Science of the Total Environment 917 (2024) 170381

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Nitrates directive restriction: To change or not to change in terms of climate change, that is the question

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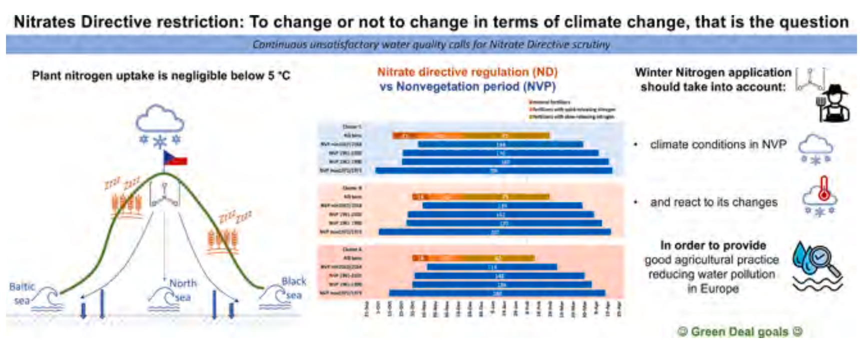
HIGHLIGHTS

- Nitrogen management in the Czechia affects water quality of 11 states.
- Continuous unsatisfactory water quality calls for Nitrates Directive scrutiny.
- We bring climatologically based contribution to the discussion on nitrogen management.
- Vegetation period in Central Europe has prolonged about 20 days over last 6 decades.
- Nitrogen application bans and non-vegetation period differ about tens of days.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: José Virgílio Cruz

Keywords:
Nitrate vulnerable zones
Nitrate leaching
Vegetation period
Fertilizers
Sustainability
Environmental quality management

ABSTRACT

The positive effect of nitrogen fertilization in agriculture inevitably increases residual nitrogen losses. Water pollution led to legal restrictions of some farm practices within the framework of the Nitrates Directive of the EU. Nevertheless, even several decades later, the situation has not improved significantly. We present a possible science-based explanation of such a state and provide it to farmers and government as a support for environmental management settings. This study aimed to compare an established approach to implementing the Nitrates Directive, specifically the climate-based zoning of nitrogen fertilization restrictions using data from the mid-20th century. We evaluated this approach by juxtaposing the initial climate data with more recent data spanning from 1991 to 2020. Subsequently, we examined this zoning framework from the perspective of the non-vegetative period, characterized by temperatures below 5 °C, which is widely acknowledged as a critical threshold for nitrogen intake by plants. We found out that i) the employed climate-born zoning does not correspond to recent climate data; ii) nonvegetation period is longer than nitrogen fertilization restrictions. Therefore, despite a noteworthy 22 day reduction in the nonvegetation period from 1961/1962 to 2019/2020, we cast doubt on the notion that the period limiting nitrogen fertilizer application should also be shortened, while admitting that there are other abiotic and biotic factors affecting nitrogen behaviour within the ecosystem.

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https://doi.org/10.1016/j.scitotenv.2024.170381
Received 20 June 2023; Received in revised form 14 January 2024; Accepted 21 January 2024
Available online 26 January 2024

1. Introduction

Agricultural fertilizers constitute a complex nexus, not just between environmentalism, climatology and soil sciences, but also between these natural sciences and sociological ones. The overuse of fertilizers is no longer sustainable, given the associated economic and environmental follow-up costs (Mateo-Sagasta et al., 2017; Kanter et al., 2020a; Wang et al., 2019). Nitrogen and phosphorus losses from arable land has been challenging authorities responsible for environmental and food safety and security. Extensive survey (Kanter et al., 2020b) identifying gaps and opportunities in nitrogen pollution policies around the world (2726 policies across 186 countries) identified that two-thirds (ranging from broad sectoral programmes to nitrogen-specific measures) incentivize nitrogen use or manage its commerce, demonstrating the primacy of food production over environmental concerns.

Even though EU have adopted some regulations, they remain insufficient and appropriate mitigation will be required to reduce water contamination (Gomes et al., 2023). The existing Council Directive No. 91/676/EEC (European Commission, 1991) concerning the protection of waters against pollution caused by nitrates from agricultural sources (Nitrates Directive, hereinafter referred to as ND) aims to protect water quality across Europe by preventing nitrates from polluting ground and surface waters and by promoting the use of good farming practices. Its implementation lies mainly in the identification of "Nitrate Vulnerable Zones" (NVZs), the establishment of Codes of Good Agricultural Practice and action programs to be implemented by farmers within NVZs on a compulsory basis.

