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A SPATIAL MODEL OF FOREST AREA IN THE MIDDLE AGES BASED ON HISTORICAL, ARCHAEOLOGICAL AND GEOGRAPHIC DATA: A CASE STUDY OF 13TH-CENTURY CHEŁMNO LAND (NORTH-CENTRAL POLAND)

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Abstract: The settlement established under German law in Chełmno Land in the 13th century, the resultant changes in the structure of agriculture and land cultivation techniques, and the growing demand on wood as timber, fuel and raw materials for crafts, all combined to contribute to the significant deforestation of the territory. The extent of this deforestation remains conjectural. The purpose in creating a model of forest area in 13th-century Chełmno Land was to attempt to reconstruct it and determine its size and, consequently, to verify hypotheses concerning the scale and the ultimate end of deforestation in the research area. The spatial model is based on published historical and archaeological data relating to selected components of the geographical environment that pertain to the forest area. A retrogressive method combined with Multi-Criterion Evaluation (MCE) was used to build a forest area model. The basic platform for collecting, analysing and visualising spatial data was the geographic information system (GIS). The presented estimates indicate that the forest area of Chełmno Land in the 13th century was larger than had previously been assumed, at about 20–25% of the entire territory.

Key words: historical landscape reconstruction, forest area, Middle Ages, Multi-Criterion Evaluation, Chełmno Land

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Introduction

Chełmno Land is the oldest part of the territory of the Teutonic State, whose relations with Poland shaped the history of this part of Europe for 300 years (Fig. 1). In this area, in the 1220s, missionary action was initiated by the Polish Duke Konrad I of Mazovia. Retaliatory incursions by pagan Prussian tribes led to the knights of the Teutonic Order being brought into this area in 1226. Until the end of the 13th century, they carried out a campaign of colonisation, fighting the pagan tribes and gradually taking their lands.

The settlement established under German law in Chełmno Land, the resultant changes in the structure of agriculture and land cultivation techniques, and the growing demand on wood as timber, fuel and raw materials for crafts all combined to contribute to the significant deforestation of the territory. The extent of this deforestation

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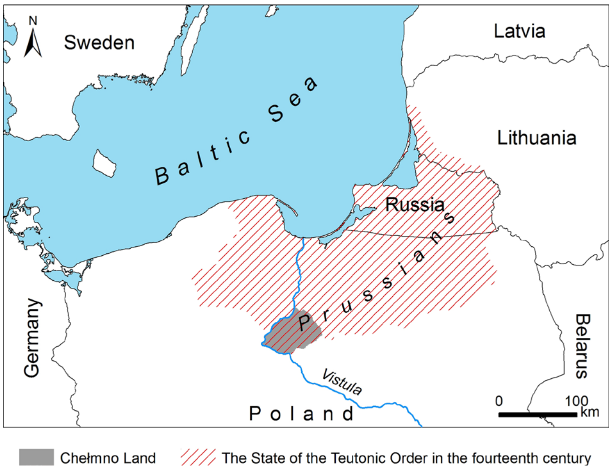

Fig. 1. Location of the research area in the background territory of the State of the Teutonic Order in the 14th century based on Czaja (2000).

remains conjectural. The oldest, unreliable cartographic images of the forest area of Chełmno Land come from the latter 16th century, and it is only portrayed in something approaching the cartometric form on maps from the turn of the 18th century (Paćko, Trzebiński 1983).

The purpose in creating a model of the forest area in 13th-century Chełmno Land was to attempt to reconstruct it and determine its size and, consequently, to verify hypotheses concerning the scale and the ultimate end of deforestation in this area. It is usually assumed that deforestation ended in the late 13th or early 14th century and that its extent can be determined based on later cartographic sources, including those from the late 18th century (e.g. Rejewski 1971, Poliński 2003). Existing studies concerning the forest area of Chełmno Land in the Middle Ages is purely historical, on account of the state of research from that time (Schlüter 1921, Paradowski 1936). Paradowski (1936) estimated its extent in the 13th century to be about 70% of the forest area. Moreover, the research subject is important in the context of numerous archaeological and historical studies on various forms of late medieval settlements (castles, fortified settlements, non-defensive settlements) in this territory (e.g. Kola 1991, Poliński 2001, Wasik 2016, Wiewióra et al. 2019, Wiewióra 2020).

The extensive literature on the issue of changes in the forest area is presented at various temporal and spatial scales (local, regional, continental, global) in the context of changes in demographics, economy, culture, climate and environmental conditions (mainly soil quality). Data for reconstructing these changes come from historical sources (written and cartographic), archaeological studies, toponymic studies and palaeobotanical research.

In the context of the subject matter at hand, works on changes in the forest area in Europe and Poland during the Middle Ages are of key importance. Classic works addressing anthropogenic deforestation include those of Hilf (1938), Rubner (1965), Semmler (1991) and Williams (2003). In most current publications, authors focus mainly on the issues of changes in the forest area in the context of settlement and related exploitation of forests (e.g. Klingelhöfer 1992, Morin et al. 1996, Szabó 2012, Szabó et al. 2015). The periods of this exploitation and the extents of forests are determined by archaeological research, for example, by using airborne laser scanning (ALS) data to locate the remains of charcoal furnaces and dating of charcoals found in them (Brejcha 2013, Paradis-Grenouillet et al. 2015, Groenewoudt, Spek 2016). A separate group of studies consists of small-scale reconstructions of the forest area/deforestation across the entire European continent based on modern digital and remote sensing techniques, databases and spatial models. They use methods from the biological sciences (mainly palynological data) as well as demographic data (including historical population density) in combination with climate data and data on the agricultural utility of soil (e.g. Kaplan et al. 2009, Roberts et al. 2018, Zanon et al. 2018). Changes in the forest area in Poland under the influence of agriculture, which has been especially intense since the beginning of the late Middle Ages, are attested by numerous palynological studies, including those covering larger regions (e.g. Wacnik et al. 2012, Noryśkiewicz 2013).

The medieval forest area/deforestation of Poland or regions thereof was the subject of geographic and historical studies mainly in the first half of the 20th century (Schlüter 1921, Hładyłowicz 1932, Buczek 1936, 1960, Paradowski 1936, Schlenger 1937, Ślaski 1951, 1954). They included attempts to reconstruct particular territories' original forest area, and changes therein as a result of colonisation. Due to the fragmentary and scant nature of the sources, including cartographic sources, the basic method of historical research was the retrogressive method (e.g.

Gieysztor 1948, Baker 1968). This method is also commonly used in the few later works on historical changes in the forest area in selected regions of Poland. They are based on written, cartographic and toponymic sources (e.g. Matusak 2005, Śliwiński 2007, Związek, Panecki 2017). One of the newer studies concerning, *inter alia*, historical forest area in the early modern period is a publication, together with a WebGIS study, on the Nowy Tomyśl region (western Poland) (Panecki et al. 2018). The WebGIS platform was used to integrate and visualise historical, archaeological, geographical and cartographic source data that constitute the basis for further analyses of forest area and settlement in the study area.

Despite the development of modern digital methods for combining data from various sources to generate maps of potential forest cover, written sources play a key role in reconstructing the extent of forests in historical times, for example, in the validation of models. With regard to the Middle Ages, the basic problem in reconstructing the forest area is the incompleteness (and more usually the lack) of historical data, including, in particular, of cartographic images.

Fundamental to the reconstruction of Chełmno Land forest cover in the 13th century were sources that contain direct information from the research period, in combination with the aforementioned retrogressive method. It consists in beginning research from later times for which we have the most complete source materials (in Poland, this means the turn of the 19th century) and progressing the study backwards through time, taking into account sources of increasing age and diminishing quality (Gieysztor 1948). In other words, it is research that attests to the past of geographical spaces known from historical sources, and that allows us to discover what their condition was in a past period. This requires that features that persist for long periods in the landscape (landform, geological structure, soils) be distinguished from those that change (waters, vegetation) more quickly (Rutkowski 2019).

As agriculture develops along with the demand for wood, vegetation (including forests) is undoubtedly the least stable component of the geographical environment. This feature of forests and the lack of historical sources mean that when historical cartography is used to present geographical and historical research, the status of forest cover is often transferred onto maps (reconstructions) from later sources, and this is explained in the map legend.

The present reconstruction of Chełmno Land's 13th-century forest cover employed incomplete, estimated data on the size of agricultural lands relative to the settlements of the time, and later sources, including modern ones. Due to the existence of agriculture in the research area, the demand for wood before the research period and the diversity of natural plant habitats, it clearly cannot be assumed that all land areas not being used for agriculture were forested in the 13th century. As already mentioned, the oldest reliable and largely cartometric depiction of the forest cover of Chełmno Land is found in maps from the turn of the 18th century. There is a 500-year time lag between the late 13th century and the publication of these maps, so in various places, the portrayal of forest cover far reflects the true state in the research period. Questions thus arise as to whether any such reconstruction is possible in view of the limitations of the sources.

Geo-historical research results can be considered either certain or to have only a certain degree of probability. Herein, the author obtained an approximate image of the forest cover of 13th-century Chełmno Land based on a multi-criterion analysis (Malczewski 2006). It consisted in selecting theoretical criteria (factors) that might affect the forest cover or deforestation in the research period and then making assumptions as to the relative impact of each. The analysed criteria are the theoretical extent of agricultural land around settlements of the time, utility of soils, limits on accessibility of land to agriculture (large denivelations), the persistence of forest in areas unfavourable to agriculture, the presence of wetlands as potential forest habitats and the density of archaeological sites from the research period as an indicator of the extent of land use. The natural criteria were analysed in the context of general knowledge about the degree to which individual components of the geographical environment of Chełmno Land were transformed from the 13th century.

As already mentioned in cartographic reconstructions of historical landscapes by using the retrogressive method, features of the geographical environment may be transcribed to an earlier period from later sources if they are relatively permanent, for example, topography, or tend to be preserved, for example, the courses of main roads or the locations of settlements. Surface waters are far less persistent, generally being transformed to varying degrees by natural or anthropogenic factors. In this context, reconstructing the very fragile landscape element, that is, forest cover is, in the absence of sources from the period of interest, practically impossible. The applied methodology for estimating the historical forest cover based on multi-criterion analysis attempts to overcome this infeasibility. Theoretically, it extends the possibilities of the retrogressive method in the field of forest cover reconstruction beyond the maximum time range imposed by the lack of historical sources. The built model of Chełmno Land forest cover in the 13th century, in the form of a reconstruction (visualisation), was the basis for estimating the size of the forest cover. The model was visualised using the geographic information system (GIS) platform as a chorochromatic map, unlike the point symbol maps or choropleth maps that are usually in reconstructions of the forest cover (e.g. Szabó et al. 2015, Związek, Panecki 2017).

