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# Spatiotemporal patterns of crop diversity reveal potential for diversification in Swedish agriculture

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ABSTRACT

Increasing crop species diversity within a region could improve agricultural sustainability, but knowledge of the spatiotemporal variation of crop species diversity and how this is related to pedo-climatic conditions is limited. In the current study, we used historical crop data records to quantify how crop species diversity is related to pedo-climatic conditions, and how crop diversity developed over time at the national and regional scale in Sweden between 1965 and 2019. Crop diversity was quantified using the exponent of the Shannon index. We found spatial differences across the country, with a significant increase in crop diversity from the north to the south, showing that there is a strong natural control of latitude and associated mean annual temperature on crop diversity in Sweden. Mean annual precipitation and soil texture had no significant relationship with crop diversity across Sweden. At the national level, crop diversity had no significant change over time. At the county level, our analyses revealed different temporal trends between counties. Crop diversity increased over time in certain counties, while in others no change or a decrease occurred. The temporal changes could not be explained by climate trends, and were likely influenced by socioeconomic factors. However, more than half of the counties showed an increase in crop diversity, suggesting that it is possible to increase crop diversity in Sweden. Our study shows that both natural and socioeconomic factors need to be considered to achieve an increase in crop diversity in the future.

## 1. Introduction

Agricultural intensification and expansion of agricultural land during the last century have led to a simplification of landscapes (Landis, 2017; Matson, 1997). Larger field sizes, removal of non-crop habitats, increased input of pesticides and fertilizers, and monoculture optimized and simplified crop production. However, these developments resulted in a loss in biodiversity (Frison et al., 2011; Matson, 1997). Biodiversity in agriculture includes species and varieties of crops and livestock, their wild relatives, as well as weeds, soil fauna, pollinators, pests and predators (Altieri, 1999; Zimmerer, 2010). Crop species diversity is crucial for the biodiversity of arable cropping systems as it strongly influences the diversity of non-crop species. High crop diversity in the landscape may increase resource continuity and provides nesting sites for insects, which has been associated with a greater diversity of pollinators (Aguilera et al., 2020) and natural antagonists of pests (Palmu et al., 2014). Moreover, higher crop diversity may also increase the diversity of soil microbial communities (D'Acunto et al., 2018; González-Chávez et al., 2010; Lupwayi et al., 1998; Venter et al., 2016), due to diversity in root exudates (Steinauer et al., 2016) and plant litter (D'Acunto et al., 2018). In summary, crop species diversity affects entire agro-ecosystems and thus multiple ecosystem services essential to crop production, such as pest and disease regulation, and nutrient and water cycling (Altieri, 1999).

It has been suggested that crop species diversity will be key to adapt arable systems to climate change (Lin, 2011) by improving crop productivity (Burchfield et al., 2019; Smith et al., 2008) as well as yield stability (Gaudin et al., 2015; Marini et al., 2020; Renard and Tilman, 2019). The frequency and magnitude of extreme weather events such as droughts and heatwaves are projected to increase in the future (IPCC, 2013). Higher crop diversity may alleviate the effects of heat stress (Degani et al., 2019; Marini et al., 2020) and drought (Bowles et al., 2020; Marini et al., 2020) on crop yields. Moreover, diseases and pests are both predicted to increase due to climate change in the future (Lin, 2011). A diverse cropping system can reduce disease pressure (Krupinsky et al., 2002) and promote populations of natural antagonists

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(Redlich et al., 2018). Therefore, crop diversity will play a crucial role in the functioning of agro-ecosystems under climate change.

The relationships between increased crop diversity, productivity and ecosystem services are complex, and depend on the type of diversification strategy used (Beillouin et al., 2020) and on agricultural inputs such as fertilizers and pesticides (Swift et al., 2004), making the effect of crop diversity context dependent. Strategies to increase crop species diversification may be achieved by including a higher number of crop species into crop rotations, intercropping of several crop species in the field, or by including cover crops (Altieri, 1999; Hufnagel et al., 2020). To a certain degree, crop diversity in a region is determined by natural factors such as soil type, precipitation, temperature and the length of the vegetation period. In addition, socioeconomic factors (Cutforth et al., 2001) and national or regional policies, such as frameworks for subsidies, may affect which crops that are grown and therefore also crop species diversity (Song et al., 2021).