However, the benefits of various water quality programmes over three decades have been less evident all over the Europe than expected as reported by European Commission (2021). One of the areas most affected is the Lombardy Plain (Italy) where socio-hydrogeological survey (Musacchio et al., 2020) identified steady or increasing 11 year trend in nitrate concentration. Gomes et al. (2023) points out that Portuguese groundwater in agricultural areas show the highest nitrate concentration due to a decrease of surface water and increased pollution, as well as inadequate agricultural practices. They conclude the existing measures remain insufficient and appropriate mitigation will be required. The analysis nitrate concentration in Spanish Gallocanta NVZs in the last 38 years performed by Orellana-Macías et al. (2020) suggested that the lack of update of action programmes, inappropriate zones delimitation and the influence of natural factors are reasons for the failure of nitrate reduction measures. Marszelewski and Piasecki (2020) claim that nutrient concentrations in Odra basin have decreased significantly since the early 1990s, yet they require implementation of several top-priority tasks in the near future for obtaining a good ecological state of waters in the basin pursuant to the Water Framework Directive. Bawiec et al. (2022) reported the large variability in N-NO_3 content in Polish waters and demand redefining NVZs, as it is essential for the appropriate implementation of programs aimed at restoring water quality according to ND. Overtime, many surveys on water quality have showed a need for full compliance regarding EU directives on nitrate pollution due to agriculture. As early as more than a decade ago, Cruz et al. (2010) emphasized that appropriate land use management measures are essential to water management practices and a successful Water Framework Directive implementation. For an enhanced European integrated nutrient directive call also Wassen et al. (2022) suggesting that it should regulate nitrogen and phosphorus application to prevent ecosystem degradation and to support the Farm to Fork initiative of the EU Green Deal programme. The ambitious targets include an 50 % reduction in nitrogen and phosphorus losses to waters and a 20 % reduction in fertilizer use by 2030 (European Commission, 2020). This approach strongly depends on respecting site-specific soil and climatic conditions in the estimation of crop demand for nitrogen and its utilization.

According to European statistical data (EUROSTAT, 2022), Czechia is among EU countries with a high input of mineral nitrogen fertilizers (3th place in nutrient inputs per hectare and 2th place in positive nitrogen balance) as for 2019. Nitrate pollution has been increasingly affected by changing climatic conditions as showed by Hrabánková (2018), who introduced a detailed monitoring of the action program of ND in 10 pilot catchments within Czechia. Typically, under a mild climate such as Dfb cold (Beck et al., 2018), which includes Czechia, chemical leaching from agriculture occurs from late autumn to early spring, when evapotranspiration and plant nitrogen uptake are negligible, and the soil water is replenished. This period is also risky as a threshold of nitrification which makes nitrogen available to plants, but with the risk of nitrogen loss by leaching. The optimum for nitrification in soils is between 25 and 30 °C; below 15 °C, nitrification is already limited, and below 5 °C, it takes place only to a minimal extent as the nitrifying bacteria tend to go dormant. The growth and uptake of nitrogen, especially the ammonium form, by crops occur at relatively low temperatures, increase significantly above 5 °C (MacDuff et al., 1987).

The temperature effect on nitrogen losses is combined with soil moisture. When the soil water content exceeds the soil water capacity, excess water with diluted nutrient ions percolates to deeper layers. In short, effective precipitation, soil nitrate and water content, as well as their distribution at the onset of winter, are the main factors influencing the nitrate leaching (Delgado et al., 2008; Kühling et al., 2021). Therefore, many farm activities restrictions, aimed at the water pollution reduction, are based on the identification of relevant climate conditions and thus the zoning of agricultural land in the context of ND is needed (Metzger et al., 2005; Chuchma and Středová, 2015; Bawiec et al., 2022). The latest study regarding Central Europe (Lukasová et al., 2020) predicts changes in climate relevant to nitrogen losses. In addition, climate change impacts plant phenology and thus nitrogen dynamics in natural and agricultural ecosystems. Chuchma et al. (2016) bio-indicated climate development, when the evaluated phenological data have showed an earlier phenophase onset by approximately 2 days per decade since 1940 in the Central Europe. The impacts of climate change and weather fluctuations complicate the fulfilment of standard fertilization schemes. Demand-oriented nitrogen fertilization and decreased efficiency of nitrogen inputs have inevitable impacts on nitrogen balance and risk of nitrogen losses (Ru et al., 2022).

Increased attention should be paid to those regions that lie in source areas, since they have the potential to pollute both surface and underground water at the beginning of the terrestrial water cycle. At the European level, these area is Central Europe, specifically Czechia, which with its three main headwater rivers influences water quality in all their courses (see Fig. 1, left); these include the Elbe through Germany to the North Sea, the Oder through Poland to the Baltic Sea and the Morava River through the Danube river to the Black Sea (HELCOM, 2014). According to European Commission (2021) all above mentioned regions have recorded bad water quality and a problem in managing nutrient losses from agriculture, while Marszelewski and Piasecki (2020) point out concentrations of some water quality parameters of the Oder River being already heavily polluted at the border with Czechia. As a result of the unsatisfactory trend of reducing nitrates in Czech waters, it has not been possible to lower the area NVZs identified in the action program. This constitutes a platform for wider applications of paper insights: arising from the Visegrad Group hydrological interconnection through ND all-European perspective to a global issue of nitrogen pollution.

