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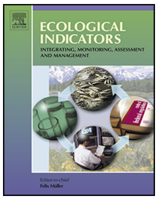

Tracking changes in the land use, management and drainage status of organic soils as indicators of the effectiveness of mitigation strategies for climate change

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ABSTRACT

The tracking of land use since 1990 presents a major challenge in greenhouse gas (GHG) reporting under the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol because there is often limited availability of data, especially for the base year of 1990. There is even less land management and soil moisture data, which are needed to track climate change mitigation activities since soil moisture is one of the main drivers of GHG emissions of organic soils. Information is also needed for the reporting of land-based activities such as grazing land management or wetland drainage and rewetting of organic soils. Different spatial and thematic resolutions of land-use data produce inconsistent time series with a strong overestimation of land-use change (LUC) if not adequately accounted for. Our aim was to create a consistent time series of land use since 1990 that is in line with GHG reporting under the UNFCCC and the Kyoto Protocol by combining official cadastral data with colour-infrared aerial photography used for biodiversity monitoring in six federal states in northern and eastern Germany. We developed a generic hierarchical classification by land use, management and drainage status, and a translation key for data harmonisation into a consistent time series. This time series enabled the quantification of LUC on organic soils between 1992 and 2013 in a spatially explicit manner. Furthermore we used this time series to develop indicators for changes in land management and drainage to evaluate the success of protection statuses on peatland restoration.

The study area encompassed one million hectares, half of which had some type of legal nature protection status. Areas with no protection status tended to become more intensively farmed and drier, while highly protected areas (*e.g.* Natura 2000) showed the opposite trend. Land-use trends also differed greatly between federal states. In Schleswig-Holstein organic soils tended to become drier during the study period, while in Mecklenburg-Western Pomerania they tended to become wetter overall. The trends and differences in LUC between federal states were linked to German reunification, changes in the European Common Agricultural Policy (CAP) and Germany's Renewable Energy Act (EEG). A large-scale peatland protection programme also had major impact.

In conclusion, our study demonstrates how data derived for biodiversity monitoring and other highly detailed land-use data can be used to track changes in land use, management and drainage status in accordance with the reporting requirements under the UNFCCC and the Kyoto Protocol.

1. Introduction

The second commitment period under the Kyoto Protocol (KP) from 2013 to 2020 offers new opportunities for accounting for greenhouse gas (GHG) mitigation by land use, land-use change and forestry (LULUCF) activities (UNFCCC, 2013). Several countries have selected eligible activities under KP, including "cropland management" (CM), "grazing land management" (GM) or the new activity "wetland drainage and rewetting" (WDR) (*e.g.* Denmark (Nielsen et al., 2015), Portugal (APA, 2015) and the United Kingdom (MacCarthy et al., 2015)). In parallel, the EU LULUCF Decision (Decision No 529/2013/EU, 2013) has introduced manda-

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tory reporting of CM and GM activities, demanding national GHG estimates from these activities in 2022. The reporting of CM, GM and WDR activities must be based on detailed activity data that track land use (LU), management and, in the case of organic soils, drainage status since or compared to 1990 (IPCC, 2014a).

In Central Europe, a large proportion of organic soils have been drained to facilitate agriculture and forestry. Drainage causes oxygen intrusion into the formerly waterlogged soils, microbial decomposition of peat and thus high carbon dioxide emissions (Maljanen et al., 2010; Tiemeyer et al., 2016). Therefore drained organic soils are a major source of GHG emissions from the sectors of agriculture and land use in many European countries (*e.g.* Lapveteläinen et al., 2007; UBA, 2015). Rewetting peatlands by raising the water level to the natural level close to the soil surfaces can initiate peat growth (=carbon sequestration) or at least substantially reduce CO_2 emissions (Wilson et al., 2016). Even accounting for increased methane emissions, rewetting of peatlands offers a high mitigation potential (Freibauer et al., 2009) for reducing GHG emissions, often at a reasonable cost and with multiple environmental benefits (Bonn et al., 2014). The modelling and reporting of GHG emissions require the detection of gross changes in LU and land-use intensity at an adequate spatial and thematic resolution (IPCC, 2014a). Land-use change (LUC) analysis by statistical data alone only allows the detection of net changes and therefore can significantly underestimate LUC (Fuchs et al., 2015). Furthermore, adequate reporting of GHG emissions and accounting for Kyoto activities (such as WDR) on organic soils are especially challenging as water table depth generally determines GHG emissions (Moore and Knowles, 1989; Tiemeyer et al., 2016). Germany currently reports GHG emissions and removals from LUC differentiating between nine land-use categories derived from the ATKIS Basic-DLM (UBA, 2015). Greenhouse gas emissions from drained organic soils are estimated based on national average emission factors by land-use category, which consider the drained area fraction in each land-use category and the drainage level (Bechtold et al., 2014) in a spatially and temporally static manner. Temporal changes in drainage status cannot yet be considered. A feasibility study at project level showed that high resolution LU and vegetation data can be used for a qualitative monitoring of peatland rewetting, but that quantitative estimates of long-term changes in mean water table depth require *in situ* measurements (Untenecker et al., 2016). Therefore suitable indicators are needed as a proxy for drainage status and changes to it over time.

Most countries face great challenges in developing adequate systems for land tracking, particularly with regard to the management intensity of grasslands and the drainage status of organic soils (Weiss et al., 2015). A further challenge is that classification keys are not constant in time or, as in Germany for example, consistent across regions within one country. As Slee and Feliciano (2015) point out, indicators for assessing climate change and climate change mitigation on rural land use have to be generated or improved. Furthermore, feasible approaches for monitoring and reporting land-based activities under KP at national level have yet to be developed.

This study aimed to demonstrate how approaches developed for biodiversity monitoring can be converted to a methodology for monitoring and reporting land-based activities under KP. In detail, we aimed to:

- develop and apply a generic classification method that converts various types of classified aerial colour-infrared (CIR) images from their original purpose of biodiversity monitoring to land-use categories in line with GM and WDR reporting requirements
- detect gross and net LUC as well as changes in the management and drainage status of organic soils in six federal states in northern and eastern Germany since 1990, for which wall-to-wall CIR images are available, and then couple them with digital landscape models of Germany
- attribute the change patterns to socio-economic and legal drivers such as nature protection status to evaluate indicators of climate change mitigation activities.

2. Material and methods

2.1. Definitions

Our definitions follow IPCC Guidelines (IPCC, 2006), the 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol (IPCC, 2014a) and the Wetlands Supplement (IPCC, 2014b).

"*Organic soils*" are defined in accordance with the IPCC (IPCC, 2006) as soils with at least 12% to 18% soil organic carbon in the upper 20 cm, depending on clay content. We used the geological map of Germany 1:200,000 (BGR, 2007) as a best approximation for organic soils. The map contains bog peat, fen peat and other organic soils. This surpasses the German peat soil classification requiring an organic horizon of >30 cm and thus includes shallow organic soils such as Histic Gleysols.

"*Land-use category*" refers to a classification of human activity according to the six IPCC land-use categories (IPCC, 2006) of forestry, cropland, grassland, wetland, settlement and other land.

"*Land-use sub-category*" (referred to below as "land use") means a refinement of the six IPCC land-use categories (*e.g.* heathland, horticulture *etc.*).

"*Management regime*" further stratifies the land-use subcategories with regard to management intensity (*e.g.* low intensity grassland) or forest type (broad-leaved, coniferous or mixed). Our datasets did not allow the detection of changes in fertiliser application, biomass export or grassland harvest dates, but did differentiate between several broad management patterns.

"*Drainage status*" is defined as the mean annual water table (IPCC, 2014a,b) whereby "deep drained" or "dry" refers to a mean annual water table more than 30 cm below the surface, and "shallow drained" or "moist, periodically wet" to intermediate conditions referring to a water table between 10 and 30 cm below the surface. "Undrained", "rewetted" or "wet" refers to a mean annual water table near or above the surface. The classifications "dry", "moist, periodically wet" and "wet" are derived from the CIR classification and are interpreted to best match the IPCC drainage classes (see Supplement A).