Historical data records on crop diversity can be used to quantify spatial and temporal patterns of crop species diversity at the regional, national or global scale (Aguilar et al., 2015; Aizen et al., 2019; Hijmans et al., 2016; Smith et al., 2019; Vannoppen et al., 2021). However, there is still limited information on spatiotemporal development of crop species diversity and how these trends are related to differences in climate or soil type. Such studies are essential to evaluate the potential to increase crop species diversity in order to adapt cropping systems to climate change. The aims of this study were (i) to quantify spatiotemporal patterns of crop species diversity at the regional and national scale in Sweden, and (ii) to examine relationships between crop diversity and climatic factors and soil texture.

## 2. Materials and methods

### 2.1. Study area

Sweden is located in northern Europe between 55° N and 69° N. Due to the large differences in latitude between north and south, the climate in Sweden varies strongly across the country. Southern Sweden belongs to the hemiboreal climate, while central and northern Sweden belong to the subarctic climate (Peel et al., 2007). Sweden is divided into 21 counties (administrative units), and the counties were used as regional entities in our analyses (Fig. 1). To identify the cropping areas of each county, we used a map layer including all arable fields in Sweden obtained from the Swedish Board of Agriculture (Jordbruksverket, 2020). Arable crops are grown in all counties of Sweden, but less agricultural fields are located in the mountain range in north-western Sweden (Fig. 1). For each county, the central coordinates of the cropping areas were determined using the field map layer.

### 2.2. Data sources and data assembling

Precipitation and temperature are measured by the Swedish Meteorological and Hydrological Institute at meteorological stations across Sweden (SMHI, 2020). Daily values of precipitation and temperature from two to eleven (average four) weather stations per county, located within the cropping areas, were included in the analyses (Fig. 1). Mean annual temperature (MAT) and mean annual precipitation (MAP) were then calculated for each county for each year from 1965 to 2019. Mean values of soil texture for each county were obtained from the national database "Miljödata MVM" (Miljödata-MVM, 2020) that includes data of topsoils (0–20 cm depth) of arable fields.

Yearly data from 1965 to 2019 of the harvested area of different arable crops at the county and national level were acquired from Statistics Sweden (SCB, 2020). The data acquisition method changed during the time period considered in the present study. Until 1999, the data were collected through paper surveys, while from 2000 onwards, the acres were mainly based on information from administrative registers. In our study, we included data for thirteen field crops in Sweden. The crops included were: winter and spring wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), rye (*Secale cereale*), oat (*Avena sativa*), potato (*Solanum tuberosum*), sugar beet (*Beta vulgaris*), maize (*Zea mays*), oil flax (Linum usitatissimum), winter and spring rape (*Brassica napus*) and winter and spring turnip rape (*Brassica rapa*). Barley and rye were separated into spring and winter varieties in some years, while in other years, spring and winter varieties were summarized. To obtain a consistent data set, we merged spring and winter barley, and spring and winter rye, for all years. Apart from these thirteen crops, another three crop species were reported in the statistics by SCB (2020): triticale (× Triticosecale Wittmack), green peas (Pisum sativum) and brown beans (Phaseolus vulgaris). Those crops were included in groups of "mixed grain" or "legumes" for all years until the 1990 s. Hence, due to many years of missing data, these three crops were excluded from the analyses. The thirteen crops included in the study accounted for 94–100% of the total harvested area of all crops (Fig. 1). The total area of all field crops in Sweden was 1.5 million ha in 1965; the area decreased with time, to 1.2 million ha in 2019 (Fig. S1).

