Journal of Maps

ISSN: 1744-5647 (Online) Journal homepage: www.tandfonline.com/journals/tjom20

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To cite this article: Judith Depenau, Marcus Schmidt, Petra Fischer, Katrin Naumann, Sebastian Wagner & Antje Schwalb (2025) Legacy effects of historical land use on the vegetation of an Inland Dune Complex and adjacent floodplains in Northern Germany, Journal of Maps, 21:1, 2591730, DOI: 10.1080/17445647.2025.2591730

To link to this article: https://doi.org/10.1080/17445647.2025.2591730

Published online: 16 Dec 2025.

JOURNAL OF MAPS
2025, VOL. 21, NO. 1, 2591730
https://doi.org/10.1080/17445647.2025.2591730

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Legacy effects of historical land use on the vegetation of an Inland Dune Complex and adjacent floodplains in Northern Germany

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ABSTRACT
The Carrenzien Inland Dune Complex (IDC) in the glacial Elbe Valley, Northern Germany, is home to highly endangered nutrient-poor habitat types. We assessed the effect of historical land use on the occurrence of today's forest habitats by analysing five maps and geographical data from 1714 to 2015, displayed land use on the Carrenzien IDC and in the adjacent river flood plains, created a multitemporal GIS-analysis using the overlay method, and evaluated the effect using a Generalised Linear Model (GLM). The dune field changed from open land biotope and habitat types to an entirely forested area within 300 years. Anthropogenic drainage systems in the river valley transformed the wetland into an agricultural landscape after 1881. The *Deschampsia Pinus* community shows a significant association with areas of historical arable land and therefore represents a legacy of historical land use. We propose that this historical context should be considered in future nature conservation planning.

ARTICLE HISTORY
Received 15 June 2025
Revised 23 October 2025
Accepted 5 November 2025

KEYWORDS
Land-use change; multitemporal GIS analysis; Inland dunes; floodplains; biotope and habitat types; nature conservation

1. Introduction

The Central European cultural landscape has been subject to repeated transformation caused by political, natural and technical developments since the Neolithic (Gömann & Weingarten, 2018; Poschlod, 2015). Today's cultural landscape is mainly characterised by industrialised agriculture with large fields, monoculture farming and little structural diversity (Bredemeier, 2007; Deumlich, 2012; Meyer & Wevell von Krüger, 2006; Poschlod et al., 2014). At least since the mid-twentieth century, land-use change has been a major threat for biodiversity (Sala et al., 2000). Land-use reconstructions often only extend to the nineteenth or late eighteenth centuries (Alexander et al., 2015; Bender et al., 2005; Kuemmerle et al., 2016; Regasa et al., 2021). For this analysis, exceptionally detailed and precise historical maps dating back to 1714 were available. This allows a comprehensive 300-year reconstruction of land-use change on an Inland Dune Complex (IDC) with rare open dune areas and river floodplains with riparian forest and bog areas.

The aims of this investigation were to (1) reconstruct land use on the Carrenzien IDC and adjacent river floodplains and (2) test if and how historical land use has affected the occurrence of today's plant communities. The overall goal of these land-use reconstructions is to develop a basis for protecting endangered habitat types.

2. Materials and methods

2.1 Study area

The study area is located in the Biosphere Reserve 'Niedersächsische Elbtalaue' in northern Germany, in the transition zone between the maritime climate of the northwestern regions neighbouring the North Sea and the more continental climate towards the east. The nearest weather station in Lüchow (approx. 25 km further south) shows an annual average temperature of 9.2°C and annual precipitation of 548 mm for 1981–2010 (Deutscher Wetterdienst, 2024).

The study area covers 7400 ha and is oriented along the geomorphological extension of the Carrenzien Inland Dune Complex (IDC) at the western, northwestern and south-eastern limits (Map 1). The Carrenzien IDC covers nearly half the study area with 3478.3 ha, is oriented from north-northwest to south-southeast and today is mostly covered with scots pine forest and some open dunes. Peatlands in the study area, such as the Laaver Moor, are located on the eastern edge of the IDC. Furthermore, areas

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Supplemental map for this article can be accessed online at https://doi.org/10.1080/17445647.2025.2591730.

Map 1. Research area of the cartographic reconstruction with the dune field and the strict forest reserve. In the north-east, the study area is delimited by the course of the Rögnitz, a small stream, and by the state borders between Lower Saxony and Mecklenburg-Western Pomerania. The north-western boundary of the study area is defined by the extent of the historical maps as well as by the present-day forest boundary.

of the Sude and Rögnitz river valleys east of the dune complex were examined more closely.

The strict forest reserve 'Kaarßer Sandberge' (Map 1) is mainly characterised by dunes distant from groundwater level (Meyer & Wevell von Krüger, 2006) and served as a case-study for detailed mapping and analysis of the distribution of biotope and habitat types.

2.2 Reconstruction of land use

Four historical maps from 1714, 1776, 1881 and the mid-twentieth century (1950), and one shape file of the biosphere reserve from 2015 were digitised and evaluated for historical land use (Table 1). The mid-twentieth-century map is based on two time periods, around 1930 and 1958, because of a lack of consistent cartographic material. The maps were georeferenced in QGIS Version 3.22.2 (QGIS Association, 2022) using control points. All maps were converted in the coordination system ETRS98 UTM Zone 32N (25832). Surviving landmarks like churches marked on historical maps served as control points, for example the churches of Amt Neuhaus, Stapel, Kaarssen and Tripkau. The older the map, the fewer points could be used. However, at least four points per map sheet were applied. Most settlements are located on the western edge of the study area rather than on the eastern edge. During georeferencing, an attempt was

Table 1. Historical maps and shape-file for the reconstruction of historical land use on the Carrenzien Inland Dune Complex.

