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Field-level land-use data reveal heterogeneous crop sequences with distinct regional differences in Germany

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ABSTRACT

Crop cultivation intensifies globally, which can jeopardize biodiversity and the resilience of cropping systems. We investigate changes in crop rotations as one intensification metric for half of the croplands in Germany with annual field-level land-use data from 2005 to 2018. We proxy crop rotations with crop sequences and compare how these sequences changed among three seven-year periods. The results reveal an overall high diversity of crop sequences in Germany. Half of the cropland has crop sequences with four or more crops within a seven-year period, while continuous cultivation of the same crop is present on only 2% of the cropland. Larger farms tend to have more diverse crop sequences and organic farms have lower shares of cereal crops. In three federal states, crop rotations became less structurally diverse over time, i.e. the number of crops and the number of changes between crops decreased. In one state, structural diversity increased and the proportion of monocropping decreased. The functional diversity of the crop sequences, which measures the share of winter and spring crops as well as the share of leaf and cereal crops per sequence, remained largely stable. Trends towards cereal- or leaf-crop dominated sequences varied between the states, and no clear overall dynamic could be observed. However, the share of winter crops per sequence decreased in all four federal states. Quantifying the dynamics of crop sequences at the field level is an important metric of land-use intensity and can reveal the patterns of land-use intensification.

1. Introduction

The global demands for food, feed, fibre, and fuel have been rapidly increasing over the past decades (FAO, 2017). Most of this demand growth has been satisfied with higher intensity of agricultural production (Stevenson et al., 2013). Since the green revolution, the success of intensification in increasing crop production has relied on higher applications of fertilizers and pesticides, mechanisation of the production process, and genetic improvements of plant material (Dornbush and von Haden, 2017). Intensification has also been associated with a reduction in the diversity of crop species planted and an increasing reliance on a few profitable crops (Khoury et al., 2014). Particularly, in developed countries farming systems often shift to narrower crop rotations and the continuous cropping of single crops (Barbieri et al., 2017; Plourde et al., 2013). However, our knowledge about the changes in crop rotations remains patchy due to a lack of field-level land-use data.

Land-use intensity can be measured by analysing the inputs into or the outputs from a production system (Erb et al., 2013). Traditional input-based land-use intensity measures are cropping frequency, i.e. the number of harvest per year and area (Wu et al., 2018) or inputs per land

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area, such as fertilizer (Potter et al., 2010) and pesticide applications (Maggi et al., 2019). However, analyses of land-use intensity often rely on national-level statistics in the absence of fine-scale input data (Kuemmerle et al., 2013). As a result, empirical evidence about intensification or disintensification mainly exists at broad scales or at the farm level for small areas (Kristensen et al., 2016) Fine-scale assessments of changes in land-use intensity for large areas are lacking to date.

Changes in crop rotations are an indicator of land-use intensification. Crop rotations capture specific cycles of crop combinations that recur in a field on a regular basis, e.g., every two, three, or four years. They help to control excess nutrients, weeds, pests, and diseases and maintain or improve the long-term fertility of the soil (Blanco-Canqui and Lal, 2009; Melander et al., 2013). Modern pesticides and fertilizers have permitted to abandon centuries-old recommendations on proper crop rotation. Planting fewer crop species results in less diverse cropping structures and narrower crop rotations jeopardize food security by reducing the resilience and diversity of agricultural production and adversely affect ecosystems and their biodiversity (Bommarco et al., 2013; Bowles et al., 2020; Tilman et al., 2001; Tscharntke et al., 2005). Thus, analysing changes in crop rotations lengths and crop rotation composition can be used to approximate changes in land-use intensity. Rotations with only a few profitable crops may increase farm profits, at least in the short and medium terms, due to gains in specialisation from mechanisation and agronomic knowledge (Halloran and Archer, 2008). However, long-term yields may decline due to higher pressure from plant diseases in homogenous rotations (Bennett et al., 2012; Rusch et al., 2013; Seifert et al., 2017), greenhouse gas emissions might increase due to the higher demand of synthetic fertilizers (MacWilliam et al., 2018). Homogenous rotations may also require higher fertilizer applications due to declining soil fertility. In contrast, more diversified crop portfolios have positive effects on biodiversity, soil quality (Beillouin et al., 2019). They can support pest control (Bennett et al., 2012), increase plant disease resistance (Ikeda et al., 2015), raise time-averaged yields (Cernay et al., 2018), contribute to higher resilience to extreme weather (Bowles et al., 2020), and help to maintain soil fertility and productivity (King and Blesh, 2018; McDaniel et al., 2014).

The analysis of changes in crop rotations is difficult, as thousands of different rotations are possible due to variations in rotation length, composition and starting year. Additionally, farmers decisions on which crops to plant also follow economic considerations, which may overrule agronomic principles. Consequently, tracking predefined crop rotations is not possible. The concept of crop sequences, as defined by Clément (1981); cited in Leteinturier et al. (2006), allows to include all observed crop combinations in the analysis, i.e., tracking the planting of crops in the same field over a specified period instead of assessing entire crop rotations. Crop sequences depict the order in which crops appear during a predefined period (Leteinturier et al., 2006). At the extreme, continuous cropping with one recurring crop type planted over a predefined period represents a crop sequence without variation. Analysis of crop sequences to determine their agronomic value was performed using IACS data in Belgium from 1997 to 2003 (Leteinturier et al., 2006). For the federal state of Lower Saxony in Germany, a typology of crop sequences has been developed to describe the diversity of crop sequences in two dimensions: the structural diversity, determined by the number of crop types planted and their transition frequency, as well as the functional diversity, determined by the combination of leaf and cereal crops and of winter and summer crops (Stein and Steinmann, 2018). These and other previous analyses of crop sequences or crop rotations target only small regions or brief time periods, which precludes insights into longer-term changes in crop sequences and hence into changes in land-use intensity.

Quantifying crop sequences and their changes requires time series of field-level land-use data. In Europe, the most accurate source for land-use information at the field level is data from the Integrated Administration and Control System (IACS). The IACS was introduced by the European Commission in 1992 to assign European Union (EU) subsidies to farmers. Since 2005, farmers have been obliged to use an online geographic information system, the Land Parcel Identification System (LPIS), to indicate the main crop planted in each field of their farm in May each year. The IACS data features spatially accurate field-level data with unique identifiers for each farm unit. The correctness of the IACS data is validated on a sample basis by the chambers of agriculture or other agricultural departments of the federal states of Germany. The data has been used to study crop sequences or cropping patterns (Leteinturier et al., 2006), albeit only for small regions and only for short time periods. Analysis of changes in rotation practices at a fine spatial scale, for large areas, and longer time spans remain, to our knowledge, absent to date.

Here, we exploit field-level IACS data from 2005 to 2018 for almost half of the territory of Germany and 60,000 km^2 of cropland, covering the federal states of Brandenburg and Saxony-Anhalt in former East Germany and Lower Saxony and Bavaria in former West Germany. We use the crop sequence typology of Stein and Steinmann (2018) to answer the following research questions: First, what were the paramount crop sequence types in the selected federal states between 2005 and 2018? Second, how do these crop sequence types vary among different production strategies and farm sizes? And, third, how have these sequences changed in structural and functional diversity over time?