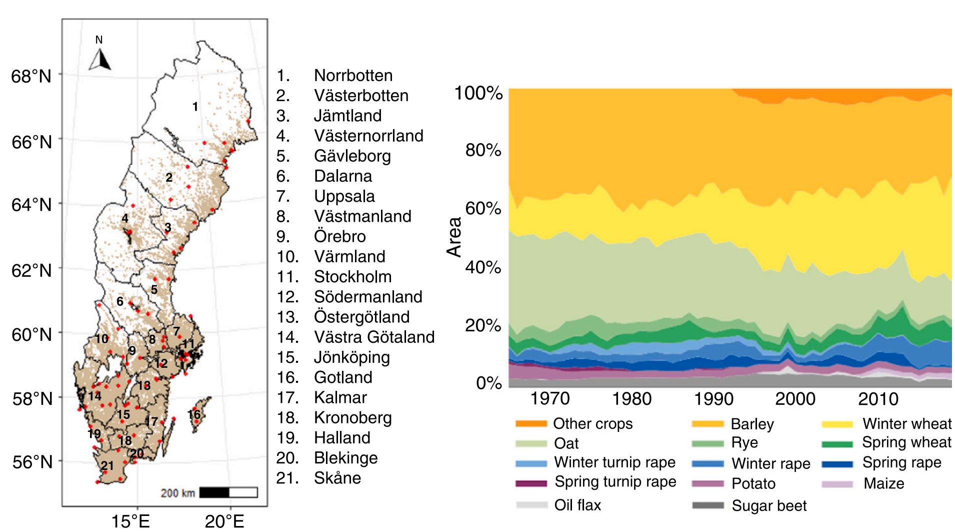


**Fig. 1.** (Left) Map of Sweden divided into the 21 administrative counties, with cropping areas indicated in brown and the location of representative weather stations indicated by red dots. The figure to the right displays the distribution of different arable crops in Sweden as a percentage of the total harvested area between 1965 and 2019.

### 2.3. Quantification of crop species richness and crop diversity

Crop species richness and crop diversity were determined at the county and national level for every year from 1965 to 2019. We excluded crop species with a harvested area smaller than 0.1% of the total area from any further analyses. Crop species richness was defined as the total number of crop species. Crop species diversity ($D$) was calculated as the exponential of Shannon diversity index ($H$) as follows:

$$D = e^{H} = e^{\left(-\sum_{i=1}^{n} p_i \ln p_i\right)} \quad (1)$$

where $p_i$ is the proportion of crop $i$ of the total crop area. The value of $D$ is equivalent to $D$ species at equal areas (Jost, 2006).

### 2.4. Data analysis and statistics

To evaluate the temporal changes in mean annual temperature, mean annual precipitation, crop species richness, and crop diversity, a five-year moving average was used. The moving average included the four preceding years and the year of interest, and was calculated as:

$$Y_{av} = \frac{1}{5}\sum_{n-4}^{n} Y_n \quad (2)$$

where $Y_n$ denotes the value in the year of interest and $Y_{av}$ denotes the five-year moving average of the year of interest.

A principal component analysis (PCA) was performed to identify general patterns between crop species richness, crop diversity, mean annual temperature, mean annual precipitation, longitude, latitude, and clay and sand content. The variables were scaled to obtain the same standard deviation and due to the differences in units of the variables. Linear correlations were applied to relate crop species richness and crop diversity to mean annual temperature, mean annual precipitation and soil texture. Linear regression analysis was used to evaluate temporal trends of crop species richness, crop diversity, mean annual temperature and mean annual precipitation. All statistical analyses were conducted with R version 3.6.3 (R Core Team, 2020) using the packages dplyr and sf to process spatial data, and ggplot2, tmap, plotly and factoextra for visualization of data in plots and maps (Kassambara and Mundt, 2020; Pebesma et al., 2021; Sievert et al., 2021; Tennekes et al., 2021; Wickham et al., 2021, 2020).

## 3. Results

### 3.1. Spatial variation of crop diversity and pedo-climatic conditions

Soil texture varies across Sweden, and soils in the central-eastern parts are generally rich in clay, while soils in the south are lighter (Fig. 2; Fig. S3). The climate pattern differs across the country, with mean annual temperature increasing from north to south, from about 1–8 °C (Fig. 2). Mean annual precipitation decreases from the west coast with about 800 mm per year to 500 mm per year at the east coast (Fig. 2). Since 1965, the mean annual temperature has increased in Sweden. Across counties, the increase in average annual temperature varied between 0.02 and 0.05 °C/year ($p < 0.05$). In the same period, the average annual precipitation increased in most counties with yearly increases between 0.87 and 4.54 mm/year ($p < 0.05$) (Fig. S2).

We found a strong effect of latitude on crop species richness and crop diversity. In the north of Sweden, only a few crops are grown, and these are barley, potato and oat. In the southernmost counties, nine to eleven crops were grown on average during the years 1965–2019. Similarly, the crop diversity increased from north ($D = 2.1$) to south ($D = 6.3$). Some neighbouring counties had similar average crop diversity, for instance Jämtland and Västerbotten county in the north of Sweden ($D = 1.7$; Fig. 2; Table 1).