Year	Map	Source
1714	Karte des Amtes Neuhaus	Arcinsys Niedersachsen Bremen, 2021
1775	Bleckede (HL069)	Landesamt für Geoinformation and Landesvermessung Niedersachsen (LGLN), 2021a
1775	Stapel (HL070)	Landesamt für Geoinformation and Landesvermessung Niedersachsen (LGLN), 2021a
1776	Hitzacker (HL075)	Landesamt für Geoinformation and Landesvermessung Niedersachsen (LGLN), 2021a
1881	Neuhaus (PL2731)	Landesamt für Geoinformation and Landesvermessung Niedersachsen (LGLN), 2021b
1881	Dannenberg (PL2832)	Landesamt für Geoinformation and Landesvermessung Niedersachsen (LGLN), 2021c
1881	Besitz (PL2631)	Fachbereich Geodatenbereitstellung, 2021
1881	Jessenitz (PL2732)	Fachbereich Geodatenbereitstellung, 2021
1930/40	2631 Besitz	Digital Collections BYU Library, 2022a
1930/40	2731 Neuhaus	Digital Collections BYU Library, 2022b
1930/40	2732 Jessenitz	Digital Collections BYU Library, 2022c
1958	Dannenberg (2832)	Landesamt für Geoinformation and Landesvermessung Niedersachsen (LGLN), 2022
2015	Biotopgruppen	NUMIS – Niedersächsisches Umweltportal, 2015

made to select control points that comprehensively covered the area. Nevertheless, certain inaccuracies were unavoidable. Obvious differences were taken into account during the digitisation of the areas. Due to these uncertainties, the percentage shares of land use were taken into account instead of the absolute shares. The resulting differences in location and area proportions, however, should be negligible. In the post-1881 maps, roads and intersections were also included. To record the land-use sequence, the four layers from the map analysis and shape file were superimposed using the overlay method (Bender et al., 2005; Prentice et al., 2006; Rubanschi & Poschlod, 2019). Thus, sequence categories were determined for the areas that were examined for vegetation and soils, presenting a land-use sequence from 1714 to 2015.

2.3 DTM1 mapping

A digital terrain model with a resolution of 1×1 m (DTM1) was used to identify areas of historical arable land, mainly ridge and furrow systems, on the dune field. It was created as part of a countrywide laser-scanning project in 2015 (LGLN 2021c). With the Hillshade-Command in ArcGIS Desktop 10.8, the surface shapes of the research area became recognisable on the DTM1, and historical arable land, preserved under forest cover, was mapped. A grid of 10×10 m was eventually placed over the ICD.

2.4 Biotope and habitat type mapping

The biotope and habitat type mapping took place in July and August 2021 on 97 sites measuring 100 m^2. Eighty-five sites in the strict forest reserve ‘Kaarßer Sandberge’ were mapped on the sample plots created by the Northwest German Forestry Research Institute. Additionally, the biotope types were determined on twelve historical arable-land sites, which were also pedologically examined. Following Fischer et al. (2009), biotope mapping identified three biotope types in the study area: the habitat type 91T0 ‘Central European lichen pine forest’ (*Cladonio-Pinetum*), which is protected under the Habitats Directive (European Commission, 2013); the white moss pine forest (*Leucobryo-Pinetum*); and the wavy hair-grass pine forest (*Deschampsia-flexuosa-Pinus-sylvestris*-community, abbreviation: *Deschampsia Pinus* community). The lichen pine forest is a habitat forest type that occurs on particularly dry and nutrient-poor soils (Fischer et al., 2009) (Supplement). The white moss pine forest (*Leucobryo-Pinetum*) is a succession stage that can follow lichen pine forest (Fischer et al., 2014; Meysel et al., 2007), also on nutrient-poor, dry soils (Supplement). The *Deschampsia Pinus* community is a forest biotope type which occurs on more nutrient-rich and humus-rich soils (Fischer et al., 2009) (Supplement). During mapping, first the plant species in the tree, shrub, herb and moss layers were identified, then the percentage coverage of each species was noted using the Braun-Blanquet scale (Mueller-Dombois & Ellenberg, 1974). In the forest reserve ‘Kaarßer Sandberge’, soil and biotope type mapping was conducted at GPS-measured locations implemented by the Northwest German Forest Research Institute using a Tablet PC with the software ‘FieldMap’ of the Institute of Forest Ecosystem Research. Outside the forest reserve, locations were determined using the ESRI’s Collector app.

2.5 Analysis of historical land-use influence on biotope and habitat types

To investigate the possible influence of historical land use on today’s forest biotope types, the occurrence of the mapped biotope types on the land-use sequences was visualised. A Generalised Linear Model (GLM) was then implemented, with the occurrence of individual forest biotope types as presence/absence data as target values. The historical land use, broken down into historical arable land or other use (e.g. open dunes), groundwater level and height above sea level were used as predictor variables. The dataset of the biotope type mapping was examined for correlations (Hollander & Wolfe, 1973) and for quadratic terms. Subsequently, the GLM was run on the dataset for each individual forest biotope type (Nelder & Wedderburn, 1972). The model accuracy was then calculated using the area under the ROC (receiver operating characteristics) curve (AUC). The software RStudio (RStudio Team, 2020) with the packages ‘ggplot’ (Wickham, 2016), ‘nlme’ (Pinheiro et al., 2021) and ‘mgcv’ (Wood, 2004) was used to evaluate all statistical analyses.

