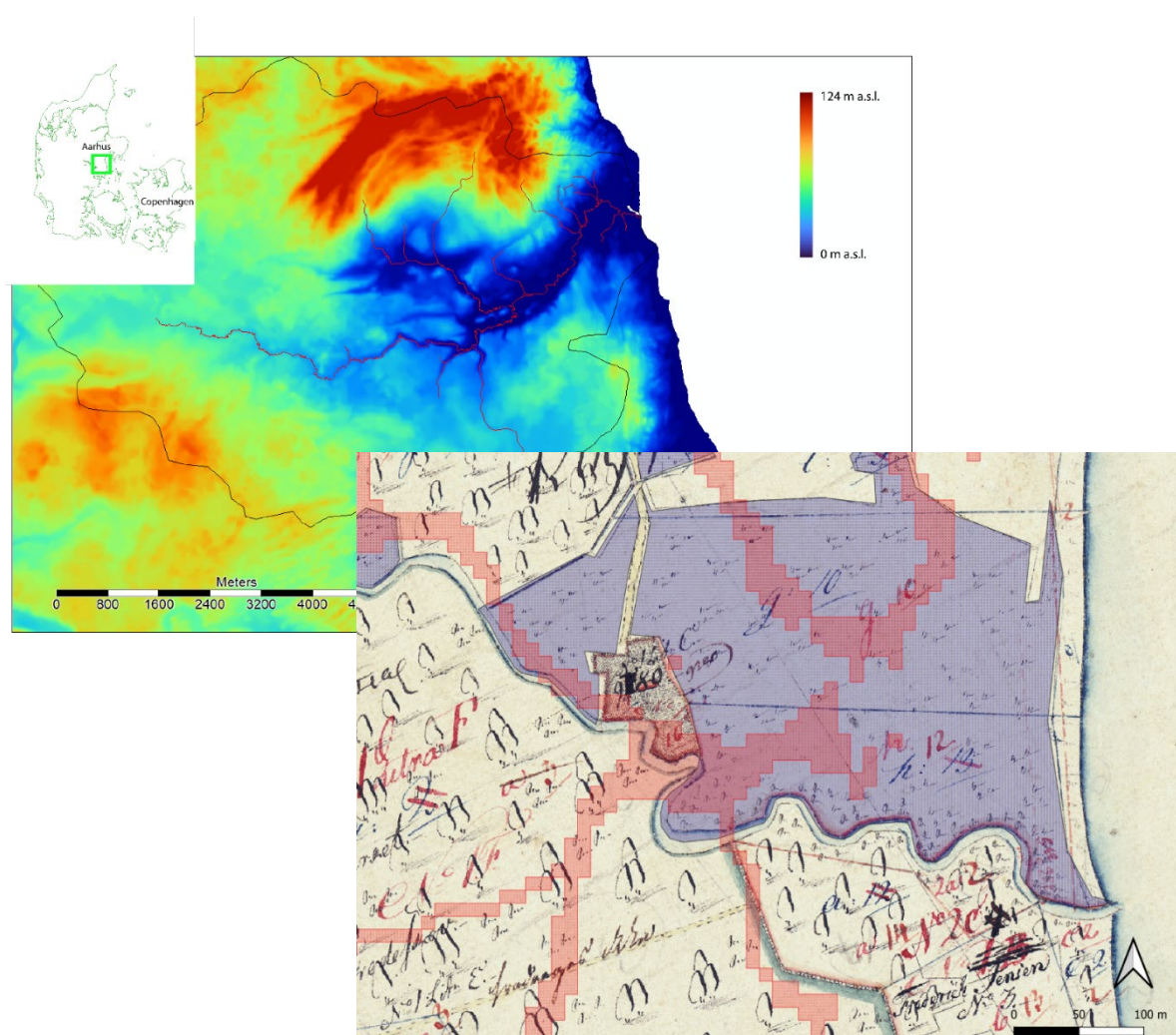# Historic maps as source for hydrological reconstruction of pre-industrial landscape wetness in Denmark: a methodological study

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Content

Abstract

Historic maps are an important primary source which can be utilized in the reconstruction of environmental variables of the pre-industrial landscape. However, methodological constraints have hitherto prevented large scale and systematic approaches. In this paper a novel methodology is presented, which documents the usefulness of the maps in the study of paleo-hydrology and thus serves a better understanding of the conditions for agricultural production under pre-drainage conditions. The methodology is developed based on eighteenth and nineteenth century maps from a 100 km^2 study area in one stream catchment in East Jutland, Denmark. It combines information from two types of historic maps in order to correlate computed soil hydrology (wetness index) and recorded historic land-use. The calculated wetness indexes are derived from contour lines on topographic (military) maps (in Danish: Høje Maalebordsblade), whereas the spatial overlays are land-use classes from economic maps (in Danish: Matrikelkort - Original 1). This study demonstrates – for the first time - that the wetness index is explanatory for the agricultural suitable/non-suitable dichotomy (tilled land versus "wetland": meadows, fens, and peat bogs) on the historic economic maps. Furthermore, the study shows that pre-industrial arable areas were stretched to their limits in respect to cropping wet soils in this agricultural dominated landscape. The study confirms the existing belief that the historic economic maps constitute the best available source of these mosaic-landscapes for periods before the intense subsurface tile drainage began. This finding opens for further methodological development and up-scaling using automatic feature detection, contour line extraction and text recognition of historical maps.

Introduction

Currently, societies worldwide have a need to enhance and balance the environmental, social and economic goals and to set human exploitation of the land on a path towards sustainability. One of these is the need to mitigate the on-going loss of biodiversity, global warming and environmental impact of farming as a result of the anthropogenic changes of land cover/use (hereafter denoted land use). Here, recent studies have shown the potential of historic maps on both a global level and national levels. As an example, Hunter & Sluyter [1] used historic maps from Mexico to suggest that Medieval climate was globally influenced by land-use changes as a consequence of massive terrestrial carbon uptake after the depopulation of the Americas. In Europe, the use of historic maps in combination with modern digital elevation models based on airborne laser scanning (Lidar) has also been shown useful for pre-modern and palaeo-landscape models [2]. Historic maps have also shown to be an important primary source for reconstruction of the environment and land-use of the pre-industrial landscape [3, 4, 5, 6, 7]. In Scandinavia, as an example, Gammeltoft [8] showed that the Norwegian cadastral records can be linked to other historical sources in order to explore the temporal development of land and estates.

The spatial distribution of farming in NW Europe prior to the intensive drainage of the landscape is hence seen as a mosaic of smaller and larger patches intersected by high ground-water levels and/or low-permeable subsoils - even in what we today perceive as upland soils. Due to poor soil drainage systems before AD 1800, almost a quarter of Denmark's potential the arable land was unusable for grain production [9]. The best agricultural soils were on well-drained land, while also three main land-cover types dominated the landscape in general; namely *Calluna*-heathlands, woodlands, and agricultural land with little woodland [10, 11]. Pre AD 1800 land-cover characteristic was furthermore likely already in existence by 1000 BC, indicating that the macro-scale historical cultural landscape was stable for more than 3000 years in Denmark [11]. Understanding of the with-in main cultural land-cover types has, however, been more difficult to establish as pollen-based studies even from minor lakes integrate land-use signals from many hectares [12].

The Danish pre-drainage landscape was speckled with patches of moist terrain that interrupted the less-than perfect layout of field systems in a pre-drainage mosaic landscape, where even some of the arable area suffered from a lack of drainage according to written sources [13, 14]. Agricultural reforms at the turn of the nineteenth century resulted in the first Danish attempts to systematically dig open ditches to drain the land. First after 1853 when modern drainage clay-pipes were introduced to drain surface and rainwater, this was efficient [15]. Since then, the landscape was not only drained but also levelled by intentional filling-in of natural depressions, by slow tillage-erosion and by removing obstacles such as stones, prehistoric burial mounds, etc. The reason for these drastic changes and

transformations of the landscape were manifold, but in general a consequence of mechanisation of agriculture. One important reason was also that decisions on farming issues changed from collective to private, while also changes in taxation and population size influenced. From the 1950s onwards, the mechanisation of agricultural production altered the terrain of the Danish countryside faster and even more dramatically. Thus, both the form and the perception of the Danish landscape as a gently undulating, continuously arable land intersected by regular squares of forests and meadows are modern phenomena [16].