The principal component analysis revealed that crop diversity was positively related to mean annual temperature and negatively associated

**Table 1**
Total crop area, average crop diversity (D), species richness (n) and the slopes of the linear regression of crop diversity and species richness as a function of time for all Swedish counties, sorted by latitude. Also, crop diversity and slope of linear regression for the entire Sweden. NS indicates non-significant correlation ($p > 0.05$).

| County | Latitude | Area [$\times 10^3$ ha] | D | D slope | n | n slope |
|---|---|---|---|---|---|---|
| Norrbotten | 66.4 | 7.0 | 2.1 | 0.010 | 4.7 | 0.042 |
| Västerbotten | 64.5 | 19.2 | 1.7 | 0.003 | 4.6 | 0.029 |
| Jämtland | 63.1 | 5.7 | 1.7 | NS | 4.6 | 0.034 |
| Västernorrland | 63.0 | 11.6 | 1.9 | 0.006 | 4.9 | 0.028 |
| Gävleborg | 61.4 | 27.0 | 2.6 | 0.013 | 7.6 | NS |
| Dalarna | 60.8 | 26.8 | 3.1 | 0.038 | 8.3 | NS |
| Uppsala | 60.1 | 98.1 | 4.6 | -0.007 | 10.2 | 0.036 |
| Värmland | 59.8 | 44.2 | 3.7 | 0.014 | 9.1 | 0.029 |
| Västmanland | 59.8 | 81.7 | 4.4 | 0.007 | 9.4 | 0.020 |
| Stockholm | 59.5 | 49.0 | 5.1 | -0.021 | 10.3 | 0.032 |
| Örebro | 59.4 | 66.8 | 4.7 | 0.021 | 9.7 | 0.018 |
| Södermanland | 59.1 | 78.6 | 5.0 | NS | 10.3 | 0.028 |
| Östergötland | 58.4 | 124.3 | 5.6 | -0.022 | 10.2 | 0.008 |
| Västra Götaland | 58.2 | 259.2 | 4.4 | 0.023 | 9.6 | 0.029 |
| Jönköping | 57.5 | 26.2 | 3.0 | 0.011 | 8.8 | -0.029 |
| Gotland | 57.5 | 41.8 | 5.6 | -0.016 | 10.7 | -0.028 |
| Kalmar | 57.2 | 52.4 | 5.4 | -0.008 | 10.5 | NS |
| Halland | 56.9 | 63.0 | 4.6 | 0.032 | 10.1 | NS |
| Kronoberg | 56.7 | 15.6 | 3.1 | 0.014 | 9.1 | NS |
| Blekinge | 56.2 | 17.4 | 6.2 | 0.005 | 9.4 | NS |
| Skåne | 55.9 | 325.9 | 6.3 | -0.025 | 10.0 | -0.018 |
| Sweden | | | 5.8 | NS | | |

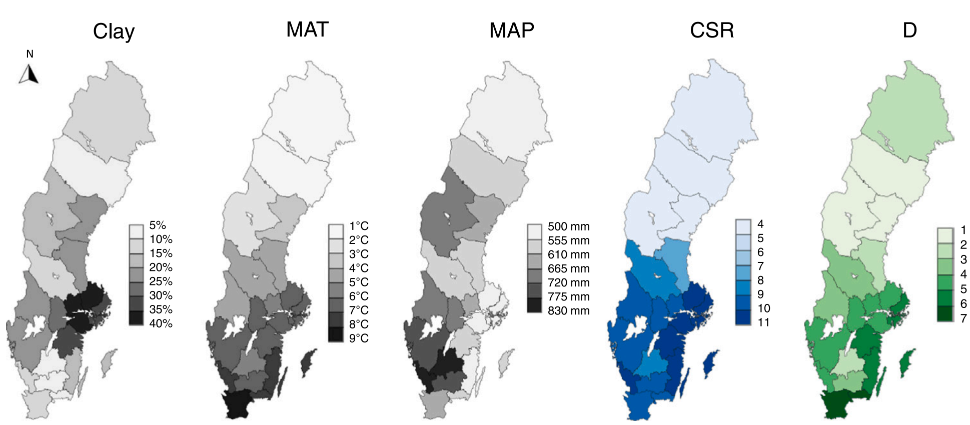


**Fig. 2.** County mean values (average for the years 1965–2019) of clay content, mean annual temperature (MAT), mean annual precipitation (MAP), crop species richness (CSR) and crop diversity (D).

with latitude (Fig. S4), which was also obtained from correlation analyses. Crop species richness and mean annual temperature were strongly correlated ($r = 0.93$, $p < 0.001$). Similarly, the average (1965–2019) crop diversity was positively correlated to mean annual temperature ($r = 0.88$, $p < 0.001$; Fig. 3). The principal component analysis and the correlation analyses also indicated that crop species richness and the crop diversity were not related to soil texture or mean annual precipitation (Fig. 3; Fig. S3 and S4). However, latitude and mean annual temperature could not explain all differences in crop species richness and crop diversity among counties. We found pronounced differences in average crop diversity between certain neighbouring counties located at similar latitudes, for instance Jönköping ($D = 3.0$) and Kalmar ($D = 5.4$) county located in the south of Sweden (Fig. 2; Table 1).

