Journal of Plant Nutrition and Soil Science

WILEY-VCH

RESEARCH ARTICLE OPEN ACCESS

Hydrological Conditions Outweigh Soil Texture, Temperature, and Terrain in German Agricultural Land Use

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Received: 18 July 2025 | **Revised:** 30 January 2026 | **Accepted:** 3 February 2026

Academic Editor: Thomas Scholten

Keywords: cropland | grassland | land use | land-use change | LUC | site-specific

ABSTRACT

Background: The availability of fertile land suitable for agriculture is limited. In the European Union, political demand for self-sufficiency in staple food production currently competes with increasing ambitions for nature restoration and green energy. Meanwhile, the overall agricultural area shrinks due to land sealing. This makes an efficient use of land area essential.

Aims: With Germany as a case study, we determined which soil, terrain, and climate properties govern current agricultural land use and historic land-use change (LUC) to inform future land-use decisions.

Methods: Using data from the 3104 sites of the German Agricultural Soil Inventory, we defined land-use categories based on 100-year histories for permanent cropland, permanent grassland, and conversions between cropland and grassland. Conditional inference forest models used static edaphoclimatic variables to predict land-use type likelihood.

Results: Low precipitation, deep groundwater, or Luvisol or Cambisol soils favored the centennial continuous use of land as cropland. High precipitation, shallow groundwater, or Gleysol/Fluvisol/Histosol soils favored permanent grassland. LUC sites showed drivers similar to their destination permanent land use. For example, the likelihood of cropland-to-grassland conversion increased with higher precipitation and showed sharp increases, especially on land with mean annual precipitation >900 mm y^{-1}, whereas slope terrain was of secondary importance.

Conclusions: Land use in Germany largely depends on factors related to hydrological properties (i.e., precipitation and drainage properties) rather than soil texture, temperature, and terrain per se. The patterns outlined in this study provide novel insights into how differences in site properties affect land use and can be used to inform future LUC priorities.

1 | Introduction

Driven by the increasing need for biomass from a limited land area, Central European agriculture has intensified since the mid-19th century, similar to other industrialized countries, but especially since the mid-1950s (Gömann and Weingarten 2018; Jepsen et al. 2015). Increased intensity of arable land comes alongside crop management techniques (e.g., mineral fertilization and application of agrochemicals for plant protection) that aim to enhance crop yield per unit area (Mueller et al. 2012). Grasslands, meanwhile, historically have been converted from seminatural grasslands with low management intensity in favor of more productive managed meadows and pastures (Krause and Culmsee 2013; VELA 2014). About half of German landmass is used for agriculture (Destatis 2019), the majority of which has undergone major land-use changes (LUC) in the past (Emde

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et al. 2024). Previous research has attributed these changes to institutional (land reforms, reclamation, subsidies, protections, etc.), technological (advances in fertilization and machinery), and socioeconomic factors (changes to market demand, historical events, etc.; Jepsen et al. 2015; Meyer and Früh-Müller 2020; Niedertscheider et al. 2014). There is, however, a lack of quantitative and representative assessments of environmental drivers explaining land use and LUC.

The specific terrain, climate, and pedology of a site all play an important role in enhancing, inhibiting, or mediating the effects of management on agricultural areas. For example, landscape features such as slope and elevation can affect the ease of management and likelihood of flooding, irrespective of soil texture. This is particularly evident in lowland areas that are often near bodies of water with relatively high groundwater levels (Miura et al. 2022). Climatic characteristics, meanwhile, directly impact the plant-available water and evapotranspiration (Lambers et al. 2008). Excess water, however, can make it difficult to manage fields, increase the risk of soil compaction, erosion, and crop disease, and increase the risk of crop rot (Hess et al. 2020; Rosenzweig et al. 2002). Soil compaction inhibits root proliferation and thereby has the potential to limit crop yield; crop rot and disease can ruin whole harvests; and waterlogged fields may be inaccessible to heavy machinery. Consequently, it is likely that a combination of numerous site characteristics governs land use.

Agricultural manuals in Germany offer a qualitative characterization of the site characteristics common to cropland and grassland, but these descriptions are limited in their utility for land-use modeling and planning in the face of ongoing land-use conflicts (VELA 2014). Agricultural area in Germany has lost approximately 77,000 km^2 (22% of German land area) to soil sealing and afforestation since the late 19th century (Niedertscheider et al. 2014); a trend that competes with agricultural land requirements and is not likely to change course in the near future. Transportation networks in Germany continue to expand—as do efforts to re-nature ecologically valuable areas. Meanwhile, plans for greatly expanded construction of ground-mounted photovoltaics and increases in set-aside land due to agricultural extensification policies increase the need for area (Osterburg et al. 2023). Simultaneously, dietary shifts toward more plant-based foods may shift land-use priorities further in the future (Stahl et al. 2009).

As ongoing climate change shifts temperature and precipitation patterns and demand for limited land area forces difficult decisions, understanding which, and to what degree, edaphoclimatic properties influence land use and having the ability to model efficient land use will become increasingly important to developing effective land-use strategies. Historical uses of current agricultural land can enable us to better understand land-use suitability. Using data from sites of the German Agricultural Soil Inventory alongside data on 100 years of land-use history, we applied data-driven modeling techniques to (1) explain site properties of cropland and grassland in Germany, (2) determine which edaphoclimatic site properties drove LUC in present German agricultural sites, and (3) discuss potential priority areas for future LUCs.

2 | Materials and Methods

2.1 | Study Area

German agricultural land extends across a wide range of edaphoclimatic conditions (Table 1). Croplands (70% of agricultural area) are largely cropped with cereals (wheat and barley), canola, and maize, whereas grasslands (28% of agricultural area) are predominantly intensively managed pastures (58% pasture, 42% meadow). The remaining 2% are perennial cropping systems like orchards and vineyards (Destatis 2019; Food and Agriculture Organization 2022). Cambisols account for the largest portion of soil types for agricultural sites (27%), followed by Stagnosols (13%) and Chernozems/Phaeozems (13%; Poeplau et al. 2020).