"*Land management type*" is the combination of land use, management regime and drainage status.

Gross changes in land use, management or drainage status cover all changes in all directions in a spatially explicit way, *e.g.* from forest to grassland plus from grassland to forest.

Net change shows the resulting net balance of all changes, *e.g.* the difference between all forest/grassland changes. For example, between two dates if four hectares of forest were converted to grassland and two hectares of grassland were converted to forest, the net change would be two hectares (gain in grassland).

To summarise potential intensification trends and water level changes across LU sub-categories, we defined an "*intensity indicator*" to indicate the quality of changes in land-use intensity and a "*drainage indicator*" for changes in soil wetness.

For the intensity indicator, cropland, settlement and horticulture were defined as the highest intensity level. Heathland, shrubs, forest, fen, bog, water body and abandoned land were defined as the lowest intensity level. Grassland use could be high or low intensity, therefore we set its intensity level to medium for datasets without information on the management regime. Additionally, the attribute "wet soil" also indicated low intensity. We set values of

Table 1
Map of study area.

Federal state	Abbreviation	Organic soils[a]			CIR records for 1992	CIR records for 2009	Reference to CIR classification
		(ha)	Proportion of organic soils in Germany (%)	Proportion of federal state's area (%)			
Brandenburg	BB	4,42,483	22.8	14.9	1991–93	2009	LUGV (2013)
Mecklenburg-Western Pomerania	MV	2,90,003	14.9	12.5	1991–92	–	LUNG (2002)
Saxony	SN	17,005	0.9	0.9	1992–93	–	LfUG (1994)
Saxony-Anhalt	ST	96,289	5	4.7	1992–93	2009	LAU (1992)
Schleswig-Holstein	SH	2,03,074	10.5	12.9	1988–91	–	LANU (without year)
Thuringia	TH	805	0.04	0.05	1993	–	TLUG (1995)
Research area		10,49,658	54.1				

[a] Organic soils derived from the geological map (1:200000) (BGR, 2007).

1 and −1 for changes between high and low intensity, where positive values indicated an increasing intensity and negative values a decreasing intensity (*e.g.* 1 for changes from bog to cropland). Negative and positive values of 0.5 were given to changes of medium intensity (*e.g.* −0.5 for changes from cropland to grassland). For an overall trend, the weighting of averages was calculated by the length (years) of each period. Thus, the more negative the result, the greater the decrease in intensity. Positive values indicated increasing intensity. Small, unclear and variable classes of "bare land" and "various" were not classified by intensity and omitted from the land-use intensity analysis.

For the "*drainage indicator*" the amount of areas that became wetter during the study period was multiplied by −1. We then calculated the average of the proportion [%] (weighted by the length (years) of each period) of areas that became wetter or drier, stratified by protection level and by federal state. Therefore positive values represented drier conditions, negative values or wetter conditions.

2.2. *Research area and spatial datasets*

The study area encompassed six federal states in north and eastern Germany: Brandenburg (BB), Mecklenburg-Western Pomerania (MV), Saxony-Anhalt (ST), Saxony (SN), Schleswig-Holstein (SH) and Thuringia (TH) (Fig. 1). Overall, organic soils in the research area covered 1,049,658 hectares (ha), which is equivalent to 54% of the total hectares for German organic soils. Brandenburg had the largest organic soil area of the federal states in the research area (Table 1). The research area was restricted to these federal states as the others do not have any wall-to-wall classified land cover datasets in an adequate spatial and thematic resolution for 1990.

2.2.1. *Land-use data*

For detecting LUC, 12 remotely-sensed datasets were used for the following years:

1992: 6 × CIR datasets (Table 1)
2000: 1 × ATKIS Basic-DLM
2008: 1 × ATKIS Basic-DLM
2009: 1 × DLM-DE and 2 x CIR datasets
2013: 1 × AFIS-ALKIS-ATKIS Basic-DLM

The CIR datasets contain biotope types from processed colour-infrared aerial photos at a resolution of at least 1:10,000 (Table 1). The ATKIS Basic-DLM (Authoritative Topographic-Cartographic Information Systems – Digital Basic Landscape Model) and the AFIS-ALKIS-ATKIS Basic-DLM (official control point information system "AFIS" – Authoritative Real Estate Cadastre Information System "ALKIS" – Authoritative Topographic-Cartographic Information Systems "ATKIS" – Digital Basic Landscape Model) (hereafter DLM) have a spatial resolution of at least 1:25,000 (AdV, 2003). Since 2008, the DLMs contain the additional attribute "wet soil", which indicates very wet areas. The AFIS-ALKIS-ATKIS-DLM was semantically translated to the older ATKIS Basic-DLM classification in line with the German greenhouse gas inventory (UBA, 2015).

The early CIR datasets were recorded between 1988 and 1993 (Table 1). As most of them were recorded in 1992, we set all datasets to 1992. The DLM is continuously updated, and thus the temporal accuracy of the different objects within one DLM dataset (except DLM-DE) is three months to five years. This is a considerable source of uncertainty for the allocation of LUCs to short time intervals (AdV, 2003), but not for total LUCs over the entire period since 1992. One exception is the DLM-DE 2009, which is based on the DLM of April 2009 and was corrected and updated by satellite images from 2009 (BKG, 2012).

2.2.2. *Protected areas*

The German Nature Conservation Law defines seven types (statuses) of protected areas with different legal restrictions for LU (BNatSchG, 2009, §23–§25, §27, §31–§36). These types substantially overlap and thus a particular land area can belong to several protection types. The six highest protection statuses of 2012 were used in this study, adding up to 530,697 ha (50.6% of the organic soils in our study area) under some degree of nature protection. These six statuses are explained in detail in Supplement B. The seventh status (landscape protection area) was not considered since it has much fewer restrictions for LU, indicating areas with special importance for recreation.

Furthermore, we grouped statuses of protected areas into "moderate" and "high" protection levels. Nature conservation areas (NC), flora-fauna-habitat areas (FFH) and special protection areas (SPA) were allocated to "high" protection levels as they have strict legal restrictions for LU. National park (NTP) areas on organic soils are almost completely (98%) included in NC, FFH or SPA. Biosphere reserves (BIO), nature parks (NP) and NTP areas outside other high protection levels were pooled into a "moderate" protection level as they are large-scale conservation areas with moderate LU restrictions.

2.3. *Workflow*

The following subchapters explain the workflow with regard to procedures for achieving specific aims, as stated in Fig. 2.

2.3.1. *Development of a common land management classification*

We created a common generic land classification key on three levels to compare the different LU datasets and develop consistent time series:

1) land-use sub-categories (LU)
2) management regime

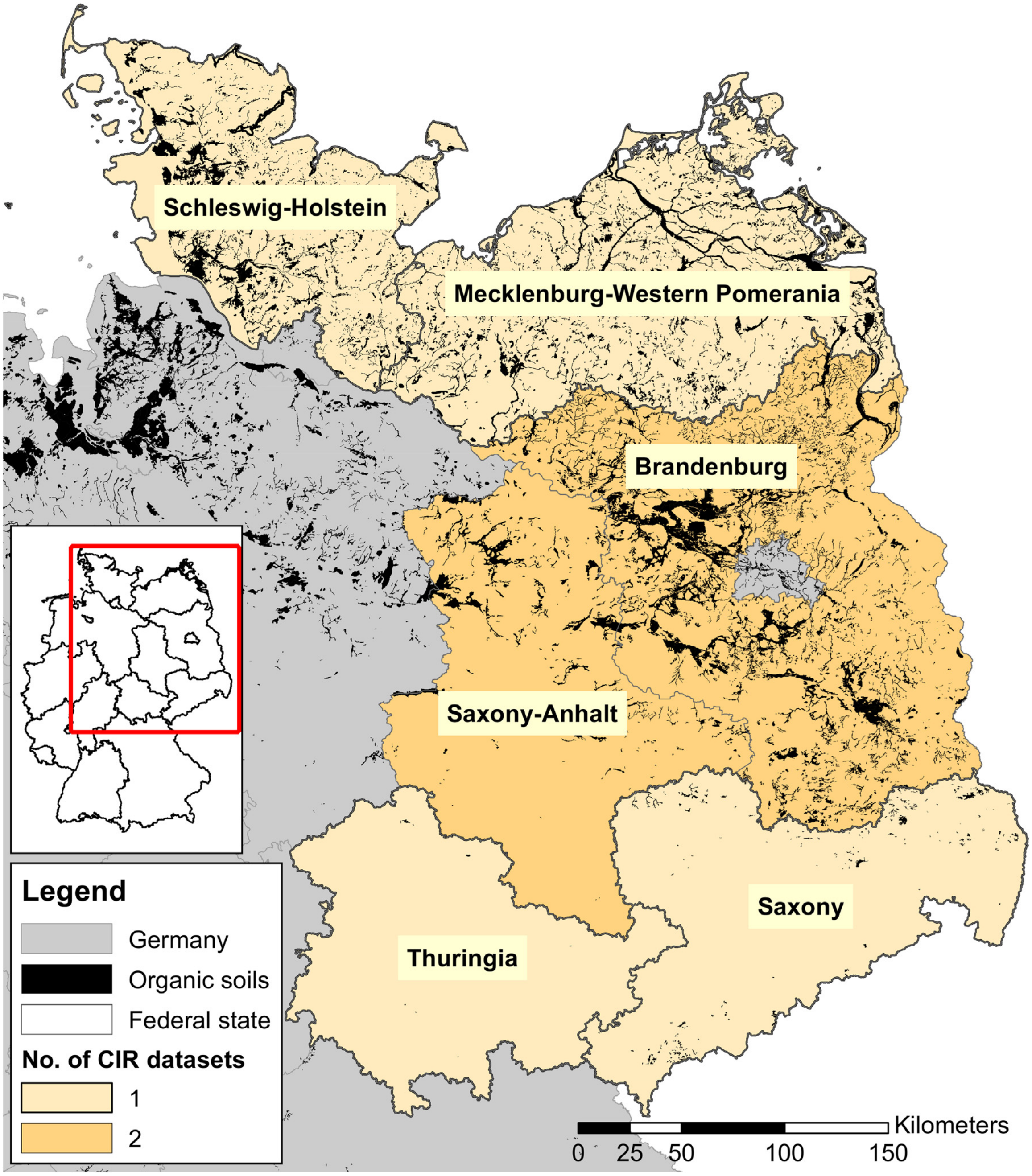

Fig. 1. The research area covering six federal states in Germany, differentiated by the number of CIR datasets.
Source: BKG (2011): VG250 (modified)

3) drainage status.

This required the following steps:

1) application of a common grid for all spatial datasets
2) reclassification of the different CIR datasets in line with the common key
3) translation of the CIR data (1992) to DLM-LU by applying the “translation key” developed by Untenecker et al. (2016).

The information in the datasets was stratified so that the classification matched the requirements for reporting under the UNFCCC and KP. Table 2 shows the applicability of the three LU stratification levels to the various land-based activities under KP.

The accounting for land-based Kyoto activities follows a hierarchical system. Reporting for ARD (afforestation, reforestation, deforestation) and FM (forest management) is mandatory under KP. CM and GM are also mandatory under the EU LULUCF Decision (Decision No 529/2013/EU, 2013), while RV (revegetation) and WDR remain voluntary. A certain land area is always reported under the mandatory or chosen Kyoto activity with the highest hierarchical level, but there is some flexibility between CM, GM and RV. WDR has the lowest hierarchical level. For example, if GM is chosen, re-wetted grassland will be reported under GM, not under WDR. However, it depends on the elected activities and to some degree on national choices as to which Kyoto activity or detected changes in LU, management regime or drainage status are accounted for at all.

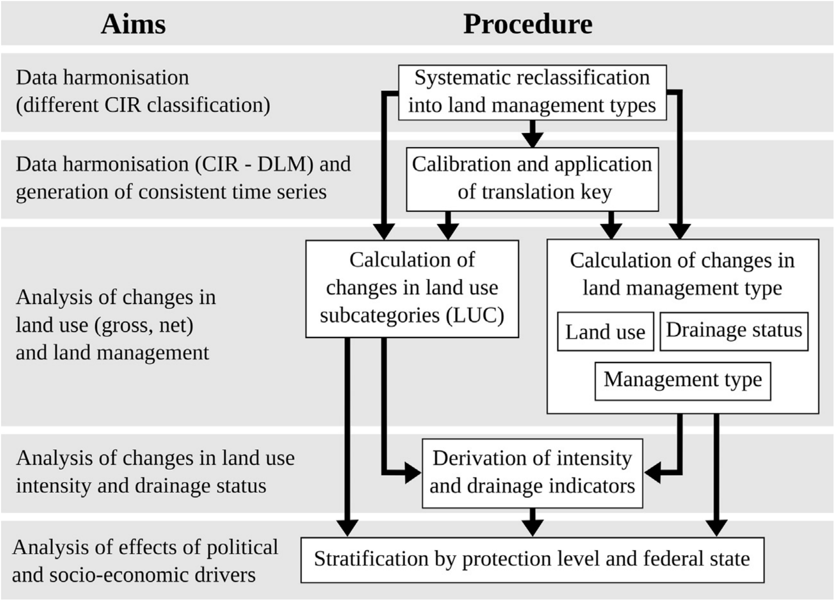

Fig. 2. Flowchart of the procedures performed.

Table 2
Facilitation of the three classification levels of land use (LU), management regime and drainage status to account for Kyoto activities (ARD = afforestation, reforestation, deforestation, FM = forest management, CM = cropland management, GM = grazing land management, RV = revegetation, WDR = wetland drainage and rewetting).

Practices	LU	Management regime	Drainage status
ARD	Yes	Limited to forest type	Yes (but not relevant in Germany)
FM	Yes	Limited to forest type	Yes
CM	Yes	Not detectable with available land-use data	Yes
GM	Yes	Yes	Yes
RV	Yes	Incomplete: limited to drastic changes in land cover associated with changes in management regime	Yes (but not relevant in Germany)
WDR	Yes	Yes	Yes

2.3.2. The grid sample approach

We applied the grid sample approach, which is one of the methodologies under the so-called “Approach 3” to derive spatially-explicit land-use conversion data found in the 2006 IPCC Guidelines (Chapter 3). The grid sample approach is common practice in constructing national LUC matrices for national GHG inventories in Europe (*e.g.* Germany (UBA, 2015) and Portugal (APA, 2015)).

A 25 m grid of sample points was applied to the original polygons to generate spatially consistent datasets. The grid density was chosen to conform to IPCC guidelines. One sample point represented 0.06 ha, which is smaller than the German definition of the minimum area of forest under KP (0.1 ha; UBA, 2015), nearly the same as the smallest spatial unit definition for assessing LUC under KP (0.05 ha) and below the minimum area of WDR of 1 ha (IPCC, 2003, 2014a). At the same time, the chosen grid-spacing reduced pseudo-LUCs that could occur because of spatial accuracy problems and technical updates of datasets (Untenecker et al., 2016).

2.3.3. Reclassification of CIR datasets

The LU classes of all our datasets had a hierarchical structure. Land use on organic soils in Germany is dominated by grasslands, croplands and forests, which are classified in as much detail as possible. Settlements are of minor relevance for Kyoto activities and were not differentiated any further. A reclassification of CIR datasets was necessary because each of the six federal states employs an individual classification system for biotope types (Table 1). All biotope types in CIR were reclassified into LU, management regime/forest type and drainage status (Table 3, Fig. C1 in Supplement C).

The reclassification was based on the description of biotope types and species given in the CIR-dataset legends according to a set of rules (Supplement A). If there was insufficient information, default classes were used (bold in Table 3). Default classes for the management regime and the drainage status reflect the predominant conditions of the respective LU. The DLM classification corresponds to LU sub-categories shown in Table 3. The DLM attribute “*wet soil*” indicated the drainage status “*wet*”. No information on management regime is available for DLM datasets.