### 3.2. Temporal patterns of crop species richness and crop diversity

Dominant arable crops in Sweden are winter wheat, barley and oat (37 %, 27 % and 13 %, respectively, of the total area in 2019). Since 1965, the acreage of winter wheat has more than doubled, while the area of oat and barley decreased considerably over the same time. More recently, the area of spring rape, winter turnip rape and spring turnip rape have decreased and cover now less than 1 % of the total area (Fig. 1). The crop diversity at the national level experienced fluctuations over time and was in 2019 at a similar level as at the end of the 1960s. Thus, crop species diversity had no significant change over time for the entire country ($p > 0.05$) (Fig. 4; Fig. 5).

The temporal change in crop species richness and crop diversity differed among counties (Fig. 5). Between 1965 and 2019, crop species richness increased in twelve counties mainly located in the north and central parts of Sweden, with average yearly increases between 0.008 and 0.042 ($p < 0.05$). In three other counties, located in the south of Sweden, crop species richness decreased, with linear regression slopes between − 0.029 and − 0.018 ($p < 0.05$). Between 1965 and 2019, Norrbotten county in the north of Sweden (cf. Fig. 1) showed the largest increase in crop species richness, while Jönköping county, located in the south (cf. Fig. 1), showed the largest decrease (Fig. 4).

Crop diversity increased in several counties from 1965 to 2019. In 2019, the crop diversity was highest in the southern and central parts of the country, but still at a low level in the north. Between 1965 and 2019, the crop diversity increased in thirteen counties located in the northern and southwestern parts of Sweden, with average yearly increases between 0.003 and 0.038, ($p < 0.05$). In six other counties, located in the southern and eastern parts of Sweden, the crop diversity decreased, with linear regression slopes between − 0.025 and − 0.01 ($p < 0.05$). Between 1965 and 2019, Dalarna in the central part of Sweden (cf. Fig. 1) showed the largest increase in crop diversity, and Skåne in the central part (cf. Fig. 1) showed the highest decrease (Fig. 4; Fig. 5; Table 1).

## 4. Discussion

In the current study, we used historical crop data records, which allowed us to analyse spatiotemporal patterns of crop diversity in Sweden. The crop species richness increased from north to south and increased with increasing mean annual temperatures, which implies that there is a strong natural control of geographic location (i.e. latitude) on crop species richness. Latitude controls both the mean annual temperature and the length of the growing season. Therefore, crop diversity also increased from north to south within Sweden. Despite differences in mean annual precipitation and soil texture among counties, precipitation and soil texture were not significantly related to crop diversity at the national scale (Fig. 2; Fig. 3).

At the national level, the crop diversity experienced fluctuations over time with values between five and seven (Fig. 5; Fig. 4). Earlier research suggests that a high crop diversity in agricultural systems is beneficial (Aguilera et al., 2020; D'Acunto et al., 2018; Lin, 2011; Palmu et al., 2014). However, it is difficult to define a critical threshold for crop diversity, above which a system significantly improves important ecosystem services. Crop diversity was lower in Sweden ($D = 6.4$) than the average global level ($D = 8.8$) in 2016 according to data from Aizen et al. (2019). However, cropping systems vary greatly between countries. In comparison to countries with similar climatic conditions, Sweden had a higher crop diversity than the neighbouring counties Norway and Finland ($D = 4.6$ and 5.0, respectively) (Aizen et al., 2019). Crop production in Finland is more concentrated at higher latitudes than in Sweden (Mela, 1996), and the mountainous terrain in Norway affects Norwegian agriculture (Fjellstad and Dramstad, 1999). Hence, differences in crop diversity between countries might be explained by natural factors such as climate, soil properties, or topography that set