2.2 | Data Sources

Data used in this study were gathered from an 8 × 8 km^2 grid as part of the first German Agricultural Soil Inventory (Bodenzustandserhebung Landwirtschaft; Poeplau et al. 2020). Each of the 3104 data points represents a composite sample from a single farm/site within that 8 × 8 km^2 area. Static site features used to characterize current edaphoclimatic conditions in this study were split into three broad categories: pedology, terrain, and hydrology. Pedological features were limited to variables that are not impacted by land use (soil texture and World Reference Base [WRB] soil group). Sand (63–2000 μm), silt (2–63 μm), and clay (<2 μm) contents were determined by the pipette method as described by Poeplau et al. (2020). Soil group was determined according to the German soil classification system by field surveyors and converted to WRB soil groups for the purposes of this study. Terrain features (slope, aspect, relief type, and elevation) were mostly recorded directly in the field at the time of sampling; elevation, however, was extracted from open-source rasterized data from the Federal Agency for Cartography and Geodesy (BKG 2021). Hydrological features were groundwater and climate data. Groundwater levels were measured at the time of sampling, typically post-harvest. Climate variables were extracted from 30-year average (1981–2010) climate raster (mean annual precipitation and temperature) from the open data server of the German Meteorological Service using site coordinates (DWD Climate Data Center 2018a, 2018b). Monthly and seasonal climate data were not included in the final analyses because of their high correlations with annual mean values. All included feature pairs showed Spearman rank correlation coefficients <0.7.

Per-site land-use histories were established using a combination of questionnaires filled out by farmers at the time of soil sampling, historical land-use/land cover maps, *ortho*-photos, and, for the more recent decades, high resolution satellite imagery (Emde et al. 2024). From these resources, land use was recorded as one of seven distinct land uses: annual crops, grassland, peatland, heathland, forest, perennial woody crops, or other. The oldest land-use/land-cover maps available at a spatial resolution that still allowed the positioning of agricultural inventory sites on the map were maps from the electoral Hanoverian survey (Kurhannoversche Landesaufnahme n.d.) from 1764 to 1786. For the late 18th and early 19th centuries, we queried maps (Meßtis-

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TABLE 1 | Range of edaphoclimatic conditions present in topsoil (0–30 cm) of agricultural sites in Germany collected from an 8 × 8 km^2 grid.

	Min	Median	Max
Mean annual precipitation	484 mm y^{-1}	738 mm y^{-1}	2462 mm y^{-1}
Mean annual temperature	4.4°C	9.5°C	11.5°C
Clay content	0.7%	17.1%	87.1%
Silt content	0.9%	34.5%	87.4%
Sand content	0.7%	40.4%	98.1%
Slope	0°	1.5°	35.0°
Elevation	−1.6 m	141.8 m	1482.4 m

Note: Clay, silt, and sand contents are given in mass percent of fine soil <2 mm.

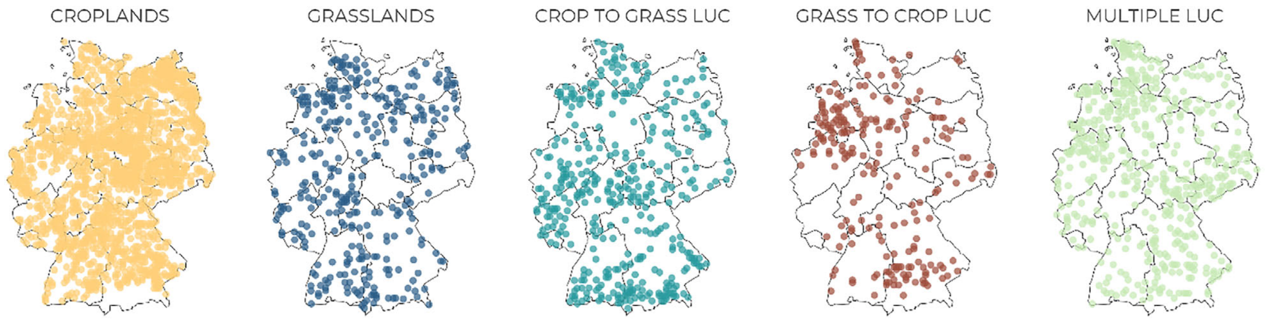

FIGURE 1 | Locations of sites with permanent cropland land use, permanent grassland land use, sites that have undergone LUC from cropland to grassland or grassland to cropland, and sites that have undergone multiple instances of LUC in the last 100 years. LUC, land-use change.

chblätter) for each inventory site at the scale of 1:25,000 (e.g., the Preußische Landesaufname) via various platforms provided by SLUB Dresden, arcanum.com, and archives of individual Landesämter (Arcanum Karten—Das Portal für Historische Karten n.d.; SLUB Dresden n.d.). For the period after World War II, we accessed historic topographic maps and *ortho*-photos as provided via individual Landesämter, for example, the online BayernAtlas for Bavaria (BayernAtlas n.d.). Google Earth was queried for recent high resolution satellite imagery. As many qualifying historical maps as possible were obtained for each region with a minimum goal of one map per 30 years for the 120 years prior to sampling. The extent of site-specific land-use histories obtained from farmer questionnaires during our inventory was highly variable but averaged 40 years of land-use history for the sampled areas.

Each time series was harmonized using a nearest neighbor approach, whereby unknown years are filled with the nearest known land use. For example, if for a given inventory site there was one map from 1940 showing cropland use, and the next available map for 1960 showed grassland use, we assumed that the LUC occurred in the middle, that is, in 1950. Plausibility checks were conducted where necessary to evaluate recent land uses using soil profile photos and soil survey data (e.g., the presence of plow horizons).

The most recent 100 years of these histories were then used to determine which of six LUC types each site falls into: permanent cropland, permanent grassland, sites that have undergone LUC from cropland to grassland, sites that have undergone LUC from grassland to cropland, sites that have undergone LUC multiple times between cropland and grassland, or sites that have non-agricultural land-use histories (Table 2, Figure 1). Sites that underwent LUC between cropland and grassland more than once were only included in a prior exploratory analysis and post hoc site suitability assessments but were excluded from data-driven models because of too many convoluting factors (e.g., number of instances of LUC, initial land use, and current land use) that hindered further in-depth analyses.