Research area

The study area, which covers about 2790 km^2 (of which about 1% is lakes) in north-central Poland, east of the Vistula River, is the historic Chełmno Land according to its borders from the first half of the 13th century (Fig. 2). The region's name derives from the city of Chełmno (city rights granted in 1233). At the beginning of the 13th century, the borders of the region were marked by, other than the Vistula, the following rivers: the Drwęca to the south, the Osa to the north, and the Lutryna to the east. In the

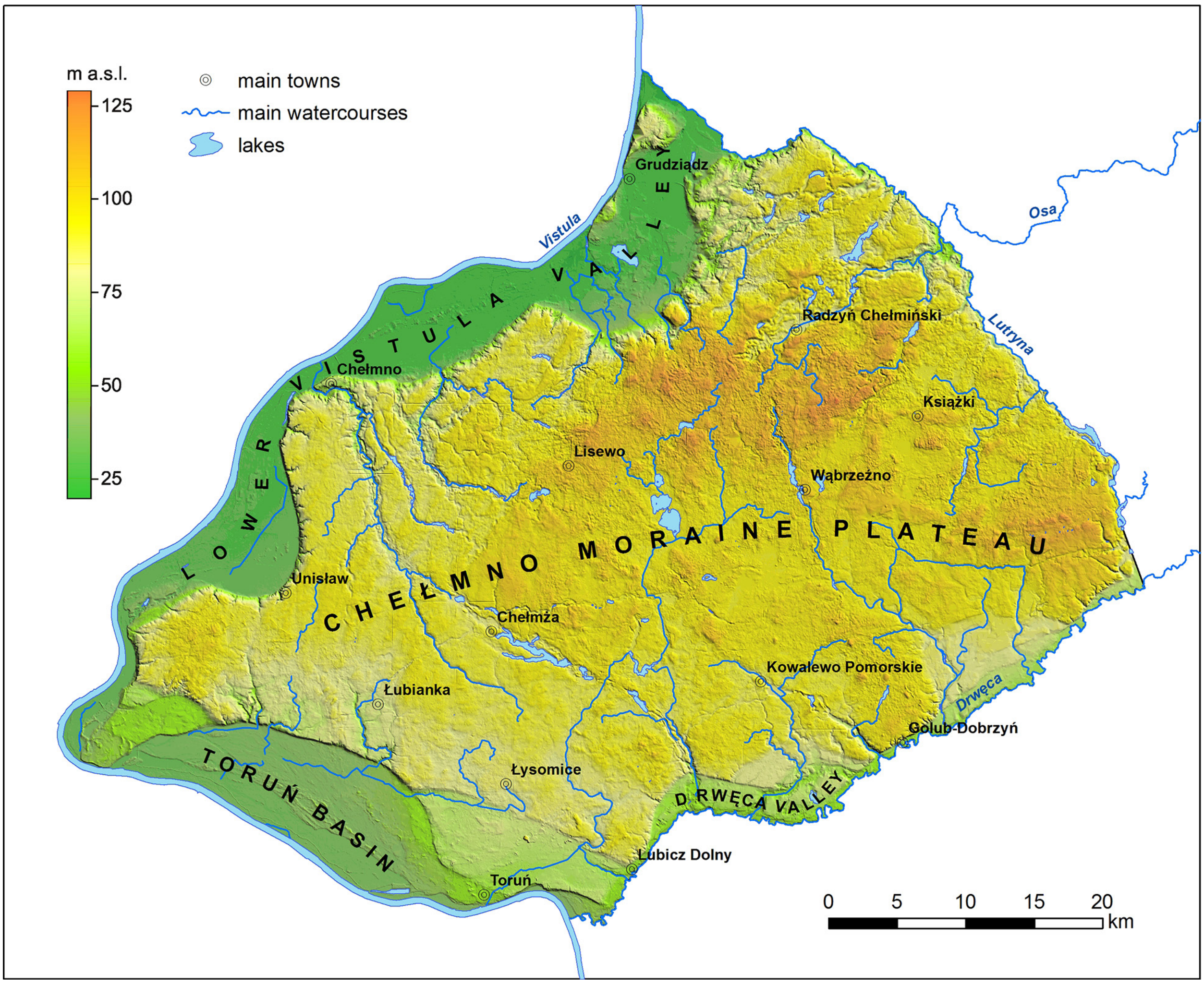

Fig. 2. Physical map of Chełmno Land.

latter half of the 13th century, Chełmno Land was expanded to include some adjacent territories: Lubawa Land, Michałów Land and part of Pomerania (Biskup 1961). In terms of physical geographical terms, Chełmno Land (in the initial borders) covers the Chełmno Lakeland (the Chełmno Moraine Plateau), part of the Lower Vistula Valley, east of the river, and parts of the Toruń Basin and the Drwęca Valley to the north of these rivers (Kondracki 1998).

The contemporary geographic environment of Chełmno Land differs significantly in condition from the 13th century. Since then, it has undergone multiple transformations, mainly anthropogenic, which intensified as settlements and economic development increased in the territory. Individual components of the geographical environment have changed to different degrees. Undoubtedly, the most significant transformations were in the original vegetation, manifesting principally as deforestation and a significant expansion of agricultural land, beginning in the 13th century. From then on, natural hydrological conditions were changed by regulatory, drainage and hydro-engineering works, which intensified from the end of the 18th century onwards.

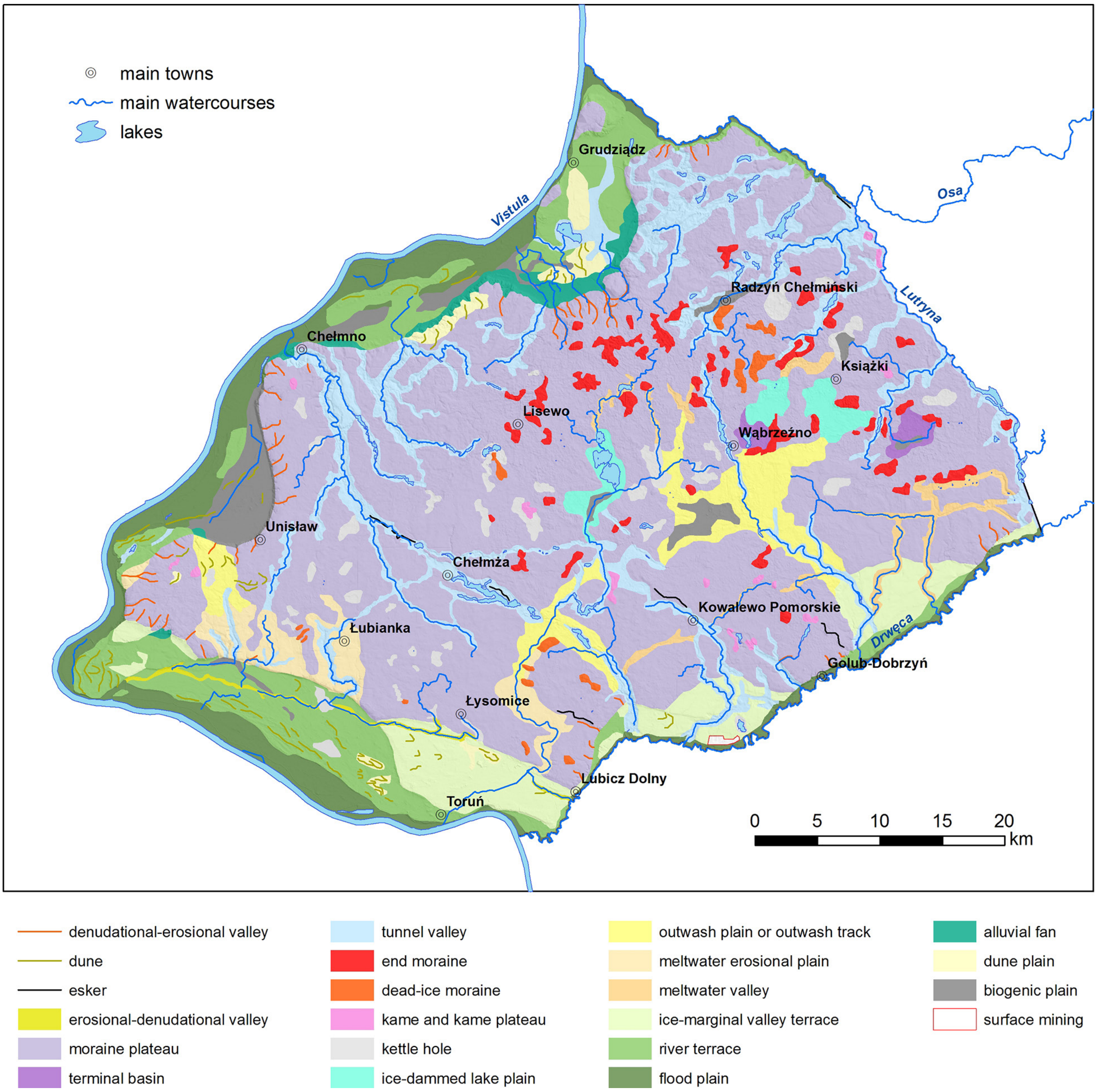

Fig. 3. Geomorphological map based on Molewski and Weckwerth (2017).

Lesser were the changes in the topography and soil which progressed alongside deforestation, changes in land cultivation techniques and the introduction of new types of crops. These were transformed and degraded mostly as a result of human economic activity from the beginning of the 19th century onwards. This period and the beginning of the industrial era are also associated with the human influence on climate.

The contemporary relief and surface geological structure of Chełmno Land were created as a result of complex morphogenetic processes that began at the end of the last glaciation (Molewski, Weckwerth 2017). In their effect, the dominant varieties of the modern natural landscape in the area in question are the moraine plains located on a moraine plateau, which in the north is diversified with tunnel valleys and end moraines used for agriculture, and in the south is diversified with outwash and meltwater erosional plains used for agriculture and partially forested (Kot 2015). Within the ice marginal valley and valley of the Vistula and the Drwęca are mainly flood plains, which are used for agriculture, and meadow terrace plains, either forested or not, with dunes in the Toruń Basin (Fig. 3).

The hypsometric differentiation of Chełmno Land results from it being located on a moraine plateau and in an ice marginal valley and a river valley (Fig. 2). The Chełmno Moraine Plateau rises predominantly from 75 m to 100 m a.s.l. In its northern and eastern parts, absolute heights increase to 120–125 m a.s.l. In the Toruń Basin and the Drwęca Valley, which is connected to it, the absolute heights fall from about 75 m to 30 m a.s.l., and in the Lower Vistula Valley, from about 30 m to 20 m a.s.l.