2. Materials and methods

2.1. ND implementation in area of interest according to current legislation

Implementation of ND in Czechia basically combines NVZs with restrictions and rules of nitrogen fertilizers applications. The NVZs are legislatively anchored in Government Regulation No. 262/2012 Coll., on Determination of Vulnerable Areas and Action Program/ (amendments under No. 277/2020 Coll.). Demarcation of NVZs is carried out by the Ministry of the Environment on the basis of identification of surface

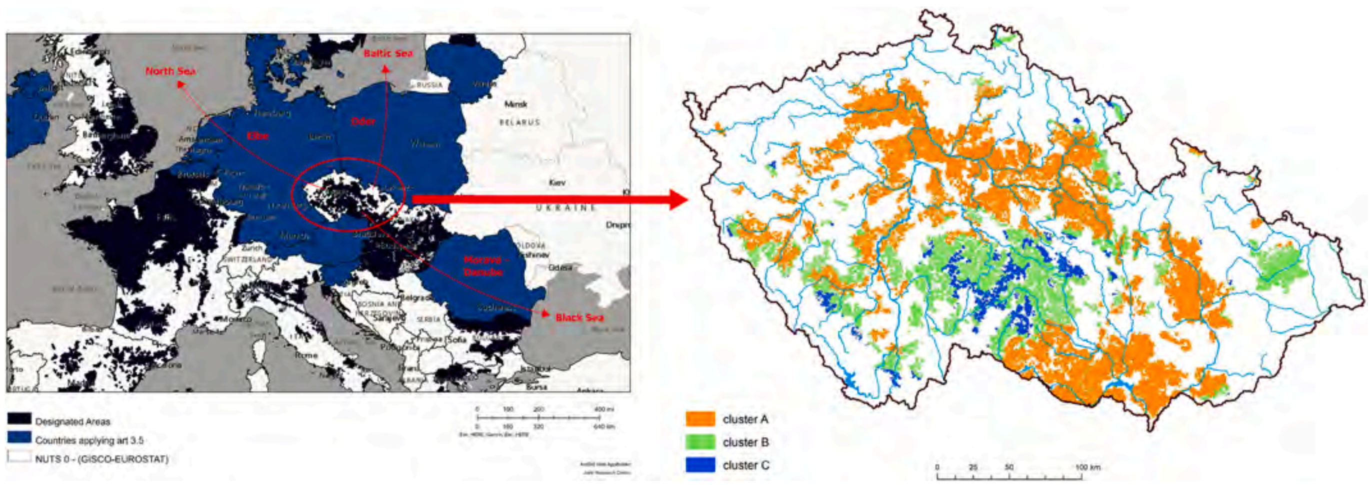

Fig. 1. Area of interest in frame of the Europe (left) and the NVZs in clusters of Czechia (right).

or groundwater polluted or threatened by nitrates from agricultural resources taking into account the quality and quantity of surface and underground water and quality of raw water monitored by water supply operators. These NZVs cover half of the agricultural land of the country (total area of all clusters in Fig. 1).

Government Regulation No. 262/2012 Coll. then employs climate conditions in order to set bans on nitrogen fertilizer application on agricultural land (ND bans) in the NVZs, relying on Decree No. 227/2018 Coll., on characteristics of valued soil ecological units and the procedure for their management and updating. This soil ecological units' system distinguishes ten climatic regions from warmer and drier to colder and wetter based on data from 1901 to 1950. For the purposes of ND, climatic regions were subsequently clustered into 3 areas to enforce appropriate nitrogen fertilizer management: cluster A (very – slightly warm; dry – slightly wet), cluster B (slightly warm; wet), and cluster C (slightly cold – cold; wet). These clusters combined with NZVs (Fig. 1) constitute a climatic baseline for ND bans setting.

As winter is most susceptible in terms of nitrogen leaching and runoff, volatilization, limited plant uptake and lower microbial activity, ND bans focus mainly nonvegetation period (NVP). The approach takes into account the form of nitrogen and climatic conditions expressed by Clusters A, B and C and thus is by its nature based on climatic data relevant for the first half of 20th century. Table 1 lists the periods in which Government Regulation No. 262/2012 Coll. prohibits application of nitrogen fertilizers of different types: mineral, fertilizers with quick-releasing nitrogen and fertilizers with slow-releasing nitrogen. Application of the latter type of nitrogen fertilizers is also prohibited during vegetation period/growing season, namely form June 1 to July 31, as this period is risky due to high air and soil temperatures supporting the mineralization of organic substances and the release of nitrogen. As ND bans relevant to NVP are most robust, our study is focused on them.

As a reaction to increasing temperature even in NVP, Government Regulation No. 262/2012 Coll. approves some exemption from the ban given in Table 1. It concerns fertilizers with quick-releasing nitrogen on agricultural land with an average slope not exceeding 5 degrees. The fertilizers can be applied 14 days after the beginning of the ND ban (for instance mineral fertilizers in the cluster A can be applied 14 days after November 1) but only if the average daily air temperature is higher than 5 °C. The number of such days was determined and statistically evaluated for all clusters and for all three types of nitrogen fertilizers.

2.2. *Employed indicators – Parameters of the nonvegetation period (NVP)*

As the temperature of 5 °C is recognized as a threshold for nitrification and root uptake of nitrogen, especially the ammonium form, the employed indicator was NVP defined as the period when the daily average temperature drops below 5 °C for at least 3 days in a row (COOL-BEG) until it again rises to 5 °C and does not drop below that threshold for three days (COOL-END). The difference between COOL-END and COOL-BEG is NVP-LEN (the length of NVP). To sufficiently grasp the effect of climate development, the evaluated period was set as 1961–2020.

2.3. *Data specification*

Data on the COOL-END and COOL-BEG were obtained from 278 climatological stations. The input data were subjected to ProClimDB software (Štěpánek et al., 2009), which is being recognized by national authority Czech Hydrometeorological Institute as a standard method for data processing and its quality control.