3. Results and discussion

3.1 Changes in land use

The most relevant changes in land cover and land use of the Carrenzien IDC and the river valleys are summarised in Figures 1 and 2. Due to the age of the maps and the uneven distribution of landmarks in the study area, inaccuracies can be assumed. This was considered during the digitisation of land use. The digitised areas were then compared with today’s structures and the historical structures still visible on the terrain model, and adjusted where necessary. The deviations found in relation to the size of the study area and the significance of the results are considered acceptable.

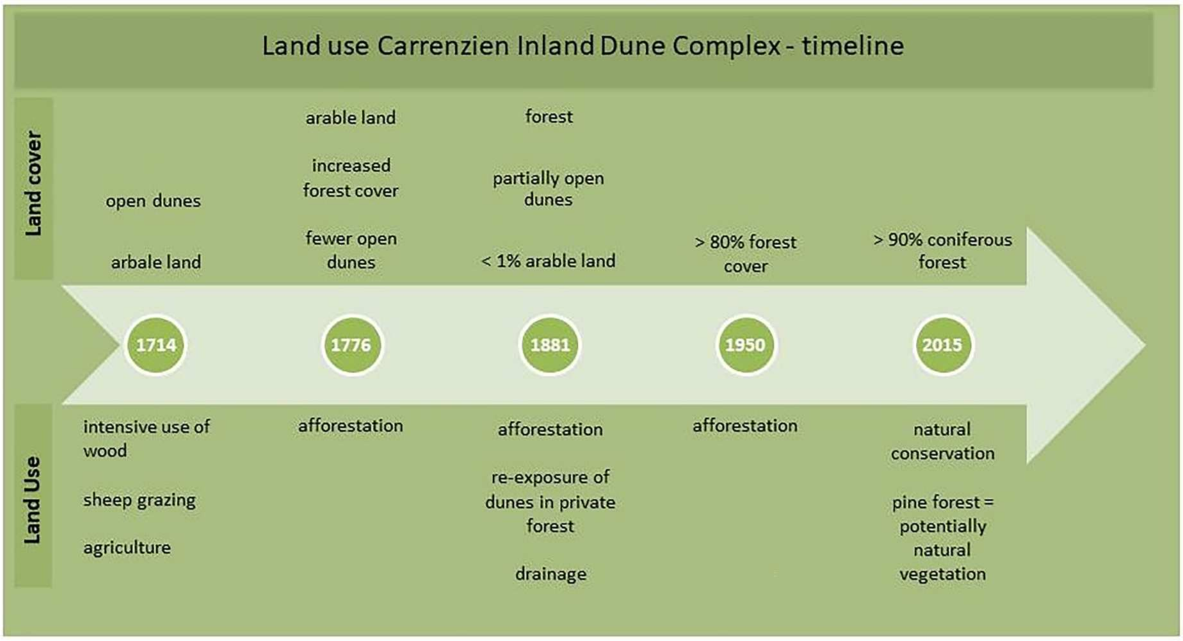

Figure 1. Timeline of the land use and the land cover of the Carrenzien Inland Dune Complex.

3.1.1 Carrenzien Inland Dune complex

In **1714,** the proportion of open land biotopes and biotope types on the dune sites was over 90% of the area (Figure 3). Open dunes made up 60%, characterising the Carrenzien IDC as predominantly open landscape (Main Map, Map A). This resulted from the intensive cutting of wood (Kremser, 1990; Meyer & Wevell von Krüger, 2006), litter raking, and grazing and browsing on young trees by sheep (Hüls, 1996).

Arable land made up the second largest proportion of open land biotope types in 1714, with a share of around 20%. Oats, rye, malting barley and grain for bread production were mostly grown on the fields (Beste, 1970; Hüls, 1996). Forests were very limited on the dunes, and may have been the first measures to cover and stabilise the dune field (Meyer & Wevell von Krüger, 2006). Alternatively, these trees may also be related to ancient woodland.

Around **1775/76,** the share of open land was over 40%, while forests had a share of about 50% (Figure 3). The proportion of arable land decreased from 1714 and only covered about 11%. Deciduous, coniferous and mixed forests were mapped, with deciduous and coniferous forests making up the largest proportion with 49.47%. There was a clear decrease in open landscape and a strong increase in