2. Material and methods

2.1. Study area

The study area comprises the federal states of Bavaria, Brandenburg, Lower Saxony, and Saxony-Anhalt, which together cover 47% of the territory of Germany. Agricultural areas amount to 81,936 km^2, of which 59,140 km^2 (72%) is cropland (Table 1). Lower Saxony is in Northwest Germany, and Bavaria is situated in Southeast Germany at the border with Austria and the Czech Republic. Saxony-Anhalt borders Lower Saxony in the east; Brandenburg lies northeast of Saxony-Anhalt, surrounds Berlin, and borders Poland to the east. Saxony-Anhalt and Brandenburg were part of former East Germany.

Bavaria has a higher average elevation, rising towards its southern areas where the Alps form the border with Austria. The other three states are characterised by low elevations of the North German Plain, which are bounded by the Central German Uplands to the south.

The four states have distinct agricultural structures shaped by different landscape characteristics and climate patterns and by their institutional history. Bavaria possesses the largest amount of agricultural land and cropland, but the share of cropland in the total land area is largest in Saxony-Anhalt (Table 1). Animal husbandry plays a larger role in terms of value added and in terms of the number of animals in Lower Saxony (hog and cattle production) and Bavaria (mainly cattle) than in the two eastern federal states.

Table 1
Agricultural and climatic characteristics of Bavaria, Brandenburg, Lower Saxony, and Saxony-Anhalt. The statistics on the area of the federal states are from Statistisches Bundesamt (2019); agricultural and cropland area from Statistische Bundesamt (2018); mean field and farm sizes are our own calculations with IACS data of 2018.

	Saxony-Anhalt	Brandenburg	Lower Saxony	Bavaria
Area [km^2]	20,545	29,654	47,710	70,542
Agricultural area [km^2]	11,690	13,234	26,013	30,999
Cropland [km^2]	9929	10,118	18,867	20,226
Cattle [1000 heads]	333	529	2572	3095
Hogs [1000 heads]	1165	755	8500	3238
Mean (median) farm size [ha]	235.6 (62.4)	220.2 (40.0)	54.9 (29.4)	29.9 (16.9)
Mean (median) field size [ha]	7.5 (2.6)	8.0 (3.0)	2.8 (1.9)	1.6 (1.0)

Farm and field sizes are smallest in Bavaria; the former East German states harbour larger farms and larger fields than those in the former West German states (Table 1; Fig. A 1). Farm sizes in the former East German states of Brandenburg and Saxony-Anhalt average 247 and 270 ha (ha), respectively (Table 1). These large agricultural structures discrepancies are a legacy of the large agricultural production cooperatives and state farms formed under the socialistic regime in East Germany after World War II. In contrast, the average farm sizes in the former West German states of Bavaria are 35 ha and 69 ha in Lower Saxony (Table 1).

2.2. Data sources and processing

We obtained IACS data for Brandenburg and Bavaria from 2005 to 2018, for Saxony-Anhalt from 2008 to 2018, and for Lower Saxony from 2012 to 2018. The data include all agricultural fields above the minimum eligible size of 0.3 ha for which farmers can apply for subsidies, hence covering almost all agricultural areas. For our analysis, we considered only cropland and temporary grassland, which is part of the cropland category in the IACS, but we ignored permanent grassland. As the ploughing of permanent grassland is strictly regulated, only minor transitions between cropland and permanent grassland occur. The data provide information on the field size, geometry, and crop type planted in the field on May 15th of each year. The data contain a farm identifier, which allows the calculation of farm size, number of fields, and average field size per farm. The farm identifier also carries the binary categorization specifying whether a farm is organic or conventional. The spatial topology of the data varies. In earlier time steps, the data suffer from duplicates, erroneous geometries, and parcel overlaps. We therefore established an automated cleaning procedure that corrects problems with geometry (Fig. A 2).

The number of fields strongly differ between the states. In Brandenburg and Saxony-Anhalt, there were approximately 160,000 fields in 2018; Lower Saxony had approximately 900,000 fields and Bavaria had almost 2 million fields. The number, size, and geometry of the fields frequently change from year to year. For this reason, tracking the fields over time is not possible using the original vector data. We therefore rasterized the vector data into a grid with a 5 m spatial resolution (25 m^2) and performed all analyses with these raster cells.

We aggregated more than 350 individual crop types from the original IACS data into 15 composite crop classes (Table 2). We categorized the 15 crop classes by sowing date (winter and spring crops) and into leaf and cereal crops (Stein and Steinmann, 2018; Table 2). For Bavaria, we added the crop class multiple crops because farmers in Bavaria were able to designate several crops in one year per field until 2016. We classified a field into "multiple crops" if the largest crop class covered less than 50% of the field. Multiple crops occurred on 15% of the cropland area in Bavaria at least once between 2005 and 2014.

Table 2
The 15 crop classes with sowing time and distinction into leaf and cereal crops.

Crop class	Acronym	Crop type	Sowing season
Maize	MA	Cereal	Spring
Winter wheat	WW	Cereal	Winter
Sugar beet	SB	Leaf	Spring
Winter oilseed rape	WR	Leaf	Winter
Potato	PO	Leaf	Spring
Spring cereals	SC	Cereal	Spring
Triticale	TR	Cereal	Winter[a]
Winter barley	WB	Cereal	Winter
Winter rye	RY	Cereal	Winter
Legumes	LE	Leaf[b]	Spring[a]
Arable grass	AG	Leaf	Winter[a]
Vegetables	VE	Leaf	Spring
Fallow	FA	–	–
Unknown	UN	–	–
Multiple cropping (only in Bavaria)	MC	–	–
Others (multiannual use, no cropland)	OT	–	–

[a] Not all crop types that could be assigned to a crop class were assigned to the same functional classes, e.g., summer triticale and winter triticale were assigned to the crop class triticale (TR) but fell into spring-sown crops and winter-sown crops, respectively. Such instances affected only a very minor share of the overall cropland area.

[b] Some crop types could be assigned to a crop class but not to the categories of leaf and cereal crops, such as "green manure". We categorized these fields into unknown (UN). Again, this affected only a very minor share of the overall cropland area.

2.3. Crop sequence typology

We used a crop sequence typology that characterises crop sequences by their structural and functional diversity values over seven years. The structural diversity is determined by the number of crop classes in a sequence and the number of transitions between the crop classes in subsequent years (Fig. 2). Structural diversity is higher when more crop classes are present and when more changes between them occur from one year to the next. We merged the crop classes "fallow", "unknown", and "others" into one crop class. If more than two years of a seven-year crop sequence belonged to fallow, others, unknown, temporary grass, or "multiple crops", we assumed that the sequence was part of a crop-livestock system, which we excluded from the typology. Overall, this occurred in only 2% of the cropland area. We assigned capital letters to the types of structural diversity in ascending order. Types A to D denote simple structural sequences; types E and F have moderate structural diversity; and types G to I represent structurally diverse crop sequences.