The spatial interpretation of NVP parameters in each year was divided by GIS tools into 98 020 rasters in a 10 m grid – each one defined by the COOL-BEG and COOL-END.

Each clusters thus possesses two levels of variability: i) spatial variability given by raster value, and ii) temporal variability given by their interannual fluctuation. To describe both, source data were employed as follows:

- Raster data: data on the COOL-END and COOL-BEG of the NVP for each raster and each year (1961–2020).

The difference between the COOL-END and COOL-BEG reveals the

Table 1
ND bans in NVP for all clusters and all types of nitrogen fertilizers.

Clusters and their climatic regions	Mineral fertilizers	Fertilizers with quick-releasing nitrogen	Fertilizers with slow-releasing nitrogen[a]
A: 0 – 5	Nov 1–Feb 28	Nov 15–Feb 15	Dec 15–Feb 15
B: 6 – 7	Nov 1–Feb 16	Nov 15–Feb 28	Dec 15–Feb 28
C: 8 – 9	Oct 15–Feb 28	Nov 5–Feb 28	Dec 15–Feb 28

[a] Fertilization is also prohibited from June 1 to July 31 (unless there is subsequent cultivation of winter crops or intercrops).

length of the NVP (NVP-LEN = ⟨COOL-BEG, COOL-END⟩).

Amount of values: 60 years (1961–2020) multiplied by the number of rasters (98020) and 3 employed indicators (COOL-BEG, COOL-END, NVP-LEN) = 17,643,600 values.

- Normal raster data: average raster data for normal periods 1961–1990 and 1991–2020.

Amount of values: 98020 rasters multiplied by 2 normal periods (1961–1990 and 1991–2020) and 3 employed indicators (COOL-BEG, COOL-END, NVP-LEN) = 588,120 values.

- Annual cluster average data: annual average values for each cluster based on raster data belonging to individual clusters. Amount of values: 60 years (1961–2020) multiplied by 3 clusters (A to C) and 3 employed indicators (COOL-BEG, COOL-END, NVP-LEN) = 540 values.
- Normal cluster data: average annual cluster average data for normal periods 1961–1990 and 1991–2020 for each cluster. Number of values: 2 normal periods (1961–1990 and 1991–2020) multiplied by 3 clusters (A to C) and 3 employed indicators (COOL-BEG, COOL-END, NVP-LEN) = 18 values.

3. Results

The first step was to bring a critical look at climatic clusters' relevance for current climate conditions. A comparison of original (1901–1950) and current (1991–2020) data shows a significant shifts (Supplement 1) as temperature-related characteristics show a significant increase in almost all cases while precipitation-related ones show an extension of their boundaries, implying their increasing variability.

Secondly, spatial expression of NVP changes in a long-run perspective based on normal raster data showed how long-term periods differ from each other. The most significant shift is apparent in COOL-END, which logically also influences NVP-LEN, while the shift in COOL-BEG is not very evident (Supplement 2). This is then proven by long-term trend analyses of NVP parameters describing changes based on annual cluster average data. The long-term 60 yr trend in COOL-BEG, COOL-END and NVP-LEN was investigated by regression analysis and statistically evaluated by the Mann–Kendall test. Shifts in COOL-END and NVP-LEN were statistically significant (α = 0.05) in all clusters, while shifts in COOL-BEG were not. A detailed yearly course with confidence intervals for the COOL-END where the change is the most evident is shown in Fig. 2.

In order to understand interannual variability of NVP we investigated long-term changes based on annual cluster average data. Boxplots in Fig. 3 show that, analogous to spatially expressed changes (Supplement 2), two normal periods (1961–1990 and 1991–2020) also differ from each other in terms of their interannual variability. The later onset of the COOL-BEG, the shortening of the NVP-LEN and the earlier COOL-END in the second period are relevant to all clusters, while this period is also characterized by a general increase in interannual variability.

Finally, findings of NVP changes based on normal cluster data were applied in the ND realm. Fig. 4 clearly summarizes how ND bans for individual types of nitrogen fertilizers correspond to NVP (average values for two normal periods $NVP_{1961–1990}$ and $NVP_{1991–2020}$ and