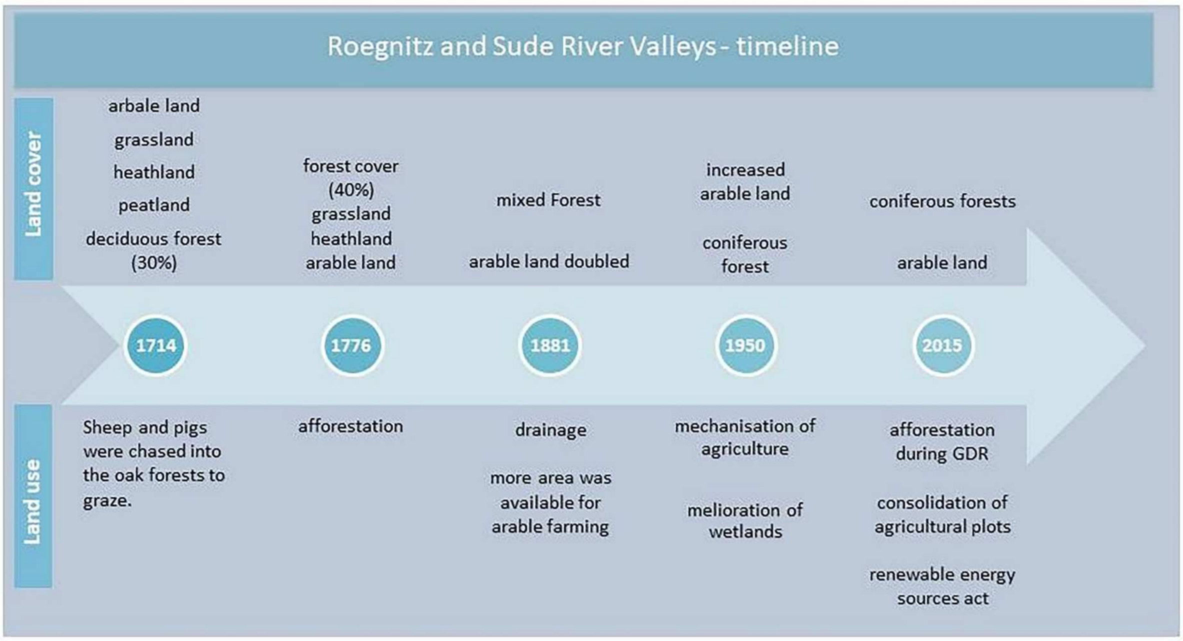

Figure 2. Timeline of the land use and the land cover of the Roegnitz and Sude River Valleys.

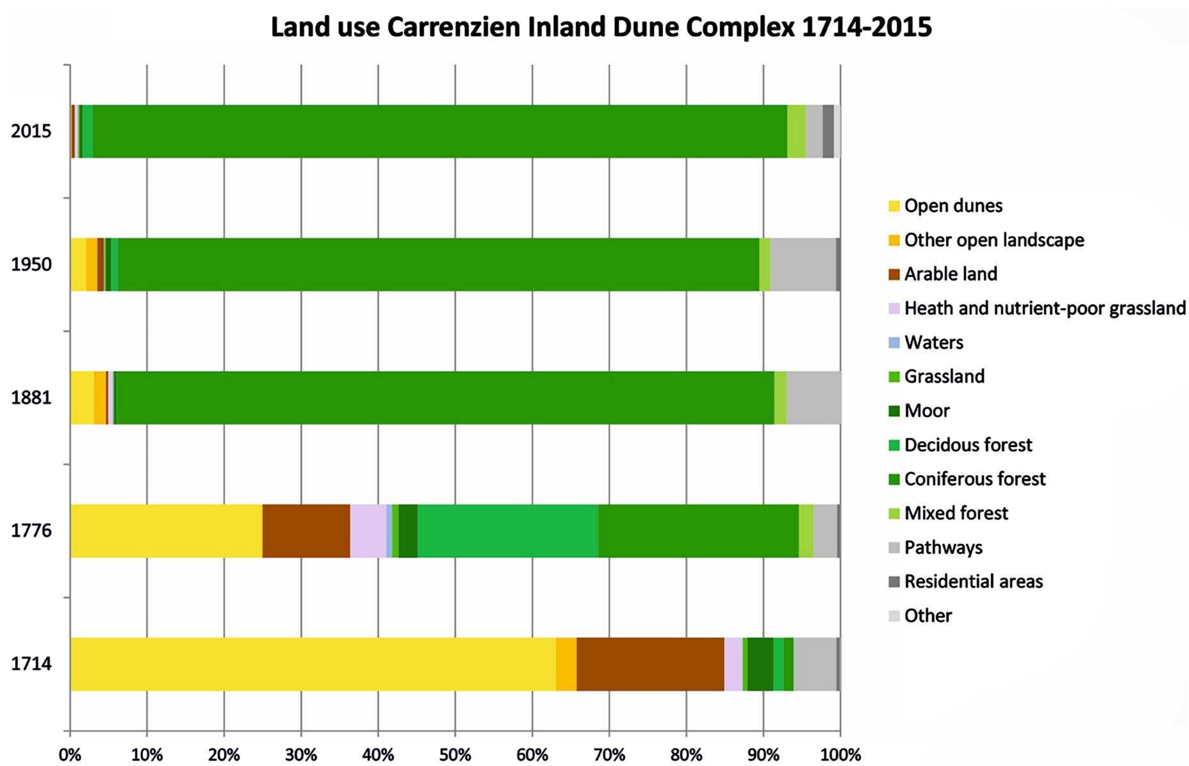

Figure 3. Proportions of historical land use of the Carrenzien dune field from 1714 to 2015 (1776: 1775/76; 1950: mid-twentieth century). For the reconstruction of historical land use, the area proportions of land-use attributes were calculated as percentages of the whole research area per time step, related to their shares on the Carrenzien dune field.

the proportion of forest on the dunes. In the early eighteenth century, efforts were made to reforest areas without vegetation in order to minimise sand drifts (Kremser, 1990; Meyer & Wevell von Krüger, 2006). In the study area, more than 1000 acres of the dune field were sown with pine (*Pinus sylvestris*) and spruce (*Picea abies*) from 1747 to 1750 (Kremser, 1990). There were also several areas covered with deciduous forest in the southern part of the dunes, which may have resulted from natural regeneration (LGLN, 2021a) (Main Map, Map B). From 1820, the Hanoverian forestry administration organised large-scale forestation in the Neuhaus district, mainly with pine (Meyer & Wevell von Krüger, 2006).

