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ON THE USE OF INTEGRATED PROCESS-MODELS TO RECONSTRUCT PREHISTORIC OCCUPATION WITH EXAMPLES FROM SANDY FLANDERS (BELGIUM)

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ABSTRACT

A major problem in palaeolandscape reconstruction is that basic data useable for inference are scattered in both the temporal and spatial sense. To improve the understanding of occupational patterns by means of landscape reconstruction methods, we propose the application of different process-models in the soil-water-landscape reconstruction in an interdisciplinary approach. These process-models include a digital elevation model, a hydrological model, a pedogenesis model and a land evaluation model. Due to the multiple disciplines involved, no single model can be used but a model framework is defined in which the various discipline-specific models are integrated. In this paper, each of these models is explained and illustrated for a case-study in Flanders (Belgium) and difficulties occurring when integrating the different models, e.g. grain, extent, coverage, are discussed.

INTRODUCTION

Geoarchaeological research is often motivated by the desire to understand observed occupational patterns. A first check is how strong the evidence for these occupational patterns actually is. Data and knowledge driven predictive mapping techniques are valuable tools here. If predictive mapping does not provide strong evidence for any occupational pattern, possible reasons may be: (i) non-systematic recording of presence/absence of finds; (ii) biased sampling; (iii) current landscape attributes do not explain old occupational patterns; (iv) the landscape attributes used for predictive mapping do not give a physical explanation for occupational preferences; (v) a deterministic approach like that based on the physical landscape cannot explain occupational patterns completely. Reason (iii) would motivate a palaeolandscape reconstruction; (iv) would motivate to search for biophysical factors that, with the land use at that time, give a physical-deterministic explanation for occupational patterns; (v) would motivate for the inclusion of social, economical, cultural, ideological and ritual drivers that explain occupational patterns (Jordan, 2001; Thomas, 1993; Tilley, 1994; Tilly,

2004; Zvelebil, 2003). In situations where data collection possibilities are limited because of the available time and funds, dealing with issues (iii) to (v) of the above list appears to offer the best perspective to improve understanding of occupational patterns. In this paper we focus on landscape reconstruction methods and the derivation of relevant landscape attributes to tackle (iii) and (iv). Although the post-processual approach (v) is not discussed here, it should not be excluded, however not without bearing in mind the recent critiques formulated by A. Fleming (2006).

These landscape reconstruction methods will be applied to the area of Sandy Flanders (NW Belgium). This area is situated at the southern limit of the lowland cover sand region of the NW European plain (Fig. 1) and it is one of the most intensive surveyed areas of NW Europe (Sergant, Crombé, & Perdaen, 2009). During the Late Pleniglacial and the Late Glacial numerous, generally small but elongated sand dunes and shallow mires and wet depressions were created. The largest palaeomire, being ca. 15km long and 2,5km wide, is called the Depression of the Moervaart. At the onset of the Early Holocene depressions and mires probably ran dry as a result of the increasing vegetation and evaporation (Heyse, 1983; Verbruggen, 1999; Verbruggen, Denys, & Kiden, 1996).

Landscape can be defined as (translated after Berendsen, 2005) the part of the earth surface functioning as an integrated entity with both static and dynamic equilibriums between its components. A landscape can be characterized by its appearance (physiognomy), structural components such as soil and vegetation types and their interrelations, dynamics and evolution. With landscape reconstruction in an archaeological context we mainly consider the evolution of properties and interrelations of the components soil, relief and vegetation over time and pay less attention to the physiognomic evolution as the latter is hard to assess without historical maps. However, historical maps can be used to filter the current cultural landscape so that the relief of the pre-existing near-natural landscape remains. Thus, part of landscape reconstruction can be considered a de-construction of the current landscape. The preceding genesis of the natural landscape must be analysed with a forward temporal arrow, starting from an assumed initial landscape, taking the natural (deconstructed cultural) landscape as final reference and using local reconstructions based on sedimentological, palaeooecological, pedological (et cetera) research as benchmarks in space and time. Some models exist that calculate the production and redistribution of soil material in -mainly alluvial- landscapes (e.g., Schoorl, Veldkamp, & Bouma, 2002; Minasny & McBratney, 2001), which deals with some but not all aspects of the above landscape definition. Most landscape reconstructions however are knowledge assemblages.