Two hundred years of radical landscape transformation have meant that former areas of wetlands may not be identifiable on the surface today in loamy-till dominated glacial landscape types, while they on glacio-isostatic adjusted coastal areas in Denmark are easily visible [17, 18]. Woodlands seen on the historical maps, on the other hand, have in some cases been forested since the Iron Age, and with changes in soil hydrology due to draining taking place after the industrialization [19, 20]. However, their pre-drainage hydrology is generally changed as ca. 50% of the Danish land is currently tile drained, and as peatlands and peat-rich meadows have disappeared fast since [21, 22]. Up to 90% of the late nineteenth century wetlands and wet soils have disappeared today, and up to 35% only since 1975, with drastic environmental consequences. However, effects of this on e.g. soil organic carbon stock changes and CO_2 emissions are only based on observed changes since the last few decades [23, 24]

Knowledge of the extent and exact location of past grass- and wet-land is necessary in order to reconstruct ancient land-use, determine historic agricultural organization, and estimate agricultural production over time [25-27]. A variety of direct and indirect methods have been used in efforts to determine the location and boundaries of soil drainage, wet areas and wetland. Among these are measurements of geophysical properties, questioning farmers about the location of subsurface drainage pipes, analyzing aerial photographs, and combinations of many datasets, e.g. by artificial neural network analysis [28, 29]. Examples where the historic landscape drainage was attempted evaluated was in the area of the Iron Age necropolis at Himlingøje, Sealand, where the physical geographer K. Dalsgaard demonstrated that a dense net of core drillings may reveal subsurface lentils with high organic content originating from former ponds, grass- and wetlands [9]. He was the first to combine field analysis with historical records in Denmark. Dalsgaard matched the location and boundaries of these lentils with information from economic maps dating to about AD 1800 and showed close correlations (Fig. 1).

Evidence from pollen-based vegetation studies indicates that Denmark had a net surplus of precipitation during the entire Postglacial although with temporal and geographical variations in the water balance [30]. Drainage of soil is dependent on many parameters, but in general wet soils are in Denmark due to either high

groundwater or low-permeable subsoils. Depending on the texture of the topsoil, the topography of the surface, and the composition of subsurface strata, any surplus of water beyond field capacity will be transported either through overland flow, inter-/throughflow or as groundwater flow. Whereas soil texture and topography are relatively static and observable entities, past sub-surface composition and flow is very difficult to measure and model today. This means that we can only approximate paleo-topsoil wetness, since the major entities are complex, interrelated, and dynamic. In relation to this case study this means, that even though geological surveys at different geographical scales cover the entire area of Denmark, we have no detailed, local knowledge of topsoil textures and permeability in the past.
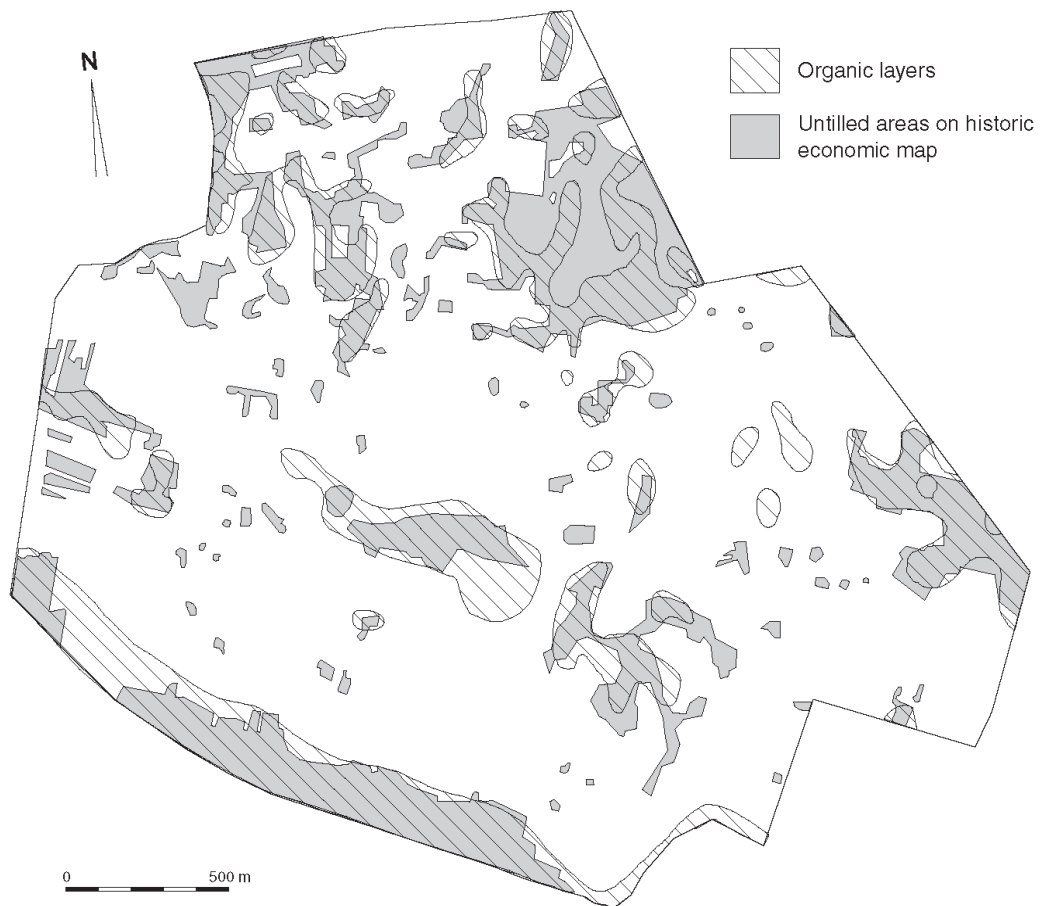
Fig. 1. Information from a modern geological survey (Jordartskortet, GEUS) compared to information from an economic map from 1844 in an area at Himlingøje, Zealand. Redrawn after [9]. The map demonstrates the strong spatial correlation of meadow areas without tillage (i.e., wetlands) on the historical map and wet, organic surface soils as recorded in the systematic geological mapping of the same area.

Here we test the hypothesis that specific soil moisture themes on historic maps can be evaluated by modelling techniques from Geographical Information Systems

(GIS). This will be achieved by combining maps from the eighteenth and nineteenth century Denmark which allows us to evaluate the correlation between wetness index and land-use patterns in a study area, the Giber Å (stream). This catchment is equivalent to one permille of the total area of the kingdom of Denmark today, but the investigations may be representative for a larger part of Northern Europe' historic and prehistoric land-use.

Materials and Methods

Study site
The study are in the Giber Å (river) catchment, which is located south of the city of Aarhus and covers a region of about 41.5 km^2. An example of surface water and vegetation in the are is seen in Fig. 2 while the geographical extent is shown in Fig. 3.

Fig. 2. Examples of surface water in a contemporary wetland in the study area (village of Hørret, Region Midtjylland, Denmark). Similar shallow groundwater or spring water has been used in historic times as places for supplying livestock with fresh water. The site was until the end of the nineteenth century connected with the village with a fenced pathway to one side and grazing areas to the other and served on a daily basis as a local station for milking cows.

