Published in : European Journal of Agronomy (2026), vol. 178, article 128133
doi.org/10.1016/j.eja.2026.128133
Status : Postprint (Author's version)

LONG-TERM EVOLUTION OF CROP SEQUENCES AND THEIR AGRONOMIC PERFORMANCE IN WALLONIA

Tom Desmarez [a,*,1], Julien Péters [b,1], Fanny Boeraeve [a], Jérôme Bindelle [c], Benjamin Dumont [a]

[a] *University of Liège, Gembloux Agro-Bio Tech, TERRA Teaching and Research Centre, Plant Sciences Axis, Gembloux 5030, Belgium*
[b] *University of Liège, Gembloux Agro-Bio Tech, TERRA Teaching and Research Centre, Biodiversity and Landscape Axis, Gembloux 5030, Belgium*
[c] *University of Liège, Gembloux Agro-Bio Tech, TERRA Teaching and Research Centre, Animal Sciences Axis, Gembloux 5030, Belgium*
[*] *Corresponding author. E-mail address: tom.desmarez@uliege.be (T. Desmarez).*

Abstract

Sustaining agricultural productivity while improving agronomic sustainability and resilience of farming systems requires understanding how cropping practices evolve at the landscape scale. Crop rotation is central to this challenge, yet long-term, region-wide evidence on its structure and agronomic quality remains scarce. Here, we reconstructed 26 years (1998–2023) of crop sequences across Wallonia (Belgium) using harmonized Integrated Administration and Control System (IACS) data, and evaluated temporal and spatial trends with the Crop Sequence Indicator (CSI), an integrative metric combining succession compatibility, crop return times, and crop diversity. We found a slight but consistent increase in CSI across Wallonia (5.41 to 5.69), indicating modest improvements in the agronomic quality of crop sequences, although values remained within the moderate quality range. Improvements were primarily driven by better crop succession compatibility, while crop diversity and return time components changed only marginally. Regional trajectories diverged: productive loamy lowlands showed clearer improvements in the structuring of crop sequences, whereas upland regions remained dominated by forage-based systems with agronomic and ecological legitimacy. At the same time, the expansion of high-input crops such as potatoes (+64 %), combined with a decline in grasslands, suggests that agronomic improvements in crop sequence design might not translate into ecological gains. However, several diversification crops also expanded, including oilseeds (+29 %) and legumes (+63 %), indicating a gradual, though still limited, diversification of cropping systems.

By providing the first long-term, fine-grained depiction of crop sequence dynamics in Wallonia, this study offers a comprehensive regional assessment of their evolution. Our findings highlight the need for regionally tailored incentives and complementary indicators to better capture the environmental implications of crop sequence dynamics and to support the design of cropping systems combining agronomic performance with ecological sustainability.

Keywords

Wallonia, Crop rotation, IACS, Crop sequence indicator

Published in : European Journal of Agronomy (2026), vol. 178, article 128133
doi.org/10.1016/j.eja.2026.128133
Status : Postprint (Author's version)

1. Introduction

Over the past century, farming systems have progressively shifted toward an agro-industrial model in which chemically-synthesized fertilizers and pesticides, irrigation, and mechanization have largely replaced many ecological processes and have led to an overall simplification of the landscape and the agricultural system (Matson et al., 1997; Tscharntke et al., 2005). This transition has favored monocropping and short-term cash-crop rotations (Krebs et al., 1999; Van Zanten et al., 2014), making agricultural production increasingly dependent on a narrow set of profitable, high-yield varieties adapted to such high input systems (Khoury et al., 2014), where crop choices are driven more by economic policies and market pressures than by agronomic considerations (Song et al., 2021). While this transition significantly increased per capita food availability (Krebs et al., 1999), it has also generated severe environmental consequences: the food system is now responsible for nearly 30% of global greenhouse gas emissions (Whitmee et al., 2015), 70% of freshwater consumption (Molden, 2007), widespread biodiversity loss (Tilman et al., 2017), eutrophication from nutrient surpluses (Conley et al., 2009), and pesticide-related ecological and health risks (Geiger et al., 2010; Van Maele-Fabry et al., 2010).

At the field scale, planting the same species or closely related species for many years has been shown to reduce the diversity of functional soil microbial communities, to foster the accumulation of host-specific soil- borne pathogens, to increase the soil seed bank, and to lead to imbalances in soil nutrient content (Cardina et al., 2002; Yang et al., 2020). These changes compromise soil biodiversity and functionality, ultimately degrading soil health and increasing the vulnerability of agroecosystems to disease and productivity decline (Bennett et al., 2012).

Growing concerns about the sustainability of agricultural systems have renewed attention toward diversification strategies capable of enhancing agronomic resilience while maintaining productivity (Gliessman, 2014). Among these strategies, crop rotation, defined as the cyclic sequential cultivation of different crops on the same land over multiple growing seasons, represents a fundamental and operational lever, as it structures temporal diversification at the field level and directly influences soil health, pest regulation, and nutrient dynamics (Francaviglia et al., 2019; Yang et al., 2024). Assessing how crop rotations evolve over time is therefore essential to understand whether farming systems move toward more agronomically robust configurations.

While several methodological advances have been made to quantify and typify crop-sequence patterns, most studies have focused on limited time spans, specific production systems, or structural typologies rather than long-term regional dynamics (Chopin et al., 2026; Javourez et al., 2025; Upcott et al., 2023). In Wallonia, Leteinturier et al. (2006) developed one of the first regional-scale assessments of crop sequences using Integrated Administration and Control System (IACS) data, adapting the INDIGO method (Bockstaller and Girardin, 2008) to derive a Crop Sequence Indicator (CSI) that quantified the agronomic quality of rotations based on previous crop effects, return times, and crop diversity. Their work provided a pioneering spatial diagnosis of crop management in Wallonia but was limited to a seven-year period (1997–2003) and excluded grasslands and forage crops. Later, Stein and Steinmann (2018) proposed a generic typology of crop sequences in Central Europe, combining structural (number of crop transitions and crop types) and functional (balance between spring and winter or leaf and cereal crops) diversity dimensions. This framework enabled the mapping of crop sequence diversity across large territories but, like previous approaches, did not account for multiannual fodder crops or long-term temporal dynamics. More recently, Vandevoorde and Baret (2023) worked on the integration of temporary and multiannual grasslands into crop sequence analyses for livestock-dominated regions of southern Wallonia. However, their study covered only part of the Walloon territory and a short six-year period (2015–2020), leaving open the question of how rotation practices have evolved over the past decades across the entire region. Beyond Belgium, several studies have reconstructed multi-year crop sequences using administrative data. Reumaux et al. (2023) analyzed 10-year sequences to characterize diversity patterns across production systems. Jänicke et al. (2022) examined changes in crop sequences as indicators of land-use intensification, accounting for both structural and functional diversity within crop rotations. Whippo et al. (2026) derived complexity metrics from 16-year U.S. sequences, and Palka et al. (2026) combined historical reconstruction with modeling to assess how drivers shape rotational configurations. While these contributions substantially advance crop-sequence analysis, to our knowledge no study has provided a continuous, fine-resolution and region-wide assessment of long-term crop rotation dynamics in Wallonia.

Because crop choices are often driven by economic and policy incentives rather than strictly planned rotational cycles (Song et al., 2021), we refer to crop sequences when describing observed crop successions and use crop rotations only when recurring cyclic patterns are identified.

Building on the CSI framework and recent methodological developments, this study provides a spatially explicit reconstruction of crop sequences over 26 years (1998–2023) across the entire Walloon territory (16,901 km²). Specifically, we (i) identify the dominant crop- sequence patterns and their agronomic quality across production zones, and (ii) analyze their temporal evolution over the 1998–2023 period. By linking crop sequences to their agronomic quality, we establish a long-term empirical baseline of crop sequence dynamics within a diversified European agricultural region and assess the implications for the sustainability of Walloon farming systems.

2. Materials and methods

2.1. Study area

In addition to the three administrative regions (Wallonia, Flanders and Brussels) that differ in their regulatory frameworks, Belgium is conventionally subdivided into agricultural regions (Ministry of Agriculture, 1951) which are commonly used to distinguish areas with distinct agronomic practices (mostly related to crop types) and pedo-climatic contexts. The present study focused on Wallonia, where ten agronomic regions are recognized: “Sandy-Loamy”, “Loamy”, “Hainaut Campine”, “Condroz”, “Famenne”, “Fagnes”, “Herbaceous”, “High-Ardenne”, “Ardenne” and “Jurassic”. The Utilized Agricultural Area (UAA) covers 44% of the regional territory, representing approximately 734,000 ha, with 426,000 ha of arable land (Statbel, 2025). For analytical clarity, the ten agricultural regions were aggregated into three macro-zones reflecting similar production orientations. Zone 1 (Sandy-Loamy, Loamy and Hainaut Campine) represented predominantly arable systems and accounted for 42% of the Walloon UAA and 60% of Walloon arable land. Zone 2 (Condroz, Fagnes and Famenne) corresponded to mixed crop–livestock systems and covered 28% of the Walloon UAA and 28% of Walloon arable land. Zone 3 (Ardenne, High-Ardenne, Herbaceous and Jurassic) comprised mainly grassland-dominated systems and represented the remaining 30% of the Walloon UAA and 12% of Walloon arable land (Fig. 1).

The data used in this study originated from the IACS of the Common Agricultural Policy (CAP). Field-level parcel geometries and annual crop declarations were derived from the Geo-spatial Application (GSA), through which farmers annually delineate the parcels they cultivate and declare their main crops. We used the anonymized IACS dataset provided by the Public Service of Wallonia for the period 1998–2023. The combined dataset provided a spatially explicit representation of agricultural parcels together with annually declared main crops (reference date: 31 May) (European Commission, 2026a, 2026b).