In the CIR dataset of Schleswig-Holstein, the implementation of settlement areas was much more detailed than in all the other datasets. Therefore, some additional corrections were necessary to achieve time series consistency (see Supplement D).

2.3.4. The translation key between CIR and DLM datasets

Both the thematic resolution and the implementation of LU classes strongly differed between the CIR and DLM datasets. A translation between CIR and DLM was necessary to create consistent time series. Such a translation key was developed, tested and described in detail for a heterogeneous peatland complex of 12,758 ha (Untenecker et al., 2016), which was part of the research area. Briefly, the key calculates the proportions of each land-use class of the CIR dataset within the LU classes of the DLM dataset recorded at the same time. LUC is calculated as a shift in these proportions. Here we used reclassified records of CIR 2009 for Saxony-Anhalt and Brandenburg and DLM-DE 2009 to calibrate the translation key. Those two federal states represented 51% of the research area. For details see Untenecker et al. (2016). Even though the translation key was not fully geo-referenced, it was spatially

Table 3
Reclassification approach: stratification of land-use categories by land-use sub-category, management regime/forest type and drainage status. All datasets contain as a minimum information at the level of land-use sub-categories. Default values of management regime/forest type and drainage status used in the event of missing information are printed in bold.

Land-use category (IPCC)	Land-use subcategory	Management regime/forest type	Drainage status
Grassland	Grassland	**High intensity**	**Dry**
			Moist/periodically wet
		Low intensity	**Dry**
			Moist/periodically wet
			Wet
	Heathland	**Unmanaged**	**Dry**
			Moist/periodically wet
	Shrubs		Dry
			Moist/periodically wet
Cropland	Cropland	**High intensity**	**Dry**
	Horticulture	**High intensity**	**Dry**
Forest	Forest	Broadleaved	**Dry**
			Moist/periodically wet
		Mixed	**Dry**
			Moist/periodically wet
		Coniferous	**Dry**
			Moist/periodically wet
Settlement	Settlement	–	–
Wetland	Fen	**Unmanaged**	Moist/periodically wet
			Wet
	Bog	**Unmanaged**	**Wet**
	Water body	–	–
Other land	Abandoned land	–	–
	Bare land	–	–
	Various	–	–

explicit. Thus it was possible to quantify gross and net LUCs for each LU sub-category.

Overall, the translation key converted CIR and DLM datasets consistently because all CIR LU classes to a great extent matched the respective DLM classes, and the other LU classes occurring with small proportions were plausible (Fig. 3). Key land-management types such as different types of grassland$_{\mathrm{CIR}}$ mainly contained grassland$_{\mathrm{DLM}}$. However, there was a remarkable amount of cropland$_{\mathrm{DLM}}$ in grasslands$_{\mathrm{CIR}}$ and grassland$_{\mathrm{DLM}}$ in cropland$_{\mathrm{CIR}}$. In the CIR classes of grassland, 15% of the grassland was allocated to cropland$_{\mathrm{DLM}}$, with the wetter grassland types showing a lower proportion of cropland, while 11% of the cropland in cropland$_{\mathrm{CIR}}$ was allocated to grassland$_{\mathrm{DLM}}$. This misallocation reflects the differences in spatial and thematic resolution between CIR and DLM datasets, but also some potential classification errors, which seem to be a common problem in several remote-sensing products (*e.g.* Büttner et al., 2004).

The dry forest types of the CIR classification matched the forest category of the DLM dataset by more than 90%.

Small land-management types such as shrubs, fen and bog contain a mixture of different DLM-LU classes. This reflected the variety in the occurrence of broader LU classes such as shrubs (*e.g.* household gardens, natural peatlands *etc.*). The bog and fen areas of the CIR datasets were mainly represented by wet fen, (wet) grasslands, bog and forests, which is consistent with the most common types of land cover in near natural peatlands. Water bodies in the CIR dataset contained more than 79% of water body$_{\mathrm{DLM}}$ and smaller proportions of wet (probably riparian) vegetation types. The small land-management types of heathland were the most uncertain land-management type of the translation key as their sample size was smallest.

As already found by Untenecker et al. (2016) on a smaller scale, the DLM attribute “wet soil” is suitable for indicating wet areas. Therefore we created an additional translation key for drainage status, including the drainage status of the CIR datasets and the DLM attribute “wet soil” independently of the LU sub-categories. Indeed, a much higher proportion of “wet soil” was present in land-management types with moist/periodically wet and wet drainage status.

2.3.5. *Analysing changes in LU, management and drainage status*

LUC was analysed for the period 1992–2000 (by applying the translation key) and directly for the periods 2000–2008 and 2008–2013. All LUCs were also studied separately for areas of high (FFH, SPA or NC), moderate (NTP, NP or BIO) and no protection level (exemplary map in Supplement C (Fig. C2)).

CIR LU classes that occurred in just one federal state or were not transferable to any explicit LU sub-category, such as “coast” or “unknown”, were aggregated to the sub-category “various” (<0.5% of the study area). Thus an application of the translation key to the LU class “various” was not advisable. We fixed LUC for those areas between 1992 and 2000 at 100% to minimise underestimations.

Changes in drainage status were analysed for the periods 1992–2008 and 2008–2013. The DLM dataset of 2000 was omitted as it did not contain any information on “wet soils”.

Changes in grassland management were tracked at the level of the management regime of herbaceous grasslands (grassland and heathland) in a spatially explicit and fully geo-referenced way by using the CIR 1992 and CIR 2009 datasets of Brandenburg and Saxony-Anhalt.

All spatial operations and queries were processed by *pgAdmin III PostgreSQL Tools Version 1.20.0* (pgAdmin Development Team, 2011).

3. Results

In the first instance we describe the general distribution of the LU in the study area. Then, gross and net LUC rates stratified by protection level and federal state are shown, followed by changes in drainage status. For these results, DLM and translated CIR datasets were used. Finally, changes in grassland management intensity are presented. The latter analysis is limited to Branden-