Water run-off has in this study been modelled using topographic information only, but the complexity of the parameters governing topsoil wetness, including root zone capacity and transmissivity (both phenomena influence the relative wetness downslope) make it difficult exactly to model the movement of water, why water may appear at 'unpredictable' spots from the wetness index or disappear into the subsurface (Fig. 2).
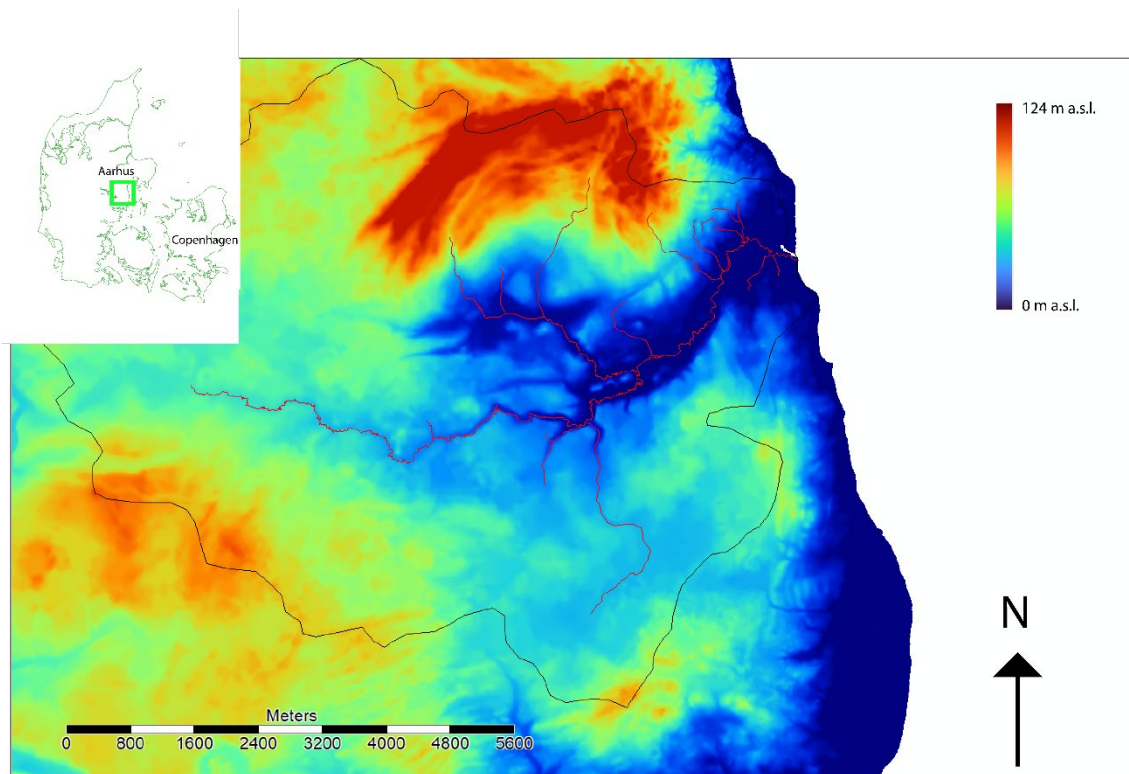
Fig. 3. Digital elevation model (DEM) of the study area in the Giber Å (stream) catchment in Denmark. Notice, that the DEM is for this study generated by interpolation of the contours on the nineteenth century military maps. Superimposed is the catchment area outline (thin black line) and the course of the Giber Å stream (thin red line).

Surface hydrological modelling

Using the well-established computer model TOPMODEL, water run-off is computed by the formula:

(1) $Ln(a/\tan\beta)$

where a is the upslope area per unit contour length and $\tan\beta$ is the slope gradient. This formula is basically an inverse distance algorithm which estimates the contribution of surface water to a given cell from the size of the contributing area in relation to the size of the cell, the contour length [31, 32]. The computed slope for each cell is considered equal to the hydrological gradient: the steeper the slope, the greater the hydrological effect. In a theoretical case with a vertical gradient, water will run off almost like raindrops on an impermeable window, leaving the points where the water passed almost dry. The reverse is true for a completely flat terrain: water will not escape, and it will gradually accumulate in the area. Maximum wetness will therefore appear at points with maximum upslope area and very small slope gradients.

In general, erosion will shape glacial soils in the landscape in such a way that the derivatives of geometrical curves describing the surface are continuous and

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therefore applicable to modelling. In general, slope gradients will vary between 0 and a maximum of 45 degrees in landscapes dominated by glacial sediment, ultimately resulting in areas where water disappears and areas where water accumulates. This is the reason why the computation of the size of the upslope area and the run-off pattern is of paramount importance. In a theoretical case with no evaporation and no transmission of water through the soil, 'sinks' would fill up with water, creating lakes, and in a given span of time, the sinks would overflow at a certain threshold, creating streams.

Soil wetness and pre-industrial agriculture

Since the last glacial period geological processes and biological agents (including humans) have continuously re-modelled the physical landscape of Denmark. Still, deliberate human influence on soil and topography must be considered relatively modest compared with the human influence on vegetation cover. Mesolithic (approximately 9300-3900 BCE) settlements in this area were located near open water (lakes, streams and sea) and inhabited for short periods even under very wet conditions. Current research discusses whether the hunter-gatherer-fisher societies in the Mesolithic promoted certain plants to the detriment of others (i.e., the spread of hazelnuts) or even experimented with the cultivation of plants. It also discusses whether Mesolithic peoples managed game (by shooting males, not females of the hunted species for example) or even kept livestock. For the most part, however, agricultural land use began with the Neolithic (approximately 3900 to 1700 BCE). Analyses of pollen diagrams clearly demonstrate some clearing of virgin forest from the Early Neolithic onwards [33]. The mapping of prehistoric finds has revealed a systematic pattern in the spatio-chronological distribution of the first farmers [34]. Clusters of settlements spread to low elevations near coasts and streams and to higher elevations, ending at the top of the moraine deposits. Bones of pigs, sheep/goats and oxen from the Middle Neolithic onwards document husbandry. From the late Bronze Age (1000 to 500 BCE) onwards, the presence of three-aisled longhouses with stables – the house-byre (German: 'Wohnstallhaus') – may indirectly document the collection of hay for foddering the livestock during the winter and early spring [35]. Rare but important finds of tools such as sickles and rakes from the Early Iron Age (500 BCE to 1 BC) may be interpreted as direct evidence of the prehistoric collection of hay. The outwintering of livestock is hardly probable in Danish latitudes [36]. Pig breeding primarily took place in more or less forested areas dominated by oak and beech; in fact, beech forests are promoted by pig breeding, which, combined with finds of faunal remains, gives reason to believe that pig breeding started at the beginning of the Early Iron Age [37].

The spatial relationship between infields and outfield areas from the Neolithic to historic time is still a complicated and debated question [38, 39]. It is obvious that regional aspects have to be considered. From Norway, Middle Sweden, Gotland, the Faroe Islands and other places, a clear demarcation between the infield and outfield

can be observed in preserved deserted landscapes from the Late Iron Age. But in lowland Denmark the evidence hitherto is sparse and fragmented. From the geographical position of recorded prehistoric (and historic) settlements it is possible to infer that most settlements were located at the boundary between permanent grazing areas (Danish: 'overdrev') and hay-producing wet areas (Danish: 'kær' / 'eng') with the tilled fields (Danish: 'mark') in the nearest vicinity of the settlement area [40].

Medieval sources and pictorial information about meadows are few and scarce [41]. Researchers seem to agree upon a subdivision of the infield (Danish: 'vang') characterized by crop rotation in a cyclic manner: rye-barley-[fallow/oat] or barley-rye-[fallow/oat]. This means that in the first case, applied mainly on sandy soils, the dunged infield is sown with rye, the second year it is sown with barley and in a varied number of subsequent years sown with oat and/or left as fallow land. If the soil is clayey, then the rye and barley crops are reversed in their order. Consequently, a permanent outfield may have been obligatory, since otherwise grazing areas are only found in the self-sown fallow areas [13]. Also important is the introduction of oat, which was necessary if horses were used as draught animals instead of oxen. There are strong reasons to believe that in the Viking Age or perhaps in the early medieval period, pure oat fields replaced the former permanent grazing areas.

Around AD 1800 the agricultural production in the clayey soils of East Jutland was optimised for grain production without artificial fertilizer. The total potential area could not be used for grain production since land use had to be balanced with, for instance, the need for domestic fuel and fodder for livestock, which in turn produced necessary organic fertilizers. Some researchers think that the situation at that time was out of balance – that there was a lack of grazing areas, and that this over-exploitation necessitated a fundamental agricultural reform [42].

Since vegetation growth is dependent on the availability of water, various plant species have evolved and adjusted themselves to different milieus following the rules of biological succession. This is the reason why vegetation has long been used as an indicator of soil wetness. Therefore, it should be possible to quantify the extent to which a topographically modelled wetness index correlates with historic data of land use prior to the agricultural reforms made after AD 1800. It should also be possible to investigate diversions from this hypothetical correlation and explain spatial patterns as results of surface geological (e.g., soil types) or culturally determined factors.

Map sources

Danish economic maps

The first available sources of information on Danish land use comes around 1800 AD and are economic maps and written protocols linked to their creation [43, 44]. The exact number of these maps preserved until today is unknown, as some are in private possession. The archives of the National Survey and Cadastre at the Danish National Archive holds about 10,000 of these maps (in digital format available at https://hkpn.gst.dk/) covering the whole kingdom of Denmark but excluding the duchy of Schleswig and the island of Bornholm. The maps were kept and archived because they document property rights and were used for taxation purposes.

It is important to distinguish between two types of Danish economic maps. One type was made to serve the enclosure movement (in Danish: udskiftningskort), while the other had primarily fiscal functions (Danish: Matrikelkort-Original 1). Both types of maps had a central documentary role in privatization of the tilled fields, woods and commons at this time. Trained surveyors (i.e., former army officers) drew them at the scale of 1:4000 while in the field [45]. The mapping followed strict procedures, but surveyors facing unforeseen variability in land cover or land use, had to make their own decisions in the field. The symbols of the ridge-and-furrow fields on the oldest maps (the "Udskiftningskort") are easily discernible. The surveyors drew thin lines indicating the furrows. Following the instructions, any area that showed signs of ploughing had to be classified as a tilled field. However, tilled fields were rotated into fallow and used for grazing livestock, and commons might be ploughed at very large time intervals to improve the growth of the vegetation. Surveyors might therefore have found it difficult to distinguish between tilled fields and more or less permanent commons[1].