The Prussian land survey of **1881** shows a distinct increase in the proportion of coniferous forest: most of the dune field was covered with conifers (Figure 3, Main Map, Map C). This shows the success of the ongoing afforestation and consequent stabilisation of the open dunes in the eighteenth and nineteenth centuries (Wundram, 1862). Nevertheless, deforestation continued, especially in private forests, leading to some re-exposure of the dunes (Sabban, 1897). Open land biotopes accounted for less than 10% in 1881, most of which were still open dunes. Arable land covered less than 1% (Figure 3). In 1842, interventions on the Rögnitz and Sude Rivers lowered the groundwater level in the research area (Beste, 1970; Hüls, 1996). This rendered arable land on sandy areas at higher elevations within the dune field unusable (Beste, 1970; Hüls, 1996).

In the **mid-twentieth century,** the proportion of deciduous forest on the dunes increased slightly. Open landscapes accounted for less than 5% of the total area, and the proportion of open dunes decreased again by 1% (Figure 3). Additionally, heath and nutrient-poor grassland only accounted for 0.01% of surface cover. Arable land increased slightly by 0.6% in comparison to 1881. This may have been the effect of afforestation measures during the nineteenth century. Overall, significant changes were not detected between 1881 and the mid-twentieth century.

By around **2015**, the proportion of forest cover had increased again. However, deciduous and mixed forests accounted for only 4%, while coniferous forest still had the largest extent on the dune field with 90% (Figure 3). Until 1990 and German reunification, the study area was in the German Democratic Republic (GDR), thereafter becoming part of the Federal Republic of Germany (Hüls, 1996). In 1967, the GDR government decided to intensify agriculture (Bauerkämper, 2009; Dix & Gudermann, 2006) and further afforestation measures. In 2002, the biosphere reserve 'Niedersächsische Elbtalaue' was established (Meyer & Wevell von Krüger, 2006; Succow, 2013). In Germany, biosphere reserves are primarily designated in areas with cultural landscapes that are particularly worthy of protection (UNESCO, 2024). Together with various deciduous forest types, the pine forests on the Carrenzien IDC were assessed as potentially natural vegetation (Forstplanungsamt

Niedersachsen and NMELF, 1995). The pine forests are part of the biosphere reserve concept, which views areas with lichen pine forests as particularly worthy of protection (Jungmann et al., 2009). A similar status is given to several open dune areas that house grey hair-grass swards (Jungmann et al., 2009; NUMIS – Niedersächsisches Umweltportal, 2015). Nowadays, open dune areas are considered rare habitats and therefore nature conservation measures aim to keep these areas open (Jungmann et al., 2009). This contrasts with former land-use concepts that focused on stabilising open dunes.

Overall, the Carrenzien IDC has changed from the open landscape of 1714 to an entirely forested area within the last 300 years. Within the European sand belt, this development was also observed on other inland dunes and sandy sites. For example, the Kootwijkerzand drift sand area in the Netherlands. This area was exposed over the course of the last millennium due to human overuse and was reforested after the second half of the nineteenth century (Heidinga, 2010). Thus, the developments on the IDC provide an example for the change in the land use of Central European sandy landscapes (Koster, 2010; Poschlod et al., 2014) (Main Map, Map A–E).

3.1.2 Roegnitz and Sude river valleys

In **1714,** open landscape accounted for up to 60% of the total area of the river valleys (Figure 4). Arable land, grassland, heath and nutrient-poor grassland, and peat land had a similar share of around 10% each. Forests, mainly deciduous, accounted for just over 30%. The lowland deciduous forests were used for wood pasture (Arcinsys Niedersachsen Bremen, 2021; Beste, 1970). Pigs and sheep were chased into the oak forests for fattening until the nineteenth century (Beste, 1970; Hüls, 1996). Dominant deciduous tree species probably included alder (*Alnus glutinosa*), oak (*Quercus robur*) and beech (*Fagus sylvatica*). Alder wood was mainly transported to the Lüneburg Saline (Beste, 1970).

By **1776,** as a result of afforestation measures in the research area, the proportion of deciduous and coniferous forests had increased to cover more than 50% of the total area of the lowlands (Figure 4; Kremser, 1990). Grassland, heath and nutrient-poor grassland and moorland had decreased from 1714, each accounting for less than 10% of cover in the lowlands. In contrast, arable land had increased by 4%.

By **1881,** the proportion of forest cover had decreased by 8%. Mixed forest covered almost 20% of the lowlands and was the dominant forest type (Figure 4). The proportions of open landscapes and forests were similar to 1775/76. There was, however, a distinct decrease in heath and nutrient-poor grass- and moorland with percentages of generally less than 1%. The proportion of arable land had hardly changed from 1776, while the proportion of grassland