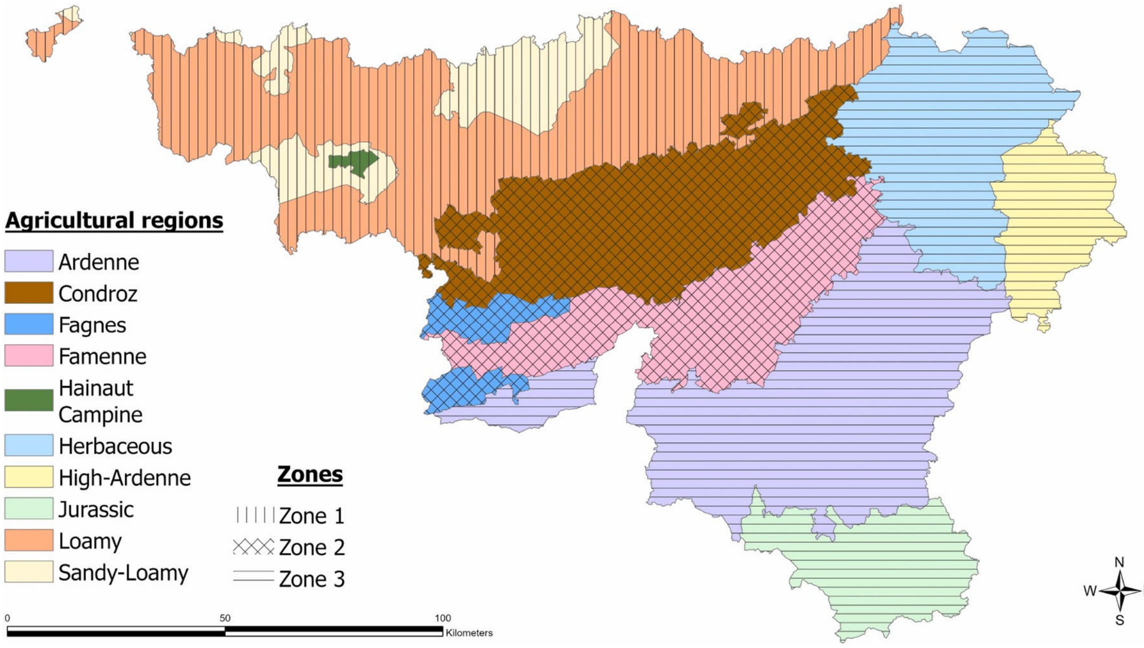

Fig. 1. Spatial distribution of the ten agronomic regions of Wallonia and their aggregation into three production-oriented macro-zones. Zone 1 (Sandy-Loamy, Loamy and Hainaut Campine) corresponds to predominantly arable systems and is represented by vertical hatching. Zone 2 (Condroz, Fagnes and Famenne) forms a transitional mixed crop–livestock belt and is represented by a cross-hatched grid pattern. Zone 3 (Ardenne, High-Ardenne, Herbaceous and Jurassic) comprises grassland-dominated upland systems and is represented by horizontal hatching.

2.2. Data preprocessing and integration

Parcel data were pre-processed in a PostgreSQL/PostGIS environment to ensure spatial and temporal consistency across the annual series. Although parcels were digitized annually from orthophotographs and corrected by the administration in the context of CAP payments, the raw datasets contained two categories of issues that required systematic correction. First, the attribute structure was inconsistent across years: column names for the same field (e.g., crop type, parcel identifier, area) differed between annual layers. All tables were therefore standardized to a unified schema by mapping each year-specific column name to a common reference name, and missing attributes were filled with null values to ensure a homogeneous structure across the full time series. Second, within each annual layer, individual parcel polygons were not guaranteed to be spatially exclusive: overlapping geometries occurred between parcels belonging to the same year. These intra-annual overlaps were resolved by processing parcels sequentially and applying iterative geometric subtraction: each incoming parcel was clipped against the union of all previously processed parcels, yielding a strictly non- overlapping layer for each year. Residual intersections were verified programmatically and confirmed to be absent in the final output. Additionally, invalid geometries were systematically detected and repaired prior to overlap resolution, and all layers were projected to a common coordinate reference system.

To minimize the effects of annual changes in parcel delineation (mergers, splits or boundary redefinitions) on temporal analyses, vector layers were rasterized to a regular 2 m × 2 m grid (pixel area = 4 m^2) using ArcGIS Pro. This approach enabled tracking crop transitions at the pixel level rather than at the parcel level, thereby bypassing the instability of parcel-level analyses caused by frequent polygon mergers, splits and the reassignment of parcel identifiers between years. Annual and thematic raster layers (GSA 1998–2023 and agronomic regions) were then aligned, merged and resampled where necessary to ensure exact grid congruence. Pixels exhibiting identical full-length crop sequences over the 1998–2023 period were grouped into unique sequence units within each agricultural region, and their areas aggregated. This procedure reduced data dimensionality while preserving the total spatial extent associated with each distinct long-term trajectory, which constituted the analytical unit.

The resulting attribute tables, containing the full occupation and crop-succession history for each sequence unit, were imported into R for subsequent statistical analyses and modeling. Sequence units with no crop information for all years were removed, and only units with an area ≥ 1 ha were retained. This threshold excluded small residual units arising from minor year-to-year shifts in parcel boundaries.

To enable consistent long-term analysis across the 26-year time series, all IACS crop labels were harmonized and grouped into 21 agronomically coherent crop classes (listed in Table 1) and 8 non-agronomic classes. This standardization step was necessary because IACS nomenclature evolved substantially over time, with changes in crop naming, level of detail, and the introduction or disappearance of certain categories. The full list of harmonized classes and their IACS correspondences is provided in Supplementary Material S1.

Table 1. recommended return time (t_R) for each crop group used in the Crop Sequence Indicator (csi) calculation, adapted from Leteinturier et al. (2006).

Crop	t_R [years]
Winter wheat / spelt	2
Other winter cereals	3
Pseudocereals	3
Winter barley	4
Spring cereals	2
Cereal–legume mixtures	4
Maize	2
Pea	6
Faba bean	6
Other legumes	6
Perennial legumes	4
Grassland	3
Forage	3
Winter oilseeds	4
Flax	6
Sugar beet	3
Potato	5
Spring oilseeds	4
Vegetables	6
Fallow	1
Chicory	3

2.3. Temporal partitioning and crop sequence reconstruction

For each sequence unit, crop sequences were reconstructed over the 26-year period. The time series was then divided into two subperiods: 1998–2010 (*Historic*) and 2011–2023 (*Recent*), to assess temporal changes in crop sequencing. This temporal partitioning allowed for a balanced comparison between two time intervals of equal duration.

To characterize crop sequences, we applied a 7-year moving window to each sequence of continuous annual crops. This duration represented an agronomic and methodological compromise: the window had to remain as short as possible to maximize the number of uninterrupted sequences retained, while being long enough to cover at least one full rotation cycle (Leteinturier et al., 2006). The longest agronomic return time in our dataset corresponded to six years for some legume species (Table 1); a 7-year window therefore ensured that such crops could be observed within a complete sequence segment, including both the crops preceding and following their occurrence within the same sequence. Within each 13-year subperiod, a complete uninterrupted sequence could generate up to seven shifted windows (years 1–7, 2–8, …, 7–13).

Windows were only created when all seven years were available and contiguous; any missing value or interruption in the time series prevented the construction of a window. Each valid window was then weighted by the surface area of its source sequence unit, with each window inheriting the full surface of that unit so that crop sequences covering larger areas contributed proportionally more to the aggregated indicators presented in 2.6.

2.4. Handling of exclusion categories

We discarded windows containing any non-agronomic classes. To avoid including permanent grasslands or long-term fodder systems, we further excluded all windows containing continuous sequences of perennial legumes, grassland, and forage lasting six years or more. This conservative threshold ensured that only sequence units including periodic arable phases were retained, effectively removing permanent grasslands from the analysis, as these systems do not exhibit crop succession dynamics relevant to the CSI. Windows could still include years of temporary grasslands when these alternated with arable crops.

The analyzed surface decreased from 651,502 ha (after the 1-ha threshold) to 303,168 ha after applying all filters, corresponding to approximately 41% of the Walloon UAA.

2.5. Calculation of CSI

To assess the agronomic quality of crop sequences, we used the CSI developed by Leteinturier et al. (2006), proposed as a large-scale methodological adaptation of the I_{SC} indicator used in the INDIGO method (Bockstaller and Girardin, 2008). The CSI provides an empirical assessment of the agronomic quality of crop sequences based on the combined effects of crop succession, return times, and diversity:

$$CSI = \overline{k_p} \cdot \overline{k_r} \cdot k_d$$

Where $\overline{k_p}$ represented the mean crop succession coefficient of the sequence, $\overline{k_r}$ the mean return time coefficient, and k_d the crop diversity coefficient. The $\overline{k_p}$ parameter was the most important one in driving CSI values while $\overline{k_r}$ and k_d acted as contraction or dilation coefficients to correct for (un)favorable situations. Higher CSI values indicated agronomically favorable crop sequences, combining compatible successions, adequate return times, and high crop diversity. Adapted from Leteinturier et al. (2006), we defined three qualitative classes of crop sequence agronomic quality based on CSI values: low (CSI ≤ 4), moderate (4 <CSI ≤ 7), and high (CSI > 7).

2.5.1. Crop succession coefficient (k_p)

The k_p coefficient quantified the agronomic compatibility between two successive crops. It reflected the cumulative effect of the preceding crop on the following one in terms of soil structure, pest and disease pressure, weed dynamics, and nitrogen contribution. Each crop-to-crop transition was assigned an expert-based score ranging from 1 (strongly detrimental) to 6 (highly beneficial). The base matrix of pairwise succession scores originated from Leteinturier et al. (2006). We expanded it following the broader crop typology detailed in the CropRota model (Schönhart et al., 2011) and in Bockstaller and Girardin (2008), which included a larger set of arable and fodder crops. We also adapted the values for perennial and multiannual crops according to the recommendations of Vandevoorde and Baret (2023). In particular, temporary grasslands and perennial legumes were assigned more positive compatibility values with other crops, reflecting their beneficial soil-structuring and phytosanitary effects in crop sequences. For each 7-year sequence window, the mean k_p was computed across all consecutive crop pairs. The matrix of pairwise succession k_p scores used in this study is available in Supplementary Material S2.