The largest height differences in the area are associated with the slopes of the Drwęca–Wisła ice marginal valley and the slopes of valleys of

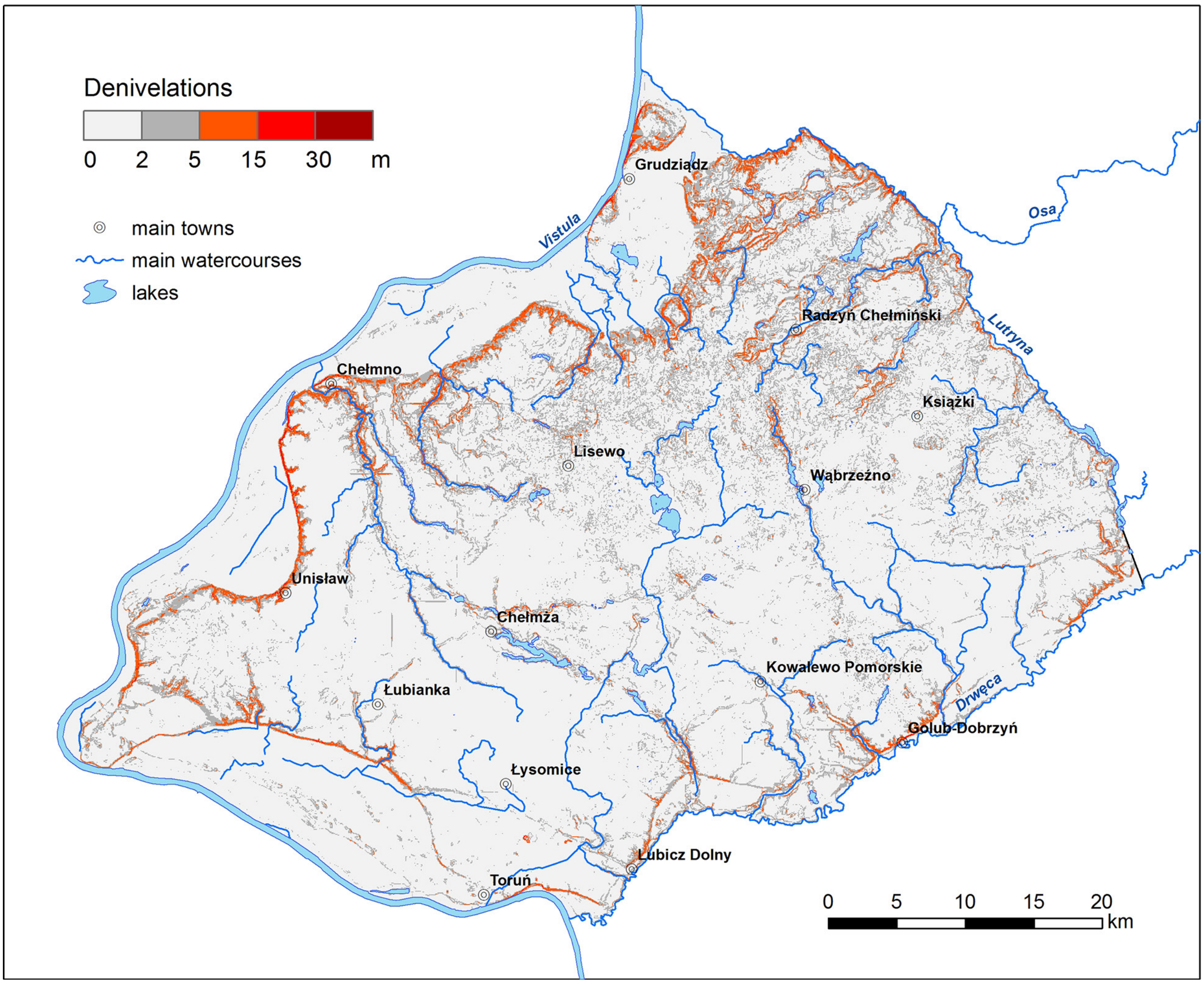

Fig. 4. Relative altitude map.

this river. The maximum height differences reach 60 m on the slopes of the Lower Vistula Valley, 40 m in the Toruń Basin and 30 m in the Drwęca Valley (Fig. 4).

The present state and layout of Chełmno Land hydrographic network undoubtedly differ from those in the Middle Ages and are the result of natural changes, mainly climatic, but all of the anthropogenic transformations began in the 13th century. One particularly unfavourable result of these transformations are the lowering of the first layer of ground waters and the disappearance of wetlands and endorheic areas.

Recognition of these changes and determining water relations in the 13th century are difficult due to the small number of medieval written sources about Chełmno Land that relate to this issue (Poliński 2003). There is also a lack of historical plans, maps or hydrological data for the research period.

Both pollen analyses and historical records provide evidence that the groundwater level was mostly much higher in medieval Poland than it is today (Górczak 2012). Originally, wetlands occupied a far greater share of the study area, in particular in the ice marginal valley and the Vistula Valley. This is evidenced by the names of places such as Czarne Błota and Błotka in the Toruń Basin, or Błoto, Bruki Unisławskie and Bruki Kokocka in the Lower Vistula Valley

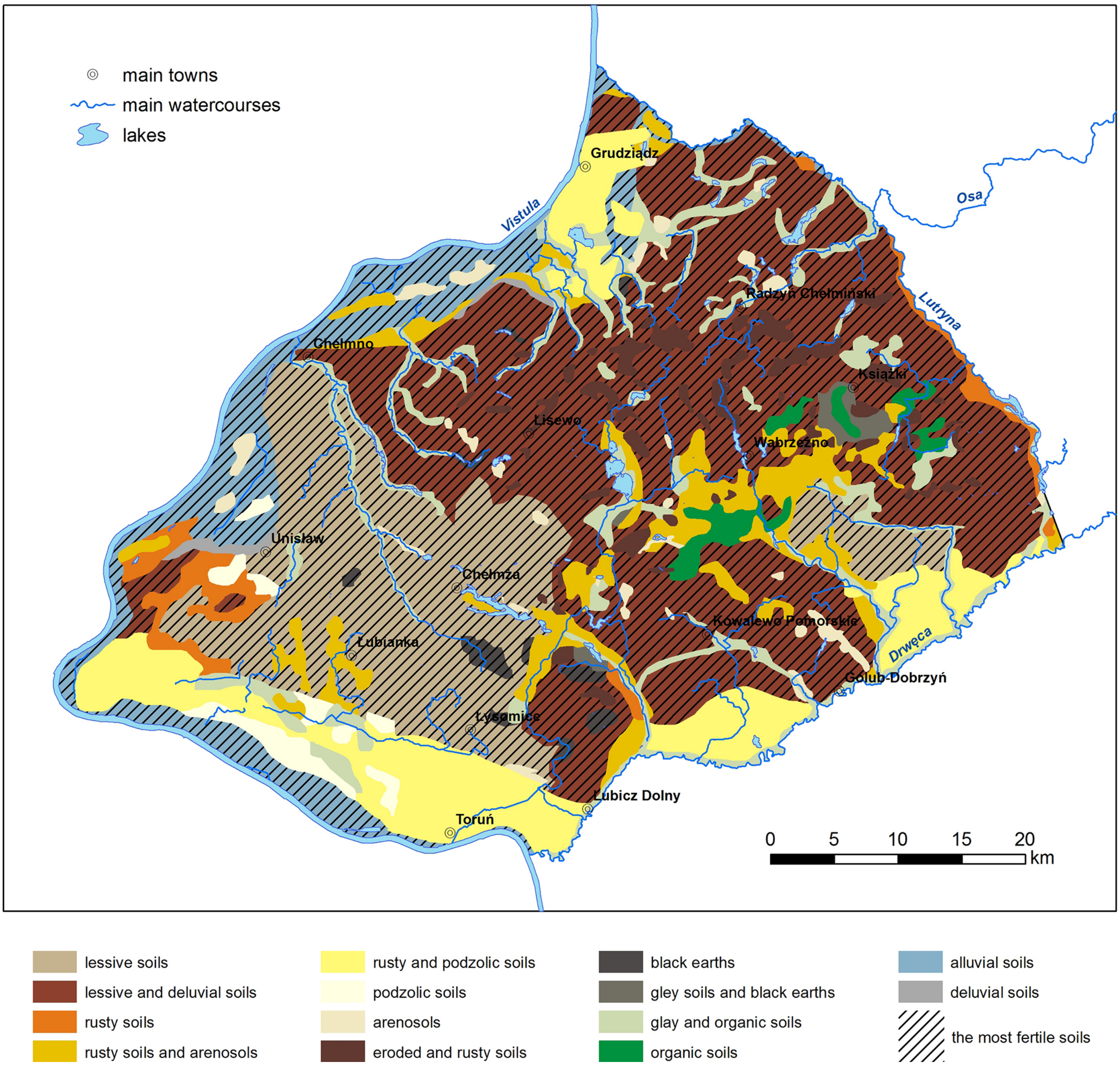

Fig. 5. Soil map based on Bednarek et al. (2015).

(place names derived from Polish *błoto* – mud and German *Bruch* – bog) (Długokęcki 2016). This significantly larger share of wetlands in the area under consideration, including on the moraine plateau, is still visible on historical maps from the turn of the 18th century (Schrötter 1802). It can be assumed to be highly probable that five centuries earlier, wetlands, including wetland meadows, occupied even larger areas. The deforestation of the area may also have contributed to the rise in groundwater levels by reducing the retention function of forests. Similarly, the share of lakes in the land cover was higher, including small melt-out lakes on the moraine plateau.

The most extensive coverings in the research area are of soil lessives and deluvial soils on the Chełmno Moraine Plateau, rusty and podzolic soils in the Toruń Basin and alluvial soils in the bottom of the Vistula Valley (Fig. 5) (Bednarek, Świtoniak 2017).

The anthropogenic transformation of the soils of Chełmno Land is the result of deforestation, the spread of crop cultivation, changes in water conditions and natural plant cover, and settlement processes. The greatest changes in the soil cover in the agricultural areas of the plateau were the result of anthropogenic denudation (Sinkiewicz 1998). They manifest as a predominance of soil lessive associations with deluvial and erosive soils in the northern and eastern parts of the study area. As a result of natural and anthropogenic changes in water conditions in depressions of the terrain, there were changes in the characteristics (including drying) of hydrogenic and semihydrogenic soils, including black earth. Changes in soil properties also occurred as a result of anthropogenic transformations of the natural plant cover, as exemplified by rusty soils being transformed into podzolic soils under the influence of the pine monocultures that replaced deciduous and mixed forests. The largest modifications of the soil cover took place in urbanised areas (Bednarek, Świtoniak 2017).

Sources and methods

To develop the forest area model of 13th century Chełmno Land, in addition to the incomplete, estimated historical data, later sources and indirect data were used. The model was the basis for estimating its size.