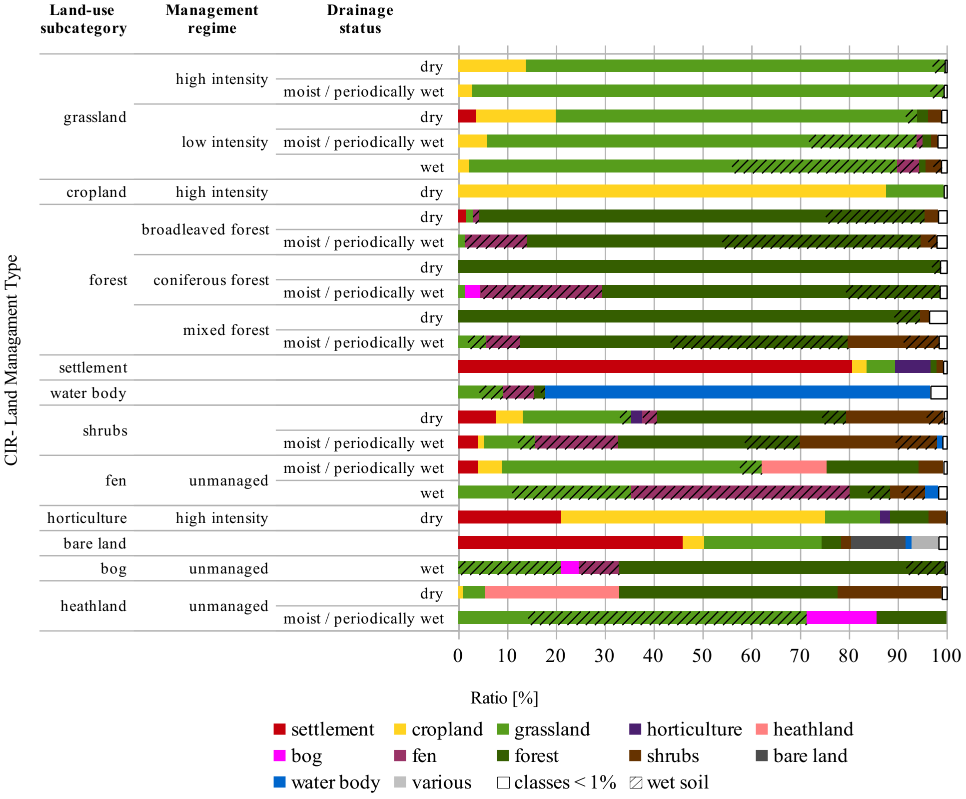

Fig. 3. The translation key shows the proportions of DLM sub-categories within each CIR land management type (x-axis). The y-axis displays ratios of the DLM-DE 2009 dataset on the land management types of the CIR 2009 dataset. For example, cropland in the CIR consists of 87.7% Cropland$_{\mathrm{DLM}}$ and 11.7% Grassland$_{\mathrm{DLM}}$ when no land-use change takes place. The order of land-use types follows the size of the land-use sub-categories in the calibration area of Brandenburg and Saxony-Anhalt. The largest classes range from 269,162 ha for grassland and 23,441 ha for settlement. Water body, shrubs and fen range from 9255 to 7193 ha. The smallest classes are horticulture (460 ha), bare land (201 ha), bog (45.3 ha) and heathland (44.8 ha).

burg and Saxony-Anhalt, using the re-classified, but un-translated CIR datasets of 1992 and 2009.

Table 4
Land use in the research area in 1992, 2000, 2008 and 2013.

Land use	Proportion of the research area [%]			
	1992	2000	2008	2013
Grassland	49.5	50.2	48.5	47
Cropland	23.2	24	23.9	24.5
Forest	15.6	14.4	15.5	15.6
Forest	4.7	3.6	3.9	4.2
Water body	2.1	1.5	1.7	1.8
Shrubs	1.7	0.7	1.3	1.2
Fen	2.4	3.6	2.8	3.2
Horticulture	0.4	0.4	0.3	0.3
Bare land	<0.1	<0.1	<0.1	<0.1
Bog	0.1	1.2	1.5	1.7
Heathland	0.1	0.1	<0.1	<0.1
Various	0.1	0.2	0.3	0.3
Abandoned land	<0.1	<0.1	0.1	<0.1

3.1. *Land use*

The dominant LU in 1992 covering nearly 50% of the research area was grassland (519,522 ha), followed by 23.2% cropland (244,000 ha) and 15.6% forest (163,756 ha) (Table 4). These three LU classes continued to dominate in roughly the same proportions (percentage cover) for the whole study period. Net LUC did not exceed 3.2%, 1.3% and 1.2% for grassland, cropland and forest respectively. The remaining LU classes covered less than 13% of the research area during the entire study period.

Settlements covered 38,026 to 49,155 ha. Fens encompassed a similar area (38,171 ha), followed by water bodies (16,109–22,446 ha) and shrubs (7080–17,803 ha). Five of the six smallest LU classes (horticulture, bare land, heathland, various, abandoned land) covered less 0.5% in total of the study area. Only bog exceeded 1% since 2000.

3.2. *Land-use change*

The lowest gross LUC but the highest net LUC occurred in the period 1992–2000 (Table 5). Relative gross LUC between 1992 and 2000 increased with protection level. Highly protected areas had the highest net LUC and the highest net-gross-ratio of 61.6%, which indicates that LUC was unidirectional in most protected areas – in this case towards lower intensity. The ratio in the period 1992–2000 for moderately protected areas was smaller than for areas without protection (Table 5).

During the second period (2000–2008), areas of moderate protection showed the lowest gross LUC and highly protected areas showed the highest gross LUC. From 2008–2013, the highest gross LUC occurred in non-protected areas. The ratios of net-gross LUC were lowest in the second period (Table 5).

While there was a net gain of grassland in the first period, areas without a protection status showed considerable grassland losses since 2000 (-1542 ha year^{-1}) (Table 6). Under moderate protection, grassland was lost in all periods, whereas in highly protected areas, grassland increased (around 1000 ha year^{-1}) from 1992 to 2000. However, the losses in the periods that followed exceeded this gain.

Cropland expanded in non-protected and moderately protected areas, but not in highly protected areas, where it reduced in the first

Table 5
Land-use change rates of each period stratified by protection level.

	Protection status	Unit	1992–2000	2000–2008	2008–2013
Gross LUC [year^{-1}]	None	%	0.9	2.1	1.4
		ha	4847	10,796	7524
	Moderate	%	1.1	2	1.1
		ha	1227	2262	1295
	High	%	1.4	2.2	1.2
		ha	5698	9316	4864
Gross LUC	None	ha	38,776	86,368	36,270
	Moderate	ha	9816	18,096	6475
	High	ha	45,584	74,528	24,320
Net LUC [year^{-1}]	None	%	0.4	0.3	0.4
		ha	2118	1807	1872
	Moderate	%	0.4	0.4	0.2
		ha	484	446	187
	High	%	0.8	0.4	0.4
		ha	3509	1844	1528
Net LUC	None	ha	16,944	14,456	9360
	Moderate	ha	3872	3568	1496
	High	ha	28,072	14,752	7640
Net-gross ratio	None	%	43.7	16.7	23.2
	Moderate	%	39.4	19.7	12.9
	High	%	61.6	19.8	24.2

Table 6
Net land-use changes in ha *year^{-1} per land-use sub-category, stratified by protection level. Positive values indicate net gain and negative values indicate net loss in ha.

Land use	Protection status	1992–2000	2000–2008	2008–2013	Weighted average
Grassland	None	87	−1472	−1629	−916
	Moderate	−122	−299	−138	−193
	High	988	−499	−1329	−130
Cropland	None	1433	455	1178	1000
	Moderate	330	20	9	135
	High	−792	−607	185	−489
Forest	None	−495	400	187	8
	Moderate	−105	254	−1	56
	High	−953	807	49	−44
Settlement	None	−741	343	335	−72
	Moderate	−73	37	119	15
	High	−577	48	24	−196
Water body	None	−241	73	70	−48
	Moderate	−31	5	15	−6
	High	−520	146	165	−103
Shrubs	None	−606	357	−19	−100
	Moderate	−136	93	3	−16
	High	−598	352	−93	−116
Fen	None	8	−233	61	−71
	Moderate	28	−135	32	−33
	High	1546	−715	717	487
Horticulture	None	48	−77	−46	−22
	Moderate	−11	−11	−16	−12
	High	−50	−7	−5	−23
Bog	None	496	−23	−2	180
	Moderate	108	4	9	45
	High	900	431	297	578
Remaining sub-categories	None	13	177	−135	41
	Moderate	11	32	−30	9
	High	57	44	−10	36

and second periods. Forests, settlement and water bodies showed the same trend at all levels of protection, reducing from 1992 to 2000, but increasing again since 2000. This growth mainly happened at the expense of grassland. Fen expanded from 1992 to 2000 and from 2008 to 2013, while in the intermediate period large areas were lost. Overall, fens increased only in highly protected areas. Surprisingly, bogs increased irrespective of the protection levels. Areas without a protection status showed a loss of bog from 2000 onwards, but the loss was smaller than the gain made in the first period (Table 6). Bogs mainly emerged from broadleaved forests and grasslands.

LUC of shrubs was variable, with a loss in the first period and overall. Horticulture gained about 49 ha per year from 1992 to 2000 in non-protected areas. From 2000 onwards and in the complete time series of moderately and highly protected areas, horticulture decreased. The category "remaining sub-categories" included heathland, bare land, abandoned land and various. These small classes changed by a maximum of −166 ha and +99 ha per year (abandoned land). None of the other values exceeded 100 ha per year.

3.2.1. Gross land-use change patterns by federal state

Schleswig-Holstein (SH), the only former West German federal state in the research area, showed the highest gross LUC in all periods and for all levels of protection (Fig. 4). Mecklenburg-Western Pomerania (MV), Brandenburg (BB) and Saxony-Anhalt (ST) showed a similar gross LUC in the first period, while between 2000 and 2008 LUC in BB was slightly higher than in MV and ST, but not nearly as high as in SH. On the other hand, BB showed the smallest LUC in the last period regardless of the protection level. In the last period, the differences between protection levels were highest for MV and ST, with the highest values in MV being found in highly protected areas. In ST, highly protected areas saw the smallest changes.