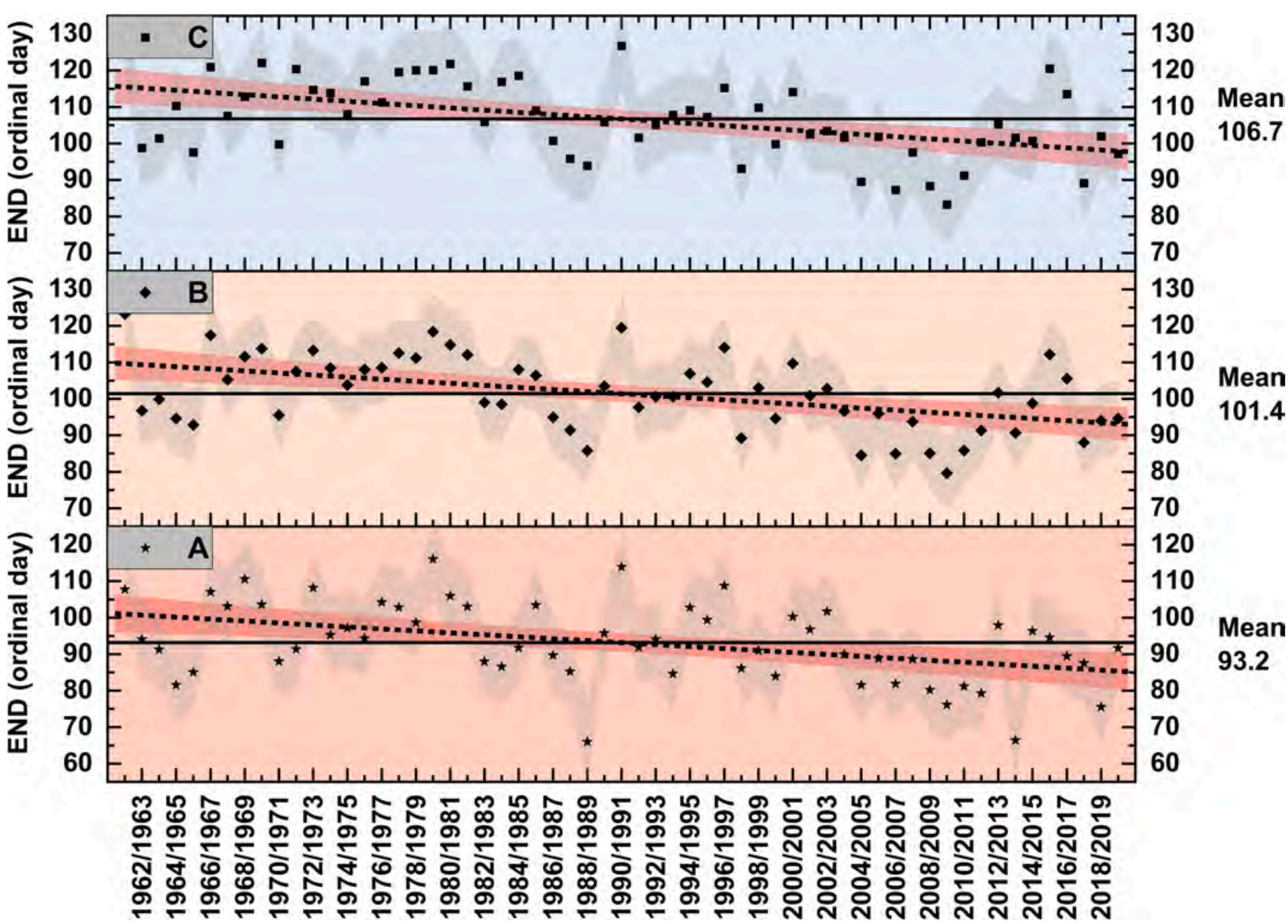

Fig. 2. Detailed analyses of the long-term 60 yr trend in end of COOL-END with confidence intervals.

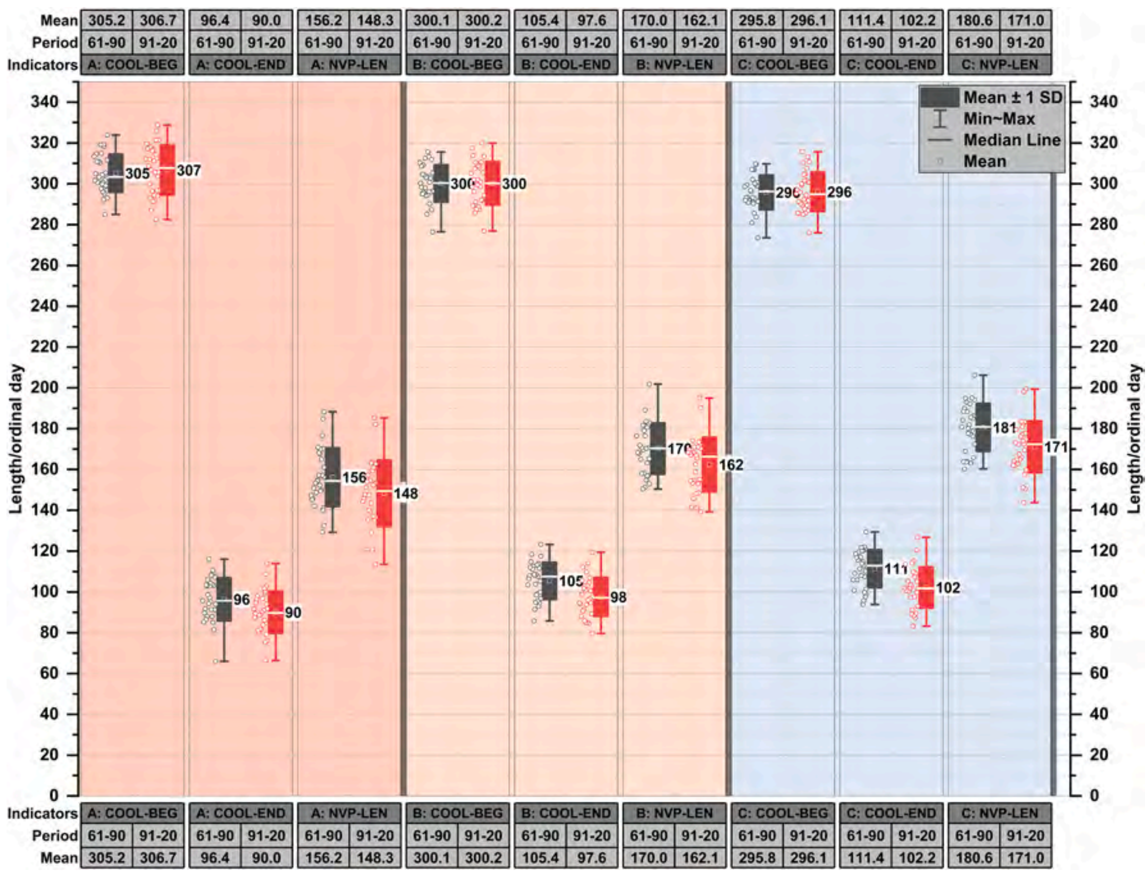

Fig. 3. Interannual variability NVP parameters within two normal periods (1961–1990 and 1991–2020).