The basic source of data on the size and distribution of settlements in Chełmno Land was a monograph by Poliński (2003). The estimated size of areas exploited by individual settlements presented therein is based on references in written sources. Because these sources are relatively poor and fragmentary (especially for the first stage of Teutonic rule), when establishing the location of settlements, the mentioned author also used archaeological sources, that is, the results of excavations and surface archaeological research (Polish Archaeological Record; pol. *Archeologiczne Zdjęcie Polski*, AZP). These sources are auxiliary and verify mentions in written sources. Moreover, based on these sources, the author periodised the time from the 1230s to the turn of the 16th century in Chełmno Land (Poliński 2003). This was based on pottery production, with a particular emphasis on changes in the pottery production in workshops of Chełmno Land. Conclusions about the period in which individual settlements' production were drawn based on chronological analyses of archaeological materials from these settlements, augmented with information available in written sources. The boundaries between identified periods of pottery phases correlate with the most important political and economic events in the research area, since changes in pottery techniques were associated with the changing populations brought by colonisation and wars. These studies show that within historic Chełmno Land, the late medieval layout of rural settlements was largely preserved. At the same time, although most of the settlements are known from written sources, about 7% of them are known only from archaeological studies (Poliński 2003).

The work contains, among other things, maps of the distribution of settlements and, in some cases, estimates of the size of the agricultural land they occupy in the period specified by Poliński in the so-called first phase of late medieval settlement in Chełmno Land – around 1230–1343. In the study area, 228 settlements were distinguished in this phase: villages, villages with a grange, granges, fortified settlements, castles, towns and undefined rural settlements. For 100 settlements (villages, villages with a grange, granges and undefined rural settlements), there are historical data on the area of agricultural land they occupy, which are quantified in terms of *lan* (1 łan = 16.8 ha, the size of 1 łan most commonly used in the literature for Chełmno Land in the Middle Ages). A map of archaeological sites (movable finds) that correlate with the aforementioned first phase of late medieval settlement in Chełmno Land was also used to indicate the economic exploitation of a given territory (Poliński 2003).

In constructing the model, the hand-drafted 1:50,000 topographic map of Friedrich Leopold Schrötter (more properly the Schrötter–Engelhardt Map) from the beginning of the 19th century was used, as well as its printed, generalised 1:152,600 version (Schrötter 1802). This map is considered to be the most accurate, broadly cartometric, image of most of Prussia at the turn of the 18th century. The map contains detailed information on the land cover of the study area, including the extent of forests, wetlands and meadows. In addition, modern thematic and topographic maps of the study area were used: soil types and subtypes (Bednarek et al. 2015), Polish wetlands (habitat types, IMUZ 2020), and the digital database of general geographic objects (BDOO) for the Kujawsko-Pomorskie Voivodeship, within which the study area is located (Data of Head Office of Geodesy and Cartography, Poland). A digital elevation model (DEM) with a resolution of 20 × 20 m was also used (Data of Head Office of Geodesy and Cartography, Poland).

The basic platform for collecting, analysing and visualising the spatial data for reconstructing possible forest area was the GIS. This allowed the integration of all spatial data from historical and contemporary sources, both qualitative and quantitative (discrete and continuous). In the reconstruction, raster and vector spatial data models were used, converting all vector spatial data to the raster form with a 20 × 20 m raster cell.

Multi-Criterion Evaluation (MCE) was adopted to build the forest area model (Shekhar, Xiong 2008). In essence, multi-criterion analyses are used in spatial planning (Malczewski 1999, Malczewski, Jaroszewicz 2018). They are based on maps of criteria determining the suitability or non-suitability of a given area for a specific use. The model employs the fundamentals of one type of this method – that is, weighted linear combination (WLC).

It was assumed that the WLC method can be used to designate areas of forest area occurrence, taking into account selected criteria determining the potential presence or absence of a forest: this potential can be determined based of the collected data. In the first stage of the research, raster maps of criteria were prepared in two groups: maps of criteria favourable and unfavourable to the potential forest area. Then, on individual criteria maps, the attributes (raster cells) indicating the potential forest area of a given area were given a value of 1, and those suggesting deforestation a value of −1, while others irrelevant to the analysis were assigned a value of 0. Attributes with the value of 1 or −1 were assigned significance weights by using the rank-sum method separately for each group of criterion maps (Table 1) (Stillwell et al. 1981). In this method, significance weights depend on the place of a criterion in a ranking of criteria according to subjectively presumed significance. In the last stage, map algebra was used to generate the resulting map (e.g. Gregory, Ell 2007), the values of which were calculated using the WLC method:

Table 1. Criteria of potential forest area of the research area.

Criterion	Attribute values A	Ranking of criteria	Weighting w
Extent of forests on the Schrötter map	1	1	0.33
Extent of wetlands based on the Schrötter map and maps of Polish wetlands	1	2	0.27
Extent of modern forests	1	3	0.20
Wetness index (SAGA WI)	1	4	0.13
Relative altitudes	1	5	0.07
		Sum:	1.00
Hypothetical extent of agricultural land	−1	1	0.50
Soils favourable to agriculture	−1	2	0.33
Density of archaeological sites	−1	3	0.17
		Sum:	1.00

$$\mathrm{RM} = \mathrm{A}_1 \times w_1 + \mathrm{A}_2 \times w_2 + \mathrm{A}_3 \times w_3 + \mathrm{A}_4 \times w_4 + \mathrm{A}_5 \times w_5 + \mathrm{A}_6 \times w_6 + \mathrm{A}_7 \times w_7 + \mathrm{A}_8 \times w_8$$

Explanations: $w_j = (n - r_j + 1) / \sum(n - r_j + 1)$, where w_j is the normalised weight for the jth criterion, n is the number of criteria under consideration and r_j is the rank position of the criterion (Malczewski, Jaroszewicz 2018).

Analytical maps

Map of the hypothetical extent of agricultural land

Determining the hypothetical extent of agricultural land, which is to say anthropogenically deforested areas occupied by individual settlements, began with reconstructing their theoretical settlement territories. Among the methods used to determine these, an irregular Dirichlet–Voronoi tessellation was used – that is, the research area was divided into Thiessen polygons based on the location of settlements (see Alessandri 2015). It was assumed that the polygons theoretically correspond to the areas exploited by individual settlements (Clarke 1977, Kobyliński 1987). It was assumed also that within their boundaries, there were agricultural lands belonging to the settlements. It is practically impossible to determine the location and spatial arrangement of these adjacent areas. Therefore, it was assumed that these areas were arranged around the settlements and roughly oval. Individual examples of such a system can be seen on the Schrötter map from 1802 in what

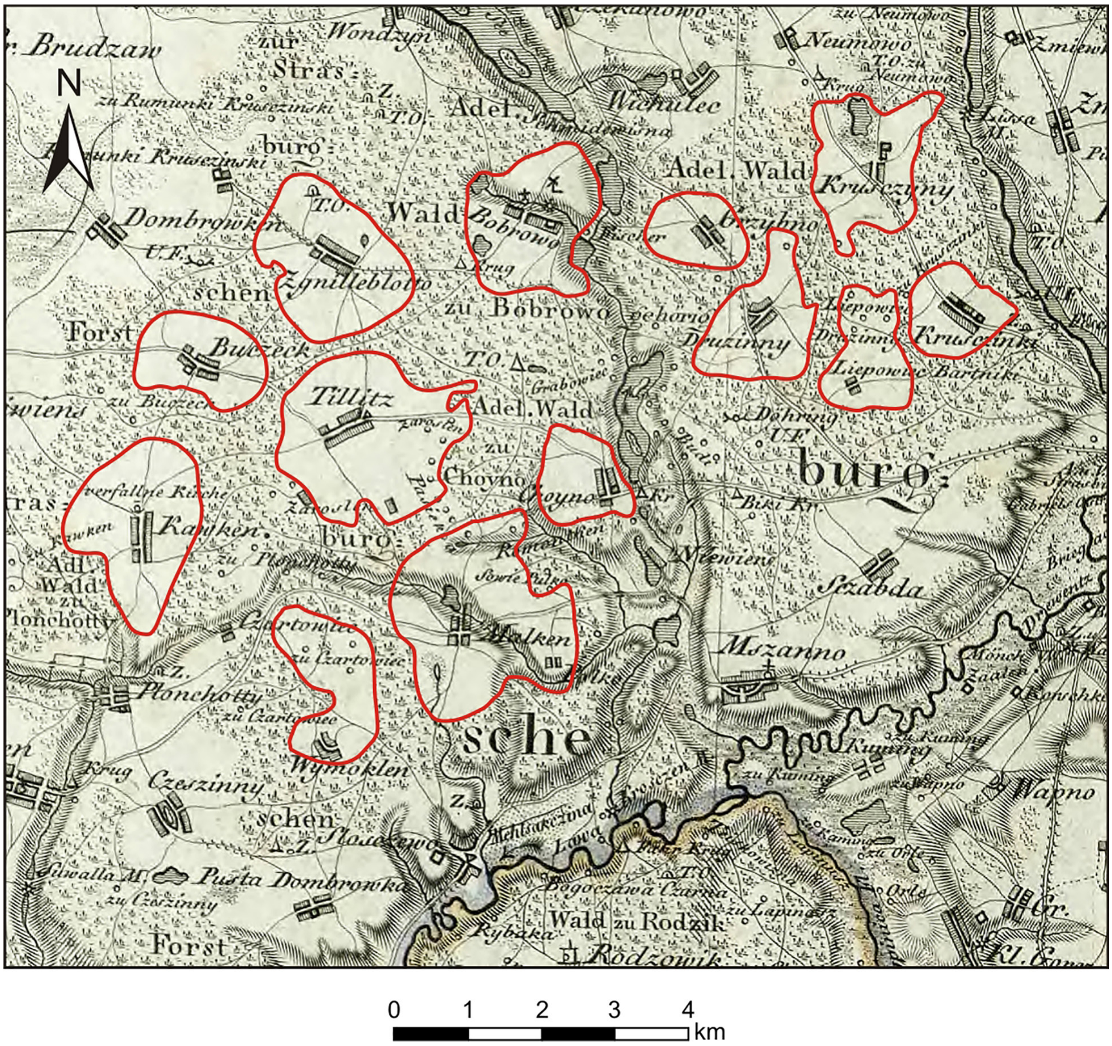

Fig. 6. Deforested areas around settlements in the eastern part of Chełmno Land on the Schrötter map from 1802.

was in the late 18th century the more forested, eastern part of Chełmno Land (Fig. 6) (Schrötter 1802). A good example of such a structure of medieval settlement from the second half of the 13th century is the distribution of small rural enclaves (140–800 ha) within dense forest complexes of the historic Nowa Marchia province of western Poland (Pieńkowski, Kupiec 2015). The authors of the cited publication associate the characteristic structure of the settlement network with the post-1250 period of colonisation in this area. Due to the poor soils that were unfavourable for agriculture, this area's land-use structure has been preserved to the present day with only slight changes in shape.