Non-arable land was marked in accordance with its vegetation: heaths, woodland, shrubs, grassland, meadows, peat bogs, and so forth. This means that we do not know for certain today which areas were 'wet' and which were 'dry'. The signature for peat bogs is an almost certain indicator of wetness, and place names and topographic information can qualify the judgement. Concurrently with the mapping process, the resources were valued and then the straight boundaries of the valuated areas were drawn on the map on top of the image of the former landscape. This valuation served as an internal re-allocation of the resources only. The new boundaries of valued soil performance/fertility (in Danish: Bonitet) were in most cases re-used in the subsequent taxation process, which concluded in 1844. In the

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[1] As an example, an inspection of the location of a reconstructed field system dating to 1683 compared to the land surveyors map from 1794 illustrates this issue in its westernmost part [46] (Frandsen 1983 fig. 24).

process of this taxation, older maps could be re-used or copied or new maps drawn in the field. The valuation at this time followed a national scale (see details in [9]).

Danish topographic (military) maps

After being defeated by the Prussian army in 1864, (a defeat that meant the loss of the duchy of Schleswig), the Danish military intensified the mapping of the kingdom. This work began in 1842 and concluded in 1899 and was the first large-scale topographic survey to be published [47], today known as the "Høje Maalebordsblade". It was printed on sheets at the scale of 1:20,000. The military had a great interest in mapping how soldiers, horses and vehicles could navigate the landscape. This is why wet and boggy areas are very clearly depicted with a bright green colour. The instructions to the surveyors were very detailed in this respect and a written record with detailed descriptions was planned to accompany every map sheet, but these have not been located. Some of the information on the survey maps came from the aforementioned economic maps. These were downscaled to 1:5, and roads, buildings, and other characteristic landscape elements were copied to the new set of working sheets and archived at the Danish Mapping Agency [48, 49].

The architecture of the Danish geodetic system, which was established in order to produce the military topographic maps, is a collection of nodes in a layered triangulation network. The purpose of this layered structure is to prevent the accumulation of error and to distribute error as evenly as possible. Nodes in the top layer are called points of first degree; nodes in the second layer are called points of second degree, and so on [50] (10ff). Surveyors were equipped with survey maps attached to a plane table. With an optical instrument and helpers with levelling staff in the field, the surveyor was able to measure distance as well as height information from his observation point and to transfer this information directly onto the map. Height information according to the Danish Normal Null (the older official Danish level of the sea) was gathered from points of the highest degree available on the sheet. Using chain measurements, transects of points were dotted along major roads in the area. These points were recorded with two decimals, in Danish feet in some areas and in metres in others. The height information in the landscape was measured with one decimal precision. Contour lines were drawn directly in the field using linear interpolation between measurements. It is not possible to generate the contour lines from the point measurements alone, which means that other techniques were used, such as directing the helpers to follow a certain contour directly in the landscape. The topographic information was drawn on top of the downscaled economic map sheets and then transferred to square map sheets before printing[2].

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[2] While these remarks may lift eyebrows concerning their validity compared with modern scientific standards, our feeling is that we should have great confidence in the curves drawn and that they represent a reliable and emphatic perception of the then investigated terrain.

Only in the last two decades airborne laser scanning have improved the quality of digital elevation models (DEM) significantly. Tempting though these data are for historic terrain modelling, modern data may reflect the current and not the past situation: modern embankments and other human-made structures could significantly disturb the analytical historical applicability. Also, modern drainage has led to metres of subsidence of organic soil and on a local scale created surfaces very different to the surface curvature in the nineteenth century [21]. So far, this problem has not been investigated in-depth nationwide, and the authors reluctance to use modern surface data may be overestimated in this study. At the time the authors took the decision to use DEMs from a period as close as possible to the information from the economic maps, e.g. from the late 19th century "Høje Maalebordsblade", the choice was made at the expense of precision and the speed of data capture.

Taxation records from the 17TH century

Taxation records can only be fully exploited if the textual information they contain is geo-referenced. This is not always possible and means that they can only be used as a supplementary - albeit very valuable - source. The taxation records from 1682/83 list groups of or single ridge and furrow fields in the kingdom of Denmark, again except the duchy of Schleswig and the island of Bornholm. The records are preserved and archived at the Danish National Archives (Rtk. 312.6 - 1699), scanned and online retrievable (https://www.sa.dk/ao-soegesider/da/other/index-creator/43/6754/16522553). Each field or group of fields was measured geometrically, valued and assigned to a user and/or owner. A description of the soil and the rotation system was also recorded. Other resources such as meadows are enlisted too, although these were not measured. Their valuation differs from the tilled fields too, as they are valued to claim 'real production' in terms of loads of hay, number of pigs etc. A final valuable source of information is the so-called grazing register: in principle, every common from every Hundred (Hundred is an administrative unit, the equivalence of a Shire.) should be listed here with an assessment of the number of livestock the common could carry, but in reality this source is fragmentary and neither the position nor the geometrical properties of the commons are recorded.

It is a non-trivial procedure to link the taxation records to the exact position on historic map material [51]. It involves a mixture of empirical observations, interpretations, and a little guess work. Linkage is performed via field names and their order of appearance in the record, compared to field names and their topographical position

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The observation that the contour curves are only partly interpolated data is important, as is the fact that the instructions require that the curves should be drawn with a maximum margin of error of one Danish foot, approximately half a metre, depending on the age of the map sheets.

on the map. The geometrical properties of the strips must match the space assigned for the field on the map in size and area. Small details such as interruptions by untilled patches can qualify the assignment.

Transcribing historical maps to digital data

The scanned economic maps from the study area (Fig. 3) were geo-referenced using intersection lines from cadastral boundaries primarily. A geo-referencing error of about 20 m on a single map was considered acceptable[3].

Two neighbouring village territories share borders and even three or more may share a common point. No attempt has been made to polish the border information, even in obvious cases, because maps may be drawn at different times and we should accept the information as is and not try to make them look nicer. This is the reason why patches of illustrated meadows located at the border between two neighbouring maps were digitised (digitally drawn) on the basis of each of the map sources, with the result that the resulting geometrical representations (polygons) may overlap and display slivers.

The study area was chosen on the basis of accessibility of data and the potential for field investigations. It was decided to include a consecutive area of several village territories. The digitisation of neighbouring village territories, which was done back in 1997 and 1998, was the first of its kind [52, 53]. Since then, extensive digitisation projects have been undertaken including much larger consecutive areas, though not including the aforementioned area [4]. In these projects, map information has been geometrically rectified and border information polished.

The study area (Fig. 3) covers the parishes of Maarslet, Beder and a minor part of Malling. The Danish National Survey and Cadastre has scanned, geo-referenced and geometrically rectified the maps, making the overlay process of the meadows from the economic maps very easy. The digitized maps are available for download at the Danish Agency for Data Supply and Infrastructure (https://dataforsyningen.dk/data/3577). Visual inspection of their spatial distribution revealed oddities which led the authors to believe that some of the meadows were in fact fragments of permanent former common areas. Their topographic position made it impossible to consider them wet at first sight though. This finding seemed to contradict the above-mentioned investigations by [9]. Before field investigations

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[3] A divergence in the geographical position of the mapped cadastral boundary and its position in the physical landscape of this magnitude would never be accepted when the maps when produced. Since it is the position in the landscape which is recorded in official cadastral boundary data, the error of 20 metres represents an accumulation of errors, including map distortion. This is the reason why the scanned map-images were not geometrically rectified in order to compensate for the error, since this would only obliterate the effects of the error, but not remove its causes.

could clarify the findings by ground-truthing, it was decided to perform a modelling exercise. Seen in hindsight, the amount of labour involved in creating a historical DEM by digitizing by hand was underestimated. Let this be a warning to those who might become inspired by this paper.