The functional diversity captures the share of leaf crops and cereal crops and the share of spring and winter crops in the crop sequence (Fig. 1). Alternating between leaf and cereal crops as well as between winter and spring crops in a crop sequence has ample agronomic advantages over continuous cropping (Stein and Steinmann, 2018). We represent the different degrees of functional diversity with numbers ranging from 1 to 9 that symbolise the different ratios of leaf versus cereal crops and winter versus spring crops (Fig. 1). The numbers 1–3 represent sequences with only cereal crops; 4–6 are sequences with leaf crop ratios less than 0.5; and 7–9 are sequences dominated by leaf crops. The numbers 1, 4, and 7 consist of only winter crops; the numbers 2, 5, and 8 have moderate spring crop ratios up to 0.5; and the numbers 3, 6, and 9 are sequences dominated by spring crops. We consider that the functional diversity is highest with 5 because this functional type represents a well-balanced mix between leaf and cereal crops and winter and spring crops. In the final step, we combined structural diversity (A to I) and functional diversity (1−9) into crop sequence types (CSTs).

We calculated the CSTs for three seven-year periods (2005–2011, 2008–2014, and 2012–2018). Seven years is a common period for crop sequence analysis, as it includes at least one longer crop rotation of four years (Leteinturier et al., 2006; Schönhart et al., 2011; Stein and Steinmann, 2018). For Saxony-Anhalt, the IACS data only cover the latter two periods (2008–2014 and 2012–2018). For Lower Saxony, we could only access IACS records for the last period, but we obtained a subset of 24% of all cropland fields for the first period from Stein and Steinmann (2018). This subset allowed us to compare the CSTs between the first and third periods. We verified the validity of the subset data by comparing a subset of the third period data with the full set of third period data and found only minor differences (Fig. A 3). We also compared the first period subset with the third period subset.

2.4. Variation in crop sequence types by farm characteristics

We assume that farm characteristics, such as farm and field sizes, as well as different production strategies, such as if a farm is oriented towards crop or livestock production or if a farm is conventional or organic, impact crop sequences. To compare the CSTs from 2012–2018 for different farm and field sizes, we calculated each field centroid of 2018 and computed the median field size for each CST from the polygon field data. We aggregated all fields within a farm to calculate the total

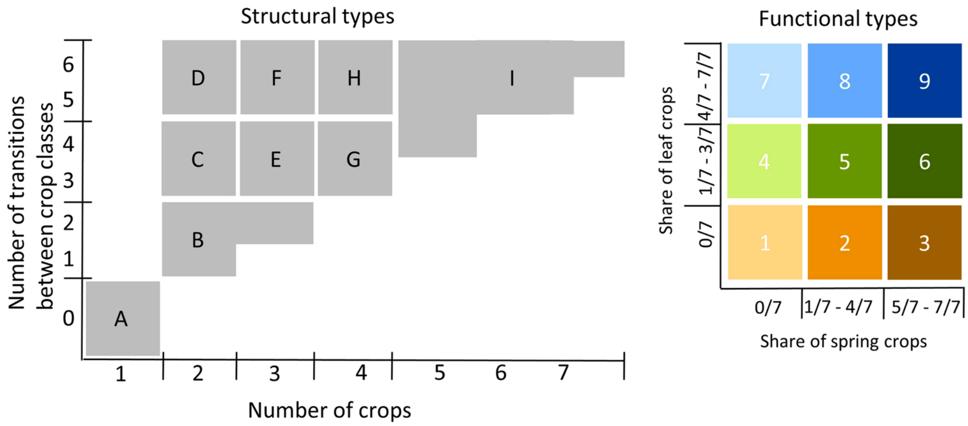

Fig. 1. Crop sequence typology for a seven-year period. Letters A to I denote the structural diversity, and numbers 1 to 9 denote the functional diversity. The share of leaf and spring crops in the right panel captures how often leaf and spring crops appear in each period.
Adapted from Stein and Steinmann, 2018.

farm size and median farm size per CST. CSTs that occurred only in 25 fields or less in a federal state were excluded.

For Brandenburg and Lower Saxony, we obtained IACS data on livestock numbers (cattle and hogs) and whether a farm pursued organic or conventional production. We grouped all farms into the classes "with cattle", and "without cattle", compared the share of all CSTs between these classes and repeated the same process for hogs. To compare organic and conventional farming systems, we calculated the share of the CSTs for fields that were under conventional and organic production in each year between 2012 and 2018. Lower Saxony provides data on organic farms only from 2015 to 2018; we therefore assumed that farms that were continuously organic over these four years were organic over the entire 7-year period.

2.5. *Analysis of changes in structural and functional diversity*

To better understand the changes in crop sequences between the different periods, we analysed the co-occurrence of changes in structural and functional diversity. For this purpose, we identified areas with a declining or an increasing structural diversity. A declining structural diversity occurred, when the number of crop types, the number of changes between different crop types or both at the same time decreased. An increasing structural diversity occurred, when either of the former increased. Secondly, we analysed how the complementary shares of spring and winter crops changed on the areas of increasing or decreasing structural diversity. The share of spring crops could either increase, stay stable or decrease. For an increasing or decreasing share spring crops the shares of winter crops would do the opposite. The same analysis was done for the share of leaf and cereal crops.

3. Results

3.1. *Variation in crop sequence types among federal states*

Our results revealed that, overall, the crop sequences showed high structural and functional diversities (Fig. 2). Overall, only 2% of all CSTs represented continuous cropping, 15% consisted of two crop classes (structural diversities A-D), and 49% had four or more crop classes (structural diversities G-I). The simple sequences mainly consisted of cereal crops (functional diversity 1–3, brown colours in Fig. 2), while the more diverse sequences had a better balance between leaf and cereal crops (functional diversity 5, medium green). Functional diversities 7–9 (blue colours) occurred in only a few cases, suggesting that sequences with a large share of leaf crops are uncommon.

Differences in the spatial distribution of crop sequences between the federal states of former East and West Germany were pronounced. In former East Germany, cereal-dominated sequences were less prevalent and both simple and diverse sequences were heterogeneously

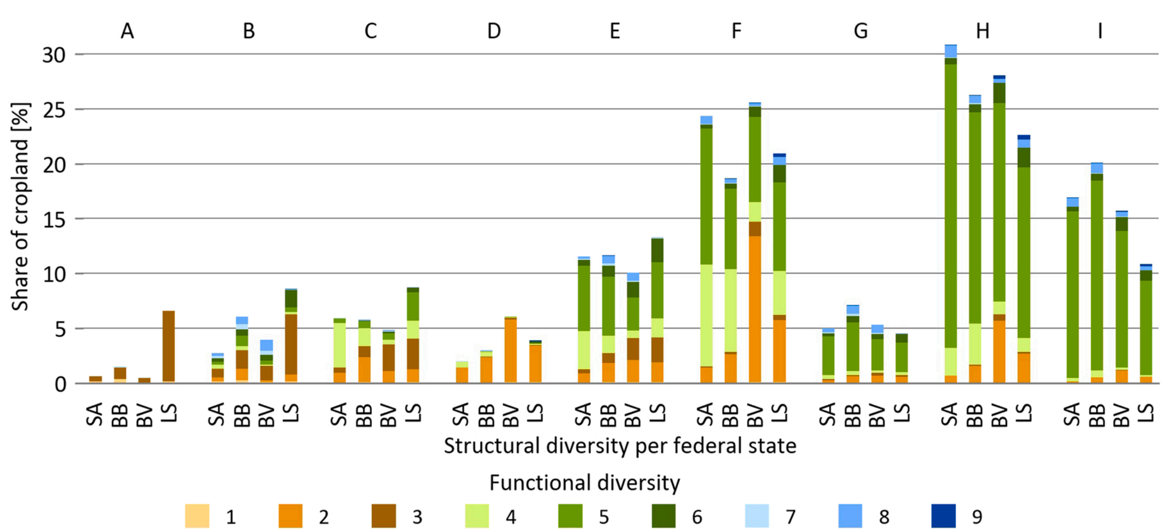

Fig. 2. Share of crop sequence types (CSTs) per federal state between 2012 and 2018. The capital letters represent the structural diversity, and the colours represent the functional diversity. SA = Saxony-Anhalt, BB = Brandenburg, BV = Bavaria, LS = Lower Saxony.