2.3 | Data-Driven Modeling

Understanding the factors that govern land use and historic LUC is a complex, multivariate problem that is difficult to assess with univariate feature comparisons. Although we can examine individual site characteristics to assess how they differ between land-use types, this would fail to capture the interactions between factors and would ultimately only allow us to characterize land-use types, rather than understand which factors are most important to each (Figure 2). Also important is the marginal effect of such factors on the likelihood that a site has a particular land use. Determining relative importance of site properties and how different levels of those properties affect land use (i.e., marginal effects) requires more complex model types.

Therefore, in this study, we went beyond univariate comparisons and used a decision-tree algorithm to explain land use and LUC as a function of the edaphoclimatic features introduced in Section 2.2. Tree-based algorithms are often used when the aim is some form of classification (i.e., categorical or binary predictions), particularly when understanding which factors drive

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TABLE 2 | Land-use type definitions based on the past 100 years of land-use history.

	n	Definition
Permanent cropland	1609	Sites that have been continuous cropland for the past 100 years
Permanent grassland	346	Sites that have been continuous grassland for the past 100 years
Cropland to grassland LUC	391	Sites that have undergone a single instance of LUC from cropland to grassland in the past 100 years
Grassland to cropland LUC	218	Sites that have undergone a single instance of LUC from grassland to cropland in the past 100 years
Multiple LUC	492	Sites that have undergone multiple instances of cropland and grassland LUC in the past 100 years (excluded from modeling)
Other	48	Sites that are currently cropland or grassland but have non-agricultural land use in the past 100 years (excluded from analysis)

Abbreviation: LUC, land-use change.

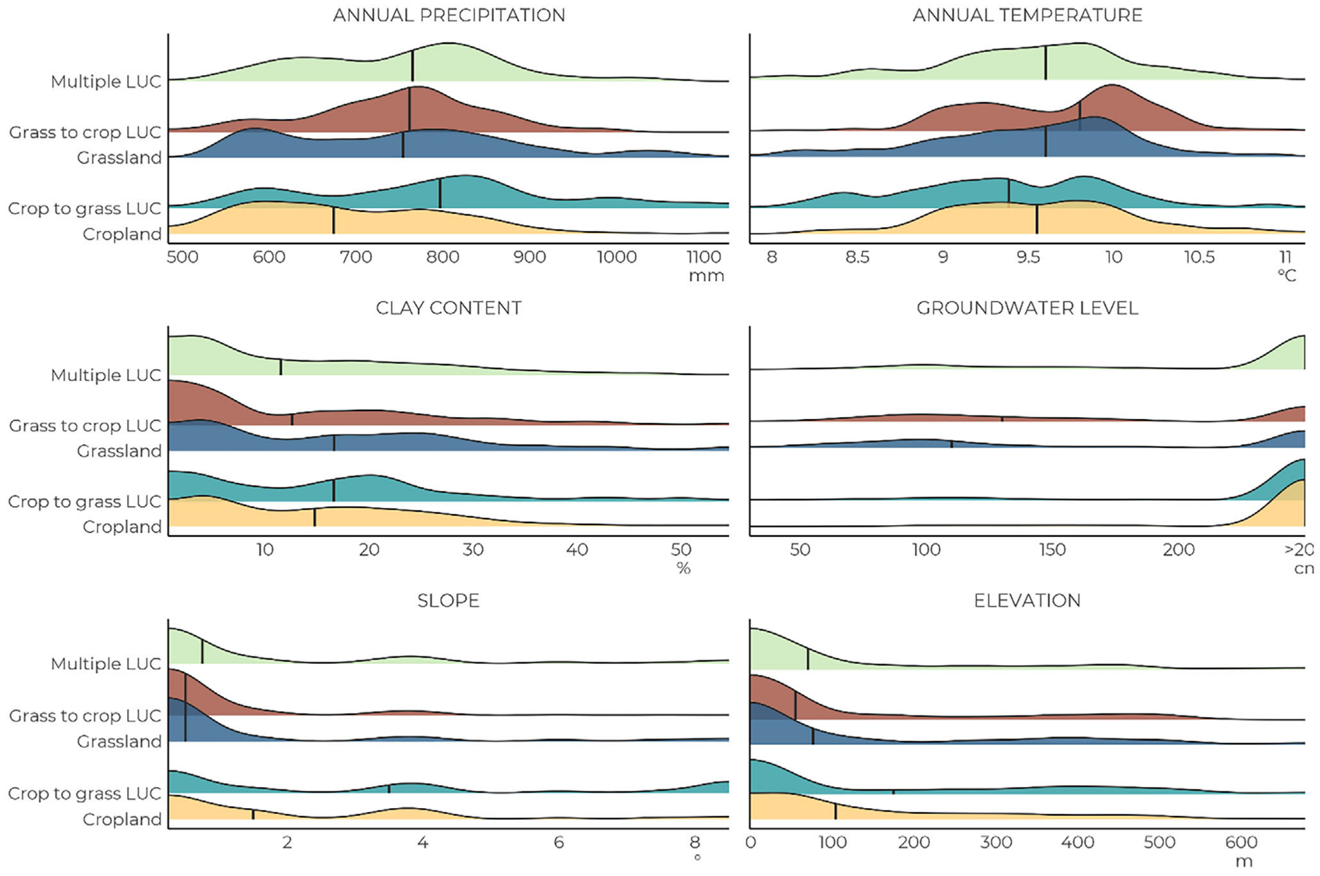

FIGURE 2 | Distribution of important numerical edaphoclimatic variables included in models for all LU types. Outliers were trimmed for readability, and, therefore, the extremes may not coincide directly with the values in Table 1. Extreme values were not, however, removed from the models. Median values are shown by the grey vertical line. LUC, land-use change.

the classification is important. Traditional tree-based models, however, are often biased toward categorical predictors when mixed numeric, and categorical predictors are included in model training; particularly when categorical predictors include many factor levels (Strobl et al. 2007). Conditional inference forest models avoid this bias by implementing multiple statistical stopping criteria and by separating the process of selecting the best predictor to split on from the selection of the best split point (Nasejje et al. 2017). Three conditional inference forest models (ntree = 500, but otherwise default parameters) were trained: one for cropland and grassland, one for cropland to grassland conversion, and one for grassland to cropland conversion (*cForest* from the *partykit* R package; Hothorn, Buehlmann, et al. 2006; Hothorn, Hornik, et al. 2006; Strobl 2009; Strobl et al. 2008; Zeileis et al. 2008).