Since the boundaries of the parishes are only part of the relevant catchment area, the DEM based on the old map (Høje Maalebordsblade) contour lines had to cover about 9 by 11 km (Fig. 3). Digitising c. 100 km^2 of contour lines is not a trivial process. No compromises were made to produce the highest possible quality in the digital representation of the data printed on the map sheets as described in [54]. A handful of small utility programmes were written in Visual Basic to check for topological errors as well as to ensure that the elevation assigned to the curves is logically correct. The result is a complete vector representation that is eminent for illustration purposes as well as for 3D-modelling. It was decided to sample along the drawn contour lines, aggregate the points, and interpolate the data set using ordinary kriging, which is a geostatistical interpolation technique. The kriging was preceded by a variogram analysis with directional parameters, which is a plot of variance as a function of distance of separation. This revealed differences in landscape modulation in relation to the magnetic north, which are caused by the SE-NW movement of the last glaciers in this area. The analyses proposed a spherical curve as the best fit. Range and sill were computed to 2600 and 1600 metres, respectively. To reduce the effect of a higher data density along the contours and to minimise artefacts in flat areas, a minimum of 10 and a maximum of 100 points in a maximum search radius of 1000 metres were set as parameters for the interpolation. The kriging was done with a nugget effect of one 0.5 metre, which admittedly is an optimistic estimation of the error in the recordings of the elevation. The resulting interpolated surface (Fig. 3) may therefore over- and undershoot actual recordings.

Results

Discussion of map representation and land use

The economic maps "udskiftningskort" dating from 1783 to 1791 display a variety of categories of land use in the 13 village territories in the Giber Å stream catchment. Here, the four oldest of the 13 maps were drawn by the same surveyor in the same season. Every one of these four maps displays a legend though. Besides settlement areas, fences, roads and so on, the mapped village territory is subdivided into three main use-classes: woodland, grassland and tilled fields. Each class is further subdivided while some classes overlap. Woodland is subdivided into shrubs, thickets and (high) woods. Untilled land without tall vegetation is subdivided into meadow (Danish: 'eng'), fens (Danish: 'kœr') and peat bogs (Danish: 'tørvemose'), probably reflecting increasing wetness and/or plant cover as indicated on the legend (Fig. 4).
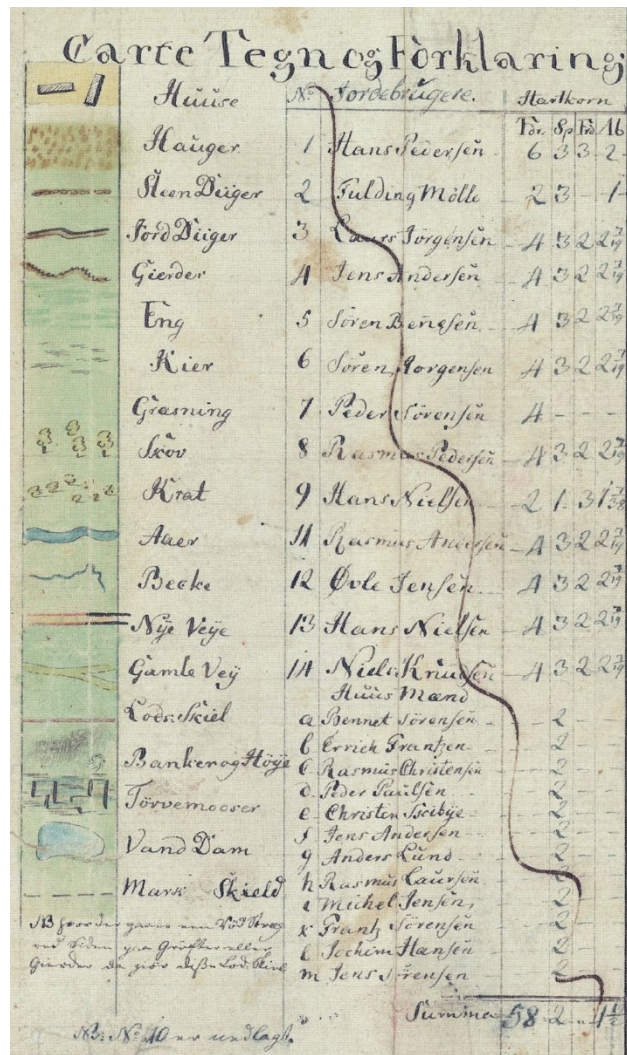
Fig. 4. Royal surveyor Friederich Wesenbergs signature on an economic "udskiftningskort" map from 1783. The legend illustrates that the surveyor distinguished between various categories of grass- and wetland, reflecting degrees of economic potential, the wettest areas being the poorest.

The economic "udskiftningskort" maps' legend also defines categories such as 'grazing' and 'green, untilled soil' – again a judgement of the surveyor who marked this *potentially* arable land. The geology of this study area is within the Main Stationary Line of the Last glacial Maximum, and the soils are dominated by sub-glacial deposited loamy soils intersected by meltwater deposits and river valleys draining to the east. The study area is the Giber Å stream's topographic catchment.

In a very strict sense, none of the symbols on the legends can be transferred from one map to another. In order to ensure maximum consistency in the data set, the subdivision of the three main classes was ignored. If we also consider that the assignment of a specific piece of land to a given class may reflect a certain degree of subjectivity on the part of the surveyor, this decision is justifiable. A problem in relation to the question of wetness is that areas assigned as woodland do not

discriminate according to top-soil wetness. This is why woodland is excluded from the analysis because the information is ambiguous towards the question of wet/dry areas here, despite also the woodlands having very large wet patches [20]. This leaves basically two classes of land use: 1) arable land, and 2) non-arable grass- and wetland. An overview is shown in Fig. 5.
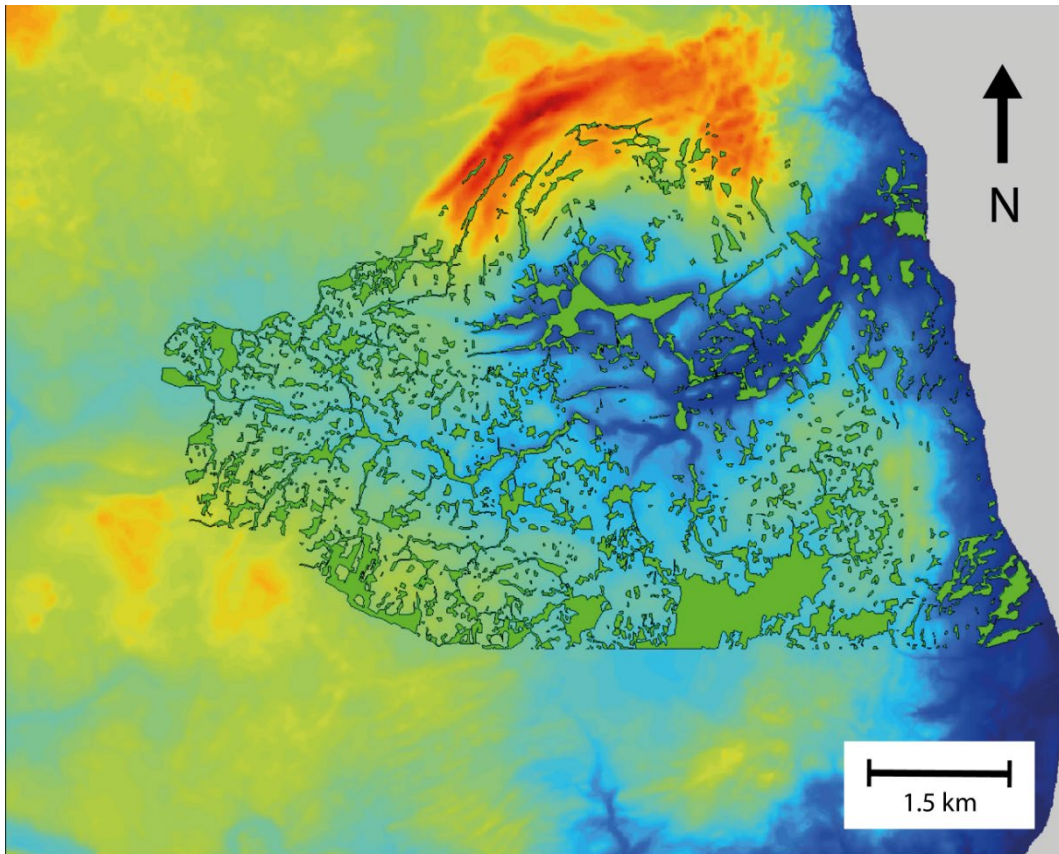

Fig. 5. Spatial correlation of the digital elevation model (DEM) based on the topographic (military) maps (in Danish: Høje Maalebordsblade) and wetland (green patches) from cadastral maps (Matrikelkort, Original 1) of the study area. Notice that the mapped area does only cover a part of the total study area (see Fig. 3), and it is this area which has been used for calibration of the computed wetness index.