As already mentioned, for 100 of the 228 distinguished settlements, there are historical data on the amount of agricultural land belonging to them. Due to the uncertainty of some historical sources, these data should be treated as estimates (Poliński 2003). Statistical analysis of the size of these areas showed that their distribution is right-skewed (*SKE* = 0.35), which results from the low proportion of large areas (>12 km^2), and the mean (6.60 km^2) and median (6.72 km^2) being very close. As a consequence, the 128 settlements for which data are not available were assigned an area equal to the median. This size was also assigned to settlement centres (fortified settlements, castles and towns) for which there are no source data and whose surroundings were probably heavily deforested for both economic and defensive reasons. The calculated total estimated size of the agricultural land area was 1520 km^2, which is about 54% of the entire study area.

As already mentioned, to determine the hypothetical extent of the agricultural land of individual settlements (anthropogenically deforested areas), it was assumed that they were essentially located within the Thiessen polygon determined

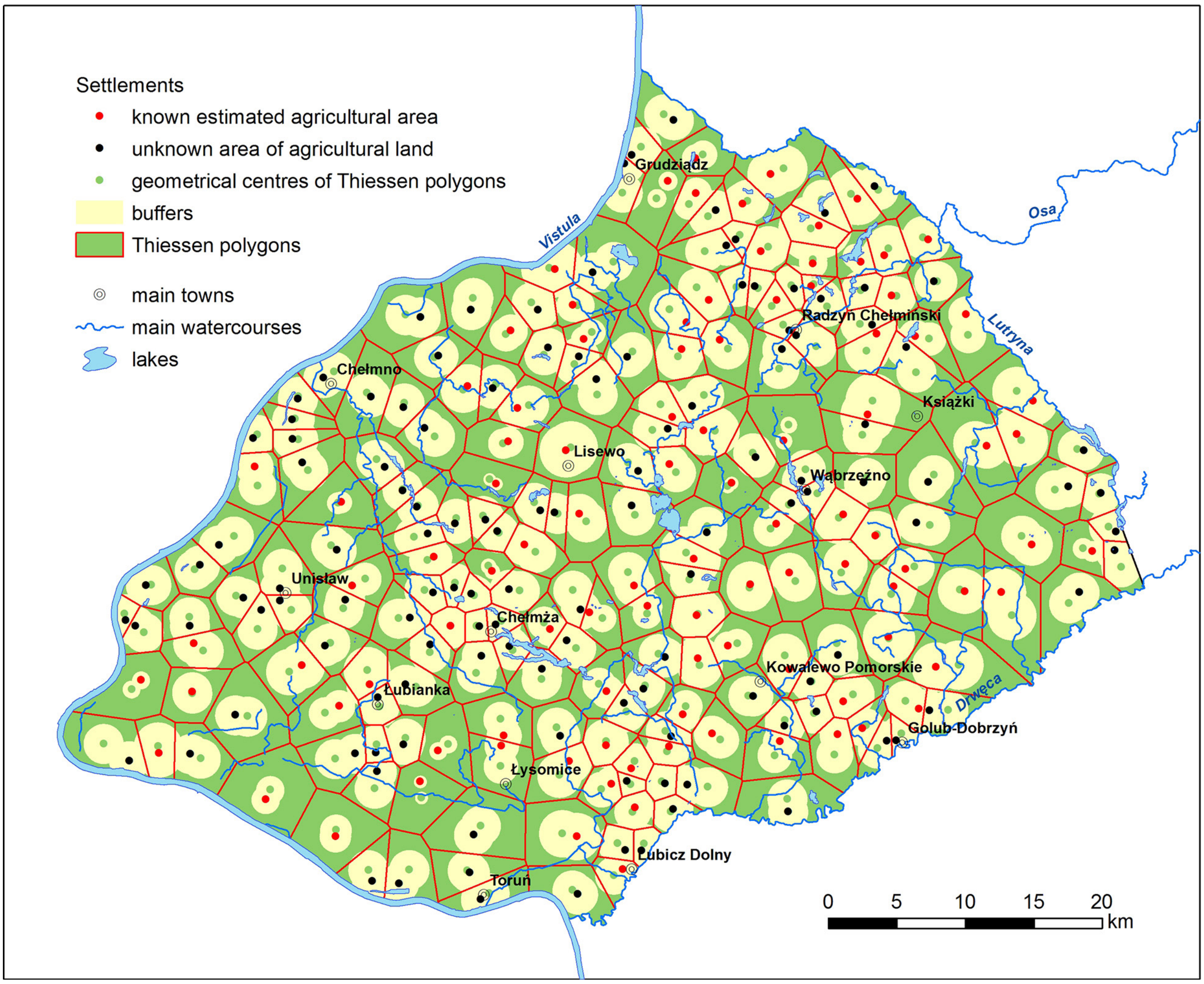

Fig. 7. Hypothetical extent of lands used for farming.

by the settlement and were approximately oval in shape. Moreover, their total area was assumed to be approximately the sum of the utilised agricultural area of all settlements. Assuming the aforementioned, for each settlement, two buffers were plotted – one around the point representing its location and one around the geometric centre (point) of its Thiessen polygon, and each buffer was of an area equal to the size of the settlement's agricultural land (Fig. 7). In the case of adjacent settlements, the buffers overlapped, and the need to divide the shared territory between multiple settlements meant that each settlement's buffer (agricultural area) was smaller than it would otherwise have been. Meanwhile, in cases where a settlement location and the centre of its Thiessen polygon were quite a distance from one another, its two corresponding buffers formed an agricultural area greater than a single buffer would have. The resulting approximate total estimated area of agricultural land was less than 5% points larger than the presumed area.

Map of density of archaeological sites

The density of archaeological sites (movable finds) was used as an indicator of the economic exploitation of a given territory and was determined using the Kernel density estimation method (Silverman 1986, Fotheringham et al. 2000, Lloyd 2010). It was assumed that the key distance of the method – the radius of the circle within which the number of archaeological sites is counted – would be double the average distance between points and thus approximately 3400 m. Areas with a site density above 1.31e^{-7} – those including at least two sites – were assumed to have been used for economic purposes (Fig. 8).

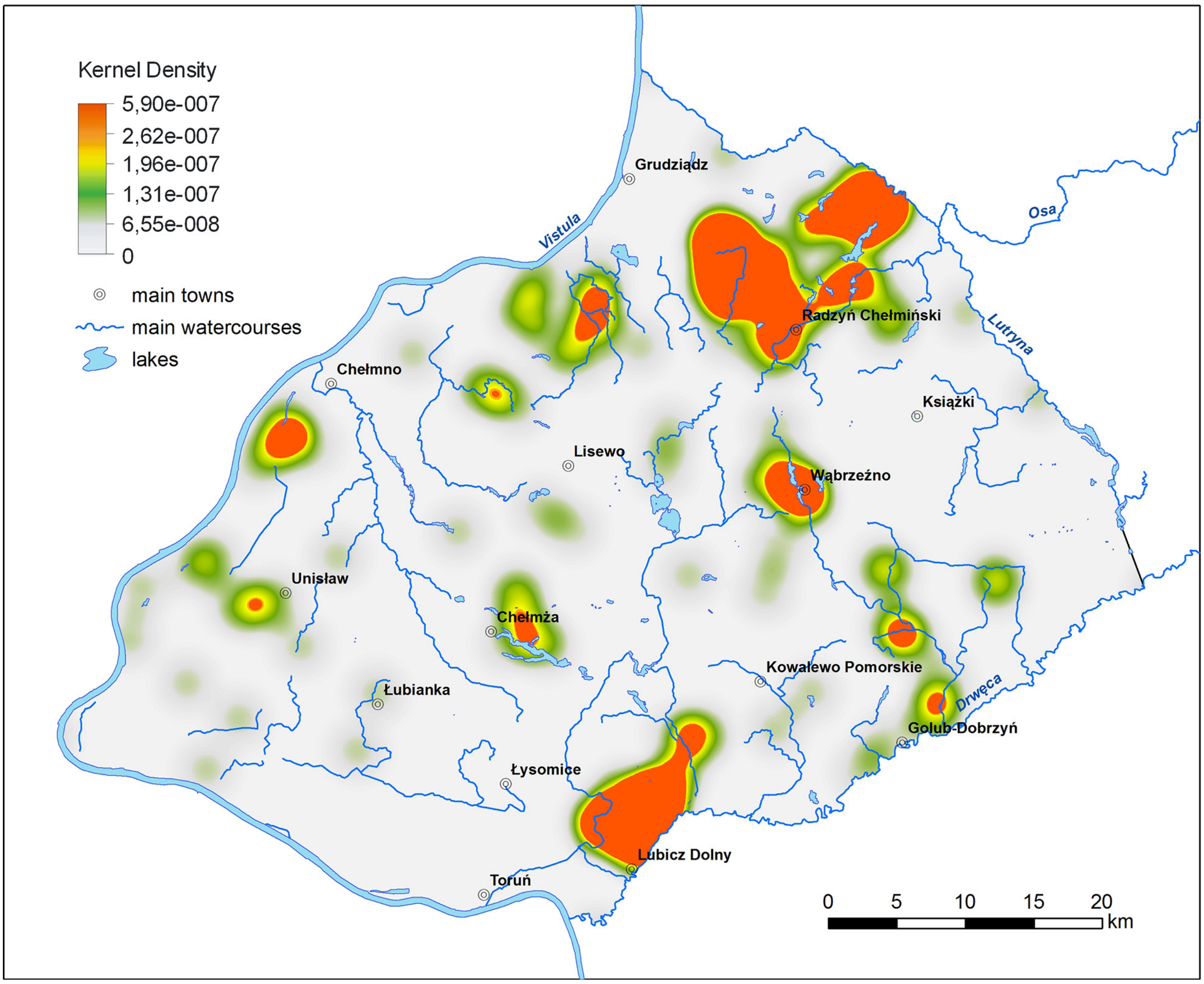

Fig. 8. Density of archaeological sites.

Map of soils favourable to agriculture

The soil condition was the main factor determining agricultural land use and thus its deforestation. This factor has been analysed in many studies on the past forest area of various territories (e.g. Hładyłowicz 1932, Buczek 1960, Ślaski 1965, Kaplan et al. 2009). An example of such a correlation on a regional scale is given by the results of an analysis of forest area in relation to soil cover in the Szczecin Lowland (north-western Poland), whose landscape has a similar origin to that of Chełmno Land (Pieńkowski, Podlasiński 2002). It showed that from the 14th to the 16th century, the fewest forests were found on black soils formed on silty lake sediments (<25% coverage by forest) and on brown soils and soil lessives developed on tills and clayey sands (50–55%). Forests grew on >90% of areas of podzolic soils formed on sands. Forests covered about 50% of water-dependent soils – peat, muck and alluvial soils – which was the result of habitat factors, and not anthropogenic factors.