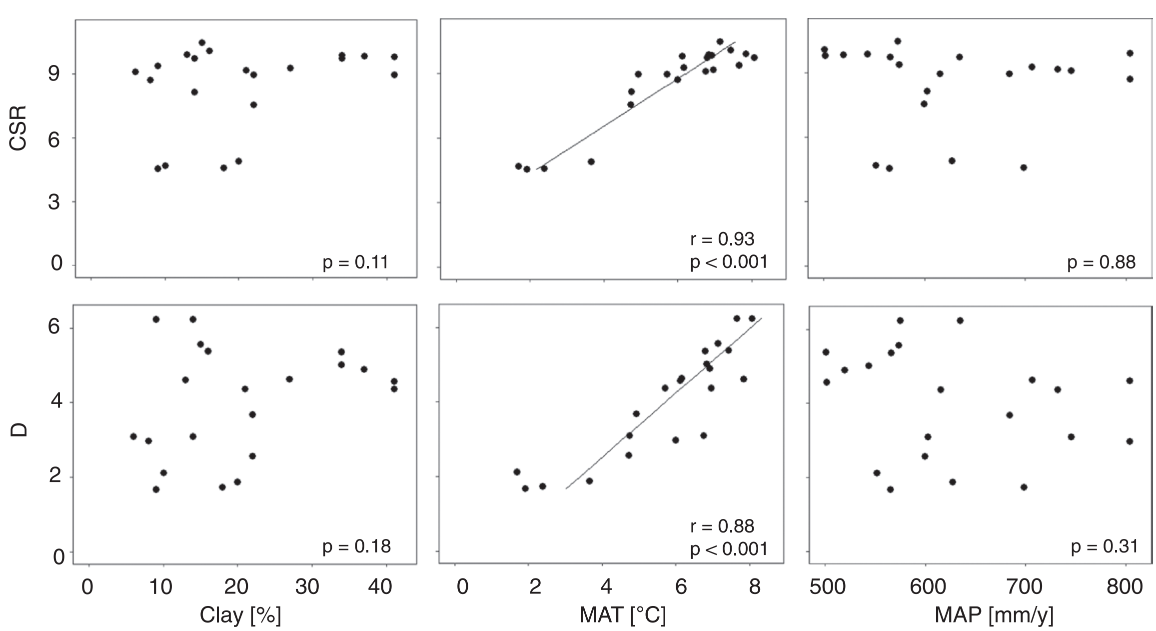


**Fig. 3.** Scatterplots between county mean values (for years 1965–2019) of crop species richness (CSR; top panels) and crop diversity (D; bottom panels), and clay content, mean annual temperature (MAT) and mean annual precipitation (MAP). Pearson correlation coefficients (r) and regression lines are included for significant correlations at $p < 0.05$.

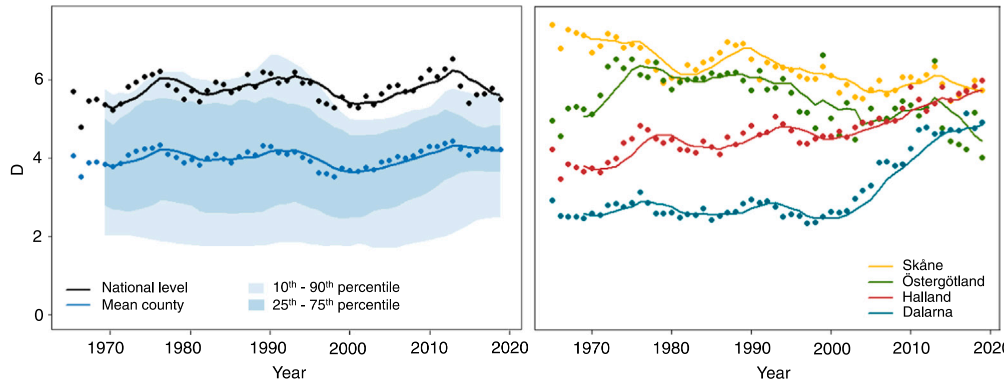


**Fig. 4.** (Left) Crop diversity (D) at the national and mean county level between 1965 and 2019. The lightest blue show the 10th and 90th percentile range and the darker shade the 25th and 75th percentile range of average crop diversity at county level. (Right) Temporal development of crop diversity in the four counties Östergötland, Stockholm, Halland and Dalarna. Displayed lines and the percentiles are based on five-year moving average values (Eq. 2).