Several attempts to make a reconstruction of the palaeolandscape have already been undertaken in the study area, but on a very local scale. In the floodplain of the river Scheldt, more precisely in the Antwerp Harbour area, elaborate stratigraphical, topographical and palaeooecological analyses resulted in a detailed view of the prehistoric landscape prior to the flooding (Crombé, 2005). Further upstream, several auger projects have focussed on the reconstruction of the palaeorelief in order to locate covered wetland sites (Bats, 2007)

The objective is to predict spatial patterns of variables at various time slices that are determinants for occupational patterns in a biophysical (deterministic, processualistic) sense. Intermediate objectives are the definition of these variables and the development of methods to map their values in the spatial and temporal domain of interest. Thus, we approach landscape reconstruction as a spatio-temporal mapping problem.

METHODS

Predictive Modelling

Predictive modelling is the activity that results in rules describing the geographical patterns of archaeological finds of predefined type. Often the end product is a map (Westcott & Brandon, 2000) displaying the expectation of find occurrences, and can be considered as an extrapolation of scattered finds to a presumed occupational pattern. The rules are based on inference which may be of statistical nature, but may also be the condensation of expert judgment or a mixture of both. Usually, the type of inference gives the predictive modelling its name (Kamermans et al., 2004):

- The inductive approach is entirely data-driven, and constructs inference using occurrence patterns of archaeological finds in combination with full-cover maps that describe soil, landscape, infrastructure, et cetera.
- The deductive approach is knowledge-driven, as experts formulate the rules that link soil, landscape and infrastructure (et cetera) attributes to the occurrence of finds. Evidently, expert knowledge is to some extent based on field data as well, but it may originate from different geographical areas and is usually of a more informal kind.
- Mixed approaches are also thinkable (Finke, Meylemans, & Van de Wauw, 2008), e.g. where experts identify the geographic attributes that are of presumed relevance, but the classification of continuous values (e.g. wetness), grouping of nominal values (e.g. soil texture class) or the weighing of different attributes is optimized using field data and statistical techniques.

Supposedly, the used attributes have the strongest explanatory power if these represent the situation at the time the current finds were deposited, thus a landscape reconstruction may be part of the procedure. Optimally, expectation maps are verified with independent field observations before publication. Depending on the statistical part of the inference, it may be possible to display only those parts of the map that are strongly supported by evidence (Finke, Meylemans, & Van de Wauw, 2008), which may be wise in a politically sensitive context.

As the end product of predictive modelling gives an indication of an occupational pattern integrated over the period represented by the finds and/or available knowledge, an expectation map can be used as a geographical 0-hypothesis at the start of a project in which occupational patterns are sought with their explanations. We use predictive modelling in this sense to formalize the state of knowledge at the onset of a project.

In the case study at hand, we apply a mixed approach to predictive modelling with Bayesian inference to typical combinations of environmental attributes ("strata") as described by Finke, Meylemans & Van de Wauw (2008). This is done for the following reasons: (i) the data configuration is geographically scattered and clustered by surveyed fields. Such data configuration causes poor performance of geostatistical methods but does not hinder the prediction to geographical strata; (ii) in part of the surveyed fields both the absence and the presence of finds was recorded. This has been shown to be an asset in Bayesian inference. Furthermore, we propose the application of an evidence filter to display only those patterns on the map that are strongly supported by the field evidence, to visualize what knowledge on occupational patterns is certain at the project start (and what knowledge is not). This will be helpful when formulating research objectives for reconstructing the occupational history in a temporal window of interest.