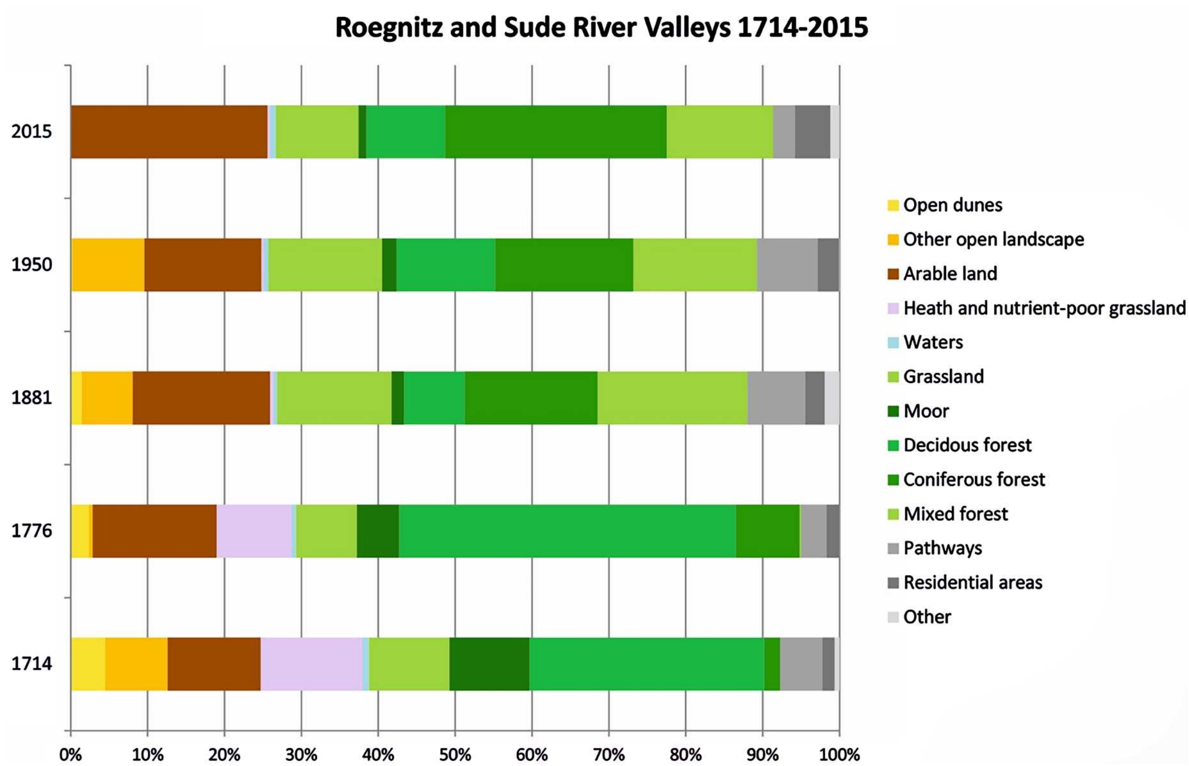

Figure 4. Proportions of historical land use in the river valleys adjacent to the Carrenzien dune complex from 1714 to 2015 (1776: 1775/1776; 1950: mid-twentieth century). For the reconstruction of historical land use, the area proportions of the land-use attributes were calculated as percentages of the whole research area per time step, related to their shares in the river valleys of both the Rögnitz and the Sude.

had doubled (Figure 4). During the nineteenth century, drainage measures were initiated in the lowlands. A large ditch was established parallel to the dune field, and mapped by the Prussian State Survey (Beste, 1970; LGLN, 2021b) (Main Map, Map C). This lowered the groundwater level and consequently the floodplains became available for agriculture (Main Map, Map C) (Beste, 1970; Hüls, 1996). In the nineteenth century, meliorations, such as lowering the groundwater table and land clearings, were more frequent, aiming to improve and maintain food production and avoid famine (Thomas, 2014).

By the **mid-twentieth century,** arable land had decreased by 2%, compared to 1881 (Figure 4). Nevertheless, it was still the largest category of the open landscape biotopes. The proportion of grassland and nutrient-poor grassland remained stable, and grassland represented, with nearly 15%, the second largest category of the open landscape biotopes. Additionally, the share of other open landscape was highest in the mid-twentieth century. We assume that most parts of this category at this time were arable land. Between the late nineteenth and mid-twentieth centuries, mechanisation of agriculture increased the melioration of wetlands, moors and river valleys to access new cropland (Poschlod et al., 2014). Consequently, the area of arable land in the river valleys increased. Deciduous forest showed the strongest increase in forest cover with an increase of 5%. The hydrological changes allowed use of riparian forests in the river valleys and the introduction of new species to the plant communities. Especially after the Second World War, the hybrid *Populus* x *canadensis* was introduced to the riparian forests (Glaeser & Volk, 2009). Coniferous forest still represented the dominant category with around 18%, with the mixed forest as the second category at 16%.

Around **2015,** coniferous forest had the largest proportion in the lowlands with a share of 30% (Figure 4), thanks to afforestation measures during the GDR era (Bauerkämper, 2009; Dix & Gudermann, 2006). The proportions of deciduous and mixed forests in the lowlands had decreased from the mid-twentieth century. The biosphere reserve recommendations included redeveloping natural forest in the Rögnitz and Sude lowlands by raising the groundwater level in the floodplain, swamp and bog forest areas (Jungmann et al., 2009). This promoting of natural development also includes gradual clearing of trees and reopening of bog areas. In addition, native tree species such as oak (*Quercus robur*), alder (*Alnus glutinosa*) and birch (*Betula pendula*, *B. pubescens*) are encouraged (Jungmann et al., 2009).

Arable land had increased by 10% and accounted for 25% of the total area of the lowlands by 2015 (Figure 4). During the GDR era, most small farms were replaced by agricultural cooperatives and acreage was merged. These large agricultural cooperatives continue to operate as civil-law partnerships (Bauerkämper, 2009) and manage single fields of 4.83 hectares on average (Leuschner et al., 2010). Hence by 2015, arable land accounted for the largest share of open landscape biotopes in the lowlands.