Taking into account the types of soils present in the study area and their subsequent anthropogenic transformations, the fertile soils in Chełmno Land include black earth, soil lessives, lessive and deluvial soils, and alluvial soils (Fig. 5). These, which occur on floodplains, are variable in agricultural suitability and often used as meadows and pastures.

Map of forest coverage based on the Schrötter map

Since the deforestation of Chełmno Land is assumed to have been complete by the end of the 13th century or the beginning of the 14th century,

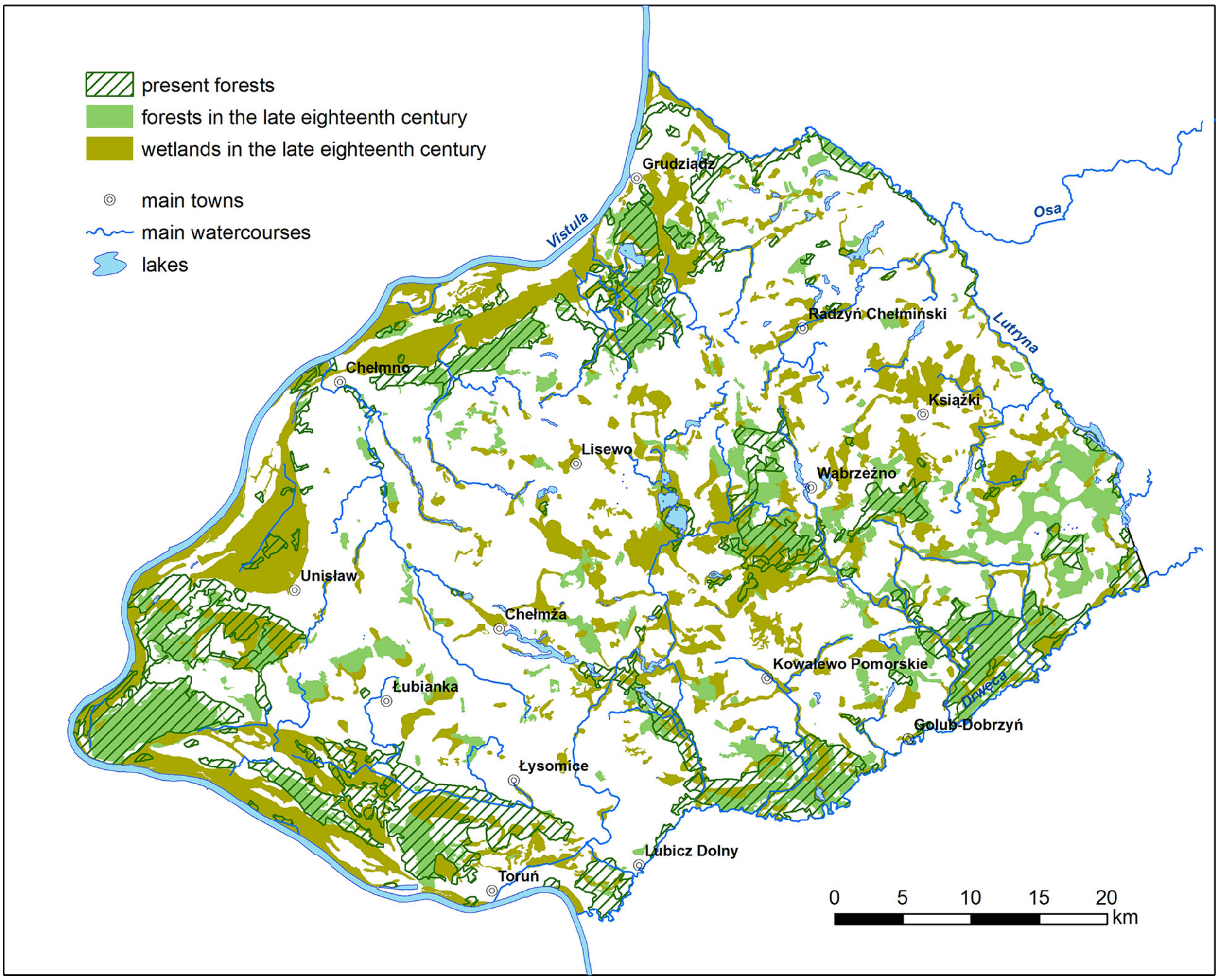

Fig. 9. Extent of forests: modern day (based on the Data of Head Office of Geodesy and Cartography, Poland), the late 18th century (based on the Schrötter map from 1802) and wetlands (based on the Schrötter map from 1802 and the Map of Polish Wetlands (IMUZ 2020)).

apart from the unreliable pre-18th-century cartographic images of Chełmno Land, the distribution of forests is precisely presented on the previously cited Schrötter (1802) map. According to Buczek (1960), although forests were significantly reduced in Poland at the turn of the 18th century, the locations where they remained can be used to deduce where they had previously been most widespread and where they had been absent. Assuming only a slight degree of natural growth (secondary succession) or the only theoretical possibility of empty spaces and idle lands being afforested (afforestation began in the 19th century in Poland), we can assume that the forests of the late 18th century presented on the Schrötter map of 1802 are approximately the remains of the original forests of the study area (Fig. 9).

Map of the range of contemporary forests

Coniferous and mixed forests (mostly pine monocultures) today occur mainly in poorer soils and in the edge zone of the Chełmno Moraine Plateau, with large local differences in relative altitude (denivelations), and on the steep slopes of the Vistula Valley, where they are preserved due to the inaccessibility of these areas for agricultural and forestry exploitation. As a result, rich multi-species stands with many characteristics of natural communities have been preserved here (Rejewski 1971). It was therefore assumed that the range of contemporary forests, which are limited to areas of the least fertile soils and areas of large denivelations not conducive to agricultural development, may roughly correspond to forested areas of the 13th century (Fig. 9). A similar assumption that today's cultural landscape holds the remains of a natural landscape, including forests, was adopted by, among others, Hładyłowicz (1932) in his research on landscape changes and the development of settlement in Wielkopolska from the 14th to the 19th century.

Map of wetland coverage based on the Schrötter map and the Map of Polish Wetlands

A significant problem in determining the potential 13th-century forest area of the analysed area is presented by the fact that it is indeterminable whether a given wetland (periodically or permanently marshy, flooded or covered with water) was at the time covered with meadow or forest vegetation. In the floodplain valleys of rivers, there used to grow deciduous riparian forests and, in the wetlands, often pine forest with admixture of birch and alder (Matuszkiewicz et al. 1995). Meadows occupied small areas, and their distribution was subject to rapid changes. They accompanied watercourses and wetlands, where, as in the bottoms of large valleys, there were riparian forests, alder forests and humid coniferous forests. Riverside carrs were deforested first – for their fertile alluvial soil and the need for fodder (Buczek 1960).

In the 13th century, lakes and wetlands covered a far greater share of the study area than they do today. At the same time, palynological studies on Chełmno Land in this period show the share of alder beginning to decrease, evidencing a general shrinking of the area occupied by wet habitat stands (Noryśkiewicz 2013). However, since the most intensive management and drainage works began in the 18th century in the area in question, the extent of the wetlands was determined mainly from the Schrötter map (Schrötter 1802). On this map, areas marked as overgrown swamps, swampy meadows and meadows were distinguished, with meadows being assumed to have been marshy in the 13th century. Due to the limited cartometric character of the Schrötter map, the range of wetlands presented on it was corrected and combined with the wetland ranges on the contemporary Polish wetland map (Fig. 9) (Schrötter 1802, IMUZ 2020).

SAGA Wetness Index (SAGA WI) map

On the assumption that the extent of wetlands presented based on the aforementioned maps does not reflect all potential wetlands, the topographic wetness index (TWI) was also used (Beven, Kirkby 1979). More precisely, what was used was the SAGA WI, which takes into account the surface slope and the area it was fed by Boehner et al. (2002) and Boehner and Selige (2006). The dimensionless value of the index represents the theoretical distribution of the surface moisture content correlated with the potential occurrence of wetlands. The SAGA WI map was

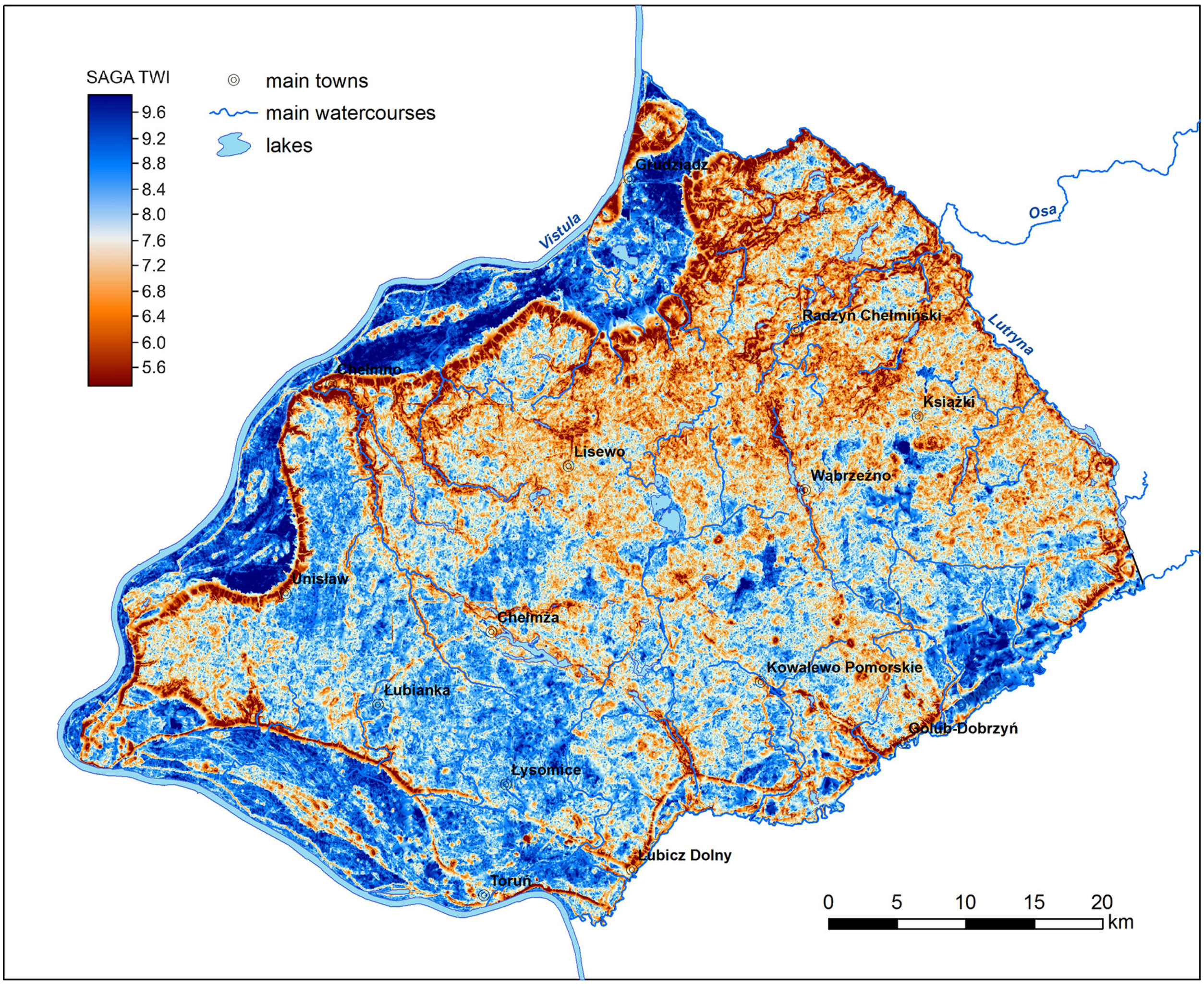

Fig. 10. SAGA Wetness Index.

generated from the DEM. The obtained dimensionless index values range from 2.36 to 11.42. The higher the index value, the more likely there was a wetland. The areas of potential occurrence were compared against the extent of wetlands on the Schrötter map and the contemporary Map of Polish Wetlands (Schrötter 1802, IMUZ 2020). As a consequence, areas with an index value >8 were distinguished on the map, creating >10 ha field of potential wetlands (Fig. 10).