The spatial distribution of non-arable land from the economic maps projected on top of the historic, e.g. based on the Høje Maalebordsblade contours, digital terrain model for the study area (Fig. 3), including information about open surface water, gives the immediate visual impression that these areas generally correlate with depressions in the surface (Fig. 6a) leaving the rest of the area of interest as arable land. The untilled patches follow the streams and low-lying areas in the terrain – not as continuous areas but in fragments. The question is how the applied mathematically model (TOPMODEL) matches the observed data and, subsequently, whether we can get a better understanding of the wetness of the undrained landscape through this comparison.
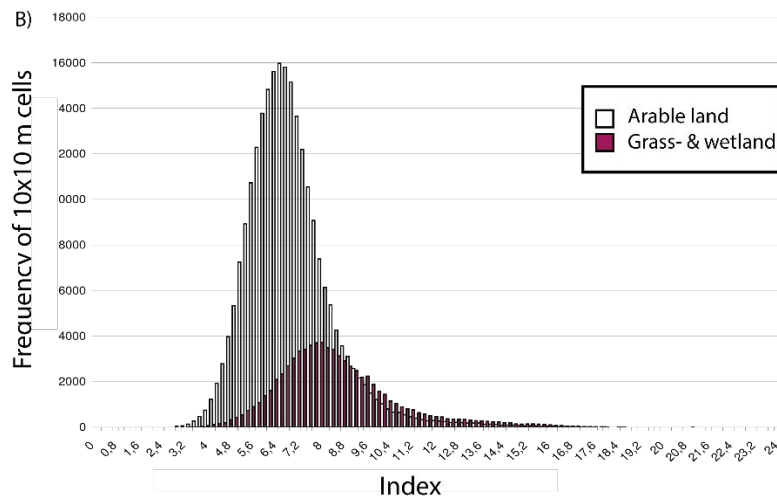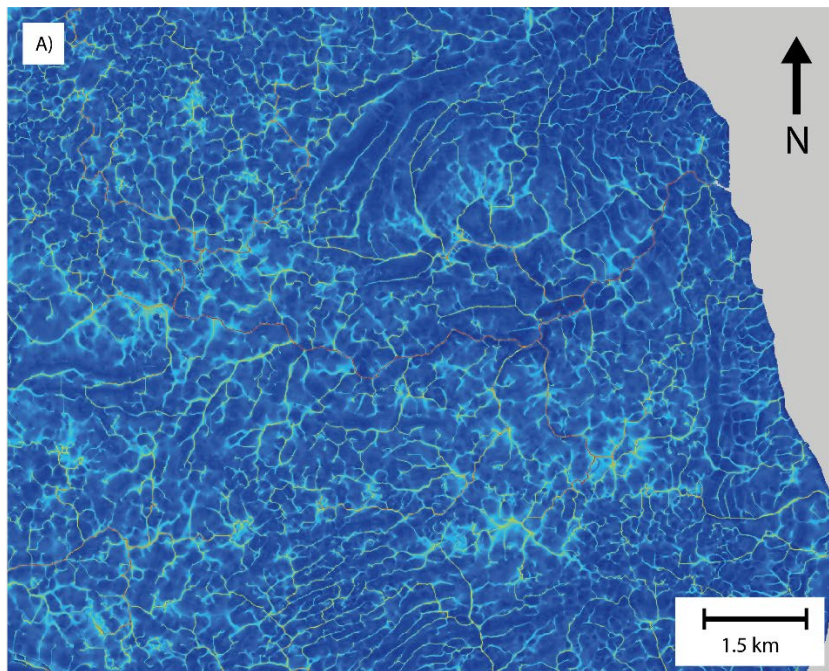
Fig. 6. A) Computed topographic wetness index of the study area based on the contours from nineteenth century topographic (military) maps (Danish: Høje Maalebordsblade). The range from dry to wet is displayed as deep blue to red, respectively. The thin red lines display areas with the highest likelihood of running surface water in the area. See also Fig. 3. B) Histogram of the frequency distribution of computed topographic wetness index based on the contours from the Høje Maalebordsblade. Arable land (N=260,783; 0,01 ha cells) has a mean value of 6.6 and a standard deviation of 1.5. Non-arable land (N=74,980) has a mean value of 8.3 and a standard deviation of 2.1.

Computing the topographic wetness index

The movement of water through soil depends especially on texture of the topsoil, subsoil permeability and on slope and direction of the landscape. To implement

these elementary dynamics a specialized GIS approach was used here (SAGA-GIS, v. 1.0), which allows a cell representing a location in space to receive and deliver moisture in principle to all eight square neighbouring cells.

Most algorithms require 'sinks' (local minima) to be 'filled' before processing. Water entering the 'sink' will not leave it again, so to speak. The 'sinks' are potentially interesting in relation to the question asked in this paper and to 'fill' them seemed inappropriate in this study. The SAGA software makes it possible to define 'sink routes', channels which direct the water out of the sink during the computation of wetness [55], and this option was used. A last pre-processing step was the computation of the catchment areas.

Before computing the wetness index, cells below sea level were masked by replacing negative levels with the 'no data' value and a few 'noisy' pixels were cleaned up. After computing the index, the area outside the area of recorded historic land use was masked. In this area, the woodland was excluded too, as well as the channel system, because open water acts differently than water in soil. These operations left 335,763 10 by 10 m cells (0.01 ha) with an assigned wetness index between 0 and 24. The higher the index value, the higher the estimated wetness. The index is unimodally distributed and slightly skewed towards the high end (Fig. 6b). This distribution is expected, since there are larger areas with very small slope values in an otherwise undulating glacial landscape.

It is a relatively simple operation to discriminate the frequencies of the computed wetness index according to land use around AD 1800. Since the area classified as 'arable' is about four times larger than the non-arable land in the study area, the frequency of arable land is accordingly larger than non-arable land. Despite this difference, the shape and position of the frequency curves vary and are reflected in their statistics. There is without doubt a correspondence between the computed wetness index and historic land use, while a wide overlap between the two chosen categories is noticeable too. Again, this is not at all unexpected given all the uncertainties and deficiencies mentioned above. It must also be stressed that the topographic wetness index itself does not define absolute classes equivalent to the arable / non-arable dichotomy. Nor has an attempt been made subsequently to find an optimal discriminating value. Instead, an arbitrary value of eight – somewhere in between the arithmetic mean and the median of the wetness index of non-arable land – has been chosen. All cells with this index number and higher have been marked for the approximately 9 by 11 km study area.

Comparing modelled wetness and recorded land use

For a comparative analysis, we below illustrate the benefits and the shortcomings of our method by the following cases: 1) comparison of recorded and modelled dry land. This comparison is exemplified by an independent control on a mapped area

on an Original-1 map which has *not* been used as source in the frequency diagram 2) the poor ability to model very small patches of low-lying wet areas correctly 3) a case where the model says wet, but the map is ambiguous, and finally 4) an example of the degree of spatial correlation between the recorded and modelled land use. An overview of the sites is shown in Fig. 7.
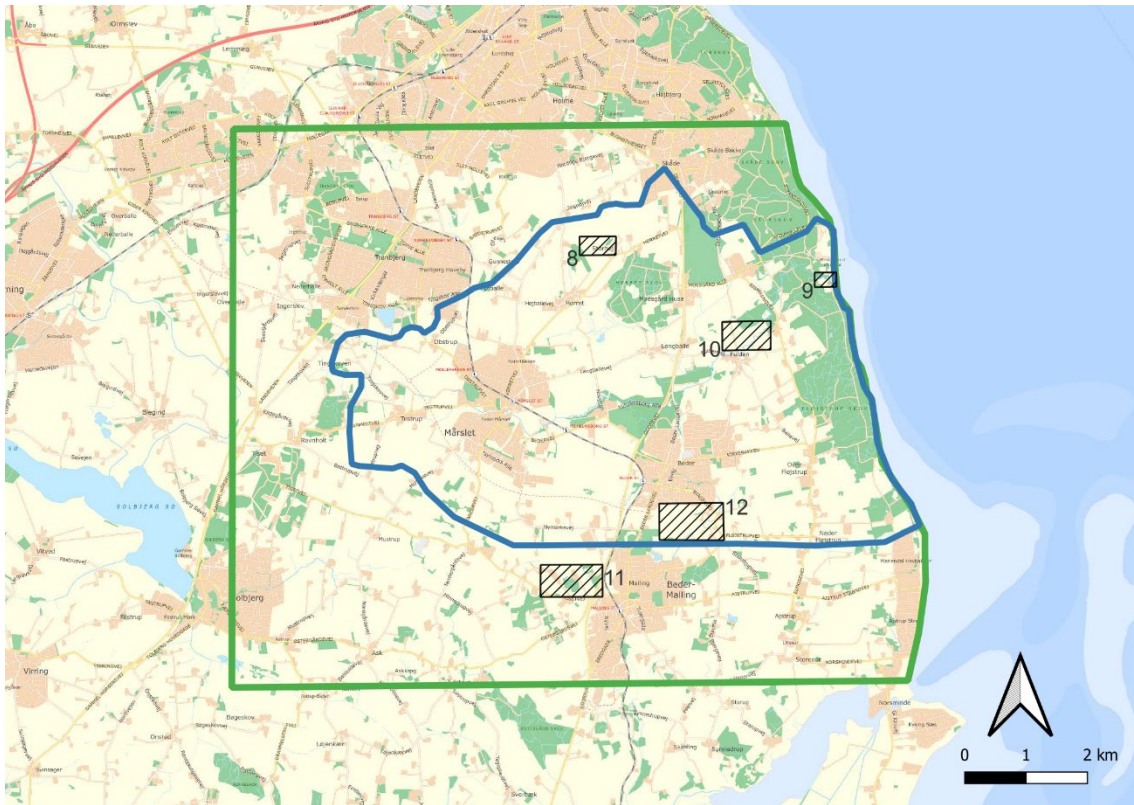