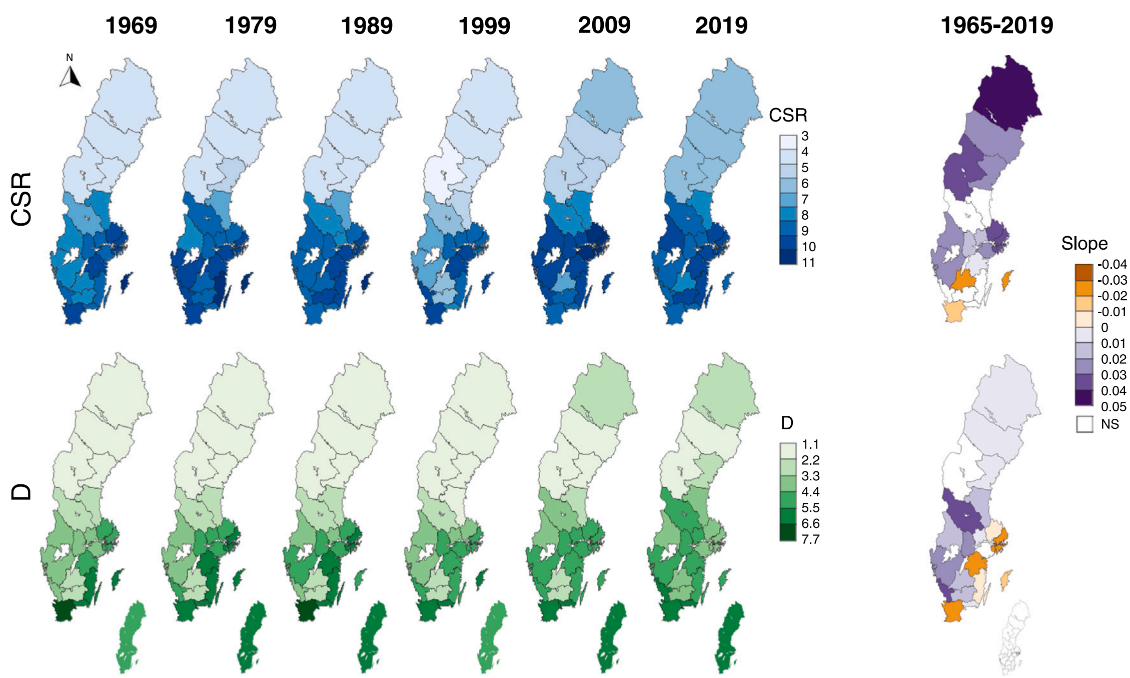


**Fig. 5.** Maps depicting temporal changes in (top) crop species richness (CSR) and (bottom) crop diversity (D, i.e. the exponent of the Shannon diversity, Eq. 1) at the county level (large maps) and at the national level (small maps). Temporal development is presented to the right using slopes of the linear regression of crop species richness and crop diversity as a function of time. NS indicates no significant temporal change ($p > 0.05$). Displayed data and analyses are based on five-year moving average values (Eq. 2).

constraints to which crops that can be grown. Furthermore, socioeconomic factors such as country-specific policies might also influence differences in crop diversity between countries. For instance in Switzerland, which is not part of the European Union, crop diversity was higher than in the bordering countries Germany and France, which was ascribed to differences in agricultural policies (Garland et al., 2021).

Crop diversity did not change significantly over time in Sweden and was at a similar level in 2019 as at the end of the 1960s (Fig. 5; Fig. 4). At the county level, the temporal trend differed between counties, for both crop species richness and crop diversity. Crop species richness and crop diversity increased in several counties, while it did not significantly change or decreased over time in other counties. Similarly, results from previous studies conducted in other countries revealed differences in temporal trends of crop diversity between national and regional scales (Aguilar et al., 2015; Hijmans et al., 2016; Smith et al., 2019). Here we show that analysing crop diversity at the national scale does not reveal enough information to identify temporal trends and to identify factors controlling diversity. Among counties, the variation in average crop diversity declined over time, which implies that crop diversity become more even across counties (Fig. 4). Mainly the counties with the lowest average crop diversity experienced a temporal increase while mainly the counties with the highest crop diversity decreased over time (Fig. 5; Table 1).

Between 1965 and 2019, crop species richness increased in the north and central parts of Sweden, while the counties with a decrease were located in the south (Fig. 5; Table 1). Oilseed crops are mainly cultivated in the southern counties, and the cultivation of spring-sown oilseed crops, especially spring turnip rape, declined in many counties mainly in response to the ban of certain neonicotinoids in 2013 (Johnsson, 2015). The cultivation of winter turnip rape has decreased over time and even disappeared now in most of the counties. Warmer climate, more winter hardy varieties and higher yields for winter rape in comparison to winter turnip rape all contributed to this decline (Jordbruksverket, 2011). In central Sweden, the increase in species richness over time was mainly because of oil flax. Due to small production, oil flax was only reported in the statistics in 1969 and from 1996 and onwards which resulted in a temporal increase in species richness in several counties. In the most northern part of Sweden, the increased cultivation of spring oilseed crops and spring wheat resulted in increased crop species richness.