Integrative Model-based Landscape Reconstruction

The major problem in reconstructing past landscapes is that basic data useable for inference are scattered in both the temporal and geographical sense. Thus, to obtain a continuous or even a fragmented picture of past landscapes methods are required to interpolate landscape characteristics in both space and time. Such interpolation can be entirely data-based (e.g. space-time kriging, Kyriakidis & Journel, 1999), but if information on rates of change, speed of processes, et cetera, is available, this can be used as well. When rates of change obey physical laws, process models can be particularly useful as deterministic interpolators in time and sometimes also in space (e.g. Heuvelink et al., 2006). We define a model as a set of equations or decision rules that mimic the behaviour of a system, e.g. the landscape, or subsystems such as the soil-vegetation or the groundwater-atmosphere system. The advantage of using models with data instead of only data is that environments that change with varying speed, for instance in response to climatic variations, can be more reliably described with models built on process knowledge than with simple assumptions on (e.g.) linear change between dates on the time axis. Additionally, models honour relations between variables such as precipitation, vegetation water and nutrient uptake, soil moisture and leaching of soil components while predicting spatio-temporal patterns of these variables on a one by one basis may result in loss of co-variation. We therefore propose the application of process models in the reconstruction of soil-water-landscapes to improve understanding of occupational patterns as far as these can be explained by biophysical factors. The complexity of soil-water-vegetation processes and their interaction in the landscape enforce a multidisciplinary approach. Due to the multiple disciplines involved no single model can be used but a model framework must be defined in which various discipline-specific models are integrated.

We developed a conceptual framework for the purpose of an environmental reconstruction in a postglacial and mainly alluvial landscape with mostly shallow water tables in Flanders. The next sections contain a description of the development of this framework and its model components with some examples. Additionally, attention is paid to the transfer of inputs and outputs between the various models and associated issues of scale that have to be addressed.

Approach

As stated above, the final objective is to predict, with models, spatial patterns of biophysical variables that are considered to be of influence to occupational patterns at various time slices. A generic 7-step approach is proposed to reach this goal:

1: Define biophysical attractors for human occupancy and associate these with variables to be predicted by models. Examples of biophysical attractors are "suitable places for hunting", "good soils for a particular type of agriculture" or "a sheltered place that does not flood". The third example corresponds to places with low wind exposure where in the wet season the groundwater table does not reach the surface and where stream floods do not occur. These

places can be identified if the variables "wind exposure", "water table dynamics" and "flooding occurrence" can be mapped for the landscape in the relevant time slice.

2: Define a model framework that can provide the variables. In the above example the variables wind exposure and a drainage pattern can be mapped with a temporal Digital Elevation Model (DEM), while a hydrological model can calculate the water table fluctuations and flooding occurrence maps using (a.o.) the drainage pattern.

3: Define model dependencies in terms of data and knowledge flows at various scales. A hydrological model needs as input (a.o.) elevation data, but probably at lower resolutions than the DEM can provide because of computational limitations. This integration may involve upscaling activities before and during the hydrological modelling and downscaling of the obtained model results afterwards.

4: Prepare the individual models to be run. The model components must be in optimal shape to produce plausible results. This means that wherever possible the individual models must be calibrated towards existing data and maps. Afterwards model results should be verified with independent and preferably measured data. Additionally, model input data (which can be of spatial and of temporal nature) must be generated, possibly using other components from the model framework.

5: Run the models within the framework to obtain space-time coverage with the required variables identified in the first step.

6: Integrate the results so that the selected biophysical attractors are mapped, and the reconstructed landscapes at various time slices can be evaluated for optimal places to live, to hunt, et cetera.

7: Matching of the resulting maps with the occupational data from archaeological finds to identify to what extent biophysical-deterministic reconstructions can explain these patterns, and to what extent other, socio-economic attractors play a role.

The model framework presented in the next sections illustrates the above generic approach in the context of an environmental reconstruction of a late glacial and alluvial landscape in Flanders near the city of Ghent. The studied period stretches from Final Palaeolithic to the Iron Age and the Roman Provincial Era and thus covers a variety of climates, vegetations (Verbruggen, Denys, & Kiden, 1996) and types of land use (Crombé, 2005). The biophysical attractors to be defined in step 1 of the above approach should reflect the variety of environmental conditions and land use. The next two sections address model instruments and their connectivity used in the environmental reconstruction study in Flanders (steps 2-6).