Fig. 7. Overview of discussed locations where the numbers correspond to Fig. 9 to 12. Background map from Danish Agency for Data Supply and Infrastructure.

The first example is the recorded dry and modelled dry land-use combination north of the village Hørret (Fig. 8). Here, an area which has been studied quite intensively was chosen [52]. The tilled fields, 'Ært Ager' and 'Stille Krogen', have both been identified in taxation records from 1683 ('Atte Ager' and 'Sœlli Krog'). In these records the topsoil is characterized as 'cold clay', which in historical research is normally believed to be a contemporary term for fields needing drainage. The mean wetness index for the first field is 6.0 for 636 cells, and for the second field 7.1 for 130 cells. Although there are spatial discrepancies, the modelled and recorded land use correspond to a large extent, questioning the immediate assumption of a tilled but natural wet area.
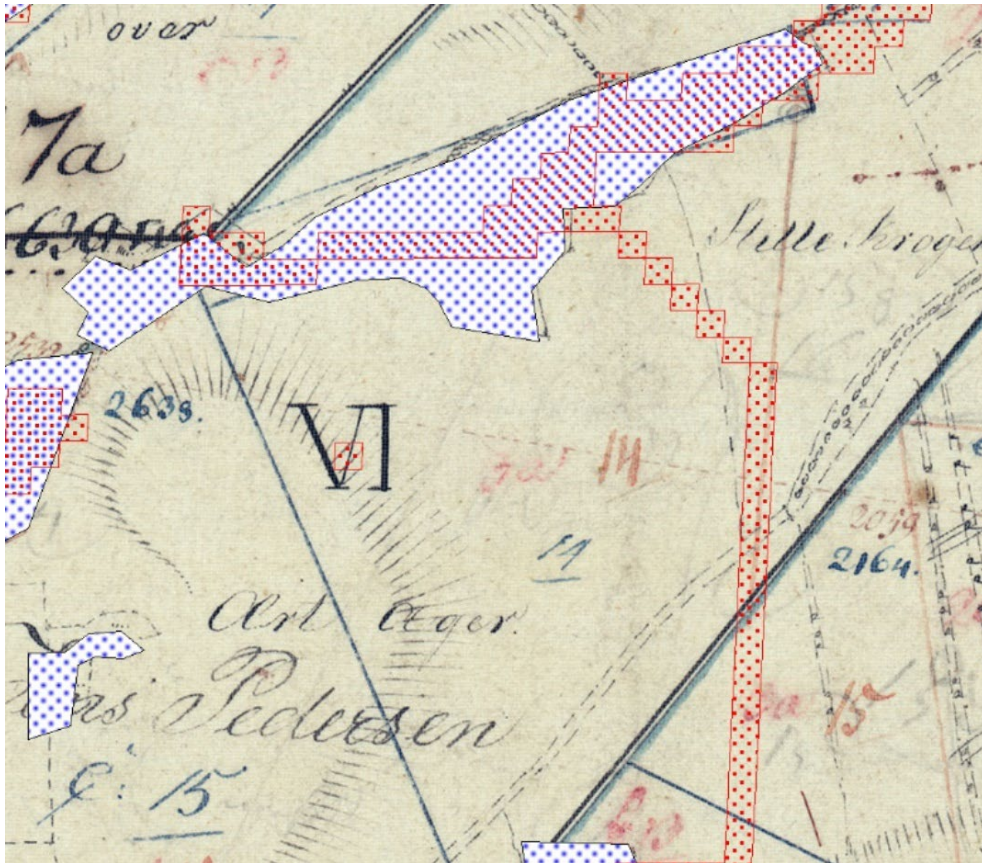
Fig. 8. Part of the economic map (Danish: Udskiftningskort) dating 1785. The two fields 'Ært Ager' and 'Stille Krogen' are overlaid with recorded "meadow" on the cadastral map (light blue raster) and computed wetness index >=8 (red).

The second example is the combination of recorded wet and modelled land-use on more dry soil (Fig. 9). This is a special case too and demonstrates one shortcoming of TOPMODEL based on historically contour lines, not modern airborne laser scanning data: the ability to model small patches of low-lying areas correctly. In the case shown in the Fig. 9, the fen is located near the coast and less than one metre above sea level and hence with likely high groundwater level the year around.

The third example is particularly interesting: the model says wet, but the map is ambiguous (Fig. 10). The tilled field is interrupted by long narrow north-south strips (ridge and furrow ploughing system) partly covered by bush vegetation. This might suggest a strategy used by the farming community to utilize a marginal area due to poor natural drainage.
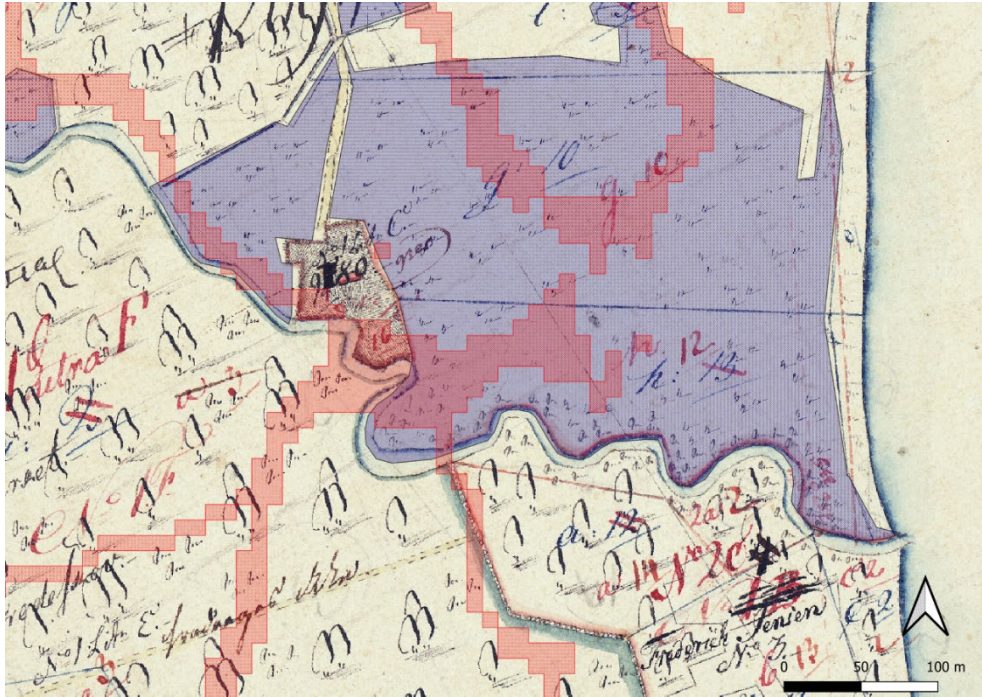
Fig. 9. Part of economic map (Danish: Matrikelkort) dating 1817. The fen 'Degn Made' nearby the coast at the mouth of the 'Giber Å' is recorded 'meadow' (light blue raster) and computed wetness index >=8 (red raster).

Fig. 10. Part of economic map (Danish: Udskiftningskort) dating 1783. A low-lying field is modelled as 'wet' (red raster), but is used as a tilled field. Recorded "meadow" on the cadastral map is shown (light blue). Notice there is evidence of furrows in the ridge-and-furrow system acting as surface drainage.