absolute maximum and minimum values of NVP for each cluster).

From Fig. 4 can be concluded that ND bans do not match long-term average NVP either 1961–1990 or 1991–2020. Neither it matches the absolute shortest NVP recorded in 2013/2014 (cluster A) and 2017/2018 (cluster B and C), leave alone the absolute longest ones.

From the viewpoint of individual NVP parameters (see Section 2.2) the best match is between COOL-BEG and beginning of ND ban for mineral fertilizers in clusters A and B., while in cluster C the ND ban for mineral fertilizers is even too strict as it precedes COOL-BEG. End of ND bans for mineral fertilizers application on the contrary has been set leniently. An illustrative simplified idea of the relationship between COOL-END and ND bans provide so-called hypothetic COOL-END_H derived by regression relationships and trend analyses (see Fig. 2). End of ND ban for mineral fertilizers in clusters A precedes COOL-END$_{1991–2020}$ about 44 days matching COOL-END$_{2190/91}$, in cluster B about 39 matching COOL-END_H$_{2163/64}$ and in cluster C about 43 days matching COOL-END_H$_{2170/2171}$. Here it is worth mentioning that NVP-LEN_H$_{2019/2020}$ is about 22 longer then NVP-LEN_H$_{1961/1962}$ across clusters.

In addition, to capture increasing climate variability we looked into ND exemption eligibility specified in Section 2.1 as days with $T_{AVG} > 5$ °C within 14 day period after the beginning of ND ban. Number of such a days increased significantly in all clusters. The average 60 yr shift was 3 days, indicating that, currently, the farmers may apply for the exception for three days longer than in the past. The detailed results are as follows: for Cluster A, the number of such days with increased from 1.0 (1961/62) to 4.6 (2019/20) ($r = 0.327$; $\alpha = 0.01$); for Cluster B from 0.3 (1961/62) to 3.7 (2019/20) ($r = 0.319$; $\alpha = 0.01$); and for Cluster C from 2.2 (1961/62) to 4. 2 (2019/20) ($r = 0.256$; $\alpha = 0.01$).

4. Discussion

Our previous study (Středová et al., 2013) indicated that vegetation season in 1961–2010 was up to 1.1 °C warmer than in 1901–1950 in Czechia. Such changes impact the demand for nitrogen as crops deplete it from soil and accumulate it in biomass, thus reducing the risk of nitrate leaching. In particular there is a strong link between the behaviour of nitrogen in the environment and the threshold of 5 °C (MacDuff et al., 1987) as under lower temperature transpiration, nitrification and plant nitrogen uptake are strongly limited. An increased temperature is favourable to microbial activity and the mineralization of soil organic matter and the release of nitrogen, phosphorus and carbon from it (Sofi et al., 2016; Yu et al., 2022). Parallel with the increase in temperature, the potential of crops for nitrogen depletion increases, and the conditions for nitrogen mineralization improve (Macholdt et al., 2020; Ma et al., 2009).

ND in Czechia imposes a ban on nitrogen fertilizers application in winter season. Declared warming and prolonging of vegetation season provoke a logical question of reassessment of existing bans. We have brought an evidence of shortening NVP which basically encourages efficient use of nitrogen in agroecosystem and thus limits its losses and subsequent environmental damages. However, mineralization also depends on soil moisture and substrate availability (Cabrera, 1993; Young et al., 2021; Krüger et al., 2021). Lower soil moisture reduces risk of water percolation and nutrients leaching during winter and early spring. This effect was studied from the viewpoint of possible negative impact on soil available water supply in root zone for spring vegetation rather than for its effects on nitrate leaching though (Gentsch et al., 2022.; Meyer et al., 2019). In general, large volumes of nitrate transport occurs during wet years, and lowers in dry years which corresponds to Tavakoly et al. (2019) study on groundwater and surface water at regional scales. General tendency of Central Europe to aridization represents a