2.5.2. Return time coefficient (k_r)

The k_r coefficient evaluated the adequacy of the observed return time of a crop relative to its recommended minimal return time (t_R) (Table 1), derived from regional agronomic guidelines (Leteinturier et al., 2006). Differences between the observed return time (t) and the recommended value (t_R) were grouped into discrete classes associated with k_r values ranging from 0.2 (excessively short return) to 1.2 (return exceeding the recommended minimum) (Table 2).

For crops without prior occurrence within a window, the position of their first occurrence within the window was used as a proxy for t. Values of k_r were set to 1.0 where $t - t_R = 0$, to 1.2 where $t - t_R \geq 1$, and left undefined otherwise. For subsequent occurrences, t was defined as the time elapsed since the previous occurrence of the same crop within the window, and k_r was assigned accordingly (Table 2). For perennial or multiannual crops (e.g., grasslands, perennial legumes, forage), k_r was computed following the block-based approach of Vandevoorde and Baret (2023). In this method, multiannual crops were treated as continuous "blocks", and t was measured between the end of a previous block and the start of the next, rather than within the block itself. Only the first year of each block contributed to the return time calculation, while subsequent years within the same block were not considered. This prevented artificial penalties for multiannual phases and better represented their succession dynamics. Mean k_r was then calculated across crops with a defined k_r value within each window.

Table 2. Relationship between values obtained for the difference $t - t_R$ and k_r coefficient according to Leteinturier et al. (2006).

$t - t_R$	k_r
≤ -4	0.2
-3	0.3
-2	0.5
-1	0.8
0	1.0
≥ 1	1.2

2.5.3. Diversity coefficient (k_d)

The k_d coefficient captured the richness of crop diversity within the crop sequence. It depended on the number of distinct crops observed in a 7-year window.

To better reflect the agronomic contribution of multiannual crops to diversity within crop sequences, we extended the original k_d by assigning a + 0.5 bonus per additional consecutive year of perennial crops within a block. The resulting effective number of crops in a 7-year window could thus be fractional. This value was converted into a corresponding k_d coefficient by linear interpolation within the standard k_d scale proposed by Leteinturier et al. (2006) (Table 3). This adjustment rewarded the temporal diversity embedded in multiannual phases, consistent with Vandevoorde and Baret (2023).

Table 3. Relationship between the number of crops in a sequence and the $\boldsymbol{k_d}$ coefficient (Leteinturier et al., 2006).

Number of crops	k_d
1	1.00
2	1.10
3	1.20
4	1.25
5	1.30
6	1.35
7	1.39

2.6. Computation and interpretation

2.6.1. Evolution of crop composition

Crop composition was quantified from annual sequence unit-level declarations by aggregating sequence unit surfaces to obtain yearly cultivated areas and proportional shares. Differences between the two subperiods (1998–2010 and 2011–2023) were assessed by comparing mean annual cultivated areas across years within each subperiod.

2.6.2. Dominant crop sequences

Seven-year crop sequences were derived from valid moving windows. For each unique sequence, frequency and corresponding agricultural surface were computed. Sequences sharing ≥ 6 consecutive crops were grouped, allowing the identification of dominant crop sequence patterns while accounting for slight temporal shifts between otherwise similar sequences. Analyses were primarily conducted at the macro-zone level, and the most prevalent sequences were further classified according to their CSI values to identify the most and least agronomically favorable crop sequences.

2.6.3. CSI

Crop sequence quality was assessed using the CSI and its components, calculated for each valid 7-year window. Temporal dynamics were analyzed both continuously, according to window starting year, and by comparing the two subperiods. Because valid windows were not available for all sequence units in both intervals, the *Recent*–*Historic* comparison did not constitute a paired design. Differences were therefore tested using the Wilcoxon rank-sum test (Mann–Whitney U) on sequence unit-level mean CSI values for each period, applied within each macro-zone. In addition, we computed sequence unit-level ΔCSI (*Recent* − *Historic*) for sequence units with valid CSI estimates in both subperiods.

2.6.4. Evolution of return time per crop

Crop return times were derived from repeated occurrences within reconstructed sequences. Mean values were calculated at the window level and aggregated using area-weighted means. Subperiod differences were evaluated for each crop separately using the same non-parametric framework as for CSI.

3. Results

3.1. Evolution of crop composition in Wallonia

Between 1998 and 2023, the regional crop composition in Wallonia, excluding grasslands, remained largely dominated by winter wheat/ spelt, which consistently occupied around 15–18 % of the total UAA. This crop showed only limited temporal variation, with a modest relative increase of + 4 % between the two study periods (1998–2010 vs. 2011–2023). Maize ranked second, covering about 6–7 % of the UAA and showing a relative expansion of + 12 %.

Among the other major crops, potato, sugar beet, and winter barley each accounted for roughly 2–8 % of the UAA. Potato showed the largest relative increase among main crops (+64 %, reaching 5 % of the UAA in 2023), whereas sugar beet experienced a marked relative decline (–25 %), and winter barley remained nearly stable (–1 %).

Several crops displayed very strong relative growth, reflecting progressive diversification of crop sequences. These included perennial legumes (+226 %), cereal–legume mixtures (+136 %), other winter cereals (+99 %), other legumes (+60 %), and spring oilseeds (+82 %). Smaller yet notable relative increases were also recorded for winter oilseeds (+35 %), vegetables (+24 %), peas (+47 %), and flax (+23 %). Pseudocereals expanded tremendously in relative terms (+956 %) but still represented only 0.02 % of Walloon UAA. Conversely, relative declines were observed for fallow (–83 %), chicory (–30 %), spring cereals (–29 %), faba bean (–13 %) and grasslands (–2 %).

Overall, the crop composition remained strongly dominated by main cereals and tuber crops, which together accounted for 81 % of the arable land in Wallonia (Fig. 2). However, relative increases in minor and alternative crops indicated a modest but consistent diversification of the arable system.

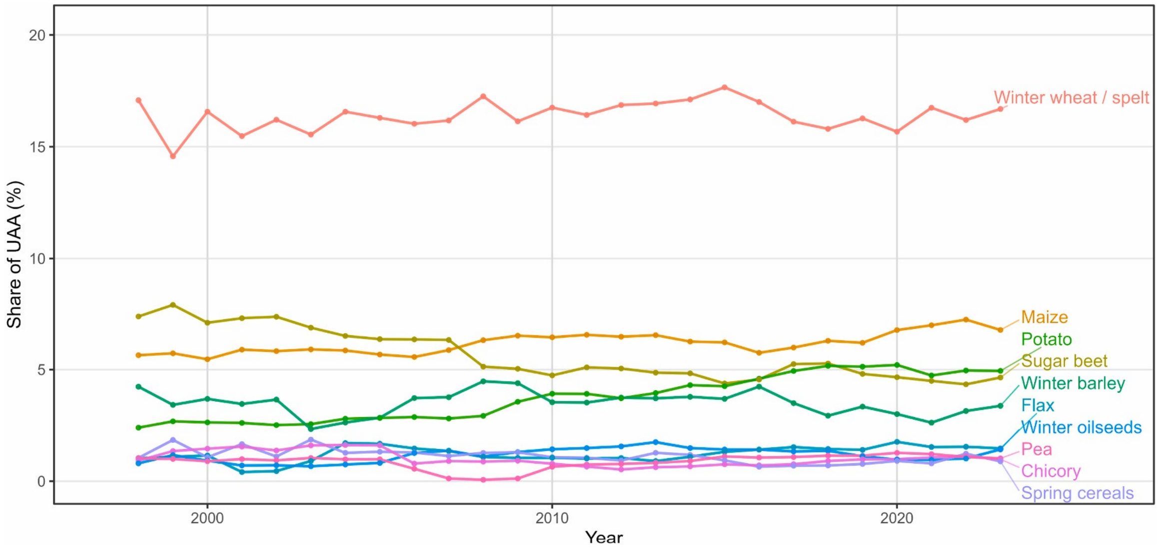

Fig. 2. Evolution of the cultivated area (% of the total Utilized Agricultural Area (UAA)) for the ten major crops (excluding grasslands) in Wallonia between 1998 and 2023.

3.2. Dominant crop sequences

The most frequent seven-year crop sequences revealed strong contrasts among the three macro-zones and across the agronomic quality gradient (Fig. 3). Although these dominant sequences represented relatively modest shares of analyzed window area (generally between ~1 % and 4 % in Zones 1 and 2, and up to ~9 % in Zone 3), they nonetheless reflected the agronomic orientation of the dominant production systems in each zone. In Zone 1, the most frequent sequences were structured around high-value cash crops such as potato, sugar beet and chicory, typically alternating with winter wheat/spelt in rotations that tended to maximize their frequency. In Zone 2, dominant successions followed structured cereal-based rotations, either centered on recurrent winter wheat/spelt and maize, or organized as triennial patterns such as wheat–barley–sugar beet or wheat–barley–winter oilseeds, reflecting mixed systems with both arable cash crops and livestock integration. In Zone 3, the most frequent sequences were either characterized by continuous maize cultivation or by alternations between grassland phases and cereals, consistent with forage-oriented production logics.

Low agronomic quality sequences (CSI ≤ 4) were consistently associated with simplified and repetitive successions. Across all zones, these were typically maize-dominated rotations with limited crop alternation, reflecting reduced rotational breaks and crop diversity.