distributed. In former West Germany, we observed higher spatial clustering with large clusters of simple sequences and high shares of cereal crops in the northwest and southwest of Lower Saxony (Fig. 3, inlay 1). Diverse CSTs with better balances between leaf and cereal crops and winter and summer crops dominated the centre and northeast of Lower Saxony; leaf-dominated sequences prevailed in the far west and east of Lower Saxony (Fig. 3, inlay 2). Sequences with more than two different crops and a large share of cereal crops were more pronounced in Bavaria and widely dispersed across the federal state with few spatial clusters, such as in the southwest (Fig. 3, inlay 10). However, the share of simple sequences increased closer to the Alps in the south. In former East-Germany, we found only small clusters of cereal-dominated sequences in the west of Brandenburg (Fig. 3, inlay 7) or the north of Saxony-Anhalt, where functional diversities 4–6 were most prevalent (Fig. 3, inlays 5–7). Both states also had higher shares of winter cropping sequences (functional diversities 1, 4, 7) than the western federal states. In cereal dominated sequences, maize and winter wheat were frequently cultivated in combination with spring cereals, rye, or winter barley or maize was grown in mono-cropping. Sequences with high shares of winter cropping, often consisted of winter wheat, winter oilseed rape, and winter barley (Table A 1).

3.2. Differences in crop sequence types by farm characteristics

Farm sizes: In Lower Saxony and Bavaria, larger farms tended to use more CSTs with high structural diversity (G, H and I, Fig. 4). The average farm sizes for farms adopting CSTs G, H and I exceeded 105 ha in Lower Saxony and 57 ha in Bavaria, while this was not the case for CSTs with lower structural diversity. This pattern seems to be true especially for CSTs with a functional diversity from 4 to 9, which are sequences with a good balance between leaf and cereal crops or a dominance of leaf crops. Smaller farms tended to utilize more cereal-dominated CSTs (functional diversity from 1 to 3). In Brandenburg and Saxony-Anhalt, these trends were less clear. Here, larger farms also adopted CSTs with low structural diversity (e.g., D), dominated by cereal crops. In both states, the largest farms use CSTs with the most balanced functional diversity (functional diversity 5). In Saxony-Anhalt and Brandenburg, the median for these large farms with the highest functional diversity was 634 ha and 779 ha, respectively. These results were similar for field sizes in all states (Fig. A 4).

3.2.1. Conventional and organic farms

Organic and conventional farms sharply differed in their crop sequences and their patterns among the states (Fig. 5a). In Lower Saxony and Brandenburg, organic farms had more leaf crop-dominated crop sequences (blue colours) and more sequences with spring crops (darker shades of green and blue), whereas conventional farms had more crop sequences dominated by cereals (brown colours) and winter-sown crops (light green). However, the sequences of organic and conventional farms strongly differed between the two states. In Lower Saxony, structurally diverse sequences constituted 70% of all sequences planted by organic farms but only 40% of the sequences on conventional farms. This pattern was reverse in Brandenburg where structurally diverse sequences comprised 54% of CSTs on conventional farms and 43% on organic farms.

3.2.2. Cattle husbandry

Differences in the CSTs for farms with and without cattle were more pronounced in Lower Saxony than in Brandenburg (Fig. 5b). In both states, the share of cereal-dominated crop sequences (brown colours) was higher on farms with cattle than on farms without cattle. In Lower Saxony, farms with cattle had a 12% share of CST A3 (mostly the continuous cropping of maize), while farms without cattle only had a 3% share of CST A3. In contrast, the number of hogs did not seem to affect the overall structural diversity or the prevalence of continuous cropping (Fig. A 5). In Lower Saxony, the results revealed a higher structural diversity of the crop sequence for farms without cattle, while this was not the case in Brandenburg.

3.3. Changes in crop sequence types

Changes in structural diversity were similar between Brandenburg, Bavaria and Saxony-Anhalt (Fig. 6). Here, structural diversities G, H and I decreased by 4–5% overall, while structural diversities D, E and F increased by the same amount. Structural diversities A, B and C remained almost the same. In Lower Saxony, the trends were opposite. The shares of the highly diverse structural diversities H and I increased by 4% respectively, while structural diversities A, C, E and F declined by 8% overall. The share of monocropping decreased by 2% in Lower Saxony, from 9% to 7% of the cropland. In the other federal states it remained on the same level, between 1% and 2% of the cropland.

Changes in the functional diversity were analysed in two dimensions: changes in the shares between leaf and cereal crops and changes in the shares between spring and winter crops. In Brandenburg and Bavaria, the cereal-dominated sequences increased their shares by 3% and 2% respectively (Fig. 6). These increases occurred at the expense of sequences with balanced shares of leaf and cereal crops (i.e. 1–3 leaf crops out of 7 crops per sequence). In Lower-Saxony, the trend was reversed. Here, the share of cereal-dominated sequences declined by 4%, while sequences with balanced shares of leaf and cereal crops increased by 4%. The share of leaf-dominated sequences remained stable in these three federal states. Only in Saxony-Anhalt did the share of leaf-dominated sequences increase by 1% at the expense of balanced sequences, while cereal-dominated sequences remained stable.

The share of winter crop dominated sequences declined in all four federal states (Fig. 6). In Lower Saxony their share decreased by 10%, in Saxony-Anhalt by 5% and in Brandenburg and Bavaria by 4%. The largest increases were in the sequences with a more balanced ration between winter and spring crops (i.e. 1–4 spring crops out of 7 crops per sequence). In Lower Saxony their share increased by 15%, in Saxony-Anhalt by 5%, in Bavaria by 2% and in Brandenburg by 1%. The share of spring crop dominated sequences declined in Lower Saxony by 5% and increased in Brandenburg by 3%, in Bavaria by 1% and in Saxony-Anhalt it remained stable.

Changes in structural diversity mostly occur without changes in functional diversity (Table 3). On 40% of the cultivated areas in Brandenburg and Bavaria, the shares of spring and winter crops remained stable, although structural diversity decreased or increased. Similarly, the shares of leaf and cereal crops remained stable on 43% of the cropland in Brandenburg and on 37% of the cropland in Bavaria in both cases. With increasing structural diversity, the trend towards higher shares of winter crops or towards higher shares of leaf crops is three times higher than the trend towards spring crops or cereal crops. With a declining structural diversity, the share of cereal crops increases three times as often as the share of leaf crops.