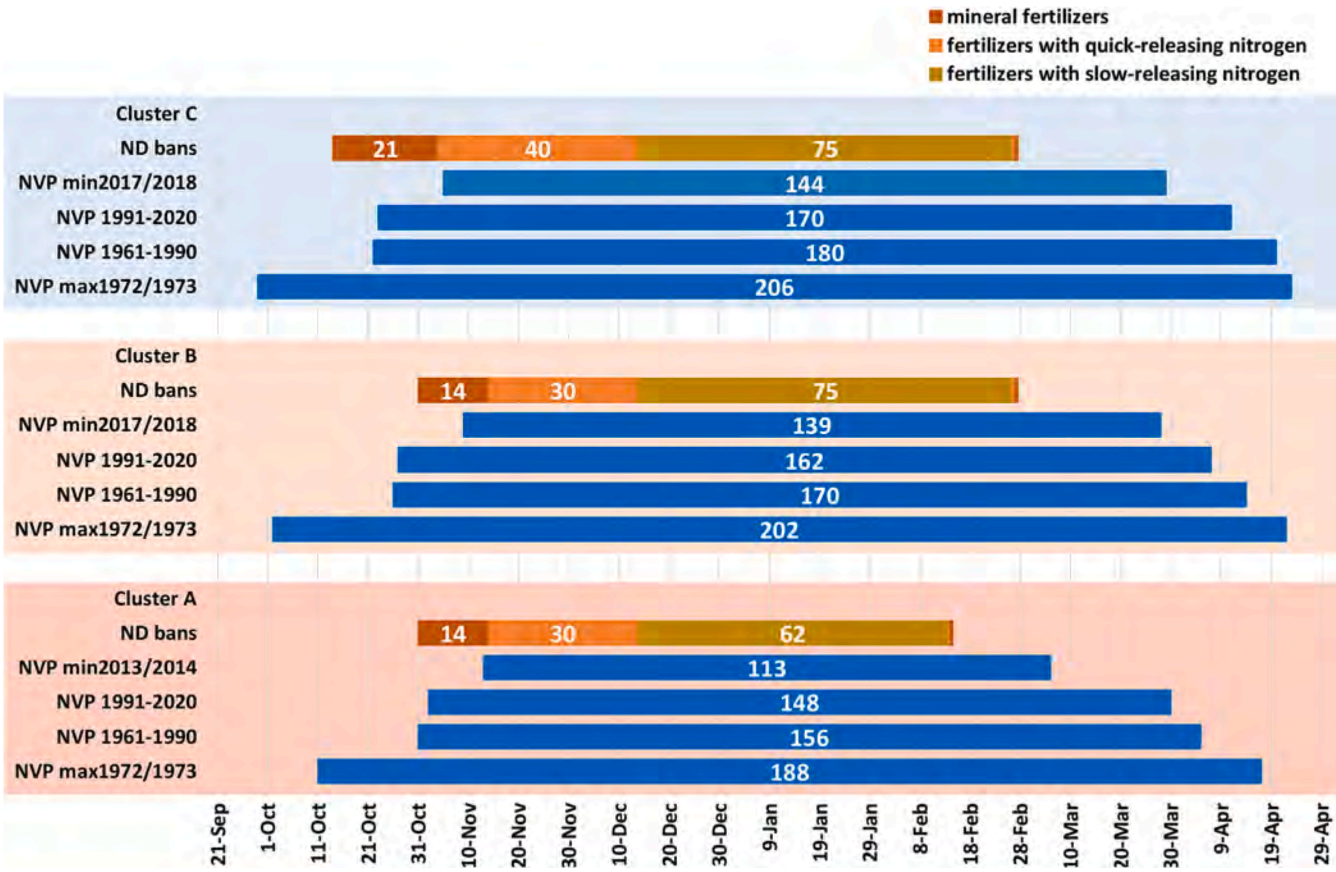

Fig. 4. Changes of NVP in the context of ND bans for different types of nitrogen fertilizers (numbers in strips represent a number of days; length of ND bans for different types of nitrogen fertilizers are to be summed up together).

supporting argument for ND ban loosening. However, Středa et al. (2019) warn that although potential duration of the growing season will be extended, its effective length may decrease due to the more frequent drought. The regular monitoring of mineral nitrogen contents in on farm fields proved increased nitrate contents particularly before winter after dry years (Haberle et al., 2009). At the onset of winter, before the NVP period with the highest risk of leaching, there is a wide range of nitrogen contents, often exceeding 100 kg N.ha^{-1} (Haberle et al., 2018). Increasingly common drought years thus result in lower nitrogen uptake in growing season and thus in enhanced residual nitrogen content after harvest, with increasing risk of nitrate leaching during the NVP. On the other hand, farmers, especially in recent exceptionally warm winters, often feel that the measures limiting application of organic and mineral fertilizers are too restrictive. For example, regeneration fertilization of winter oilseed rape in Cluster A is in general allowed from January 31 but only after February 15 in Clusters B and C. The limitations on farm practices are further differentiated according to soil traits to eliminate the most vulnerable deficit soils that are shallow, stony and have a high water table. Enforced measures may limit yields under certain conditions, and yield potentials are not fully exploited. For example, the maximum dose of nitrogen is excessive under less-favourable years and insufficient under optimal weather conditions. In spring with convenient weather, the delay of the early regeneration dose of fertilizers to winter crops by 10 or 15 days may disrupt the synchronization of the demand and supply of nitrogen. Similarly, the experience of farmers shows that the very early sowing (with a need for a starting dose of nitrogen) of some spring crops in February, in the case of a warm winter, can be advantageous to avoid later heat stress and drought thanks to earlier flowering (Shavrukov et al., 2017; Marcinkowski and Piniewski, 2018; Minoli et al., 2022). In dry years less uptake and utilization of granular nitrogen fertilizers may also be caused by their delayed application. The fertilizers are not fully dissolved, and the ions concentrate only in the surface layer. The topsoil layer repeatedly overdries; roots have poor contact with soil particles, and the transport of ions to roots by diffusion is reduced or fully ceased. Optimally, nutrients are distributed with water from the topsoil deeper in the soil and deposited in zones where suitable moisture and dense roots ensure efficient depletion (Středa et al., 2012). This suggests that earlier application may improve the efficiency of nitrogen fertilizers. In dry areas, even autumn fertilization can be recommended for deep, loamy and clay–loamy soils, without significant risk, as the winter precipitation sums are low (Ma et al., 2009; Beres et al., 2019). However, the approach is disputable under the transition climate of Central Europe, with strongly fluctuating precipitation and water balance. For example, in 2022 atypical above-average rainfall occurred, which could have caused washout even during the vegetation period.