We used these models to generate binary predictions, where a site was either the LU type of interest or a reference LU

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type. For the grassland model, the reference LU was cropland, whereas for the two LUC models, the reference LU depended on the pre-LUC land use: permanent cropland for the cropland to grassland LUC model and permanent grassland for the grassland to cropland LUC model. This allowed us to capture the overall character of German cropland and grassland and understand what influenced LUC in the past. Balanced accuracy was used as a simple performance indicator, calculated as the average of sensitivity (true positive rate) and specificity (true negative rate). With imbalanced datasets (i.e., when there are many more of one land use than the other) balanced accuracy represents the ability of the model to genuinely distinguish between categories rather than just favoring the more frequent one. The grassland to cropland LUC model performed best (balanced accuracy of 0.88), but all models performed well: Balanced accuracy was 0.83 for the permanent cropland and grassland model and 0.77 for the cropland to grassland model.

All models were interpreted by permutation importance and partial dependence plots. This allowed us to determine which features were most important to LU type classification (permutation importance), and to understand how the features included in the model affect the likelihood that a site is one of the four LU types modeled (partial dependency). Permutation importance was determined from the conditional inference forest models by computing the accuracy before and after conditionally permuting the out-of-bag values of each feature on a tree-wise basis (Debeer and Strobl 2020). Partial dependence plots were then produced for the three most impactful features to show the marginal effect of these predictors on the likelihood of a site being categorized as the target LU type (*partial* from the *pdp* R package (Greenwell 2017)). In order to compare with textbook numbers for land use, we used a statistical approach to determine demarcation lines: the point at which a site is more likely to be the target LU than the baseline LU. These demarcation lines were calculated as the proportion of the target LU type among all sites in the model:

$$\text{LU demarcation} = \frac{\text{number of sites of target LU}}{\text{number of all sites in the model}}. \quad (1)$$

Predictor values above the demarcation line are found with increasing frequency in sites of the target land use. These lines were added to the partial dependence plots.

In order to determine which sites were well suited to alternative land uses, we then applied the model trained on the permanent land uses to sites that are currently under the alternate land use. The permanent grassland model was applied to permanent cropland sites and sites that had undergone LUC from grassland to cropland. The permanent cropland model was applied to permanent grassland sites and sites that had undergone LUC from cropland to grassland. Results from these models were used in two ways: binary classification and continuous probabilities. Binary classifications were used to show that current cropland sites were identified as grasslands and vice versa. Continuous outputs, meanwhile, showed the suitability of sites for cropland or grassland use.

Density plots for visualization of numeric site characteristics (Figure 2) were generated using the *geom_density* function with default parameters from *ggplot2* (Wickham 2016). All analysis and modeling were carried out using R (R Core Team 2024).

3 | Results

3.1 | Cropland and Grassland Site Characteristics

Groundwater level, WRB soil group, and mean annual precipitation played the biggest role in determining whether German agricultural land was used as cropland or grassland (Figure 3, Figure S1). As mean annual precipitation increases, sites are more likely to be grassland and less likely to be cropland. Above about 800 mm y^{-1} of precipitation, sites were more likely to be grassland than cropland. Agricultural sites on Gleysols, Fluvisols, and Histosols were far more likely to be grassland than cropland, and sites on Cambisols, Luvisols, and Chernozems were far more likely to be croplands. Finally, sites with groundwater levels closer to the surface were more likely to be grassland, whereas below about 150 cm groundwater depth, sites were more likely to be cropland.

3.2 | LUC Site Characteristics

The most important factors that governed historic LUC from cropland to grassland were mean annual precipitation, slope, and elevation (Figure 4, Figure S2). Above approximately 800 mm y^{-1} precipitation, historic cropland sites are more likely to have been converted to grassland than to remain cropland. The same is true with increased slope and elevation. There is also, however, a higher likelihood of conversion to grassland at very low elevations.

WRB soil group, slope, and mean annual temperature, meanwhile, are the most important factors that govern LUC from grassland to cropland (Figure 5, Figure S3). Grasslands on Anthrosols, Gleysols, and Fluvisols were more likely to be converted to cropland than those that remained grassland. Counter to LUC in the opposite direction, less sloped sites were more likely to be converted to cropland. Finally, under higher temperatures, the likelihood that a grassland site was converted to cropland also increased. Above approximately 10°C, grassland sites were more likely to be converted to cropland than remain permanent grassland.

3.3 | Site Suitability for Alternate Land Use

Given the pedological, terrain, and hydrological properties of a given site, they may be well suited for the alternate land use (Figure 6). For example, if cropland sites currently reside in areas with high precipitation and shallow groundwater, they reside in conditions suited to grassland use. This was the case for 129 croplands (6% of current cropland sites), primarily in the northwestern and hilly southern grassland cultivation areas. Similarly, there were 529 grassland sites (59% of current grassland sites) scattered throughout central Germany with edaphoclimatic properties of croplands, thus suitable for cropland use.

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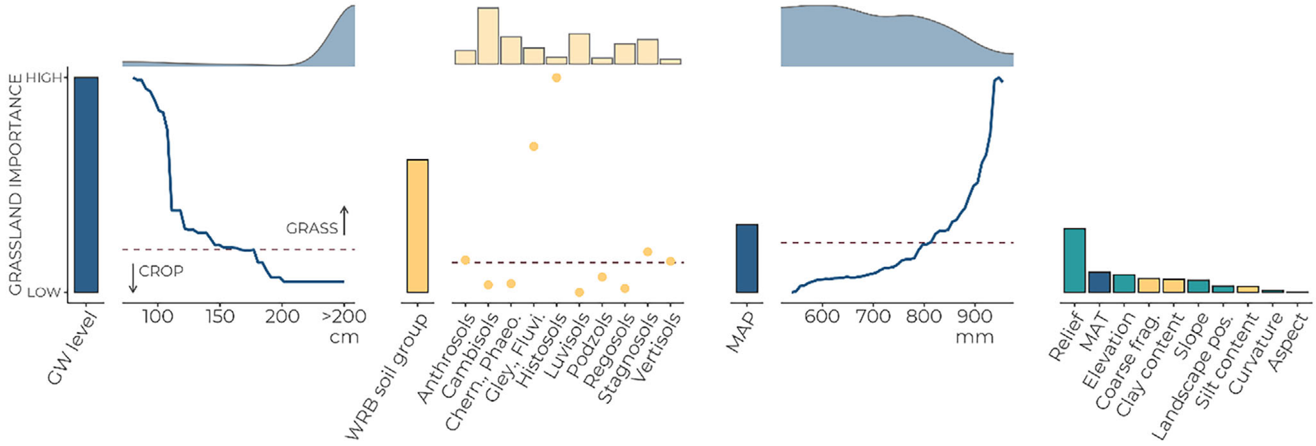