Map of relative altitudes

As already mentioned, the factors conducive to the forest area of Chełmno Land were, and are, large local denivelations and steep slopes. A similar relationship was found in the aforementioned studies of soil cover in the Szczecin Lowlands, where despite fertile soils, the share of forests in areas of diverse hypsometry was high (35%) until the first half of the 20th century (Pieńkowski, Podlasiński 2002). The map of relative altitudes was generated from the DEM. It was assumed that forest area was favoured by areas with differences in altitude of >5 m (Fig. 4).

Final map

Values calculated using the WLC rule ranged from 0.93 to −1 and were classified into eight intervals using the Jenks natural breaks method. The weighted sum values in intervals show the strength of classification as forest areas for individual raster cells. The intervals are assigned grades 1–8. The higher the grade, the greater the strength of classification (Fig. 11).

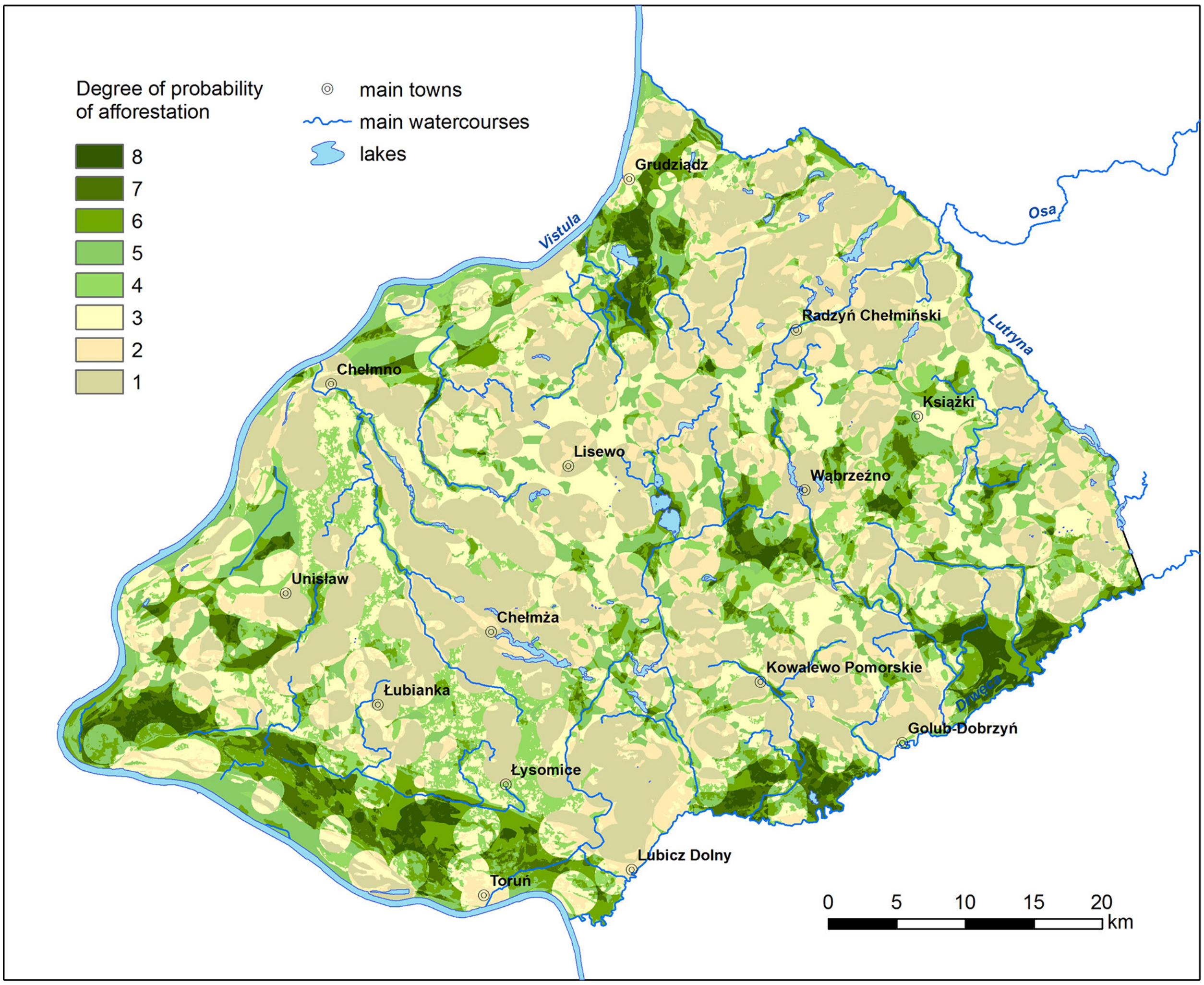

Fig. 11. Spatial model of forest area occurrence in Chełmno Land in the 13th century.

Results

In accordance with the methodology adopted for determining the hypothetical range of agricultural land (areas of anthropogenic deforestation), the largest continuous areas were determined to have existed in the Radzyń Chełmiński area in the north of Chełmno Land, near Chełmża in the central part; north of Lubicz Dolny; and west of Golub-Dobrzyń in the south. Moreover, the Radzyń Chełmiński and Lubicz Dolny areas coincide with the largest areas with a high density of archaeological sites (movable finds) – the adopted indicator of economic exploitation.

The soils classified as fertile and first subjected to agricultural management cover about 63% (1755 km^2) of the analysed area. They appear predominantly in the Chełmno Moraine Plateau and at the bottom of the Lower Vistula Valley. Infertile and less fertile soils occur mainly on sandy plains on the plateau and on valley and ice marginal valley terraces in the Toruń Basin and the Drwęca Valley.

On the Schrötter map, the extent of forests in the study area at the end of the 18th century coincides about 40% with that of today (Schrötter 1802). At that time, forests covered about 12.9% (360 km^2) of the area. The greatest concentration of forests was in the south-eastern part of Chełmno Land, and the largest complexes were in the ice marginal valley and valley of the Vistula and the Drwęca. Contemporary forests cover about 16.5% (460 km^2) of the study area, which is 3.6% points more than that at the end of the 18th century. Compared to the Schrötter map, the shrinkage mainly affected smaller forests on the plateau, while forests located in the ice marginal valley and valley of the Vistula

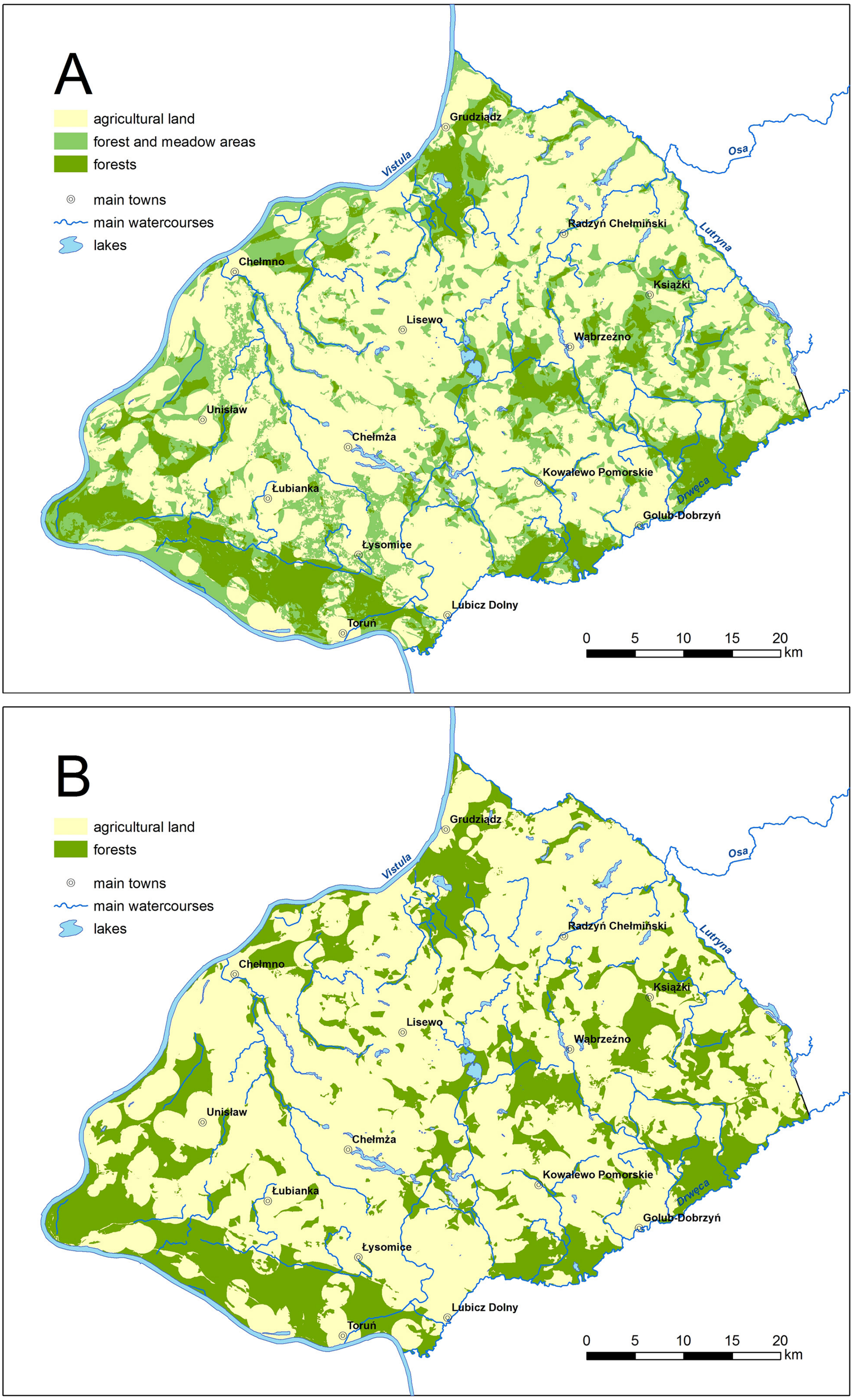

Fig. 12. Variants of the hypothetical forest area of Chełmno Land in the 13th century.