Data for Saxony (SN) and Thuringia (TH) are not shown as they had only small areas of organic soils, meaning that small changes mathematically produced high relative changes that were not comparable with the other federal states.

3.2.2. Net land-use change patterns by federal state

To interpret the trends in net LUC on organic soils by federal state, we used an "intensity indicator" (Table 7) that grouped LUC into trends of increasing and decreasing intensity by LU (Section 2.1). We gave both positive and negative values to visualise the occurrence of opposing trends (increasing and decreasing intensity at the same time within one area).

In all federal states, land-use intensity decreased in highly protected areas. This trend was strongest in MV, SN and ST. Non-protected areas underwent intensification in SH, BB, SN and ST, while in MV, land-use intensity decreased for all protection levels. Areas under moderate protection showed intensifications as well as an increase in low-intensity LU classes, depending on the federal state. Overall, TH and BB showed the smallest intensity changes. SH, the only former West German federal state, displayed the strongest intensification of LU.

3.3. Drainage status

We tested whether changes in drainage status could be directly detected independently from LU types by using a translation key solely constructed by wetness attributes. The analysis was restricted to the "wet" class as this was the only one available in both the CIR and DLM datasets (drainage status of CIR and "wet soil" attribute of DLM). About 12.7% of the land in the research area was characterised as wet (Table 8) in 2013. In 1992 wet land encompassed about 13.7% of the research area.

Differences in drainage status between protection levels showed the same patterns as in the LUC analysis. Overall, in non-protected areas, land tended to become drier from 1992 to 2008 and slightly wetter from 2008 to 2013. In contrast, in highly protected areas more land became wetter than drier from 1992 to 2008 and from 2008 to 2013 (Table 8).

Stratifying these results by federal states, patterns were also comparable with net LUC patterns. In Schleswig-Holstein more land became drier than wetter, irrespective of the protection level (Table 8). In Brandenburg, areas of high protection tended to become wetter in the first period (1992–2008), but showed an opposite trend in the period from 2008 to 2013. In Saxony-Anhalt, non-protected areas tended to become drier, but highly protected areas tended to become wetter. Mecklenburg-Western Pomerania on the other hand tended to become wetter in highly protected areas, and even in non-protected areas. The trend in moderately protected areas remained unclear.

3.4. Relationship of land-use intensity and drainage status

To test whether net changes in land-use intensity corresponded to net trends in drainage status, we combined the results of Sections 3.2.2 and 3.3. Fig. 5 shows that a change to wetter conditions coincided with decreasing land-use intensity in three out of four federal states. Drier conditions often coincided with increasing land-use intensity, but slightly decreasing intensities also occurred.

3.5. Changes in grassland management

Changes in grassland management, which among things are accountable under GM, were only detectable by CIR datasets because the DLM did not stratify grassland further. Thus this analysis was restricted to Saxony-Anhalt and Brandenburg and to the period 1992–2009. We used LU classes that correspond to herbaceous grassland (grassland and heathland) for the analysis. As expected, the share of low intensity herbaceous grassland was higher in highly protected areas than in areas under moderate or no protection. Throughout Saxony-Anhalt and Brandenburg, herbaceous grassland became less intensive in terms of the management regime from 1992 to 2009. Much more grassland moved towards low-intensity than high-intensity grassland. There were no obvious differences in management trends between protection levels.

4. Discussion

These results raised several different points for discussion. We therefore commence this chapter with a discussion about uncertainties, ranging from uncertainties of input data to uncertainties of results, discussing LUC patterns and attempting to identify their drivers.

As our study was limited to six federal states, the extrapolation of LU trends to other regions is discussed, followed by a subchapter dealing with vegetation types as LU strata for land-based activities under KP.

4.1. Uncertainties

All LU datasets possessed some degree of unquantifiable uncertainty in terms of temporal accuracy and classification (Section 2.2.1). This also affected the translation key. The combination of these uncertainties was reflected in the fact that sums of changes in all federal states did not completely match the changes for the whole research area (*e.g.* Table 8). This meant that opposite trends in different federal states were slightly smoothed out by uncertainties when handling them as 'one' research area. Nevertheless, trends and patterns were expected to be robust and could be explained by agricultural policies, rewetting incentives and project data.

The highest gross LUC occurred in the period 2000–2008 (Section 3.2 and Table 5). This coincided with incentives for intensification by the European Common Agricultural Policy (CAP) and the Renewable Energy Act (see Section 4.2). More than 27% of DLM 2000 in the research areas was recorded in 1996 or earlier. Accordingly, LUC occurring slightly before 2000 was mostly detected in the second rather than the first period. However, this uncertainty in the temporal allocation of LUC did not produce any under or overestimation over the entire time series.

The reasons for the loss of settlement in the first period (1992–2000) were partly unclear as we expected gains in all periods. Peat extraction could have re-vegetated into bogs. The loss

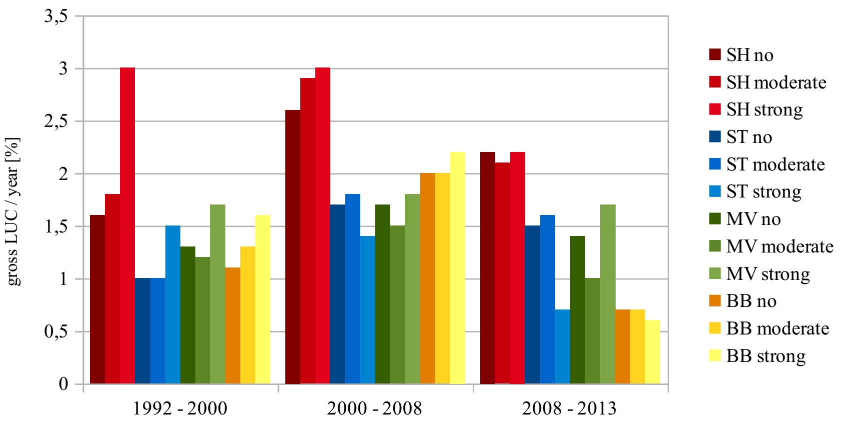

Fig. 4. Gross land use change [% *year^{-1}] stratified by federal state and protection level (none = not protected, moderate = moderately protected, high = highly protected).

Table 7
Intensity indicator. 'Lower' and 'higher' means a change towards lower and higher land-use intensity respectively. The more negative (positive) the result is, the greater the decrease (increase) in intensity. "Weighted average" means weighted by the length (years) of each period. Empty cells refer to no signals. n.d. = not detectable due to insufficient data points. Italic values refer to federal states with only small areas of organic soils and are therefore probably not representative.

Federal state	Protection level	1992–2000		2000–2008		2008–2013		Weighted average
		higher	lower	higher	lower	higher	lower	
Schleswig-Holstein	None	1	−0.5	1		1		0.8
	Moderate	0.5	−0.5	1	−0.5	1	−0.5	0.3
	High		−1	1			−1	−0.2
Brandenburg	None	1	−0.5	0.5	−1	1		0.2
	Moderate	1	−0.5	0.5	−0.5	0.5	−0.5	0.2
	High	0.5	−1		−0.5	0.5	−0.5	−0.4
Saxony-Anhalt	None	0.5	−0.5	1	−0.5	1	−0.5	0.3
	Moderate	0.5	−0.5	0.5	−0.5	0.5	−1	−0.1
	High	0.5	−0.5		−1		−1	−0.6
Thuringia	None	*1*			*−1*	*0.5*	*−0.5*	*0*
	Moderate	*n.d.*	*n.d.*	*n.d.*	*n.d.*	*n.d.*	*n.d.*	*n.d.*
	High	*0.5*	*−0.5*				*−0.5*	*−0.1*
Saxony	None	*1*		*0.5*	*−0.5*	*0.5*	*−0.5*	*0.4*
	Moderate	*0.5*	*−0.5*		*−1*	*0.5*	*−0.5*	*−0.4*
	High		*−1*		*−1*		*−1*	*−1*
Mecklenburg- Western Pomerania	None		−0.5	0.5	−1	0.5	−0.5	−0.4
	Moderate		−0.5	0.5	−1	0.5	−0.5	−0.4
	High		−1		−1		−1	−1

Table 8
Changes in the drainage status by federal state and protection level between 1992 and 2008 and 2008–2013 in ha*year $^{-1}$. Saxony and Thuringia are not presented here as the number of data points did not allow a robust analysis.