Grassland areas decreased to 10% in 2015 (Figure 4). This is due to the industrialisation of agriculture during the GDR period (Bauerkämper, 2009; Dix & Gudermann, 2006) and the German Renewable Energy Sources Act of 2000. The latter promoted biogas production, so grasslands and fallow land were converted into arable land to cultivate maize for energy production (Schöne, 2008). During on-site inspections, maize cultivation was particularly evident on the arable sites of the Rögnitz lowlands near the village Laave (Main Map, Map E). Additionally, a large farm with a biogas plant is located between Laave and Kaarßen. It seems reasonable to assume that lowland grassland areas were converted to arable land in order to increase maize cultivation.

The significant change in the lowland areas is striking; most lowland areas were dominated by moist deciduous forests and grassland around 1714. Today, these areas have been drained and are mainly used for agriculture, as in other areas of Central Europe (Quast, 2012; Schöne, 2008), causing a massive reduction in structural diversity (Main Map, Map A–E). A similar development was observed, for instance, in the Danube lowlands in Hungary, where the proportion of agricultural land increased from less than 10% in the eighteenth century to more than 60% in the twenty-first century, while the proportion of wetlands decreased from 30% to just under 1% (Erős et al., 2023).

3.2 Influence of historical land use on today's habitat types

To investigate the influence of historical land use on today's forest biotope types, the land-use sequences for areas of the biotope mapping were further evaluated. They were divided into two categories; (1) areas that had previously been used for arable farming (historical arable land) or (2) other use. According to the map analysis, 20 of the areas were used for arable farming at least once during the last 300 years. The remaining areas were used for other purposes. During the biotope type mapping of 97 areas, lichen pine forest was mapped in nine areas, white moss pine forest in 61 areas and *Deschampsia Pinus* community in 27 areas. Our results show the distinct effects of historical land use on the occurrence of today's forests on the Carrenzien IDC.

No statistical analysis was carried out for the lichen pine forest due to the small number of random

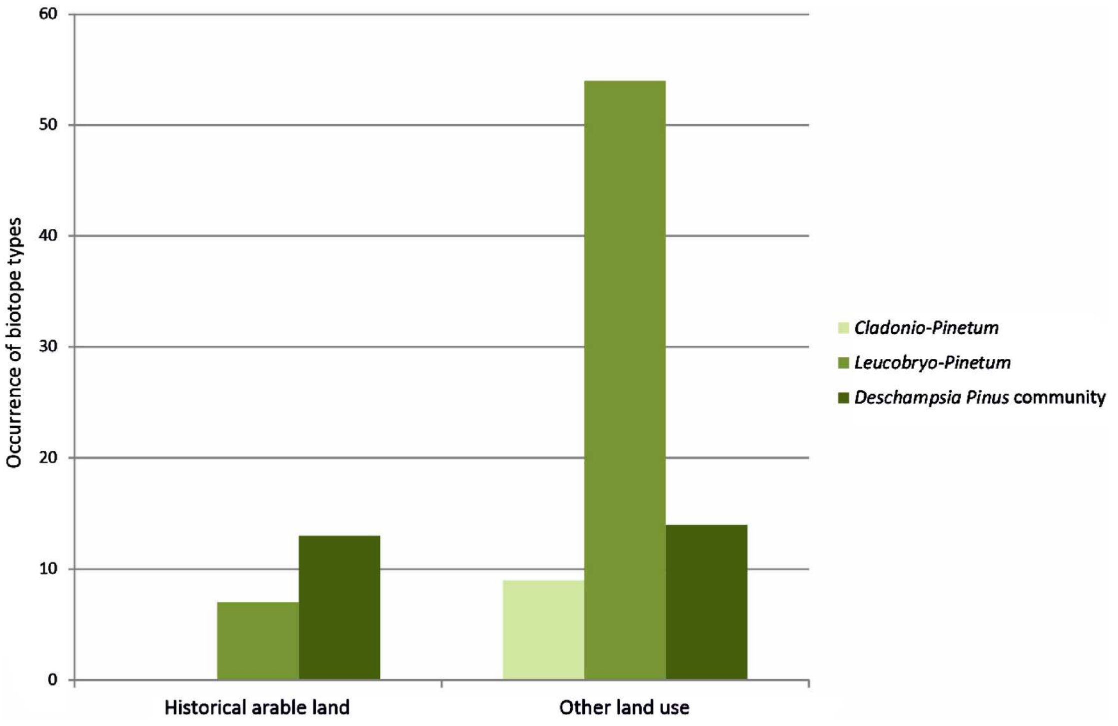

Figure 5. Occurrence of the biotope and habitat types on historical arable land and other land use on the Carrenzien IDC.

samples. However, *Cladonio-Pinetum* does not occur on historical arable land on the Carrenzien IDC (Figure 5). Such areas are mostly located close to the groundwater table, are enriched with organic soil material and are therefore moist and nutrient-rich sites.

On the Carrenzien IDC, historical land use has a significant influence on the occurrence of *Leucobryo-Pinetum* ($p = 0.01$) (Table 2). Therefore, this forest biotope type is also more likely to be found in areas not used for agriculture between 1714 and 2015 (Figure 5). The model accuracy, however, is below the acceptable range of 0.7 (AUC = 0.6); thus the model's prediction is not sufficiently specific and can only serve as an indication (Hosmer et al., 2013) (Table 2). Reasons for the poor performance of the model could include an small sample size. In addition, variables such as soil chemistry could have a greater effect on the biotope type and thus result in a better model performance and consequently provide more reliable results.