4. Discussion

We mapped and analysed the temporal and spatial patterns in crop cultivation sequences using annual field-level data on crop types for more than half of German croplands from 2005 to 2018. To quantify the crop sequences and their changes, we used a crop sequence typology that categorized the temporal dimension of the diversity of crop cultivation based on the shares of leaf and cereal crops and the shares of winter-sown and spring-sown crops. Our results revealed that, overall, the crop sequences showed high structural and functional diversities with modest changes during the study period. We also found distinct spatial clusters of areas with crop sequences that had a high share of cereals, areas in which leaf crops prevailed and areas with a high share of winter-sown crops. We surmised that the sequences were largely determined by differences in farm sizes and production strategies, which in turn resulted from institutional legacies of the distinct historical

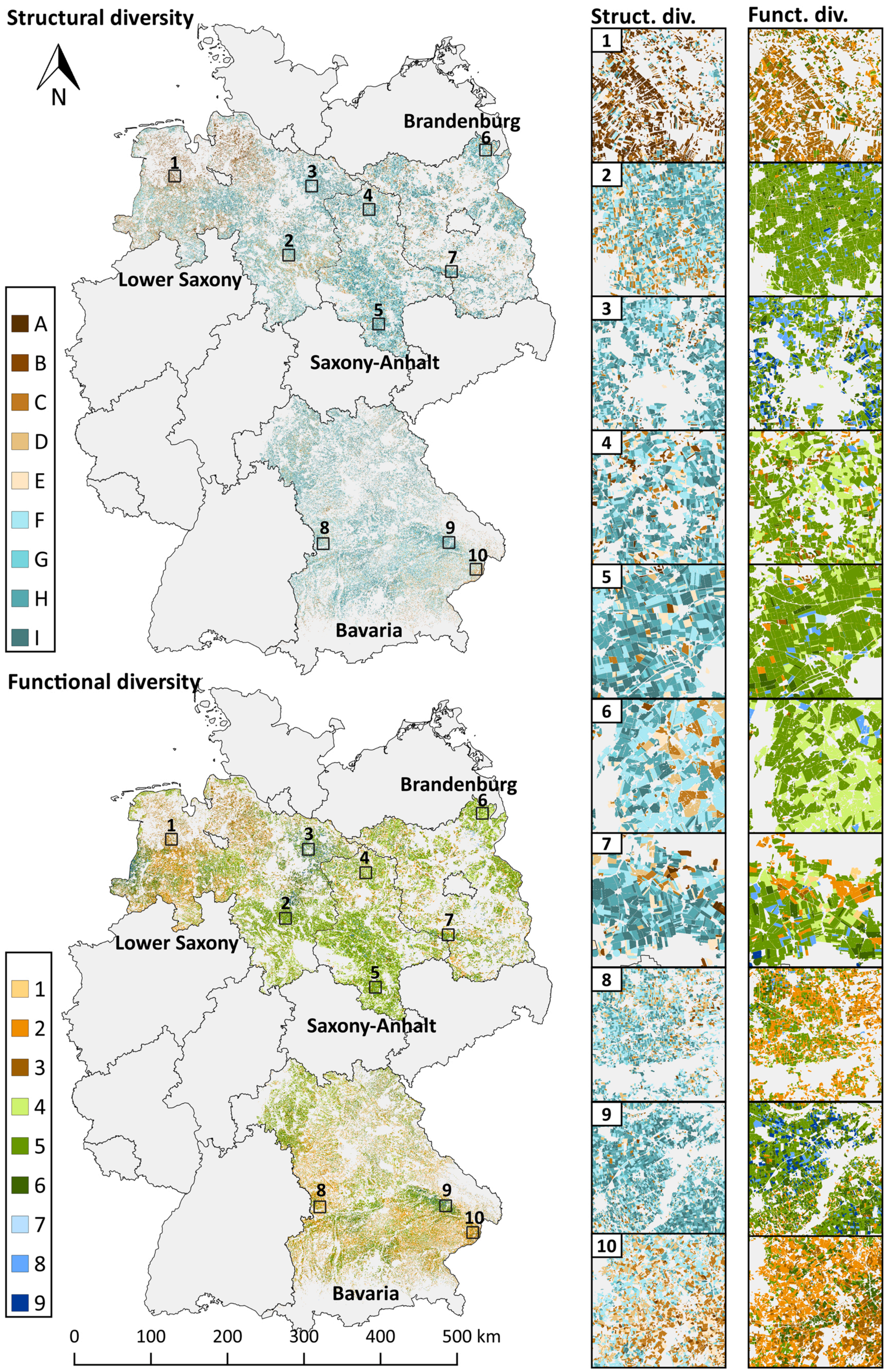

Fig. 3. Structural and functional diversities of the crop sequence types (CSTs) per federal state between 2012 and 2018 (left). The black rectangles show the locations of inlays A to I (right). Inlay size is 15 × 15 km.