In contrast, high agronomic quality sequences (CSI > 7) were characterized by greater complexity, although expressed differently across zones. In Zone 1, high CSI values were associated either with temporary grassland phases or with diversified cereal–root crop rotations integrating winter wheat/spelt, sugar beet and potato, complemented by break crops such as legumes or flax. In Zones 2 and 3, high CSI values were primarily associated with extended grassland phases intermittently interrupted by short arable episodes.

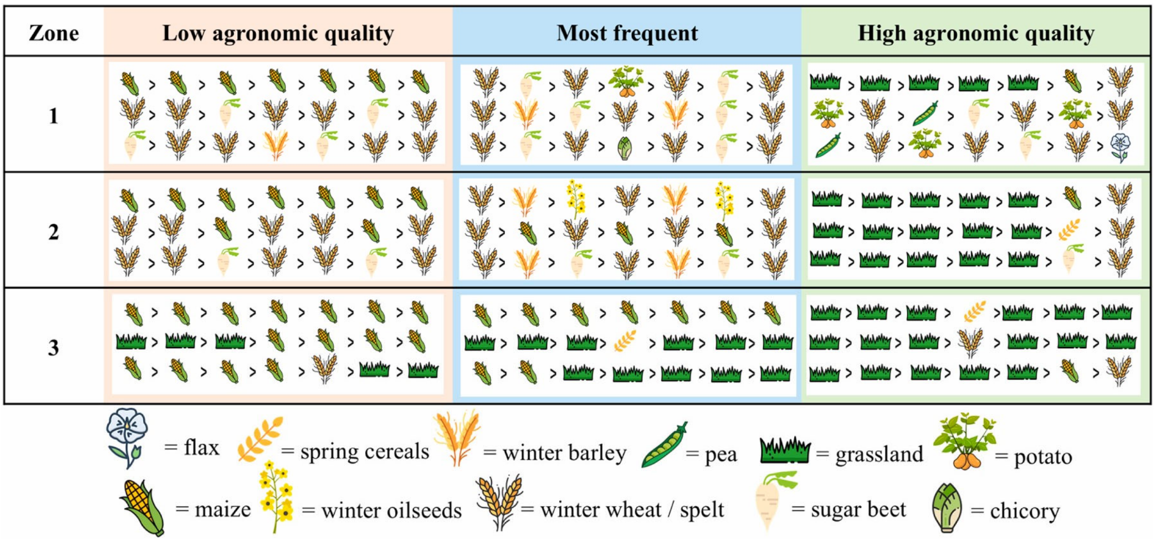

Fig. 3. Most frequent seven-year crop sequences in Wallonia (1998–2023) by agricultural zone and agronomic quality class (CSI). Rows correspond to the three macro-zones and columns to low-quality (CSI ≤ 4), all CSI values, and high-quality (CSI > 7) classes. Within each panel, the three most frequent seven-year successions are shown chronologically from left to right. Each icon represents one crop-year in the sequence.

3.3. CSI

At the Walloon scale, the mean CSI increased slightly from 5.41 in 1998–2010 to 5.69 in 2011–2023. Across all zones, mean CSI values remained within the range of moderate agronomic quality (4 < CSI ≤ 7) in both periods. As illustrated by the inter-period comparison in Fig. 4, this global increase masked spatial contrasts across zones with mean CSI ranging from 5.20 to 5.88, and different contributions from the three CSI components: crop diversity (k_d), crop succession quality (k_p), and crop return time (k_r).

Zone 1, corresponding to predominantly arable loamy systems, displayed the highest weighted mean CSI values in both periods, and exhibited the strongest increase (5.53 → 5.88; Δ = +0.35) (Fig. 4). This improvement was primarily driven by enhanced crop succession quality ($\Delta \log k_p = +0.047$), with smaller but positive contributions from crop diversity ($\Delta \log k_d = +0.011$, mean number of crops in a window: 3.92 → 4.18) and return time coefficients ($\Delta \log k_r = +0.004$). This increase in CSI was statistically significant. When considering the continuous trajectories presented in Fig. 5, which tracked CSI according to the starting year of each 7-year window, a steady and almost uninterrupted rise was observed for windows starting between 1998 and 2015, followed by a stabilization phase thereafter. Detailed temporal dynamics of CSI components are provided in Supplementary Material S3 (Supplementary Figs. A, B and C).

Zone 2, representing intermediate mixed crop–livestock systems, showed a more moderate rise (5.25 → 5.47; Δ = +0.22) (Fig. 4). Here again, succession quality was the dominant driver ($\Delta \log k_p = +0.031$), while gains in diversity and return time coefficients remained limited ($\Delta \log k_d = +0.008$, mean number of crops in a window: 3.69 → 3.87; $\Delta \log k_r = +0.001$). This increase in CSI was also statistically significant. Continuous dynamics revealed a stepwise trajectory (Fig. 5): CSI increased during the early 2000s, stabilized between 2003 and 2007, then resumed its upward trend until around 2015, after which values leveled off, indicating a plateau similar to that observed in Zone 1.

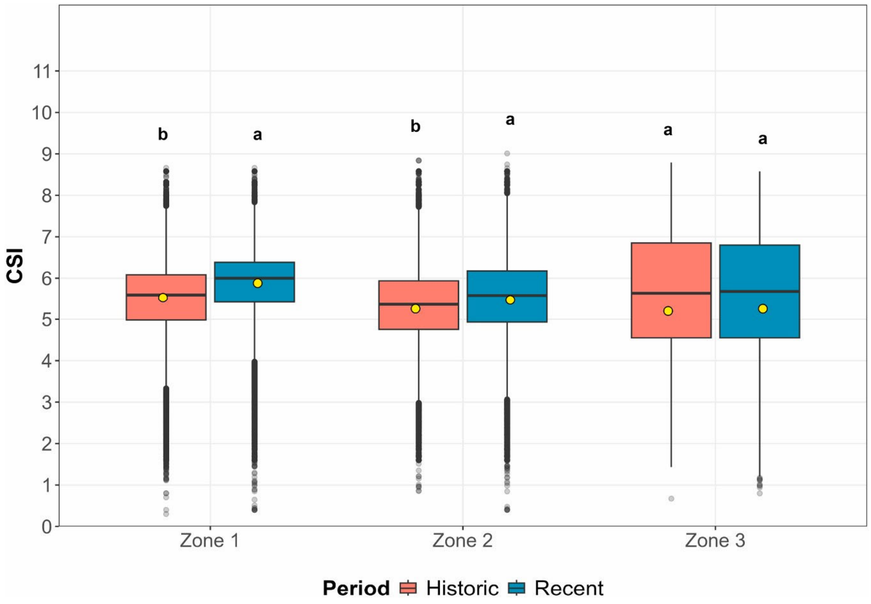

Fig. 4. Changes in the Crop Sequence Indicator (CSI) by production zone between 1998–2010 (*Historic*) and 2011–2023 (*Recent*). CSI values were computed for seven-year crop-sequence windows within each subperiod and averaged at the sequence unit level. *Historic–Recent* differences were tested within each zone using Wilcoxon rank-sum tests; different letters indicate significant contrasts ($p < 0.05$). Yellow points represent surface-weighted mean CSI values.

Zone 3, encompassing grassland-dominated and upland regions, remained comparatively stable (5.20 → 5.25; Δ = +0.05) (Fig. 4). Although crop diversity increased ($\Delta \log k_d = +0.011$, mean number of crops in a window: 3.58 → 3.79) and succession quality improved ($\Delta \log k_p = +0.012$), these gains were partly offset by a decline in crop return time coefficient ($\Delta\log k_r = -0.009$). However, this change in CSI was not statistically significant. The continuous analysis (Fig. 5) highlighted a distinct temporal pattern: an initial stable phase, followed by a slight decline for windows starting in 2004 and 2005, then a recovery culminating around 2010. This was followed by a decline over the next three window starts, after which CSI values stabilized, indicating a plateau.

Fig. 5. Continuous evolution of the area-weighted mean Crop Sequence Indicator (CSI) by macro-zone based on 7-year sliding windows (1998–2023). Each point represents a 7-year sequence (x-axis = window start year). Shaded bands indicate 95% confidence intervals around the mean.

These patterns indicated that improvements in crop sequence design were concentrated in the predominantly arable systems of Zone 1, whereas mixed and grassland-dominated systems (Zones 2 and 3) experienced comparatively smaller and more temporally heterogeneous shifts. Notably, all three zones converged toward a stabilization of CSI values after 2015, suggesting that recent changes in crop sequences may have reached a temporary equilibrium.

The contrasting evolution of crop sequence quality across zones is further illustrated in Fig. 6, which shows the distribution of CSI classes within each zone and period. Moderate-quality sequences dominated in all zones over the whole period. Over 2011–2023, the share of high- quality sequences (CSI > 7) increased most strongly in Zone 1, consistent with its substantial rise in mean CSI. Zone 2 showed little to no change in the distribution of CSI classes between periods. By contrast, Zone 3 exhibited a persistently contrasted distribution, with a slight decline in the share of high-quality sequences over time. While it maintained the largest share of high-quality sequences, it also retained the highest proportion of low-quality sequences (CSI ≤ 4) in both periods. This bimodal distribution likely reflected the coexistence of contrasting systems within the zone, including intensive maize-based rotations associated with lower CSI values and temporary grassland- based systems contributing to higher CSI values. The spatial distribution of CSI classes at the sequence unit level for both periods is presented in Supplementary Material S3 (Supplementary Fig. D), providing a detailed spatial representation of the shifts in crop sequence quality across Walloon agricultural regions and macro-zones.

Finally, the variability underlying these regional averages was captured in Supplementary Material S3 (Supplementary Fig. E), which presents the distribution of sequence unit-level ΔCSI values between periods. Despite the general upward trend, substantial heterogeneity was observed within each zone. Each included both markedly improving and declining paired sequence units across periods, leading to wide interquartile ranges and long tails in ΔCSI distributions. This variability was consistent with contrasted local trajectories, with some sequence units showing increased agronomic quality while others showed declines.