FIGURE 3 | Properties explaining permanent grassland use. Three outcomes are shown: (1) the relative importance of all factors—shown by large bars in the main body relative to each other across the whole figure; (2) the marginal effect of the three most important factors on model outcome—shown next to importance bars (groundwater level, WRB soil group, and mean annual precipitation); and density plots showing the relative distribution of values within the area of applicability of the grassland model—shown above the marginal effects as either a histogram (categorical factors) or a curve (numeric factors). Hydrological factors are shown in blue, terrain in teal, and pedology in yellow. The dark red, dashed, line denotes the point at which sites are more likely to be either grassland (above the line) or cropland (below the line) based on site properties. WRB, World Reference Base.

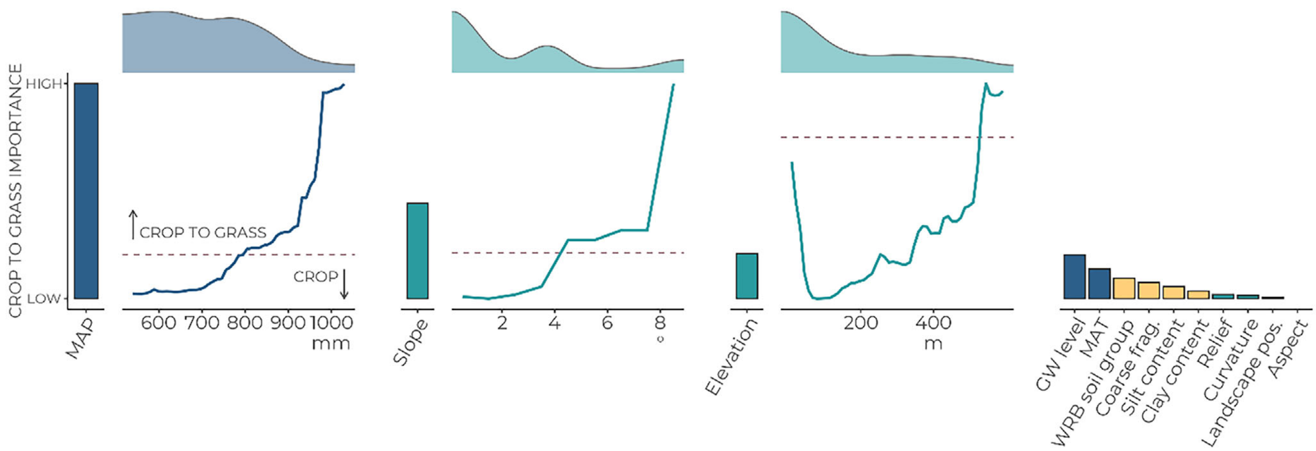

FIGURE 4 | Properties explaining LUC from cropland to grassland. Three outcomes are shown: (1) the relative importance of all factors—shown by large bars in the main body relative to each other across the whole figure; (2) the marginal effect of the three most important factors on model outcome—shown next to importance bars (mean annual precipitation, slope, and elevation); and density plots showing the relative distribution of values within the area of applicability of the cropland to grassland LUC model—shown above the marginal effects as either a histogram (categorical factors) or a curve (numeric factors). Hydrological factors are shown in blue, terrain in teal, and pedology in yellow. The dark red, dashed, line denotes the point at which sites are more likely to have undergone cropland to grassland LUC than remain cropland based on site properties.

Of the cropland sites well suited for grassland use, the majority of them (50%) are sites that have already undergone LUC from grassland to cropland once in the past. Present-day cropland sites with multiple instances of LUC in the past account for 35% of the sites well suited to grassland use, and permanent croplands only account for 15%.

The majority of present-day grassland sites well suited for cropland use are, similarly, single LUC sites (55%). Permanent grassland sites account for 25% of the sites well suited to cropland use, and grassland sites with a history of multiple instances of LUC account for 20%.

4 | Discussion

Factors related to the hydrological properties of sites were largely responsible for determining if a site was permanent cropland, permanent grassland, or had changed between the two at some point in the past (Figures 3–5). Where annual precipitation was high or the groundwater level was closer to the surface, a site was less likely to be cropland and more likely to be grassland. Because of frequent defoliation in German pastures and meadows, common grass species like *Lolium perenne* and *Poa pratensis* tend to form very dense root systems near the soil surface and require more frequent recharge to remain productive (Auerswald and

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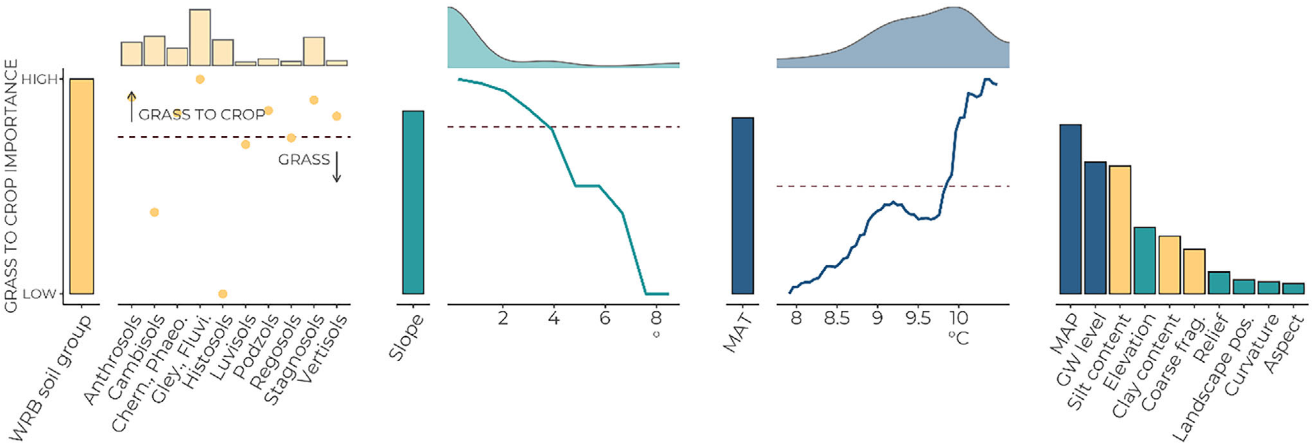