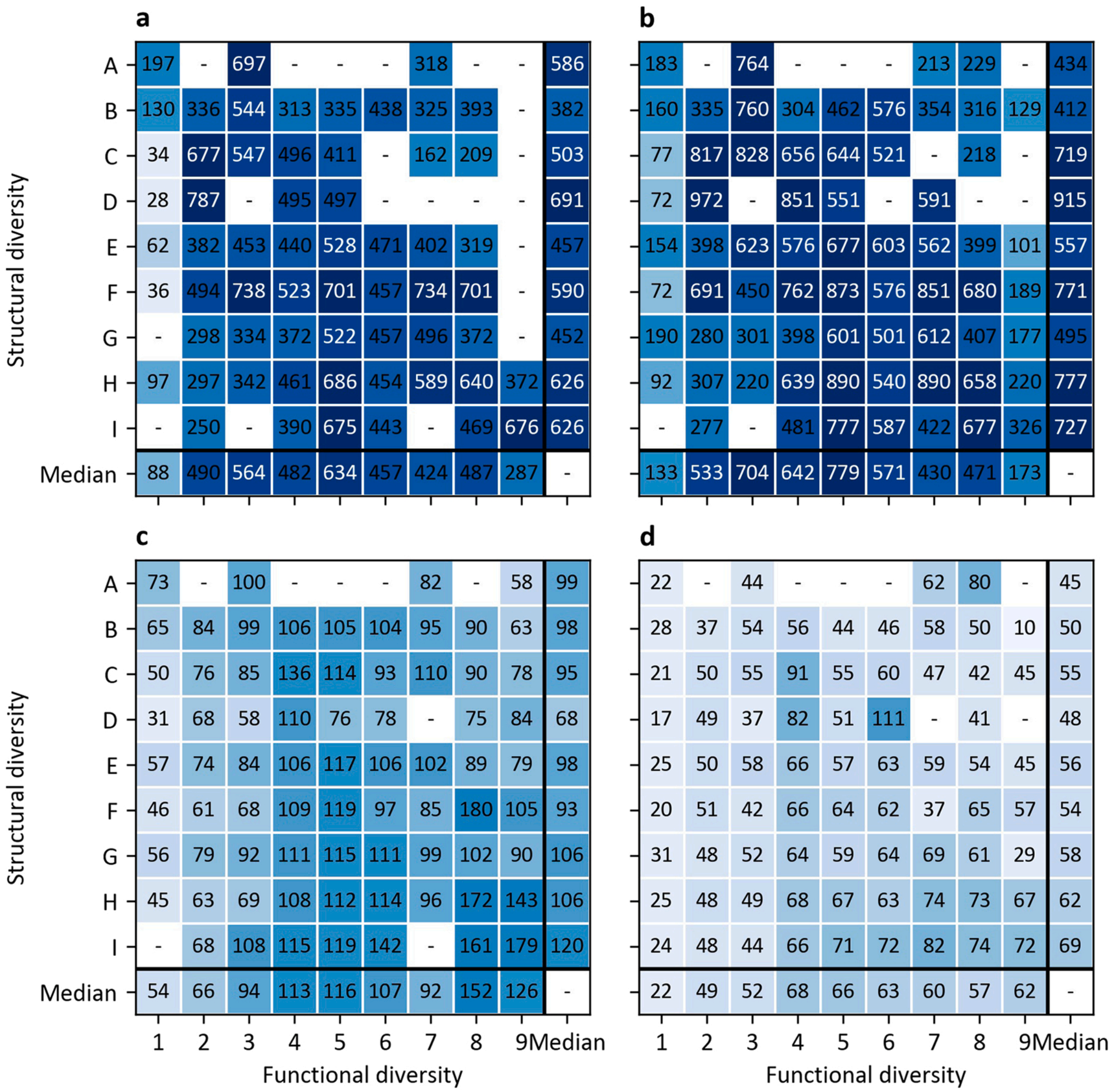

Fig. 4. Median farm size [ha] in 2018 per crop sequence type for the period 2012–2018 in Saxony-Anhalt (**a**), Brandenburg (**b**), Lower Saxony (**c**) and Bavaria (**d**). Crop sequence types that occurred in fewer than 25 fields were excluded.

developments in East and West Germany.

4.1. Differences between East and West Germany

The utilization of different crop sequences between farm sizes largely arises from historical legacies: The forced collectivization of family farms and the formation of large state and cooperative farms under the socialist regime left persistent marks on the agricultural sector of former East Germany. At present, corporate farms characterize the agricultural landscape in former East Germany, while family farms are the most common form of agricultural production units in former West Germany (Wolz et al., 2010). Our two eastern federal states had an average farm size of 227 ha in 2018, while the average farm size in the two West German states was 38 ha. Smaller farms are often part-time operations that rely on off-farm income (Weigel et al., 2018); additionally, they tend to be more specialized and have fewer resources to allow diversity and a wide range of production alternatives. Larger farms, in contrast, have more flexibility due to larger capital, land, and machinery resources; they strive for low-risk portfolios with several production strands. These results are in line with studies that suggested lower crop sequence diversity and less diverse crop portfolios on smaller farms (de Abelleyra and Verón, 2020; Weigel et al., 2018). However, while being less diverse at the farm scale, smaller farms contribute more to higher crop diversity at the landscape scale, thereby maintaining or increasing biodiversity (Sirami et al., 2019). Additionally, the higher density of field edges provides more habitat and is likely beneficial for pollinator movement, enhancing the transfer of pollen (Hass et al., 2018).

4.2. Differences between farm characteristics

The results on organic and conventional farming and on cattle husbandry indicate that the spatial differences in crop sequences within the federal states are due to the prevailing production systems: Organic farming and livestock farming strongly influenced crop sequences. In the two eastern states, a lower share of cereal crops and more leaf crops characterized the crop sequences of organic farms, similar to findings at the global scale, where crop rotations on organic farms also include significantly more fodder crops, legumes, and catch crops but fewer cereals (Barbieri et al., 2017). Abandoning chemical fertilisers and pesticides in organic agriculture compels more diverse crop management to control weeds and pests (Barbieri et al., 2017; Reckling et al., 2016). In conventional farming systems, the benefits of rotations are

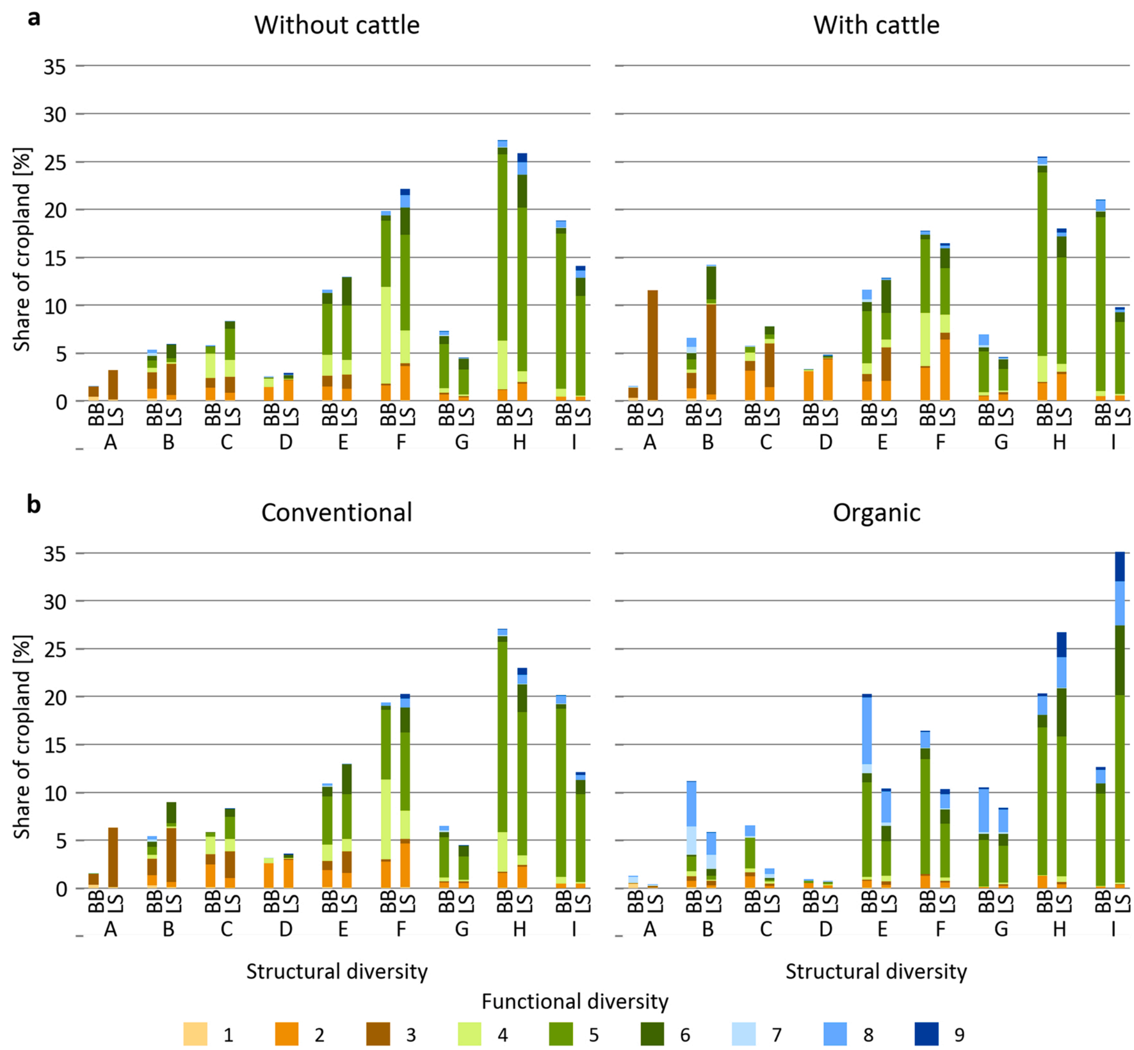

Fig. 5. Comparison of crop sequence types between farms without and with cattle (a) and between conventional and organic agriculture (b) for Brandenburg (BB) and Lower Saxony (LS) for the period 2012–2018.

substituted with applications of intermediate inputs that permit a higher share of cereals in the rotations and even the continuous cropping of cereal crops.