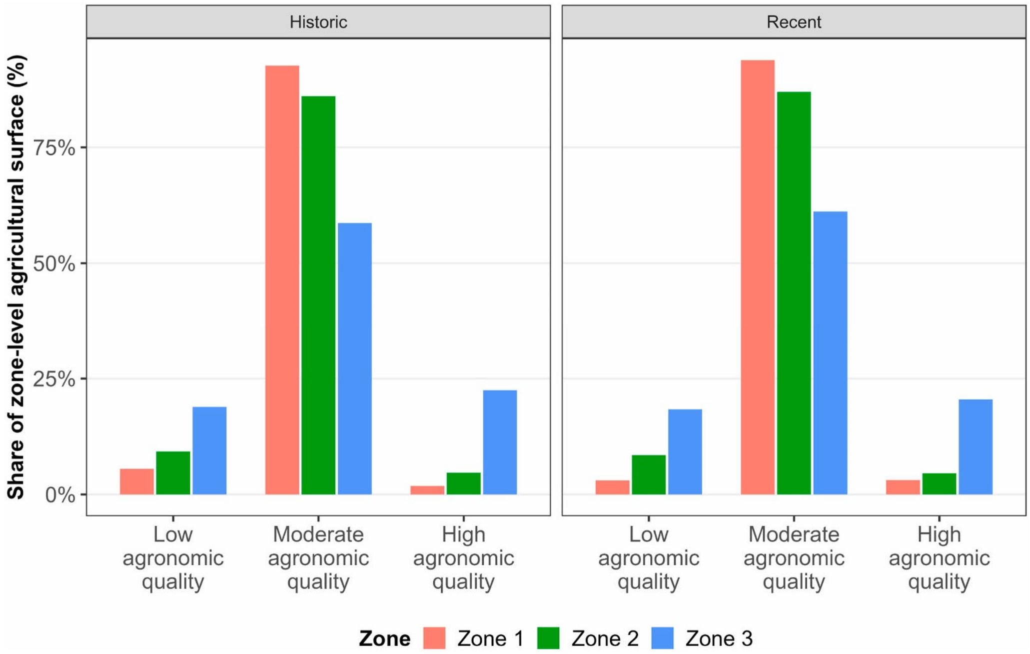

Fig. 6. Distribution of crop sequence quality by production zone in the two study periods: *Historic* (1998–2010, left) and *Recent* (2011–2023, right). CSI values were grouped into three classes representing overall crop-sequence quality: Low agronomic quality (CSI ≤ 4), Moderate agronomic quality (4 < CSI ≤ 7), and High agronomic quality (CSI > 7). Bars represent the share of zone-level agricultural surface (%) falling within each CSI class.

3.4. Evolution of return time per crop

Wilcoxon rank-sum tests indicated that changes in mean crop return time between the two subperiods (1998–2010 and 2011–2023) were statistically significant for all crops except maize, spring oilseeds, faba bean, and pseudocereals. Overall, mean crop return time lengthened for the majority of crops, indicating a general tendency toward less frequent reappearance within crop sequences (Fig. 7). The strongest extensions were observed for cereal–legume mixtures, which increased from 1.10 to 1.73 years, followed by vegetables (2.22 → 2.73 years), sugar beet (3.39 → 3.83 years), other legumes (3.10 → 3.43 years), potato (4.00 → 4.34 years), and winter oilseeds (3.22 → 3.56 years). Additional but more moderate increases were recorded for pea (4.15 → 4.43 years), chicory (4.08 → 4.30 years), forage (2.86 → 3.07 years), faba bean (3.55 → 3.73 years), grassland (2.86 → 3.00 years), and flax (3.92 → 4.06 years).

By contrast, several crop groups exhibited shorter return times in the recent period. Spring oilseeds showed a pronounced decrease (3.34 → 2.78 years), as did perennial legumes (3.25 → 3.03 years), spring cereals (2.22 → 2.14 years), and other winter cereals (2.71 → 2.62 years). Fallow also displayed a slight shortening (1.17 → 1.11 years). Pseudocereals showed a strong apparent shortening in return time (3.25 → 1.84 years), but this result relies on very low sample sizes in the first period and should therefore be interpreted with caution.

The most widespread cereals remained highly frequent in crop sequences. Return times of winter wheat/spelt (2.39 → 2.40 years), maize (2.20 → 2.23 years), and winter barley (3.30 → 3.32 years) changed very little over time and continued to recur on short cycles.

Overall, these patterns indicated a modest but consistent lengthening of crop return times for many legumes and high-value cash crops, suggesting partial diversification or lengthening of crop rotations, while dominant cereals remained cultivated at high frequencies and continued to structure the core of Walloon cropping systems.

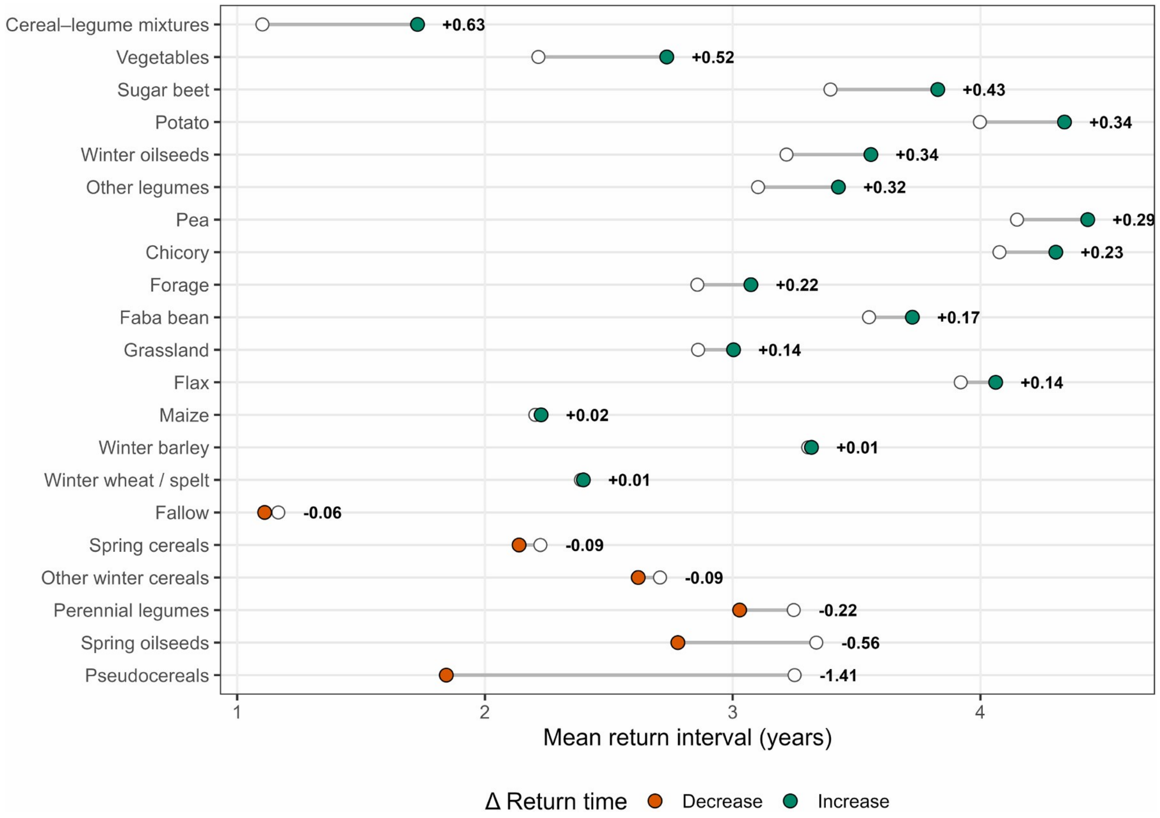

Fig. 7. Evolution of the crop return times for major crops in Wallonia between *Historic* (1998–2010) and *Recent* (2011–2023).

4. Discussion

4.1. Long-term dynamics and spatial differentiation of crop sequence quality

Our results refine previous characterizations of crop sequence quality in Wallonia. Leteinturier et al. (2006) documented moderate CSI values and highlighted the dominance of preceding-crop effects, but their analysis was restricted to a single static 7-year window and excluded grasslands. By contrast, our 26-year dataset reveals that CSI has not remained constant: it improved in arable lowland regions, whereas grassland-dominated areas maintained a substantial share of high-quality sequences despite limited temporal change. This pattern aligns with the refinements by Vandevoorde and Baret (2023), who showed that including temporary grasslands and fodder legumes systematically reveals higher agronomic quality in livestock-based systems.

These contrasted trajectories are reflected in the regional differentiation. In Zone 1, highly intensive patterns persist, with two- to four- year cycles repeated to maximize the share of high-value crops, often separated by cereals (Fig. 3), reflecting market and policy frameworks that have historically favored short-term economic returns over long- term rotational diversity (Van Zanten et al., 2014). By contrast, Zone 3 remains structurally oriented toward forage-based systems shaped by shallow soils allowing mainly grasslands to be grown (SPW, 2025a), while Zone 2 occupies an intermediate position combining elements of both contexts. Similar patterns have been documented in empirical studies across Europe, where simplified rotations are still prevalent (Ballot et al., 2023; Stein and Steinmann, 2018). The contrasts between zones mirror the central role of path-dependence highlighted in large-scale European analyses, where past cropping history consistently emerges as the dominant driver of rotation choices (Palka et al., 2026). These patterns suggest that increases in CSI may coexist with persistent structural specialization, limiting broader functional diversification and its contribution to ecosystem resilience (Tscharntke et al., 2005).