FIGURE 5 | Properties explaining LUC from grassland to cropland. Three outcomes are shown: (1) the relative importance of all factors—shown by large bars in the main body relative to each other across the whole figure; (2) the marginal effect of the three most important factors on model outcome—shown next to importance bars (WRB soil group, slope, and mean annual temperature); and density plots showing the relative distribution of values within the area of applicability of the grassland to cropland LUC model—shown above the marginal effects as either a histogram (categorical factors) or a curve (numeric factors). Hydrological factors are shown in blue, terrain in teal, and pedology in yellow. The dark red, dashed, line denotes the point at which sites are more likely to have undergone grassland to cropland LUC than remain grassland based on site properties.

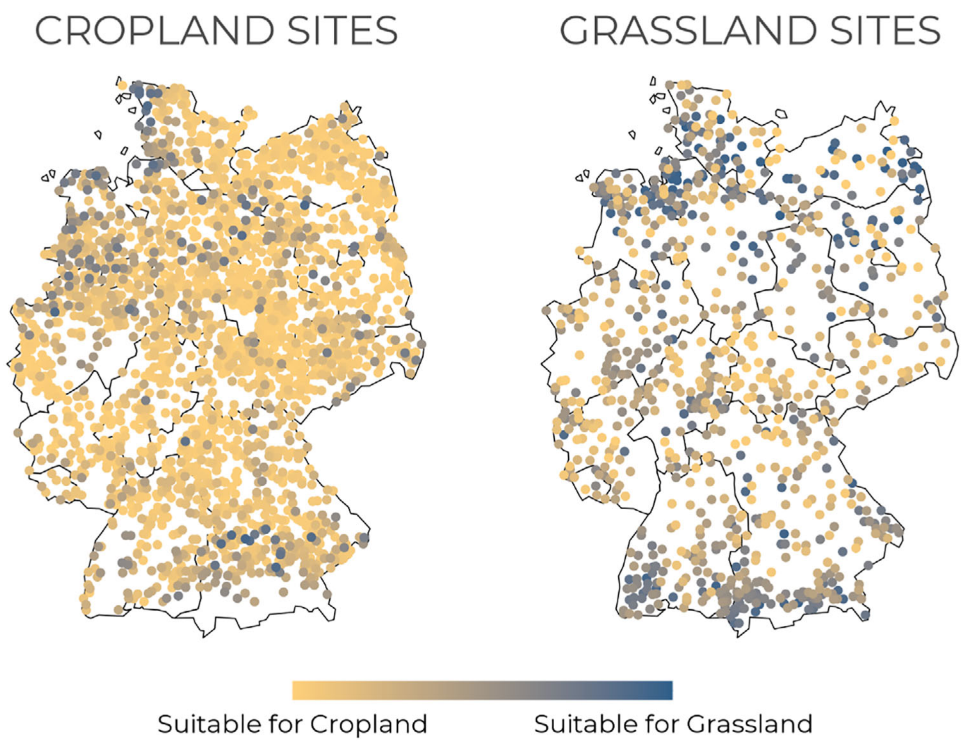

FIGURE 6 | Suitability of current cropland and grassland sites for use as the alternate land use based on current and historic land-use decisions by farmers (i.e., not necessarily the environmentally or agronomically optimal). The color gradient reflects relative suitability for each land use: the darker the blue, the more suitable a site is for grassland use, whereas increasingly yellow sites are more suitable for cropland use.

Schnyder 2014). This network of fine roots enhances grassland soil structural stability and resists trafficability issues of wetter soils (van der Ploeg et al. 1999). Croplands, by contrast, tend to grow annual crops that require dryer conditions and have root systems that turn over with harvest (VELA 2014). Enhancing productivity and avoiding potential difficulty of agricultural management associated with overly wet soils is, therefore, likely at the root of land-use decisions.

4.1 | Cropland Site Characteristics

Permanent cropland sites tended to have low to moderate mean annual precipitation, deep groundwater levels, and were largely Cambisols (Figure 3). Although water is integral to crop growth, excess water—as with abundant precipitation, waterlogging, or shallow groundwater—can result in soils that are inaccessible to heavy machinery. Wet soils are also less resistant to mechanical

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compaction (Chowdepalli et al. 2024; Mesri and Feng 2014), and saturated soils are prone to anoxic conditions (Patra et al. 2024), inhibiting root growth, nutrient uptake, and, consequently, crop productivity (Lynch and Wojciechowski 2015; McKenzie 2012; Pedersen et al. 2021). In areas with very high precipitation, arable farming (apart from silage maize cultivation) is problematic due to the high risk of fungal crop diseases and the danger of grain lodging (VELA 2014). By contrast, lower annual precipitation has the potential to stunt plant growth in nonirrigated croplands by limiting plant-available water (Lambers et al. 2008). The relatively high porosity and loamy texture typical of Cambisol soils may help mediate these tradeoffs by striking a balance between sufficient drainage to reduce the potential of hydrological issues and adequate soil moisture retention to support crop growth (Grčman et al. 2023).

A study by Peppler-Lisbach (2003) that assessed how landscape properties influenced land use between two discrete time periods (1850 and 2000) in the Hessen region of Germany similarly found that cropland sites tended to be found on flat, low-elevation areas without floodplain sediment. This study used logistic regression and raster-based geodata to determine how important a factor was (odds ratios) to each land use 150 years ago and in the year 2000. Mechanistic the drivers and occurrence of LUC were derived from the changes in odds ratios of specific factors between the two time points. By comparison, the method used here accounted for the full range of edaphoclimatic conditions in Germany utilizing known per-year land-use histories. This allowed us to evaluate the importance and relationship of each factor to land use and LUC directly.

