false springs' and frost damage to winter cereals following premature de-hardening.

The +5 °C threshold should be interpreted as a standardised agronomic tool rather than a strict biological limit. Base and optimum temperatures for nutrient uptake vary across phenological stages, and atmospheric thresholds do not immediately reflect soil thermal dynamics. Based on established physiological evidence, nutrient uptake is widely reported to be influenced by low soil temperatures: phosphorus (P) acquisition is the primary bottleneck due to reduced diffusion and suppressed arbuscular mycorrhizal fungi (AMF) activity below 10 °C. In contrast, potassium (K) uptake is less sensitive, and nitrogen (N) availability remains dependent on temperature-driven microbial mineralisation.

Agronomic management in Northern Europe may benefit from integrating soil temperature monitoring with atmospheric thresholds. Fertilisation strategies may need to account for the widening spring 'thermal lag', as suggested by existing physiological and agronomic evidence, in order to reduce nutrient losses and mitigate cold-induced deficiencies during early vegetative growth.

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