4.2. Persistent specialization and limited diversification

The expansion of legumes and oilseeds may reflect market-related incentives, as recent studies have shown that legume prices can influence crop rotation choices (Palka et al., 2026). However, the continued dominance of five major crops (81 % of arable land) illustrates the technological, commercial and agronomic lock-ins documented across European farming systems, which constrain diversification despite apparent opportunities (Chopin et al., 2026; Revoyron et al., 2022). CSI gains in Wallonia therefore stemmed mainly from improved succession quality (k_p) rather than substantial crop diversification.

These structural and compositional shifts are further reflected in crop return time. Although several major crops now align more closely with recommended frequencies, some crop return times remain below the thresholds recommended by Leteinturier et al. (2006). Winter wheat/spelt and maize broadly respect the recommended two-year return time, and sugar beet and chicory show improved spacing. By contrast, potatoes reappear earlier than the five-year recommendation, consistent with their rapid area expansion (+64 % over the study period), which has been strongly driven by the growth of Belgium's export-oriented potato-processing industry (Eggen, 2021). Several diversification crops, including flax, oilseeds, and grain legumes, also have return times below recommended levels.

On arable land, the increase in CSI was strongest in Zone 1, intermediate in Zone 2, and marginal in Zone 3. However, these differences must be interpreted in light of contrasting land-use structures. Permanent grasslands account for 17 % of agricultural area in Zone 1, 42 % in Zone 2 and 76 % in Zone 3 (Statbel, 2025). Grassland-based systems are known to provide multiple ecosystem services, including carbon sequestration, erosion control, water regulation and habitat provision (Peeters, 2009), thereby contributing substantially to landscape-level ecological resilience. Yet permanent grasslands are not captured by CSI, which evaluates only arable crop sequences. As a result, zones dominated by forage systems may appear less dynamic in CSI despite strong ecological performance. The higher CSI increases observed in lowland regions therefore reflect greater scope for adjusting crop sequences within arable areas. Similar spatial polarization has been reported elsewhere in Europe, where diversification progresses mainly in high-yielding arable regions while less productive areas remain structurally grassland-oriented (Chopin et al., 2026; Jänicke et al., 2022). In such contexts, maintaining extensive grasslands may represent the most ecologically coherent land-use strategy, and diversification efforts within arable land should be evaluated in relation to their potential trade-offs with grassland conservation.

4.3. Policy alignment and cap reform effects on crop-sequence dynamics

The CAP, which accounts for a substantial share of the EU budget, remains the central policy framework structuring European agricultural systems. Recent studies suggest that CAP greening measures can influence cropping practices (Brutti et al., 2025). In our results, several inflection points in CSI components appear to coincide with major CAP reform phases, notably the 2003 reform implemented from 2005 and the 2013 reform implemented in 2015.

Since the 1990s, CAP reforms have progressively shifted toward decoupled payments and environmental conditionality. The 2003 reform introduced the decoupling of most direct payments from production through the Single Payment Scheme, giving farmers greater flexibility in their production choices (Giuliani and Baron, 2025). In our results, this reform coincides with a stabilization of k_d across zones and a decline in k_r, suggesting shorter return times for some crops. Following the decoupling of payments, farmers may have adjusted their crop choices more closely to market signals, potentially increasing the frequency of profitable crops in rotations, as suggested by Brady et al. (2009).

The 2013 reform introduced greening measures, including crop diversification requirements (Giuliani and Baron, 2025). Farms with 10–30 ha of arable land were required to cultivate at least two crops, and farms larger than 30 ha at least three, with the main crop limited to 75 % of arable land and the two main crops to 95 % (Pe'er et al., 2017; Sauquet, 2023). In our results, the implementation of this reform corresponds to a stagnation or slight decline in k_p, k_d, and k_r. These effects on CSI may reflect the fact that the reform does not constrain crop return times or succession compatibility (captured by k_r and k_p in the CSI). Moreover, most sequences in our dataset already included more than three crop types within seven-year windows, indicating that many farms likely complied with the diversification requirement prior to its implementation, as also reported in France (Sauquet, 2023). Interestingly, the only CAP instrument explicitly targeting crop diversity coincides with a stagnation or slight decline in k_d, suggesting that broader structural or market drivers may have outweighed policy incentives.

This interpretation aligns with previous studies reporting modest effects of CAP greening measures on crop diversity and management practices at the EU scale (Lécole and Thoyer, 2017; Louhichi et al., 2017; Pe'er et al., 2017; Sauquet, 2023).

Overall, the gradual increase in CSI observed over time likely reflects a combination of structural dynamics, market developments, and possibly indirect policy influences, rather than the direct effect of a single CAP instrument. For example, market developments such as the expansion of high-value crops like potatoes (Eggen, 2021) together with advisory services and the diffusion of agronomic knowledge that likely improved crop-sequence design and contributed to the observed increase in CSI (Von Münchhausen and Häring, 2012), may have shaped crop-sequence configurations over time.

However, CAP greening measures increasingly promoted ecological practices such as agri-environment and climate measures or cover crops, which can influence cropping systems but are not captured by the CSI indicator used in this study.

4.4. Ecological implications and agroecological transition pathways

Beyond policy dynamics, these results also raise broader questions about the ecological implications of cropping system trajectories. Agricultural systems currently stand at the paradoxical intersection of biodiversity loss and conservation potential. Agricultural intensification, particularly through agrochemical inputs and landscape simplification, is widely recognized as a major driver of biodiversity decline (Chaudhary et al., 2016; Hallmann et al., 2017). In Wallonia, where farmland covers 44 % of the territory and supports a substantial share of European biodiversity (Halada et al., 2011; Overmars et al., 2014), cropping system trajectories therefore play a key role in shaping ecological outcomes. Our results show that while CSI increased over time, this improvement largely reflects enhanced crop succession quality rather than a substantial diversification of cropping systems. At the same time, the continued dominance of a limited number of major crops and the expansion of high-input crops such as potatoes illustrate the structural constraints affecting sustainability pathways. In this context, agroecological practices such as diversified rotations, cover crops, reduced chemical dependency, grassland conservation and the integration of semi-natural elements could strengthen the ecological benefits of crop sequence design by enhancing functional biodiversity and ecosystem service delivery without compromising agricultural production (Boeraeve et al., 2022; Gliessman, 2014; Grass et al., 2019; Tamburini et al., 2020).

4.5. Scope, limitations, and perspectives for integrated sustainability assessment

While increases in CSI shed light on agronomic improvements, interpreting them as evidence of enhanced sustainability would be misleading, as the indicator captures only one dimension of agroecological performance. Through its succession component (k_p), CSI embeds expert-based knowledge on pest and disease regulation, weed dynamics, soil structure, and nitrogen effects. However, because CSI is based on predefined agronomic rules and focuses exclusively on crop sequences in arable systems, it does not account for permanent grasslands, cover crops or broader management practices such as input intensity, tillage operations, landscape configuration, or within-parcel heterogeneity. Consequently, improvements in CSI should be interpreted as enhanced agronomic design of crop sequences rather than proportional gains in measured environmental performance. Empirical evidence indicates that biodiversity and ecosystem-service outcomes depend more strongly on crop identity and landscape configuration than on temporal diversity alone (Guinet et al., 2023; Hass et al., 2018). This study illustrates this limitation. The observed rises in CSI coincided with a decline in permanent and temporary grasslands (− 2 % across periods), which are key providers of carbon storage, erosion control and habitat functions (Bengtsson et al., 2019). This decline is likely underestimated, as part of the grassland area is not consistently recorded in IACS datasets (SPW, 2025b). At the same time, high-input crops such as potatoes expanded. Although occupying only a small share of the utilized agricultural area (~5 %), potatoes accounted for a disproportionate share of pesticide use (42 % between 2015 and 2022) (Squilbin et al., 2025).

Additional limitations should also be acknowledged. Although temporal breaks in CSI coincide with successive CAP reforms, this study does not include econometric assessment of policy, price or socio-economic drivers, and observed correspondences remain associative. Finally, because CSI focuses on agronomic quality, complementary indicators addressing pesticide use (Squilbin et al., 2025), nutrient surpluses (Papangelou and Mathijs, 2021), greenhouse gas emissions (Delandmeter et al., 2023), and ecosystem services (Boeraeve et al., 2020) are necessary to evaluate farming system sustainability more comprehensively, as highlighted in recent integrative frameworks linking crop diversity to ecosystem service provision (Keichinger et al., 2025).

5. Conclusion

This study provides the first long-term, region-wide assessment of crop sequence dynamics in Wallonia based on 26 years of administrative parcel data. It shows that agronomic sequence quality, as measured by CSI, has increased overall but unevenly across production zones. These improvements were primarily driven by enhanced crop succession quality, and to a lesser extent by increases in crop diversity and longer crop return times. Arable lowland regions exhibited the strongest, yet moderate, CSI gains, whereas grassland-dominated systems remained stable.

These results reveal a pattern of incremental adjustment within persistent regional production logics. Crop return times lengthened for several major crops, and the expansion of legumes and oilseeds points to a gradual diversification of arable systems. Nevertheless, arable land remains concentrated in a small number of dominant cash crops, and high-input crops continue to expand. CSI improvements therefore indicate meaningful enhancements in the agronomic quality of crop sequence design, even if they do not necessarily translate into more environmentally sustainable crop management or a fully systemic agroecological transition.

The observed temporal inflection points suggest that policy reforms and market conditions interact with existing rotational structures rather than fundamentally reshaping them. In this context, the capacity of agricultural policy instruments, including the CAP, to promote sustainability in agriculture depends on how financial incentives align with long-term agronomic and environmental objectives. As long as Walloon agriculture remains embedded in highly competitive global markets, more sustainable systems will be structurally disadvantaged by price- based competition. This calls for a fundamental rethinking of current agricultural and trade policies, beyond the CAP's compensatory logic, to reassert the primacy of fair prices, support the development of dedicated value chains for less intensive crops, and secure the long-term maintenance of permanent grasslands.

Overall, Walloon agriculture demonstrates measurable improvements in crop sequence quality, but these remain embedded within established production frameworks. Translating improvements in crop sequences into broader ecological transformation will require integrating agronomic metrics with environmental performance indicators to better align agronomic performance with sustainability objectives.