4.2 | Grassland Site Characteristics

In Germany, most (95%) of the total grassland area is subject to intensive management, either through heavy grazing or frequent cutting with the harvested grass being exported as roughage for livestock elsewhere (Destatis 2022). Unlike croplands, grassland productivity increases with increasing precipitation (Dietrich et al. 2021; Hossain and Beierkuhnlein 2018). Following defoliation, whether by grazing or cutting, grasslands require substantial amounts of plant-available water to regenerate their above-ground biomass and restore photosynthetic activity. However, the regrowth of above-ground biomass in defoliated grasslands is limited by the availability of assimilates, which in turn restricts the allocation of resources to root growth (Auerswald and Schnyder 2014). As a result, the root biomass and rooting depth of intensely managed grasslands are often reduced, making them even more susceptible to drought stress, as they have limited access to water stored in deeper soil layers. Thus, the constant availability of plant-available water—supplied either via shallow groundwater or high precipitation—is crucial to support the productivity of German grassland.

A productive grassland provides consistent ground cover which, coupled with dense root systems near the soil surface, helps prevent negative effects of elevated water content on the compaction risk of the soil that would otherwise occur under similar conditions in cropped soils (Dietrich et al. 2021; Herz et al. 2017). Generally, permanent grasslands tend to exhibit site characteristics that make them less suitable for cropland use. Groundwater levels tend to be much closer to the surface, reducing the availability of unsaturated soil in the rooting zone and exacerbating fungal crop disease risk arising from the high mean annual precipitation also common in German grassland areas. It follows that permanent grassland sites are most often found on Gleysols, Fluvisols, and Histosols; soil groups typically found in lowland areas prone to water saturation.

VELA (2014) describes permanent grassland areas in Germany as having high precipitation (>1000 mm y^{-1}), high elevation, being on slopes, in areas with shallow groundwater level (<50 cm) or periodic flooding, and areas with extremely shallow soils. Although we did not find slope and elevation to be independently important to permanent grassland on a data-driven basis, they were important to sites that had undergone LUC from cropland to grassland and were, thus, grassland in present-day. That being said, grassland on sloped sites is often less intensively managed and, therefore, potentially less productive; a limitation VELA (2014) likely took into consideration (Reinermann et al. 2023). Soil shallowness was not expressly modeled here but may be partially represented by certain WRB soil types (i.e., Leptosols), slope, and elevation: soils on slopes and at higher elevations tend to be more prone to erosion, thereby limiting thickness (Petlušová et al. 2024).

4.3 | LUC Site Characteristics

Sites that have undergone LUC between cropland and grassland have, necessarily, included cropland land use at some point in their agricultural history. As such, edaphoclimatic properties are likely to be suitable for cropland use today. Compared to permanent croplands, however, they may be limited by excess water or sloped topography (Figures 2, 4, and 5). Sites that have undergone LUC from cropland to grassland tend to have high annual precipitation, much like permanent grasslands, but may be sloped or at higher elevations than croplands. The duration of the growing season decreases with increasing elevation, whereas precipitation and water availability increase (VELA 2014). With increased water comes the increased susceptibility to compaction and difficulties in trafficability by farm machinery (discussed above), an issue compounded in sloped sites. Further, sloped sites are more vulnerable to erosion and loss of nutrients due to surface runoff (Bormann 2009; Petlušová et al. 2024). Any of these factors potentially contributed to the increased likelihood of historic conversion of upland and sloped areas away from cropland use, a pattern mirrored in the literature. Studies suggest that in the latter half of the 20th century, upland croplands in Germany and the United Kingdom were increasingly converted to grassland (Hodgson et al. 2005; Peppler-Lisbach 2003; Waesch and Becker 2009; Wellstein et al. 2007). Furthermore, for Germany in particular, sloped sites and higher elevation marginal sites were sometimes converted to grassland (Peppler-Lisbach 2003).

Gleysols and Fluvisols are the most likely soil groups to have undergone change from grassland to cropland. These soil types tend to be in lowland areas with current or historic groundwater influence (i.e., proxies for historic hydrological conditions) and may have been converted to cropland alongside implementation of proper drainage (H. Radziuk and Świtoniak 2022; Monreal et al.

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1997). Historic changes to groundwater level due to mechanical interventions for flood control also altered the viability of historic riverside grasslands, making conditions more favorable for cropland use (Auerswald et al. 2019). With the exception of such interventions, it is likely that sites with high groundwater today, likewise had high groundwater 100 years ago.

Increased incidence of higher mean annual temperature at grassland to cropland conversion sites may relate to more favorable conditions for crops. Mean annual temperature is directly linked to growing degree days (GDD), a measure that has differing implications by crop and plant type, and the length of the growing season (Mourshed 2012). For example, in the absence of water and heat stress, German maize crops have the potential for slightly higher yields with higher GDD, supported by longer growing seasons (Parker et al. 2017). Increased incidence of higher mean annual temperature at grassland to cropland conversion sites may also help to mediate the typically wet conditions of these soils by increasing evapotranspiration (Tang and Chen 2017; Wraith and Ferguson 1994).

Development of agricultural technologies in 20th century has redefined the limits of arability. Although clay-heavy soils used to be too heavy for tillage, now, more powerful machinery allows for cultivation on previously prohibitively unmanageable soils (Jepsen et al. 2015; Niedertscheider et al. 2014). Perhaps more important, however, is the development of synthetic fertilizers. Mineral fertilization allowed sites that were previously considered to be low fertility (such as sandy soils) to produce yields similar to fertile soil (Ellmer et al. 2000; Šimanský et al. 2022). Advancements such as these have allowed for crop productivity to increasingly decouple from soil properties. Although agricultural drainage has been used in one form or another for centuries to millennia, too much water, as with flooding and intense rain, can still cause difficulty. As such, hydrological conditions govern land use, more often than not, in German agriculture.