Areas with high cattle density tended to have higher shares of cereals in crop rotation. Consequently, the crop sequences in regions dominated by cattle husbandry had lower structural and functional diversities. This result was visible in the northwest of Lower Saxony and the southeast of Bavaria, both regions with high cattle densities (Fig. 3, inlays 1 and 10). Here, continuous maize cultivation consumed large shares of the cropland. The crop sequences did not differ between areas with different hog densities. Differences between cattle and hog husbandry likely arise from the different feed requirements. Since cattle are ruminants, their feed can contain much higher fibre content due to their ability to digest straw and similar forages. Hogs, on the other hand, are monogastric animals and can only digest small amounts of fibre. Consequently, hog feed contains high proportions of soy, which is mostly grown in other parts of the world (Fraanje and Garnett, 2020). Cattle feed, on the other hand, contains higher shares of straw, which can easily be produced locally.

The high proportion of cereals in the crop sequences of cattle farms reflects the dependenxe of livestock on silage maize, which provides the animals with energy. Maize grows quickly and achieves high biomass yields. Moreover, maize is used in the anaerobic digestion process to produce biogas (methane). As a result of government subsidies in the frame of the German renewable energy act instigated in 2000, biogas production became an important additional income source for farmers with livestock (FNReV, 2019). The rising share of maize in the crop portfolio compromises biotope functioning and the recreational value of landscapes (Wiehe et al., 2009), and alters weed communities with adverse consequences for biodiversity and herbicide use (von Redwitz and Gerowitt, 2018). Furthermore, monocropping of cereals such as maize reduces the ability to sequester carbon and soil organic matter in the soil, leading to lower soil fertility (King and Blesh, 2018).

4.3. Temporal dynamics

We found only minor evidence for intensification during our study period. We observed a declining structural diversity, i.e. a tendency towards fewer crop types or fewer changes between crop types in a sequence, in Brandenburg, Bavaria and Saxony-Anhalt. We surmise that the decrease in structural diversity resulted from changes in the production strategy of farms towards higher specialisation (Eurostat, 2019) or was due to a decrease in dairy production (Meyer, 2020). In Lower-Saxony, the trend was opposite, with increases of structurally diverse sequences and decreases of simple and moderately diverse sequence. The share of monocultures also decreased by 2%. Similar changes have occurred in Lombardy, Italy, where the greening measures of the European Common Agricultural Policy (CAP) have been identified

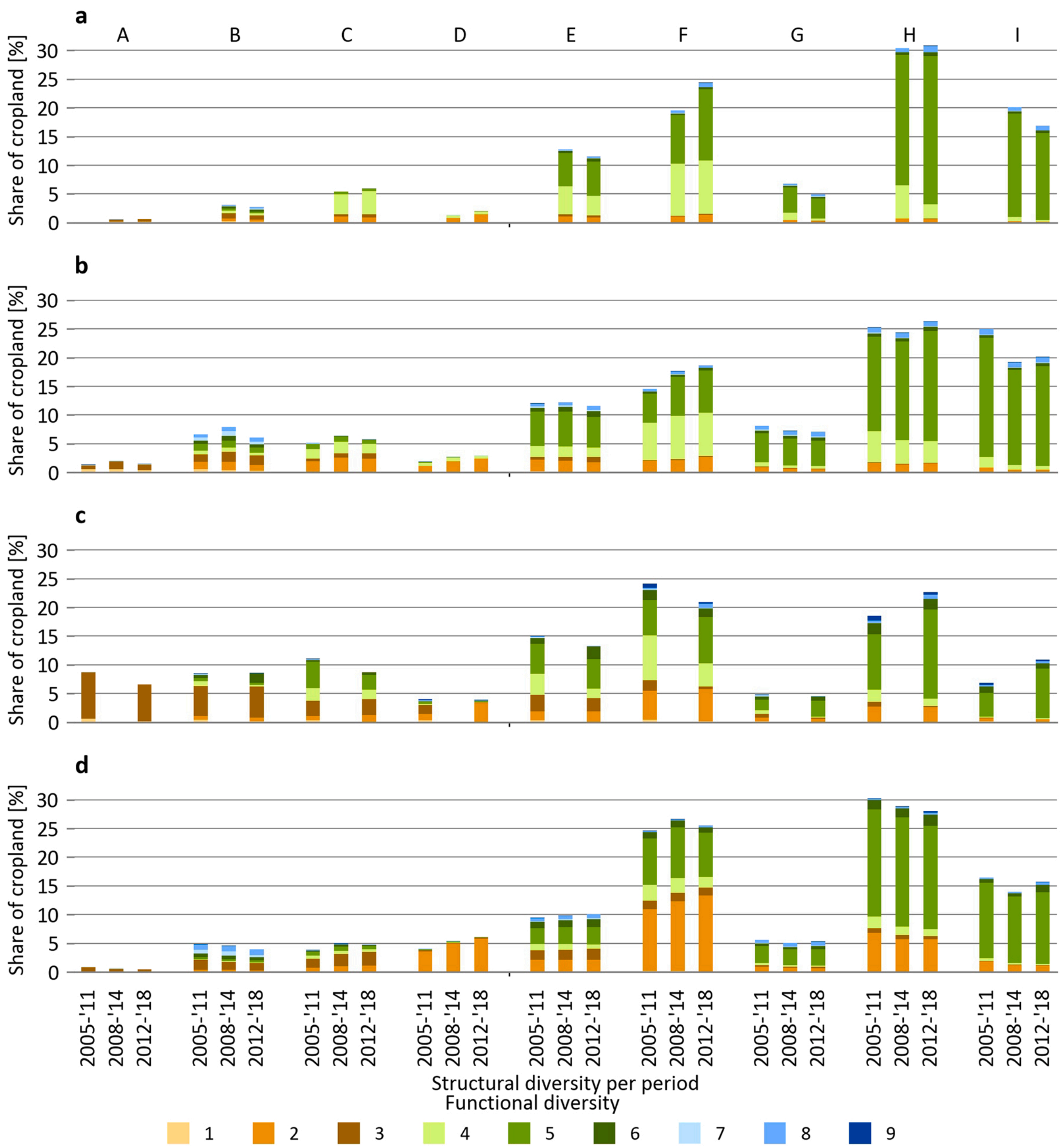

Fig. 6. Crop sequence types in the periods 2005–2011, 2008–2014, and 2012–2018 for Saxony-Anhalt (a), Brandenburg (b), Lower Saxony (c) and Bavaria (d). The capital letters represent the structural diversity, and the colours represent the functional diversity. Data for the period 2005–2011 are missing for Saxony-Anhalt and in Lower Saxony for the period 2008–2018. The crop sequences in Lower Saxony stemmed from a subset of the data.

as a possible cause (Bertoni et al., 2018). Our results may indicate similar processes but additional analysis are needed to establish a causal link between the changes in crop sequences to the CAP payments.