On the Carrenzien IDC, the *Deschampsia Pinus* community occurs in almost equal proportions on historical farmland and other-use areas (Figure 5). The predictor variables historical land use ($p = 0.01$) and distance to the groundwater table ($p = 6.07$e-0.5) both significant influence the occurrence of the *Deschampsia Pinus* community (Table 2). The model quality can be considered sufficient (AUC = 0.7) (Hosmer et al., 2013). Accordingly, the probability of the *Deschampsia Pinus* community occurring on the Carrenzien IDC increases on historical arable land. Former farmland could thus influence the occurrence of the *Deschampsia* Pinus community. On the Carrenzien IDC, historical arable land is mostly found on areas closer to the groundwater table. These sites were preferred as farmland and are therefore today richer in nutrients and humus than the uncultivated sites. Sites close to the groundwater table hence provide good conditions for the establishment of *Deschampsia Pinus* communities. Therefore, the *Deschampsia Pinus* community on the Carrenzien IDC could serve as an indicator of historical arable land. To conclusively assess the influence of historical land use on today's plant communities of the IDC, further investigations in the form of soil chemical and physical analyses are required. Increased sample sizes would facilitate a reliable statistical forecast.

Table 2. Results of the GLM using presence–absence data of the *Leucobryo-Pinetum* and the *Deschampsia Pinus* community as response variables and historical land use (arable land/other land use) and distance to the groundwater (DGW) as predictor variables.

Habitat type	Predictor	Estimate	Std. deviation	z-Value	*p*-Value	AUC
Leucobryo-Pinetum	Other land use	1.47	0.53	2.77	0.01**	0.6
Deschampsia Pinus community	Other land use	−2.05	0.76	−2.70	0.01**	0.7
	DGW	−0.81	0.20	−4.01	$6.07e^{-0,5}$***	

Note: ***p*-value = very significant; ****p*-value = highly significant.

Alternative modelling options may also be useful for such purposes.

Future measures to protect the lichen pine forest should exclusively focus on areas where the *Leucobryo-Pinetum* occurs today rather than on historical arable land. Maintenance measures like the removal of topsoil, as carried out in a project on the IDC, should be undertaken at regular intervals (Schmidt et al., 2008). Additionally, intensive research on the protection of the geological unit 'inland dunes' and its habitat types by Koster (2010), Riksen (2006), and Riksen and Goossens (2005, 2007) suggests restoring natural sand dynamics on inland dunes. Resulting sand drifts would cause disturbance that would promote the conservation of pioneer habitat types such as the grey hair-grass swards (Riksen, 2006). As part of the EU LIFE project 'Atlantic Sand Landscapes', inland dunes in Germany have also been cleared and exposed, for example to promote the FFH habitat type 'Dunes with open grasslands with silver grass and feather grass' (habitat type 2330) (Atlantische Sandlandschaften Integriertes LIFE-Projekt, 2025).

4. Conclusion

The historical developments recorded by this study uniquely document land-use change that is representative for many Central European areas over the last 300 years. The Carrenzien IDC changed from an open landscape with arable land, heathland, open dunes and some forested areas to an entirely forested area. In the adjacent river valleys, the open landscape was characterised by arable land, grassland, heathland and open dunes in 1714. Afforestation measures that followed the eighteenth-century overexploitation of sandy sites were recorded for the Carrenzien IDC. In the surrounding lowlands, intensive drainage of wetlands to promote agricultural use started in the nineteenth century. From the mid-twentieth century, agriculture was intensified by land consolidation, increases in arable land and the loss of fallow land in response to the Renewable Energy Sources Act in the early 2000s. These factors led to an overall decline in structural diversity in the study area. Today, arable land and grassland dominate the landscape.

This study documents the influence of historical land use on today's plant communities. The probability of *Deschampsia Pinus* communities occurring on historical arable land is high because of the enriched soils and the proximity to the groundwater table of these areas on the Carrenzien IDC. The lichen pine forest on the Carrenziener IDC resulted from specific geological conditions and historical land uses like litter raking. Due to the abandonment of litter raking, this habitat type is highly endangered, which is why management measures are necessary on suitable areas. In general, conservation for endangered plant communities requires detailed knowledge about historical land use to ensure the suitability of measures and protected areas. Additionally, new protection approaches should be evaluated for pioneer habitat types, such as the grey hair-grass swards and the lichen pine forest. Aiming to minimise the negative impacts of past afforestation, forest homogenisation and the loss of early successional stages due to nitrogen inputs and the cessation of historical practices like litter raking. Examples of such measures could include reactivating the natural sand regime on inland dune fields or simulating litter raking.

Software

The historical maps were georeferenced, and the land use was digitalised in QGIS (Version 3.22.2) (QGIS Association, 2022). The map was created entirely with QGIS and exported as PNG file.

Acknowledgments

The authors are grateful to Rolf Nieder and Anne-Kathrin Schneider for help with the soil analyses and statistical evaluation. This research presents results from the Master thesis of J.D. Funding was provided by the publication fund of the Technische Universität Braunschweig and Northwest German Forest Research Institute, Department Forest Nature Conservation.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that support the findings of this study such as the historical layers and scripts are available from the corresponding author, Judith Depenau, upon request.

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