Beyond this regional case study, this work provides a transferable methodological framework for analyzing long-term crop sequence dynamics in other European agricultural regions.

Code availability

The code used in this study is not publicly available but is available from the corresponding author upon reasonable request.

Author contributions

B.D., F.B., J.B., J.P. and T.D. designed the conceptual framework of the study. J.P. and T.D. gathered and pre-processed the data. J.P. and T. D. analyzed the data. J.P. and T.D. wrote the first draft of the paper. B.D., F.B., J.B., J.P., and T.D. edited and reviewed the manuscript.

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.

Acknowledgments

The authors gratefully acknowledge the financial support of the University of Liege through the ` *Action de recherche concert´ee* for the EXPLORE project (EXPLoring innovative crOpping management for sustainable futuRE-proof food systems) and of the Fonds de la Recherche Scientifique – FNRS.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2026.128133.

Data availability

All data generated or analyzed during this study are included in this published article.

References

Ballot, R., Guilpart, N., Jeuffroy, M.-H., 2023. The first map of crop sequence types in Europe over 2012–2018. Earth Syst. Sci. Data 15, 5651–5666. https://doi.org/ 10.5194/essd-15-5651-2023.

Bengtsson, J., Bullock, J.M., Egoh, B., Everson, C., Everson, T., O'Connor, T., O'Farrell, P. J., Smith, H.G., Lindborg, R., 2019. Grasslands—more important for ecosystem services than you might think. Ecosphere 10, e02582. https://doi.org/10.1002/ ecs2.2582.

Bennett, A.J., Bending, G.D., Chandler, D., Hilton, S., Mills, P., 2012. Meeting the demand for crop production: the challenge of yield decline in crops grown in short rotations. Biol. Rev. 87, 52–71. https://doi.org/10.1111/j.1469-185X.2011.00184. x.

Bockstaller, C., Girardin, P., 2008. MODE DE CALCUL DES INDICATEURS AGRI- ENVIRONNEMENTAUX DE LA METHODE INDIGO®. INRAE, Colmar.

Boeraeve, F., Dendoncker, N., Cornélis, J.-T., Degrune, F., Dufrene, M., 2020. ˆ Contribution of agroecological farming systems to the delivery of ecosystem services. J. Environ. Manag. 260, 109576. https://doi.org/10.1016/j.jenvman.2019.109576.

Boeraeve, F., Vialatte, A., Sirami, C., Caro, G., Thenard, J., Francis, F., Dufrêne, M., 2022. Combining organic and conservation agriculture to restore biodiversity? Insights from innovative farms in Belgium and their impacts on carabids and spiders. Front. Sustain. Food Syst. 6, 1003637. https://doi.org/10.3389/fsufs.2022.1003637.

Brady, M., Kellermann, K., Sahrbacher, C., Jelinek, L., 2009. Impacts of decoupled agricultural support on farm structure, biodiversity and landscape Mosaic: some EU results. J. Agric. Econ. 60, 563–585. https://doi.org/10.1111/j.1477- 9552.2009.00216.x.

Brutti, Z., Freo, M., Serlenga, L., 2025. The causal effect of crop diversification obligations on crop diversity: An EU-level analysis. Ecol. Econ. 237, 108715. https:// doi.org/10.1016/j.ecolecon.2025.108715.

Cardina, J., Herms, C.P., Doohan, D.J., 2002. Crop rotation and tillage system effects on weed seedbanks. Weed Sci. 50, 448–460. https://doi.org/10.1614/0043-1745 (2002)050[0448:CRATSE]2.0.CO;2.

Chaudhary, A., Pfister, S., Hellweg, S., 2016. Spatially explicit analysis of biodiversity loss due to global agriculture, pasture and forest land use from a producer and consumer perspective. Environ. Sci. Technol. 50, 3928–3936. https://doi.org/ 10.1021/acs.est.5b06153.

Chopin, P., Hermouet, S., Watson, C., Oborn, I., Bergkvist, G., 2026. A novel framework ¨ to study the evolution of crop rotation diversity reveals changes towards regional crop type specialisation in Sweden. Eur. J. Agron. 172, 127848. https://doi.org/ 10.1016/j.eja.2025.127848.

Conley, D.J., Paerl, H.W., Howarth, R.W., Boesch, D.F., Seitzinger, S.P., Havens, K.E., Lancelot, C., Likens, G.E., 2009. Controlling eutrophication: nitrogen and phosphorus. Science 323, 1014–1015. https://doi.org/10.1126/science.1167755.

Delandmeter, M., Leonard, J., Ferchaud, F., Heinesch, B., Manise, T., Faur´ es, A., Bindelle, J., Dumont, B., 2023. A comprehensive analysis of CO2 exchanges in agro- ecosystems based on a generic soil-crop model-derived methodology. Agric. For. Meteorol. 340, 109621. https://doi.org/10.1016/j.agrformet.2023.109621.

Eggen, M., 2021. Patates en colère - Comment la culture de pommes de terre a été dévoyée par l´agrobusiness. FIAN Belgium, Bruxelles.

European Commission, 2026a. INSPIRE Geoportal [WWW Document]. URL 〈https://insp ire-geoportal.ec.europa.eu/srv/eng/catalog.search#/overview?view=IACSOvervie w&iacs=gsaa〉 (accessed 3.27.26).

European Commission, 2026b. Integrated Administration and Control System (IACS) [WWW Document]. URL 〈https://agriculture.ec.europa.eu/common-agricultural -policy/financing-cap/assurance-and-audit/managing-payments_en〉 (accessed 2.17.26).

Francaviglia, R., Alvaro-Fuentes, J., Di Bene, C., Gai, L., Regina, K., Turtola, E., 2019. ´ Diversified arable cropping systems and management schemes in selected European regions have positive effects on soil organic carbon content. Agriculture 9, 261. https://doi.org/10.3390/agriculture9120261.

Geiger, F., Bengtsson, J., Berendse, F., Weisser, W.W., Emmerson, M., Morales, M.B., Ceryngier, P., Liira, J., Tscharntke, T., Winqvist, C., Eggers, S., Bommarco, R., Pärt, T., Bretagnolle, V., Plantegenest, M., Clement, L.W., Dennis, C., Palmer, C., Oñate, J.J., Guerrero, I., Hawro, V., Aavik, T., Thies, C., Flohre, A., Hänke, S., Fischer, C., Goedhart, P.W., Inchausti, P., 2010. Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. Basic Appl. Ecol. 11, 97–105. https://doi.org/10.1016/j.baae.2009.12.001.

Giuliani, A., Baron, H., 2025. The CAP (Common Agricultural Policy): a short history of crises and major transformations of European agriculture. Forum Soc. Econ. 54, 68–94. https://doi.org/10.1080/07360932.2023.2259618.

Gliessman, S.R., 2014. Agroecology: The Ecology of Sustainable Food Systems, third ed. CRC Press. https://doi.org/10.1201/b17881. 0 ed.

Grass, I., Loos, J., Baensch, S., Batáry, P., Librán-Embid, F., Ficiciyan, A., Klaus, F., Riechers, M., Rosa, J., Tiede, J., Udy, K., Westphal, C., Wurz, A., Tscharntke, T., 2019. Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. People Nat. 1, 262–272. https://doi.org/10.1002/ pan3.21.

Guinet, M., Adeux, G., Cordeau, S., Courson, E., Nandillon, R., Zhang, Y., Munier- Jolain, N., 2023. Fostering temporal crop diversification to reduce pesticide use. Nat. Commun. 14, 7416. https://doi.org/10.1038/s41467-023-43234-x.

Halada, L., Evans, D., Romão, C., Petersen, J.-E., 2011. Which habitats of European importance depend on agricultural practices. Biodivers. Conserv 20, 2365–2378. https://doi.org/10.1007/s10531-011-9989-z.

Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T., Goulson, D., De Kroon, H., 2017. More than 75 % decline over 27 years in total flying insect biomass in protected areas. PLoS One 12, e0185809. https://doi.org/10.1371/journal.pone.0185809.

Hass, A.L., Kormann, U.G., Tscharntke, T., Clough, Y., Baillod, A.B., Sirami, C., Fahrig, L., Martin, J.-L., Baudry, J., Bertrand, C., Bosch, J., Brotons, L., Burel, F., Georges, R., Giralt, D., Marcos-García, M.Á., Ricarte, A., Siriwardena, G., Batáry, P., 2018. Landscape configurational heterogeneity by small-scale agriculture, not crop diversity, maintains pollinators and plant reproduction in western Europe. Proc. R. Soc. B 285, 20172242. https://doi.org/10.1098/rspb.2017.2242.

Jänicke, C., Goddard, A., Stein, S., Steinmann, H.-H., Lakes, T., Nendel, C., Müller, D., 2022. Field-level land-use data reveal heterogeneous crop sequences with distinct regional differences in Germany. Eur. J. Agron. 141, 126632. https://doi.org/ 10.1016/j.eja.2022.126632.

Javourez, U., Girault, B., Martin, P., Dedieu, M.-S., Therond, O., 2025. Preprint: Generic crop rotation pattern-matching algorithm revealed dominant rotational systems for France. 〈https://hal.science/hal-05242682〉.

Keichinger, O., Viguier, L., Corre-Hellou, G., Messéan, A., Angevin, F., Bockstaller, C., 2025. I-DRo: A new indicator to assess spatiotemporal diversity and ecosystem services of crop rotations. Eur. J. Agron. 164, 127531. https://doi.org/10.1016/j. eja.2025.127531.

Khoury, C.K., Bjorkman, A.D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., Rieseberg, L.H., Struik, P.C., 2014. Increasing homogeneity in global food supplies and the implications for food security. Proc. Natl. Acad. Sci. USA 111, 4001–4006. https://doi.org/10.1073/pnas.1313490111.