In the fourth example the modelled wet area is shown on top of an economic map from the study area which has not been used in the definition of wetness (Fig. 11). Again, these maps can be a bit hard to interpret and spatially correlate. Notice the high degree of spatial correlation between the recorded and modelled land use. Notice too that areas declared as 'non-wet' are depicted with signs indicating bushes and trees.

Fig. 11. Part of economic map (Danish: Udskiftningskort) dating 1783. The modelled 'wet' areas are overlaid (red raster). It seems as if neighbouring wet and non-wet areas have been used as contiguous untilled areas for production of fencing materials, firewood etc. and not all being wet.
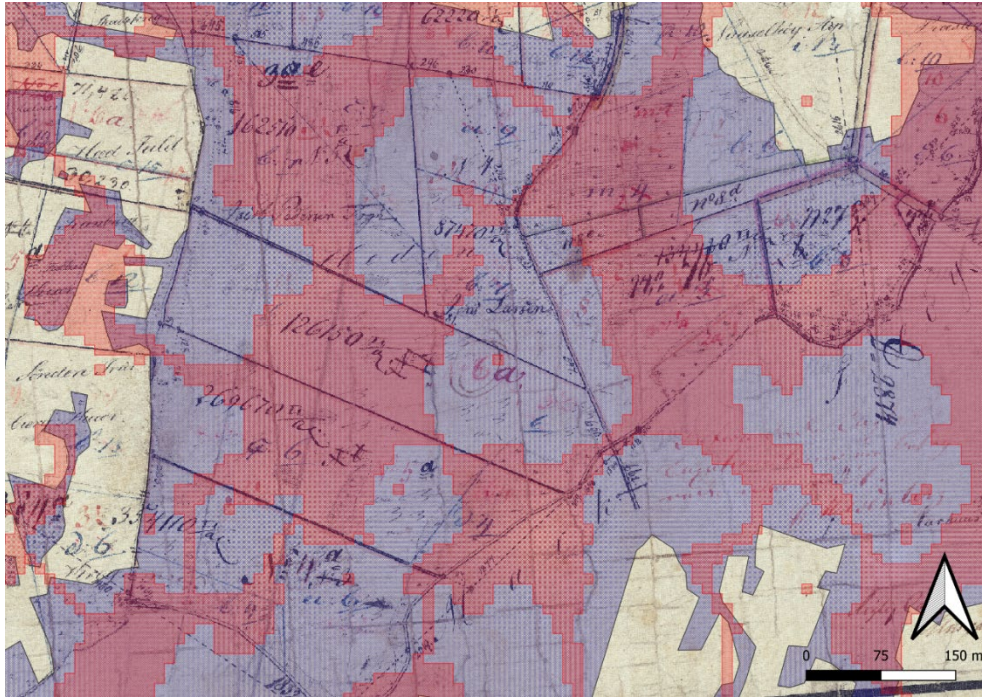
Fig. 12. Part of economic map (Danish: Udskiftningskort) dating 1784. In this very flat area the correspondence between mapped (light blue raster) and modelled wetness is not immediately obvious. Modelled 'wet' areas shown (red raster).

The fifth and final example comes from an area called 'The Heath', (Fig. 12). This is a quite extensive area which served as commons (grazing area) in the border zone between three parishes, and in East Jutland this area is rare in that it does not seem to be wet, but was still untilled (i.e., wetland signature) at the end of the eighteenth century.

Discussion

Despite the chosen cases discussed above have stressed both anomalies and other interesting cases, the correlation however is evident in the spatial distribution of dry and wet areas on the modelled map based on the computation of the TOPMODEL wetness index and the historical record from the late 18th century. Discrepancies between modelled and recorded land-use gives rise to a discussion centred on three subjects: the genesis of the modelled map, the historical records, and the correlation of the two map layers.

The data source for a historical terrain model is further improvable. It is possible to add the elevation at the original point measurement from the original source maps from the military survey [56]. In a study area of two out of thirteen village territories this was done in our case, and the two interpolated surfaces with and without extra point information were subtracted and the difference mapped. The result of the analysis was that the point information exaggerated local maxima and minima. This

in turn would have consequences for the computation of the wetness index and would primarily result in a more dispersed frequency distribution.

For the current study the main limitation lay in the still restricted possibilities of digitizing, standardizing and interpreting the historic map' raster themes on a larger scale. A better way of integrating the map information from the historic economic and military maps could very likely lead to a better spatial correlation between the wetness index and the dry/wet dichotomy. Several examples from the study area clearly show that the geographic reference between the two map sources differs. As an improvement one could discriminate between the various categories of non-arable land on economic maps, making it possible to correlate categories such as heaths, meadows, fens and peat bogs with the computed wetness index. This would open up the possibility of using finer statistical procedures such as rank-correlation measures, random forest classification and similar machine learning which have proved useful in recent large-scale soil wetness and text mining studies [57].

One example that illustrates the possible limitations of the chosen approach is, that the Medieval well-known ridge and furrow fields [58], which are also present in some of the study area (Fig. 10), did not reveal on as maps despite the furrows are known to be moister than the ridges in many cases [59].

A very promising perspective would be to compare the area and degree of wetness of modelled wetland with information of historical hay production and historical valuation of wet- and grasslands. This might potentially lead to better understanding of the economy of historic mixed farming strategies with quantitative estimations of agricultural productivity, since such analyses of much wider geographical area than the one presented here, could contribute to a deeper understanding of regional patterns and variations in historic farming strategies [60]. These trajectories of investigation might also lead to a better understanding of regional cultural responses to environmental change and tell us more about the evolution of the land-use over long time spans.

The perspectives for this and further analysis in the historical sciences are mentioned above, but these investigations may also be of interest and relevance in other scientific disciplines. I.e., the diachronic information from the undrained, historic landscape could give interesting information about the location and delineation of historic meadows which is extremely useful in current biological conservation efforts. Studies of historic land-use maps has furthermore a long tradition in Denmark [51], as they contain important knowledge about the pre- and early industrial landscape with importance for paleoecology and contemporary nature restoration projects.

Due to recent agricultural structural changes in Denmark, the role of the meadows as an extensive grazing and hay production area has come to an end in most

landscapes outside coastal areas and certain protected nature types. After several thousands of years of relative stability, this special semi-natural biodiverse biotope is thus disappearing from the Danish landscape, especially on the loamy soils in East Jutland and the Danish islands. Problems related to declining biodiversity is also related to lack of corridors as originally in the managed, semi-natural mosaic-landscape and due to lack of continuity. Specific site knowledge of the pre-industrial land cover/use can hence inform current nature restoration efforts and likely improve management of rare species and threatened nature types by focusing on sites with the highest authenticity [61].

The use of Danish historic maps has hitherto been restricted by the time-consuming and subjective interpretation step. However, recent developments using digital soil mapping tools combining many parameters, but not the historic maps, showed on a national level that current soil drainage classes can be predicted satisfactory [28]. However, contemporary problems with soil drainage are likely not always representative for the past. A review of soil drainage in Denmark as example found that modern heavy machinery significantly had compacted agricultural subsoil but could not quantify the effect on a national scale as to where water infiltration capacity was significantly affected [21]. Heavy texture and high soil organic matter stocks correlated closely with wet surface soils, and these can today efficiently be predicted nationwide by a combination of many parameters and in 3D. However, the present-day carbon stocks are likely not representative of the pre-industrial, undrained landscape [24, 62-63]. Thus, while modern digital soil mapping and machine learning tools are available for integration of knowledge from historic maps, the historic maps have not yet been made accessible for automatic mapping on a national scale. Several new studies, however, show promising digital possibilities for utilising Danish as well as other countries historic maps nation-wide with the support of environmental variables, citizen science and likely machine learning approaches [65, 28, 66].

Conclusion

The statistics of the computed wetness index for the dry/wet dichotomy on historic maps speak their clear language: areas such as meadows, fens and peat bogs displayed on historic economic maps from the end of the nineteenth century were not arable without drainage. There are even indications that the arable area was stretched beyond its limits. In this respect, this study confirmed K. Dalsgaard previous investigations and added explanatory value [9]. The model-based approach presented here gives new insight into the interpretation of the historic map material and opens pathways to a better understanding of historic land use and the evolution of the landscape. Especially digitalization and standardized by automatic feature detection on all historic maps could improve modern understanding and management of different aspects of contemporary societal needs. This includes as

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example natural soil fertility for organic farming planning, flooding risk assessment, soil organic carbon stock changes, nature restoration and biodiversity hotspots. Nationwide digitalization, georeferencing and automatic detection of natural and anthropogenic features on old maps are hence highly warranted to support contemporary research and planning in Denmark and beyond.

Acknowledgments

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