Table 2. Variants of the hypothetical forest area in 13th-century Chełmno Land.

<table>
<tr><th rowspan="2">Grade of classification as forest area</th><th>Surface</th><th>Share in the area</th><th>Variant A sum</th><th>Variant B sum</th></tr>
<tr><th>[km^2]</th><th colspan="3">[%]</th></tr>
<tr><td>8</td><td>77</td><td>3</td><td rowspan="3">16</td><td rowspan="4">28</td></tr>
<tr><td>7</td><td>119</td><td>4</td></tr>
<tr><td>6</td><td>238</td><td>9</td></tr>
<tr><td>5</td><td>329</td><td>12</td><td rowspan="2">22</td></tr>
<tr><td>4</td><td>276</td><td>10</td><td rowspan="4">72</td></tr>
<tr><td>3</td><td>507</td><td>18</td><td rowspan="3">62</td></tr>
<tr><td>2</td><td>379</td><td>14</td></tr>
<tr><td>1</td><td>840</td><td>30</td></tr>
</table>

and the Drwęca were aggregated and enlarged (Schrötter 1802).

The area of wetlands in the 13th century was estimated at about 600 km^2, which constitutes 21.6% of the study area. Their late-18th-century range on the Schrötter map has since decreased by about 28.4% (Schrötter 1802). The largest dense wetland areas are concentrated in the Lower Vistula Valley, the Toruń Basin and the central-eastern part of the Chełmno Moraine Plateau. The SAGA WI partially correlates with the extent of wetlands determined using the maps, mainly within the ice marginal valley and valley of the Vistula. The index is high in the west of the Chełmno Moraine Plateau – on the so-called Chełmża Plain, where the smallest denivelations occur (Galon 1984). In this area, there were presumably originally many small wetlands and wet meadows, which were the first to be drained.

Areas with differences in relative altitude of >5 m, which were considered conducive to forest area on account of their limited accessibility for agriculture, cover approximately 3.3% of its area (91 km^2).

According to the adopted methodology, a raster map of results was developed, and this constituted the basic spatial model of the forest area of Chełmno Land in the 13th century (Fig. 11). This was used to calculate the absolute area and percentage share of areas assigned grades 1–8, which indicate the strength of a given area of classification as forested (Table 2). Considering the uncertainty of the model, two forest cover variants were proposed. In variant A, the areas of the three highest grades (6–8) were aggregated, on the assumption that they could not have totalled less than the area presented on the Schrötter map (1802). The areas of the three lowest grades (1–3) were similarly aggregated. The forest cover of the study area was determined to be 16% and deforestation 62%, which is 8% points more than that derived from the incomplete and estimated historical data we have regarding the size of agricultural land (Figs 7 and 12). The remaining areas (grades 4–5), which cover about 22% of the area, were considered intermediate (forest–meadow), where the presence and absence of forest are roughly equal. Most of these are potential wetlands, where the presence of tree cover results from habitat factors and not anthropogenic factors. These areas may have been occupied by forests, farmlands, pastures or idle lands. In variant B, the areas of the four highest and four lowest grades were aggregated, dividing the research area into two: potentially forested (28%) and potentially deforested areas (72%) (Fig. 12).

Whichever variant of the potential forest area is adopted, it is higher than the one presented on the Schrötter map from the end of the 18th century, and the first variant is similar to the present-day forest area (Schrötter 1802, Data of Head Office of Geodesy and Cartography, Poland). Assuming that the intermediate areas that cover about 22% of the study area were partially forested, on the basis of the model, it can be assumed that in the 13th century, forests occupied at least 20%–25% of Chełmno Land.

Discussion

Causes and effects of deforestation

The deforestation of Polish lands began in the Neolithic influenced by climate changes, settlements and the cultivation of land. Until the 13th century, inhabited areas of the original forest were less contiguous, with numerous separate manmade glades and former clearings. The border between forests and wetlands was fluid as most of the marshes were overgrown mainly with alder forests and dwarf pines (Ślaski 1965). There was also no sharp border between forests and arable fields or pastures, and forest–meadow areas and forests were the main source of fodder (Dembińska 1965). This interpenetration of forests and fields persisted until the period of colonisation under German law and its related reform of the spatial arrangement of villages and arable land. At that time, there appeared sharp boundaries between forests and arable lands and pastures, and forests receded from the immediate vicinity of settlements (Górczak 2012).

The shrinkage of forests resulted not only from the development of agriculture but also from the growing demand for timber for building. Large amounts of wood – mainly oak and pine – were used to build houses, fortified settlements and towns. Wooden defensive structures dominated in the 13th and 14th centuries, while castles, fortifications and town buildings were increasingly built in stone and brick. Wood was used extensively for fuel and as an energy resource, for example, in brick factories (Dembińska 1965). The demand for wood of a single brickyard for 1 year could require the felling of a few up to 20 ha of forest (Arszyński 2016). Moreover, wood was the basic raw material for many types of craft and forest industries, for the production of charcoal, tar, etc. (Janicki 2014). The intensive use of wood for construction, heating and production purposes led to a depletion of forests around fortified settlements and towns, and thus to the creation of deforested spaces around them.

Because the development of agricultural settlement mainly affected forests growing on the most fertile soils – mainly oak–hornbeam forests, deforestation brought with it a significant change in the forest species composition (Ślaski 1965). Tree species differed in utility value, and mainly more precious tree species were felled mostly because they occupied the best soils (Buczek 1960). The woods most commonly used in Poland from the ninth to the 15th century were *Pinus sylvestris* (pine), *Quercus* sp. (oak), *Fraxinus excelsior* (ash) and *Alnus* sp. (alder). A chronological analysis of the use of wood shows that between the early and the late Middle Ages, the number of items made of hardwood decreased in all regions of Poland (Cywa 2018).

The demand for wood as the basic building, fuel and energy material was met by secondary forest succession in previously felled areas (Szwagrzyk 2004). With dispersed and fluctuating settlement, the spontaneous forest area of formerly deforested areas was probably quite frequent. One documented example of such changes may be forest growth in medieval agricultural areas after the Black Death in the Netherlands and its repercussions in atmospheric CO_2 levels (Van Hoof et al. 2006). The pollen record reflects a significant agricultural regression, accompanied by a regrowth of forest in abandoned farmlands during and following the Black Death, in 1350–1440.

In Chełmno Land, natural processes aside, as agricultural progressed, the changes in the original land cover became ever larger, as reflected in pollen diagrams. As settlements expanded, these changes were expressed in the landscape mainly as deforestation and an increasing share of arable fields and meadows. Based on palynological studies, it was identified as the settlement phase from beginning around the time of the Teutonic Knights' arrival in Chełmno Land and extending until end of the middle ages (Noryśkiewicz 2013). It was characterised by progressive deforestation, which, as indicated by the pollen diagrams, was particularly intense near the Teutonic centres (strongholds) and was correlated with areas of fertile soil. At that time, pine forests, which occupied less economically attractive sandy areas, were already beginning to dominate in the forest structure of the heavily deforested Chełmno Land, as a result of the heavy reduction in the coverage of the mixed deciduous forests that had occupied fertile soils. Moreover, the pollen diagrams show that arable lands predominated in deforested areas, with cereals predominating in the crop structure and a smaller share of meadows (Noryśkiewicz 2013). Lands in the countryside were divided into roughly geometrical plots, each called a *niwa.* In addition to fields, these consisted of pastures, idle lands and forests separating previously irregularly distributed arable fields (Chmielewski, Dąbrowski 1964).

Model limitations and criteria

In light of the limitations and lack of historical sources, including cartographic sources, it is with some justification that some believe that the forest area in Poland can only be reconstructed for the 16th century at the earliest (Związek, Panecki 2017). The first to present such an unequivocally critical attitude to the potential cartographic and quantitative presentation of medieval forest area were Arnold (1929) and Buczek (1936). The results of archaeological, palynological and toponymic research in relation to a specific space, which are also widely used in reconstructing the forest area, are mainly of a qualitative nature. They cannot be used to determine the extent of forest area – only its relative share in the landscape of a given territory.

The basic limitations of the model lie in the historical data on the size of agricultural land for individual settlements being both incomplete and estimated, and above all in the hypothetical spatial distribution of said lands. The designation of territories theoretically exploited by individual settlements using the Thiessen polygon method itself raises reservations because it does not take into account, among other things, landscape features, including natural spatial boundaries. Also, the adopted multi-criterion analysis method of WLC obviously depends on the subjective adoption of criteria and on their subjective ranking, which determined the significance of their weightings.

The spatial model presented in this study provides only a general image of the deforestation of Chełmno Land in the 13th century (Fig. 11). It can be assumed that deforestation was greater locally (based on traces of earlier, abandoned agricultural activity having been found) and that theoretically, deforested areas featured fragments of forest needed by settlements for economic reasons.

Conclusion

The hypothesis about the deforestation of Chełmno Land coming to an ultimate end in the very late 13th or early 14th century and leaving a forest area corresponding to that portrayed on late-18th century maps, is, in the author's opinion, unlikely. The presented estimates indicate that the forest area of this territory was larger in the 13th century. The extent of this forest area can be estimated at about 20%–25% of the entire research area. This estimate is double the forest area in the late 18th century and significantly less than that calculated for 13th-century Chełmno Land in the historical work of Paradowski from 1936, which, although for slightly larger borders, amounted to about 70% (Paradowski 1936).

The methodology of model building, as already mentioned, may raise a number of doubts, despite the fact that the author has attempted to make the adopted system of assumptions and relationships between them objective. In light of justifiable views that the forest area of Polish territories based on historical sources can only be reconstructed for the 16th century at the earliest, a model approach to reconstructing the forest area in the late Middle Ages remains the only alternative. This is an extension of the retrogressive method and allows the approximate forest area to be visualised when historical data are incomplete and cartographic sources are lacking.

The presented spatial model of the forest area of Chełmno Land in the 13th century, despite many limitations, may provide the necessary context for studies on individual settlement forms (fortified settlements, castles and, ultimately, towns) in this territory. Moreover, it may form a premise for verifying hypotheses concerning the conditions of the medieval growth of settlement and economy in this region of importance to the history of Poland.

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