4.4 | Implications for Agricultural Policy

Competing priorities place uneven pressures on the limited land area available in Germany. The German diet is progressively shifting away from meat and dairy; as such, agricultural use may shift to meet changing local food demand (Osterburg et al. 2023; Stahl et al. 2009). This suggests that grassland sites traditionally used for cattle grazing and fodder production may be available for alternate uses. In contrast, recent European Union regulations on Carbon Removals and Carbon Farming promote cropland to grassland LUC to achieve C removal from the atmosphere via SOC accrual (European Parliament, Council of the European Union 2024). Grassland systems can also help regulate extreme weather events by mitigating the impact of drought and floods on the landscape while maintaining feed and forage for livestock and biomass for biofuels (Brotherton and Joyce 2015; Hahn et al. 2021). Conversely, on the basis of land, farmers grow crops on elsewhere in Germany, some current grasslands could be utilized as cropland or to satisfy the growing ambition for photovoltaic electricity production. Furthermore, 14% of current grassland resides on drained peatland, contributing almost 50% of German agricultural greenhouse gas emissions. Rewetting a large portion of this area will be necessary to meet climate change mitigation goals (Umweltbundesamt 2024). Meanwhile, agricultural land area as a whole is decreasing due to soil sealing as a result of continued expansion of transport networks. Without the ability to gain more land, Germany's agricultural sector must use available land efficiently when meeting changing demands inevitably requires LUC (Osterburg et al. 2023).

Understanding how static site factors interact with different land uses is the first step to determining where future land-use decisions are best focused. Indeed, with climate change expected to alter precipitation and groundwater recharge patterns (Bormann 2009; Huang et al. 2010; Krysanova et al. 2005), LUC is inevitable and having a data-driven understanding of land-use dynamics affords the opportunity to identify the most suitable areas for future LUC in a changing environment. For example, with mean annual temperature likely to continue rising, there may be an increase in grassland area suitable for cropland use, should the need arise. As temperatures increase, dry spells during the growing period are likely to become more frequent (Intergovernmental Panel on Climate Change [IPCC 2023]). Higher temperatures may lower groundwater levels and allow for trafficability and crop management in previously prohibitively wet soils, such as Gleysols and Fluvisols. Even current land use could potentially be optimized in response to present-day site conditions (Figure 6). Being able to plan for these such scenarios affords the government and farmers time to invest in maintaining livelihoods while meeting food demand and environmental goals.

4.5 | Strengths and Limitations

This research focuses on how land is used in practice. However, this actual land use may deviate from the theoretical optimal land use from an environmental and agronomic point of view. The land-use histories used in this research were compiled from an extensive and detailed campaign of data collection, including decades of farmer records, land use, and land cover maps from regional authorities, and, in recent decades, satellite imagery. The resulting per-site land-use histories are unprecedented amongst national level agricultural datasets to our knowledge. When coupled with the detailed National Agricultural Soil Inventory, these extensive data allow us to investigate site permanency and historic LUC at a scale unique in the existing literature. It is important to note, however, that although the sites of the National Agricultural Soil Inventory were selected to capture the full breadth of agricultural soils in Germany presently, the LUC statistics represented by these sites may not necessarily coincide with national LUC patterns—for example, we found a smaller proportion of grassland to cropland LUC than is reported by the national authorities. The reason for this might be threefold: First, we use different definitions of land-use permanency in this research (e.g., no LUC for approximately 100 years); second, because land-use histories were incidental to site selection; and third, this research was carried out using data from current agricultural sites and, as such, cannot speak to patterns of historic LU and LUC on sites that are not currently cropland or grassland.

The edaphoclimatic explanatory variables for land use and LUC used in this study were selected because they were assumed to be constant over the past 100 years. Groundwater level may be an exception because of implementation of drainage and

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changes to water flow (discussed above); however, groundwater influence was only recorded to 2 m depth, and it is likely that many sites had groundwater levels well below 2 m depth. As such, the importance of groundwater to agricultural land use may be underestimated by our models. There is also the possibility, however low, that site factors examined here have changed, or that individual site histories have been misrepresented. The modeling approach used in this research limits the impact of any such cases by generalizing the results over hundreds of sites with the same land-use history nationwide.

Conditional inference forests use a combination of permutation testing, variance scaling, and strict significance testing to try to ensure that important variables are only selected if they show statistically significant importance beyond what could be explained by unequal group sizes. That said, no algorithm is completely immune to sample size differences. It is possible that, although the drivers we note here are accurate at the national scale, the relative importance of these factors differs at a regional level.

Finally, these site-based assessments do not necessarily consider the broader ecological picture for the area and instead refer simply to the use and characteristics of a site more-or-less in isolation.

5 | Conclusions

Using conditional inference forest modeling, we showed that land use in Germany is largely determined by hydrological properties. Permanent croplands are more likely to occur in well drained soils where precipitation is relatively low and shallow groundwater does not limit root growth and trafficability. Conversely, grasslands need wet conditions to thrive and are often found where hydrological properties would otherwise limit cropland productivity and make cropland management difficult: excessive precipitation, groundwater close to the surface, and soil types indicative of periodic flooding. These results coincide well with qualitative practical knowledge and show that agricultural land use in Germany can be quantitatively modeled with easy to obtain edaphoclimatic parameters. Furthermore, that the relative importance of specific factors (e.g., hydrological parameters vs. edaphic characteristics) is important to determining suitability for specific land uses. With limited land area and competing pressures on both cropland and grassland area, understanding these limitations is important for proactive planning of the future agricultural landscape in Germany, particularly in the face of shifting precipitation and temperature due to climate change (Supporting Information).

Acknowledgments

This project received funding from the European Union Horizon 2020 research and innovation program (grant agreement no. 862695, EJP Soil). The main dataset used in this manuscript was collected as part of the first German Agricultural Soil Inventory (Bodenzustandserhebung Landwirtschaft), which was funded by the German Federal Ministry of Agriculture, Food and Regional Identity (Bundesministerium für Landwirtschaft, Ernährung und Heimat).

Open access funding enabled and organized by Projekt DEAL.

Data Availability Statement

The data that support this study are available from the open sources referenced in the Materials and methods section. The code used to produce the statistics and figures in this article is available at Zenodo (10.5281/zenodo.16091122) and Worktree (https://worktree.ca/david.emde/drivers-LULUC-germany).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: jpln70055-sup-0001-SuppMat.docx.

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