A reduction in structural diversity, as observed in Brandenburg, Bavaria and Saxony-Anhalt, must not be disadvantageous per se. Sequences with three different crop types already improve crop yields and soil health (Agomoh et al., 2021), while highly structurally diverse sequences may have an unfavourable combination of crop types (e.g. sequences consisting of only cereal crops). To determine whether structural changes also lead to strong changes in the functional diversity, we analysed the co-occurrence of changes in structural and functional diversity. We found that most changes in structural diversity were not accompanied by changes in the functional diversity. This indicates a high awareness of the farmers of recommendations for crop rotation design. Yet, we found, that on 8% of the cropland that experienced a declining structural diversity, the shares of leaf crops decreased as well. This is an indication for decreasing functional diversity and a trend that should be observed with caution. A high functional diversity can help to improve soil quality, especially in low input cropping systems (King and Blesh, 2018).

Overall, we observed a slight trend towards cereal-dominated sequences in Brandenburg, Saxony-Anhalt and Bavaria. This increase could indicate a shift towards more profitable crops, such as maize, which is a key animal feed and used as input for biogas plants. Higher shares of cereals imply lower shares of leaf crops, which play a pivotal role in the nitrogen fixation and are beneficial for soil structure (Blanco-Canqui and Lal, 2009; Bullock, 1992). Reducing the share of leaf crops in crop sequences may necessitate higher input applications, such as more fertilizer use. In Lower Saxony, however, the share of cereal crop-dominated sequences decreased. This could also be linked to the decreasing dairy farming, which, as our results indicate, more often cultivate cereal-dominated sequences than other farms.

Table 3
Co-occurrence of changes in structural diversity and functional diversity. Values are provided as the share of cropland that experienced the respective combined change in structural and functional diversity. Changes are calculated between the periods 2005–2011 and 2012–2018 for Brandenburg (BB) and Bavaria (BV).

		Declining structural diversity		Increasing structural diversity	
		BB	BV	BB	BV
Change in spring crop shares	Decreasing spring crops/ increasing winter crops	6	2	2	3
	Stable	22	22	18	18
	Increasing spring crops/ decreasing winter crops	5	5	7	6
	Total	32	30	27	27
Change in leaf crop shares	Decreasing leaf crops/ increasing cereal crops	7	8	2	3
	Stable	23	19	20	18
	Increasing leaf crops/ decreasing cereal crops	2	3	5	7
	Total	32	30	27	27

In Brandenburg and Saxony-Anhalt, we observed decreasing shares of winter crops and increasing shares of spring crops. Sequences with a high share of winter-sown crops can suffer from the accumulation of pests and a decreasing diversity of the microbial community in the soil (McDaniel et al., 2014). Balancing the shares of winter crops and spring crops in a sequence, and thus interchanging typical growing cycles, can disrupt the life cycles of pests and weeds and thus reduce the use of pesticides and herbicides (Davis et al., 2012). Therefore, decreasing shares of winter crop dominated sequences might indicate improvements in agricultural practices. However, the IACS data does not provide information on the use of intermediate crops, therefore, our analysis does not completely show whether solely-winter-sown crops are used or are used in combination with break crops. Adding this information, for example with help of satellite data will improve the analysis.

4.4. Limitations

The periods of salient land-use intensification in Germany were likely before our study period, when the EU and federal state subsidies incentivized production increases and farm size increases, possibly diminishing the crop portfolio and contributing to the simplification of rotation practices (Niedertscheider et al., 2014). Data availability prevents the assessment of the effect of technological advances prior to 2005, such as the introduction of hybrid maize in Germany in the nineteen-sixties or the implementation of the renewable energy act in 2000 (Miedaner, 2014). Our study period covers the implementation of the European CAP reform of 2003, which shifted subsidies from production-based to area-based payments and should capture its effects on crop sequences, but a before-after comparison is not possible due to the lack of field-level land-use data before 2005. Assessing the effect of the greening measures that were instigated with the CAP reform of 2013 and included subsidies for catch crops was not possible because catch crops were covered by the IACS data only when they were in the field on the cut-off date of May 15. The share of biogas maize, which is planted after a whole plant silage of rye and hence towards the end of May, also escapes IACS reporting and leads to a slight underestimation of maize in areas where biogas production is prevalent. Similarly, early harvested winter rye, which is followed by maize, is also not included in the IACS data and thus slightly underestimated.

Although, our analysis covers large areas of German cropland, the data availability of IACS data limits the spatial extent of this study. Yearly land use maps derived from remote sensing data can help to cover a larger study area. Time-explicit crop type maps have already been used to analyse changes in crop rotations in the United (Long et al., 2014; Plourde et al., 2013). However, these analyses relied on broad crop type classes or a limited number of crop types. Additionally, few satellite-derived crop type maps are available for earlier time steps. Satellite data from the Sentinel-2 sensor with finer spatial resolution exist only since 2016 and validation of annual crop type maps, particularly for the past, remains cumbersome and is hindered by a lack of validation data. In recent years, the number of satellite-derived crop type maps for Germany has increased (Blickensdörfer et al., 2022; Griffiths et al., 2019; Preidl et al., 2020), which allowed the analysis of shorter crop sequences (Blickensdörfer et al., 2022). Noteworthy is that all these maps were produced with help of the IACS data, exemplifying the usefulness of the combination of satellite data with IACS data.

5. Conclusion

We analysed crop sequences in four federal states of Germany between 2005 and 2018 using field-level, annual land-use data. Our results suggest only a modest intensification of land use during the study period, as judged by the changes in the crop sequence patterns. Overall, the number of different crops used in crop sequences decreased slightly and most crop sequences remained similar in their composition. Only small trends towards more cereal crops and more spring-sown crops could be detected with partially opposite trends in the different federal states. We found that agricultural production strategies and farm characteristics shaped the spatial patterns of the crop sequences. In western Germany, larger farms tended to have more diverse and heterogeneous crop sequences than smaller farms. In eastern Germany, the picture was more complex, crop sequence diversity was similar across farm sizes. We demonstrated that organic farms provided more structural and functional diversities in crop rotations. In contrast, less diverse cropping practices, up to the continuous cropping of single crops, characterise areas that are dominated by intensive cattle production. Finally, our results corroborate the importance of historical legacies for contemporary land use with distinct spatial patterns and changes in crop sequences between former East and West Germany. We believe that our approach can provide an important impetus for the analysis of changes in the intensity of agricultural production over larger areas and will prove more valuable as longer time series of field-level land-use data become available.

CRediT authorship contribution statement

Clemens Jänicke: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. **Adam Goddard:** Conceptualization, Methodology, Formal analysis. **Susanne Stein:** Methodology, Writing – review & editing. **Horst-Henning Steinmann:** Methodology, Writing – review & editing. **Tobia Lakes:** Writing – review & editing. **Claas Nendel:** Resources, Writing – review & editing. **Daniel Müller:** Conceptualization, Resources, Writing – original draft, Supervision, Project administration, Funding acquisition.

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.eja.2022.126632.

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