Federal state	Protection level	Proportion of protection level out of federal state's area [%]	Proportion of wet* area out of protection levels [%]	1992–2008		2008–2013	
				drier	wetter	drier	wetter
Schleswig-Holstein	None	72.7	1.3	1104.4	0	51.9	82
	Moderate	9.3	1.8	261.6	0	12.5	17.6
	High	18	6.8	639.9	4.5	80.2	71.4
Brandenburg	None	41	5.6	218	0	134.7	73.3
	Moderate	13.1	6.9	53.8	0	34.6	12.6
	High	46	19.3	49.9	754.9	324.7	218.5
Saxony-Anhalt	None	60	6.4	149.5	23.8	76.1	69.6
	Moderate	12.5	4.3	46.9	0	3.4	24.3
	High	27.5	19.3	34.1	57.9	20.1	73.3
Mecklenburg- Western Pomerania	None	43.1	10.6	107.1	114.3	155	252.5
	Moderate	8.3	14	22.6	58.1	85.6	49.5
	High	48.6	33.8	30.8	881.3	471.3	1195.6
All data**	None	49.4	5.7	1441.4	0	447.3	483.3
	Moderate	11	7.2	340	7.8	137.4	104.6
	High	39.6	23.1	680.2	1668.6	1028.2	1606.2

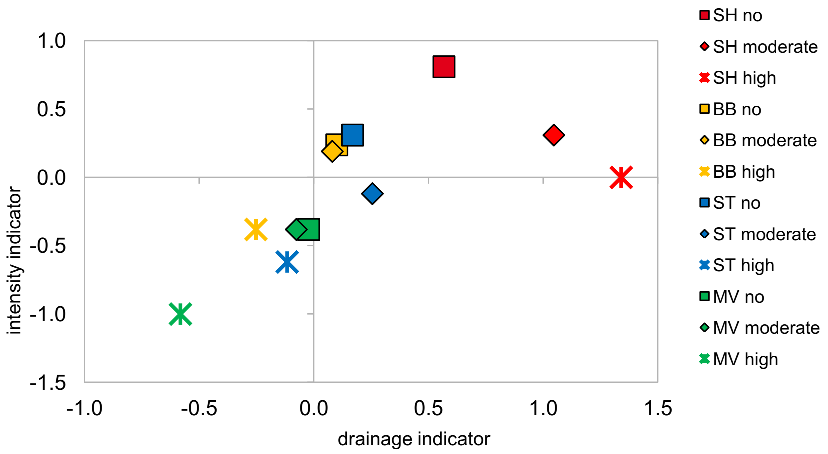

Fig. 5. Trend in land-use intensity and drainage from 1992 to 2013. Positive values represent more intensive and drier conditions, negative values less intensive and wetter conditions.

of settlement area resulted in a gain of mainly grassland (*ca.* 50%) but also cropland, with bogs, fens and forests occurring. The specific settlement types that contributed to the obviously unrealistic change rates in the first period were often poorly sealed, or strongly fragmented such as village areas, or linear structures such as road infrastructures. Therefore we assumed a frequent misclassification of those highly variable and heterogeneous areas in DLM 2000, which was resolved in DLM 2009.

Furthermore, the substantial gain in bogs in the first period (Table 6) emerging from broadleaved forests and grasslands may have partly resulted from a shift in the implementation of land classification, moving from detailed biotope types (CIR) to broader land cover (DLM), or reflect gradual changes in the vegetation type.

The fluctuation of wet fen areas could be attributed to vegetation succession when open swamp sites were overgrown by shrubs and wet forests over time. This was most pronounced in highly protected areas. The loss of water bodies could be explained by a certain amount of reclassification as bog or wet fen, which can give similar signals in remote sensing. Shrubs drastically decreased in the first period but recovered about half of the losses in later periods. In the case of shrubs, this might be caused to a certain extent by artefacts, for example by inconsistent thematic or spatial implementation in the time series. Artefacts are most likely in LU categories with diverse and complex land cover and in small and linear LU units, all of which are particularly common for shrubs.

Throughout our study we used conservative approaches to minimise underestimations, therefore overestimations cannot be ruled out.

4.2. *Land-use change patterns and their drivers*

Several large-scale political and socio-economic drivers influenced LUC patterns, particularly the effect of German reunification in 1990 (*e.g.* establishment of new protection areas) and CAP reforms in 1992 and 2003.

German reunification led to a considerable restructuring of land ownership and LU in eastern Germany, where in some areas land-use intensity was reduced, while in others it was intensified or changed LU. This effect is visible in the high net:gross ratio, which indicates steady trends in the landscape.

The CAP has had a major impact on agricultural LU types and intensity as it generates a significant proportion of European farmers' income in the form of subsidies. Until the early 1990s, the CAP mainly consisted of market measures to support production and export, which led to a domestic overproduction of food. Therefore, the MacSherry reform in 1992 reduced support for meat and cereals and introduced support linked to crop area instead of agricultural products, involving a mandatory fallow on a certain fraction of the cropland (Legislation L 181, 1992). This led to a certain reduction in LU intensity and a significant spread of fallow land, which could be classified as cropland, various grassland types or even shrubland over time. In parallel, animal numbers, in particular cattle, slightly declined in most German regions (UBA, 2015, Chapter 5.1.3). Reduced intensity was most pronounced in eastern Germany, driven by the combined effects of reunification and admittance into the new CAP regime (Table 7). Cattle numbers declined in eastern Germany by 47% and pig numbers by 60% between 1990 and 2000, in particular in the early 1990s (background data to UBA, 2015). The pressure on cropland and grassland for feed production declined accordingly, promoting the abandonment of grassland or a reduction in grassland intensity.

The 2003 CAP reform moved to decouple direct payments for agricultural area and introduced payments for permanent grasslands, defined as any grassland persisting for more than five years (Regulation (EC) No. 796/2004, 2004). The 2003 CAP reform introduced a regional maximum permitted proportion of 5% of permanent grassland being converted to cropland taking effect after 2005 (OECD, 2004). The reform stimulated the conversion of grassland to cropland in regions with high pressure on agricultural land, both as a forerunner effect in expectation of the new rules and after 2005, which is also visible in high gross and net LUC in Table 5 and Fig. 4.

The permitted 5% proportion of grassland conversion was quickly exceeded in some western federal states, including SH, in 2008 (Nitsch et al., 2012). Grassland conversion was most pronounced in regions with intensive animal husbandry such as SH, where maize had become more economical for use as feed than grass.

High agricultural commodity prices and the German Renewable Energy Acts of 2000 and 2004 further contributed to this trend. High guaranteed electricity feed-in tariffs for biogas production based on energy crops fostered their cultivation massively, particularly from 2004 onwards (Nitsch et al., 2012).

In eastern Germany, nature protection legislation changed after 1990. New protected areas were established, covering a significant proportion of organic soils. 45% of organic soils in eastern Germany were situated in high protection levels, while the proportion was only 18% in SH. This was probably due to unclear ownership in rural areas after reunification. The acquisition of these areas for conservation purposes was probably easier here than in SH, where the conversion of farmed land to unused natural sites was partly accompanied by counteractions by farmers and owners. MV introduced strongly supportive policies in an ambitious peatland protection programme (Umweltministerium Mecklenburg-Vorpommern, 2000). This programme was based on a voluntary principle to reduce peat degradation and soil subsidence as an issue for water management, climate, nature conservation and agricultural economy. The lower LU intensity on organic soils often coincided with rewetting, supporting the success of nature protection measures. Rewetting and a reduction in LU intensity were most pronounced in MV, where a general trend towards low LU intensity occurred throughout the state (Table 7, Fig. 5). This could be attributed to the combined effect of significant reduction in population and animal numbers since 1990, and strongly supportive policies for peatland conservation.