Model Components

Elevation Model

A DEM (Digital Elevation Model) was generated based on high precision airborne LiDAR (Light Detection and Ranging) data with an average sample density of one point per 2m². The altimetric

accuracy ranges from 7cm on a concrete surface to 20cm on vegetation cover (AGIV, 2003) which is significantly better than the planimetric accuracy with a typical value in the order of 50cm (Drosos & Farmakis, 2006). This exceptional accuracy at centimetre level and the regular scan pattern allows the production of a high quality DEM (Lohr, 1997; Axelsson, 1999; Drosos & Farmakis, 2006; Liu, 2008). In this paper we use the term DEM in the context of a Grid DEM which represents the relief as a two-dimensional regular grid whereby each grid cell contains one elevation value. Given that a higher ground resolution results in an increasing ability to record features but also increases the size of datasets, a resolution of 2m x 2m was chosen in order to obtain an optimal combination of efficiency and accuracy of terrain representation. However, the DEM derived from the original LiDAR data contains data points representing not only terrain elevation but also topographical objects like vegetation and buildings as well as current disturbances of the natural topography by artificial features like road banks and waste dumps, which are no parts of the natural topography. To generate a DEM exclusively representing the natural topography, three filtering steps were elaborated involving the usage of topographical vector maps and aerial photographs for the filtering, slope analysis for identifying remaining extreme non-natural relief features and interpolation to refill the grid.

The resulting high resolution DEM with a pixel size of 2m x 2m represents the natural topography free of artefacts caused by modern objects and infrastructures created since the 19th century. For modelling purposes this fine DEM needed to be resampled to a resolution of 100m x 100m. Taking into account possible remaining peaks in the DEM, the median value is used to upscale the grid size. As the DEM exclusively represents the natural terrain elevation it can also be used for downscaling the results in a later phase.

The DEM representing the natural terrain elevation corresponds to the postmedieval landscape. Creating a temporal DEM involves taking into account landscape changes occurring earlier. In the example study these changes were reported (Crombé, 2005) to be the transition of a Preglacial and Pleniglacial alluvial landscape into a landscape with niveo-aeolian deposits and coversands from pleni- and late glacial periods. These changes were associated with the formation of late glacial lakes and changed drainage patterns. At various point locations, such genesis can be reconstructed by palaeoecological research on undisturbed soil cores. At these points, the altitude and approximate dates of stable surfaces can be identified. The temporal DEM is constructed using space-time interpolation methods using the full-cover current natural landscape DEM and the point reconstructions. Examples of such space-time interpolation methods are spatio-temporal kriging (Heuvelink, Musters, & Pebesma, 1997; Kyriakidis & Journel, 1999) and space-time Kalman filtering (Heuvelink et al., 2006). Alternatively, process models describing landscape evolution (e.g. Schoorl, Veldkamp, & Bouma, 2002) can be calibrated to the point reconstructions, although existing models mostly focus on the effects of tectonical and alluvial processes and less on aeolian landscape building processes as in the research area.

Hydrological Model

In a hydrological model, the hydrological cycle is represented making various simplifying assumptions. These models are increasingly being used to enhance our understanding of hydrological processes and to make hydrological predictions, for example on flooding (Liu & De Smedt, 2005) and

groundwater contamination (Vandenbohede, Van Houtte, & Lebbe, 2009). In this study the major focus lies on the subsurface flow of the water, in particular on the dynamics of the water table during past time periods. Because of these characteristics, the model at hand can be placed in the group of palaeohydrogeological models. To our knowledge only few examples of palaeohydrogeological modelling exist, all of them trying to assess the future long-term safety of storages for nuclear waste under changing climatic conditions (Van Weert & Hassanizadeh, 2000; Wemaere et al., 2000; Degnan et al., 2005). Hence, none of them is applied in a geo-archaeological context.

In areas with shallow groundwater tables, such as the Sandy Flanders, environmental processes like pedogenesis and vegetation development are strongly influenced by water table dynamics. As a necessary part of the pedogenesis model and therefore of the land evaluation model, we therefore incorporate hydrological modelling into the process of landscape reconstruction.