Our results thus might seemingly imply that shorter NVP together with more frequent drought justify shortening of ND bans. However, when compare NVP and ND bans it is clear that in spite of NVP shortening the ND ban end have been set rather leniently and the climate reality expressed by COOL-END_H will only be met at the end of the century. To draw such a conclusion we employed simplified method for predicting future climate development based on extrapolation of linear trend. In order to interpret this general and mathematically based conclusion in more climatically relevant way we complete that according to IPCC (2023) climate change towards future does not follow a linear trend. Claimed air temperature increase affecting also NVP is related to global greenhouse gas emission pathways with rather exponential trend. NVP parameters' prediction requires employing different greenhouse gas emission pathways together with appropriate climate models providing certain scale of relevant results. Increasing temperature affects moisture balance and even though Central Europe generally tends towards more frequent drought especially in vegetation period, Patil et al. (2010) point out that winter and early spring tend to increased precipitation, elevating the risk of nitrogen losses through leaching. It suggest that documented shortening of NVP do not justify softening nitrogen fertilizer application limits. In addition, continuously reported unsatisfactory water quality and high nitrogen pollution confirm that ND does not meet its main goal to protect waters against pollution caused by nitrates from agricultural sources.

Our results also show an increasing variability of NVP towards present. For example, COOL-BEG spans 40–60 days, and this variability will most likely increase. This urges caution in drawing conclusions for farm practices. The wealth of knowledge from numerous field experiments focused on nitrogen in connection with a dense network of meteorological stations and high-quality data on soil conditions in Czechia has not yet been fully utilized for the effective fine-tuning of rules leading to reduced water pollution.

As nitrogen behaviour depends on various factors, no sole administrative measure, recommendation and restriction simply can cover all their interactions (Cabrera, 1993; Young et al., 2021; Krüger et al., 2021).

However, today, the agrosector often relies on various smart Agriculture 4.0 tools. Some farming practices, especially environmentally sensitive ones, are based on advanced monitoring and rapid data evaluation to optimize both farmers' economic profit and their environmental footprint (Silveira et al., 2021). Most of these systems provide a wide range of complex climate values derived from the general climatological measurement.

5. Conclusion

Identified shortening of NVP together with negligible nitrogen uptake by crops in NVP imply analogical shortening of the period restricting nitrogen fertilizer application. The unsatisfactory trend of nitrates concentrations in European and Czech waters in connection with the high positive balance of nitrogen however warn against the hasty softening of bans. We shoved that in terms of NVP existing ND bans for mineral fertilizers were set quite appropriately as to their beginning but leniently as to their ending as they precede end of NVP significantly in all clusters. The bans for fertilizers with quick and slow releasing nitrogen are much shorter than NVP in all clusters. Based on our results, despite increasing temperature and a shortened NVP ND bans are still insufficient nowadays from the viewpoint of NVP. Having said that, we admit that the unsatisfactory water nitrogen pollution might be the result of poorly interpreted climatic conditions as well as poor knowledge about nitrogen in the soil and vegetation as there are further abiotic and biotic factors influence nitrogen behaviour within the ecosystem.

At the same time we raise the issue of climatic baseline for ND bans setting (i.e. climatic regionalization defined by Decree No. 227/2018 Coll. based on data 1901–1950) in terms of their current climatic relevance as its temperature-related characteristics show a significant increase and precipitation-related ones show an extension of their boundaries, implying increasing variability.

The outcomes and findings of our study serve as a valuable contribution to the ongoing multilevel discourse among stakeholders regarding the update of parameters within the Nitrate Directive (ND), incorporating other perspectives and ideas from various stakeholders, fostering a more comprehensive understanding of the implications and potential adjustments needed for enhancing environmental quality and water bodies in particular.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170381.

CRediT authorship contribution statement

Hana Středová: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Petra Fukalová:** Writing – original draft, Validation, Formal analysis. **Filip Chuchma:** Validation, Investigation. **Jan Haberle:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Tomáš Středa:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Funding

This study was supported by the Applied Research Program of the Ministry of Agriculture, Czech Republic for the period 2017–2025: QK22020130 "Implementation of BPEJ innovations into the system of state administration" and by the Technology Agency of the Czech Republic (grant no. SS02030040, PERUN, "Prediction, Evaluation and Research for Understanding National sensitivity and impacts of drought and climate change for Czechia").

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Tomas Streda reports financial support was provided by Technology Agency of the Czech Republic. Hana Stredova reports financial support was provided by Ministry of Agriculture, Czech Republic.

Data availability

Data will be made available on request.

Acknowledgements

We would like to thank anonymous reviewers for their valuable remarks.

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