By 2008 in MV, 16,311 ha of grassland and 1900 ha of forest were rewetted and 11,553 ha were converted from high to low intensity grassland (Ziebarth et al., 2009). In our data, the area of wet forest in MV increased by 1761 ha from 1992 to 2008. The areas of wet grassland, fen and bog in our data increased by 19,690 ha during the same period.

Nature conservation areas (NC) and European protection areas such as Natura 2000 (FFH, SPA) have proven effective in their protection goals concerning LU. The conversion rate of grassland to cropland in highly protected areas was generally found to have been reduced by more than 50% in comparison to areas with low or no protection in other German regions (Nitsch et al., 2012). Our study confirmed the effectiveness on LU of high protection levels for nature conservation, but not on drainage status (Fig. 5). LU tended to become less intensive, but not necessarily wetter. Grassland was partly replaced by wet fen and bog in highly protected areas where some forests were also converted to wetlands (Table 6). This can be attributed to further peatland restoration incentives in highly protected areas such as in MV, but not to a general pattern of highly protected areas since SH shows a converse trend towards drier conditions (Table 8). In contrast, grassland shifted to cropland in non-protected areas. This finding proves that a high legal protection status with clear LUC restrictions and development goals triggers LUC and land management measures towards nature conservation, even against trends of intensification around highly protected zones. Nevertheless, farmers have obviously reactivated some croplands in highly protected areas after 2008, with the result that their protection cannot be considered complete.

Moderate protection levels include variable LU constraints and therefore have no clear impact on LU intensity. Indeed, cropland increased in moderately protected areas in all periods.

4.3. *Extrapolation of land-use trends to other regions*

Detailed LU, management or vegetation data are often not available at all or only for one point in time, such as the grassland management data in our study. It is not straightforward to extrapolate LU trends to other regions. The IPCC KP Supplement (IPCC, 2014a) suggests the use of proxies including natural, political and socio-economic drivers. A combination of LU data with agricultural statistics can give a general idea about agricultural LU intensity. Our study area mostly covers eastern Germany, with its particular challenges after reunification in 1990, and the results can therefore not be extrapolated to any other region in western Germany. Lower-Saxony probably shows comparable LUC rates to the neighbouring federal state SH, where the geography, political circumstances, intensive agriculture and stocking rates are comparable. Peatland conservation policies, however, differ as Lower Saxony has concentrated on bog conservation in former peat extraction areas (NLWKN, 2006) and SH has focused on water quality associated with fen conservation and restoration (MLUR, 2011). Other regions with a significant proportion of organic soils differ too much geographically and politically from the study region to be suitable for any meaningful attempt for extrapolating LUC trends.

Nevertheless, our study highlights the general success of a high legal nature protection status to reduce LU intensity. As the legal framework has a strong European and national basis, we expect that no further LU intensification take place in highly protected organic soil areas (Fig. 5). Maps of legal nature protection areas can therefore serve as a strong proxy for extrapolating LU intensity trends to other regions. The link between nature protection and drainage, however, was region specific (Fig. 5). Rewetting obviously requires more than just legal protection, and will only work with strongly supportive peatland restoration policies and programmes.

4.4. *Vegetation types as land-use strata for land-based activities under KP*

We developed a hierarchical classification system to reclassify maps of biotope types produced for biodiversity monitoring into LU and management strata suitable for reporting land-based activities under KP. The biotope-type data included information about vegetation restricted to unmanaged or wet conditions (*e.g.* swamp species) and enabled a robust reclassification into LU classes relevant for GM and WDR under KP. Furthermore the methods used in this study matched all KP reporting criteria:

4.5. *Transparency*

The uncertainty due to thematic, spatial and unknown classification differences in the products was displayed and considered in the translation key between CIR and DLM datasets. The common hierarchical classification system allowed a transparent harmonisation of all CIR products (see Section 3.2 and Supplement A).

4.5.1. *Consistency*

The systematic reclassification (Section 2.3.3) enabled us to create a consistent time series from different data sources with high detail for LU, management and drainage status by direct tracking for CIR-based time series and at coarser thematic level for combined CIR-DLM time series through the use of a translation key.

The images from 1992 provided a sufficient basis for the reference year 1990 in terms of reporting criteria for ARD, CM, GM, RV and WDR accounting. Historical aerial photos are available for more federal states, but are not pre-classified. We had the advantage of using pre-classified images, but old unclassified images can still be classified now if information for ground-truthing is available. This could provide the basis for further improvements of GHG inventories.

4.5.2. *Comparability*

The methodology can be applied elsewhere by applying the systematic reclassification approach and developing region-specific translation keys between LU data with diverging thematic resolutions.

4.5.3. *Completeness*

As the datasets cover the research area wall to wall, there is completeness for detecting LU in the research area. Tracking management for GM and WDR is limited to areas where more than one CIR dataset or other types of high detail vegetation data are available.

CIR data is very detailed and highly accurate in space and time. We still aggregated from the original level of detail in the CIR classes. A major advantage of vegetation data targeted for biodiversity monitoring was that the difficult grassland LU class and other near-natural vegetation types could be stratified in a systematic and detailed way. This has been the area in which there has been the greatest shortage of data in EU member states so far because grassland management and wetland management are not centrally recorded, *e.g.* in the Integrated Administration and Control System (ICAS)/Land Parcel Identification System (LPIS) (Weiss et al., 2015).

4.5.4. Accuracy

Changes in LU, management and drainage status are fully covered in the CIR datasets. The wall-to-wall coverage of biodiversity monitoring ensures that LU trends are detected in all directions, including changes in LU intensity, drainage and rewetting. This allows unbiased reporting and accounting as both potential greenhouse gas sinks and sources are fully considered. Biodiversity monitoring data restricted to areas of high protection interest, however, would not meet the accuracy criterion as the detected trends cannot be extrapolated to other and non-protected regions. However the monitoring data can serve for ground-truthing archived aerial photography or other spatial data sources.

5. Conclusions

No national GHG inventory has so far considered temporal changes in the drainage status of organic soils. The vegetation-based methodology presented in this paper represents a considerable improvement for national GHG inventories that can be used in several ways: time series and spatial stratification of LU categories such as grassland and drainage classes of organic soils. We demonstrated that detailed vegetation maps, as commonly used for biodiversity monitoring, could serve as a meaningful proxy to derive a consistent time series of changes in drainage level and management intensity on organic soils. There is a strong relationship between drainage level and greenhouse gases and a moderate relationship between management intensity and greenhouse gases (Tiemeyer et al., 2016), enabling average GHG emissions to be assigned to vegetation types, although with high uncertainty in deeply drained situations. As water table monitoring in 1990 was lacking, vegetation types could serve as a GHG proxy for the historical GHG emission situation against which mitigation measures or conversely deepened drainage with increased emissions could be assessed and reported. If vegetation maps are available for parts of the national territory, they can serve to analyse and understand the driving forces of drainage and rewetting trends such as nature protection status and LU-intensity changes, which can also be used with care for upscaling, monitoring and reporting changes in GHG emissions in much more detail than with the current small number of coarse LU categories in national GHG inventories. Our study area contained federal states with a political background in former East and West Germany, with some differences in agricultural and nature conservation policies, but strongly contrasting policies for peatland conservation and restoration. The vegetation maps offer improvements in the stratification of grassland types, which is one of the greatest challenges in GHG inventories. This paper used vegetation mapping for LU and changes in LU, management and drainage in organic soils. This methodology could be applied to improve GHG reporting in all carbon pools, including biomass, mineral and organic soils, as well as reporting on land-based activities under the Kyoto Protocol, such as wetlands drainage and rewetting.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2016.08.004.

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