Six counties showed a temporal decrease and thirteen counties an increase in crop diversity. The six counties with a decrease in crop diversity were located in the south and eastern parts of Sweden, and half of those counties experienced a temporal decrease in crop species richness as well. Skåne county, in the southern part of Sweden, had the largest temporal decrease in crop diversity due to both a decline in species richness and more unevenly distributed areas between the crops (Fig. 4; Fig. 5; Table 1). Over time, the cultivated area of several crops decreased while the cultivation of winter wheat increased. In 2018, there were two dominant crops in the county, barley and winter wheat, which together accounted for around 60 % of the total area. The cultivated area of winter wheat has increased in several counties in Sweden over time, especially in the southern part, and is in general the cereal with the highest yield in Sweden. In most counties, the cultivated area of barley and oat decreased over time. The cultivated area of barley has decreased in Sweden mainly due to less demand for feed grain because of the decline in the number of pigs and cows, and oat has decreased mainly due to profitability problems in comparison to other crops (Eklöf, 2014).

The thirteen counties with an increase in crop diversity were located mainly in the north and southwestern parts of Sweden. Some counties showed an increase in crop diversity in combination with no temporal change in species richness, which indicates that the cultivated area became more evenly distributed between different crops. For instance, Dalarna county had the highest increase in crop diversity, resulting from more evenly distributed areas between different crops (Fig. 4; Fig. 5). The crops became more evenly distributed with time partly because of increased area of winter wheat and winter rapeseed as a result of increased temperatures (Melin et al., 2010), and also due to a decrease in the dominant crop barley. Increased temperatures extend the length of the growing season, and due to climate change, the length of the growing season is projected to continue to increase in the future in Sweden (Fogelfors et al., 2009). Higher temperatures and longer growing seasons increase the possibilities to grow winter-sown crops in northern Sweden due to shorter winters, and to introduce new crop species especially in the south of Sweden in the future (Eckersten and Kornher, 2012). For instance, the cultivation of maize has increased during the 21st century, mainly in the south of Sweden, and was included in the statistics from 2007. With increasing temperatures, maize is projected to be cultivated at a larger extent and "migrate" north in the future (Eckersten et al., 2008; Melin et al., 2010). However, in the most northern counties, it remains challenging to increase crop diversity due to the short crop growing season and the long winter (Melin et al., 2010).

Diverse cropping systems will become more important in the future, since crop diversity may alleviate effects of heat stress and drought on crop yields (Marini et al., 2020), which are projected to become more frequent and severe due to climate change (IPCC, 2013). Mean annual temperature and precipitation have already increased in Sweden during the time period analysed in this study (Fig. S2), and the temporal increase in crop diversity in thirteen counties shows that it is possible to increase crop diversity under a changing climate in Sweden. According to our results, crop diversity can differ considerably between neighbouring counties at similar latitude (Fig. 2; Table 1). Moreover, some neighbouring counties even had opposite temporal trends of crop diversity, for example, Uppland and Västmanland county in the central parts of Sweden (Fig. 5; Table 1). Due to similar climatic conditions in neighbouring counties, these opposite trends imply that the farmers' choice of crops was likely influenced by socioeconomic factors. The ecosystem benefits of more diverse cropping systems are well known (Altieri, 1999; Lin, 2011). However, a cropping system must also benefit the farmers both economically and socially, and to increase crop diversity might require financial investments for a farmer (Knutson et al., 2011), which can hinder diversification. Therefore, to promote diversification of agricultural crops, socioeconomic factors need to be taken into account, and suitable policies may need to be developed to ensure food security.

## 5. Conclusion

Within a country, natural factors limit the number of crop species that can be grown. The increase in crop species diversity from north to the south observed here demonstrates how mean annual temperature and length of the growing season control the spatial pattern of crop diversity. At the national scale, crop diversity did not change significantly over time. While at the county level, there was an increase in crop diversity in certain counties over the last 55 years, and no change or a temporal decrease in other counties. This highlights the importance of looking beyond national scales when evaluating historical developments of cropping systems. Although crop diversity was at a similar level in 2019 as at the end of the 1960 s the temporal increase in crop diversity observed in several counties demonstrates that it is possible to increase crop diversity in Sweden. The variation in the spatiotemporal patterns between counties suggests that crop diversity is affected by an interplay between natural and socioeconomic factors. Climatic conditions constrain crop species richness and diversity, but in order to exploit the full potential of crop diversity, socioeconomic factors may need to change to promote diversified cropping systems.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.108046.

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