Krebs, J.R., Wilson, J.D., Bradbury, R.B., Siriwardena, G.M., 1999. The second Silent Spring? Nature 400, 611–612. https://doi.org/10.1038/23127.

Lécole, P., Thoyer, S., 2017. Systèmes agroalimentaires en transition, in: Systèmes Agroalimentaires En Transition. Editions Quæ, pp. 51´–70. https://doi.org/10.3917/quae.lubel.2017.01.0051.

Leteinturier, B., Herman, J.L., Longueville, F.D., Quintin, L., Oger, R., 2006. Adaptation of a crop sequence indicator based on a land parcel management system. Agric. Ecosyst. Environ. 112, 324–334. https://doi.org/10.1016/j.agee.2005.07.011.

Louhichi, K., Ciaian, P., Espinosa, M., Colen, L., Perni, A., Paloma, S.G.Y., 2017. Does the crop diversification measure impact EU farmers' decisions? An assessment using an Individual Farm Model for CAP Analysis (IFM-CAP). Land Use Policy 66, 250–264. https://doi.org/10.1016/j.landusepol.2017.04.010.

Matson, P.A., Parton, W.J., Power, A.G., Swift, M.J., 1997. Agricultural Intensification and Ecosystem Properties. Science 277, 504–509. https://doi.org/10.1126/ science.277.5325.504.

Ministry of Agriculture, 1951. Arrêté royal fixant la délimitation des régions agricoles du Royaume.

Molden, D., International Water Management Institute, Comprehensive Assessment of Water Management in Agriculture (Program) (Eds.), 2007. Water for food, water for life: a comprehensive assessment of water management in agriculture. Earthscan, London; Sterling, VA.

Overmars, K.P., Schulp, C.J.E., Alkemade, R., Verburg, P.H., Temme, A.J.A.M., Omtzigt, N., Schamiée, J.H.J., 2014. Developing a methodology for a species-based and spatially explicit indicator for biodiversity on agricultural land in the EU. Ecol. Indic. 37, 186–198. https://doi.org/10.1016/j.ecolind.2012.11.006.

Palka, M., Nendel, C., Weiß, L., Schiller, J., Jänicke, C., Gaviria, J.A., Ryo, M., 2026. Cropping history, agronomic rules, and commodity prices shape crop rotations across Central Europe. Agric. Syst. 231, 104522. https://doi.org/10.1016/j. agsy.2025.104522.

Papangelou, A., Mathijs, E., 2021. Assessing agro-food system circularity using nutrient flows and budgets. J. Environ. Manag. 288, 112383. https://doi.org/10.1016/j. jenvman.2021.112383.

Pe'er, G., Lakner, S., Müller, R., Passoni, G., Bontzorlos, V., Moreira, F., Azam, C., Berger, J., Bezak, P., Bonn, A., Hartmann, L., Kleemann, J., Lomba, A., Sahrbacher, A., Schleyer, C., Schmidt, J., Schüler, S., Sirami, C., Zinngrebe, Y.,

2017. Is the CAP fit for purpose? An evidence-based fitness-check assessment. German Centre for Integrative Biodiversity Research (iDiv), Halle-Jena-Leipzig, Leipzig.

Peeters, A., 2009. Importance, evolution, environmental impact and future challenges of grasslands and grassland-based systems in Europe. Grassl. Sci. 55, 113–125. https:// doi.org/10.1111/j.1744-697X.2009.00154.x.

Reumaux, R., Chopin, P., Bergkvist, G., Watson, C.A., Öborn, I., 2023. Land parcel identification system (LPIS) data allows identification of crop sequence patterns and diversity in organic and conventional farming systems. Eur. J. Agron. 149, 126916. https://doi.org/10.1016/j.eja.2023.126916.

Revoyron, E., Le Bail, M., Meynard, J.-M., Gunnarsson, A., Seghetti, M., Colombo, L., 2022. Diversity and drivers of crop diversification pathways of European farms. Agric. Syst. 201, 103439. https://doi.org/10.1016/j.agsy.2022.103439.

Sauquet, A., 2023. Ex post analysis of the crop diversification measure of CAP greening in France. Eur. Rev. Agric. Econ. 50, 717–742. https://doi.org/10.1093/erae/jbac022.

Schönhart, M., Schmid, E., Schneider, U.A., 2011. CropRota - a crop rotation model to support integrated land use assessments. Eur. J. Agron. 34, 263–277. https://doi. org/10.1016/j.eja.2011.02.004.

Song, X., Wang, X., Li, X., Zhang, W., Scheffran, J., 2021. Policy-oriented versus market- induced: Factors influencing crop diversity across China. Ecol. Econ. 190, 107184. https://doi.org/10.1016/j.ecolecon.2021.107184.

SPW, 2025a. Regions agricoles [WWW Document]. Etat de l´ ˏAgriculture Wallonne. URL 〈https://etat-agriculture.wallonie.be/contents/indicatorsheets/EAW-A_I_d_2.html〉 (accessed 12.8.25).

SPW, 2025b. Productions veg´ ˏetales [WWW Document]. Etat de l'Agriculture Wallonne. URL 〈https://etat-agriculture.wallonie.be/contents/indicatorsheets/EAW2.html〉 (accessed 12.19.25).

Squilbin, A., Riera, A., Vandevoorde, N., Ferdinand, M., Baret, P., 2025. Scénarios de transition pour la réduction des usages et des risques liés aux pesticides en Wallonie a l` ˏhorizon 2035. Sytra, Earth and Life Institute–Agronomy, UCLouvain, Louvain-la- Neuve, Belgium.

Statbel, 2025. Exploitations agricoles et horticoles | Statbel [WWW Document]. URL 〈 https://statbel.fgov.be/fr/themes/agriculture-peche/exploitation s-agricoles-et-horticoles#figures〉 (accessed 9.11.25).

Stein, S., Steinmann, H.-H., 2018. Identifying crop rotation practice by the typification of crop sequence patterns for arable farming systems – a case study from Central Europe. Eur. J. Agron. 92, 30–40. https://doi.org/10.1016/j.eja.2017.09.010.

Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., Van Der Heijden, M.G.A., Liebman, M., Hallin, S., 2020. Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci. Adv. 6, eaba1715. https://doi. org/10.1126/sciadv.aba1715.

Tilman, D., Clark, M., Williams, D.R., Kimmel, K., Polasky, S., Packer, C., 2017. Future threats to biodiversity and pathways to their prevention. Nature 546, 73–81. https:// doi.org/10.1038/nature22900.

Tscharntke, T., Klein, A.M., Kruess, A., Steffan-Dewenter, I., Thies, C., 2005. Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management. Ecol. Lett. 8, 857–874. https://doi.org/10.1111/j.1461- 0248.2005.00782.x.

Upcott, E.V., Henrys, P.A., Redhead, J.W., Jarvis, S.G., Pywell, R.F., 2023. A new approach to characterising and predicting crop rotations using national-scale annual crop maps. Sci. Total Environ. 860, 160471. https://doi.org/10.1016/j.scitotenv.2022.160471.

Van Maele-Fabry, G., Lantin, A.-C., Hoet, P., Lison, D., 2010. Childhood leukaemia and parental occupational exposure to pesticides: a systematic review and meta-analysis. Cancer Causes Control 21, 787–809. https://doi.org/10.1007/s10552-010-9516-7.

Van Zanten, B.T., Verburg, P.H., Espinosa, M., Gomez-y-Paloma, S., Galimberti, G., Kantelhardt, J., Kapfer, M., Lefebvre, M., Manrique, R., Piorr, A., Raggi, M., Schaller, L., Targetti, S., Zasada, I., Viaggi, D., 2014. European agricultural landscapes, common agricultural policy and ecosystem services: a review. Agron. Sustain. Dev. 34, 309–325. https://doi.org/10.1007/s13593-013-0183-4.

Vandevoorde, N., Baret, P.V., 2023. Assessing crop sequence diversity and agronomic quality in grassland regions. Eur. J. Agron. 151, 126958. https://doi.org/10.1016/j. eja.2023.126958.

Von Münchhausen, S., Häring, A., 2012. Lifelong learning for farmers: enhancing competitiveness, knowledge transfer and innovation in the eastern German state of Brandenburg. stagec 114, 86–92. https://doi.org/10.7896/j.1217.

Whippo, C.W., Coale, E., Igathinathane, C., Heintzman, L., Friedrichsen, C., Archer, D. W., 2026. Crop sequence complexity of the major land resource areas (MLRA) in the contiguous United States (CONUS). Agric. Ecosyst. & Environ. 396, 110003. https:// doi.org/10.1016/j.agee.2025.110003.

Whitmee, S., Haines, A., Beyrer, C., Boltz, F., Capon, A.G., De Souza Dias, B.F., Ezeh, A., Frumkin, H., Gong, P., Head, P., Horton, R., Mace, G.M., Marten, R., Myers, S.S., Nishtar, S., Osofsky, S.A., Pattanayak, S.K., Pongsiri, M.J., Romanelli, C., Soucat, A., Vega, J., Yach, D., 2015. Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–Lancet Commission on planetary health. Lancet 386, 1973–2028. https://doi.org/10.1016/S0140-6736(15)60901-1.

Yang, T., Siddique, K.H.M., Liu, K., 2020. Cropping systems in agriculture and their impact on soil health-A review. Glob. Ecol. Conserv. 23, e01118. https://doi.org/ 10.1016/j.gecco.2020.e01118.

Yang, X., Xiong, J., Du, T., Ju, X., Gan, Y., Li, S., Xia, L., Shen, Y., Pacenka, S., Steenhuis, T.S., Siddique, K.H.M., Kang, S., Butterbach-Bahl, K., 2024. Diversifying crop rotation increases food production, reduces net greenhouse gas emissions and improves soil health. Nat. Commun. 15, 198. https://doi.org/10.1038/s41467-023- 44464-9.