The hydrological model used is MOCDENS3D, which is based on the three-dimensional finite-difference groundwater model MODFLOW (Oude Essink, 1998). In order to simulate groundwater flow, full-cover information on topography, drainage pattern, illustrating the close relationship between surface and subsurface waters, subsoil-properties and recharge to the water table, is required as a model input. In a first step, a steady state simulation is performed, with a user-specified head as an initial estimation. This only affects the number of iterations required to converge to an acceptable approximation of the solution of the steady state flow equation and has normally no effect on the solution itself (Harbaugh, 2005). As a result, an average water table for every cell of the study area is produced. This gives information on the average wetness of a site through time, which will partly determine the suitability of a site for settlement. Monthly minimum and maximum fluctuations influence soil formation and determine if a site is seasonally wet. These fluctuations are calculated during a non-steady state flow simulation, in which the specific yield or storage coefficient near the water table, derived from soil characteristics, and the monthly recharge to the groundwater reservoir, obtained from meteorological data such as precipitation and evapotranspiration, are also taken into account. This leads to the production of monthly mean lowest (MLW) and mean highest (MHW) water table maps.

Modelling in a geoarchaeological context proves to be quite challenging because of the large temporal extent of the periods of interest. This results in computational limitations and constraints on data availability. To overcome these problems, we calculate water table dynamics for time windows of 30 years, which correspond to a climatic period (Finke et al., 2004), and afterwards obtain a continuous set of groundwater heads by means of interpolation. Furthermore, the spatial units considered are set to 100m x 100m grid cells. Data availability is mainly limited to present-day groundwater heads, which implies that calibration can practically only be performed on the present-day time window. Furthermore, calibration of the entire area based on measured heads proves to be hard because of the size of the study area and the restricted spatial distribution and temporal extent of the available data. Full-cover information, however, is present as drainage classes on the soil map of Flanders (scale 1:20,000), which was mapped during the 1950's. During this survey, next to soil profile and texture, information on the groundwater dynamics was recorded and translated into drainage classes. These drainage classes are related to MHW and MLW (Van Ranst & Sys, 2000), expressed as classes of depths below surface. By means of a recently mapped detailed drainage class map of part of the study area (Zidan, 2008), average values for MHW and MLW are calculated per drainage class, and a mean water table map (MWT) is derived. By comparing the results of the steady

state simulation of the present time window with this MWT map and the results of the transient or non-steady state flow with the MHW and MLW maps, the model can be calibrated for the present time. By means of palaeoecological observations at different locations, simulated groundwater heads for previous time windows can be verified.

Another consideration that has to be made is that topography, river network and climate are variable, considering the long time periods involved. This as opposed to the geological layers and their hydrogeological properties, which are assumed to be rather continuous for the time considered. In order to take the changing climatic factor into account, present-day meteorological measurements are combined with palaeoprecipitation (Davis et al., 2003) and palaeoevapotranspiration series based on pollen data. As a consequence, a reconstruction of palaeotopography and palaeodrainage pattern, which is derived from the palaeotopography, is required for each time window. This reveals again the close interconnection between the different models as presented in this article.

Pedogenesis Model

The main reason to include a soil genesis model in the framework is that the natural chemical and physical fertility of the soil determines to a large extent the suitability for Neolithic and later types of agriculture. Liming was only introduced in the Iron Age. The suitability is determined in the land evaluation model (c.f.), but this model needs information on soil pH, soil texture, calcium carbonate content and organic matter content at the relevant time slice. A soil genesis model is then needed to reconstruct these variables. Such model should take into account the effects of (changing) climate, vegetation, topographic position, parent material and human influence such as ploughing and erosion on the soil properties mentioned above. Soil processes involved are (a.o.) flow of water, chemicals and heat, chemical equilibration, C-sequestration, physical and chemical weathering and perturbation of the soil by soil organisms and by ploughing. The model SoilGen, described in detail by Finke & Hutson (2008), has these abilities and produces annual values of the required variables for desired depths in the soil profile at a point location.

The model needs initial values of soil properties at the starting year. These can be taken from chemical and physical analysis of C-horizons in the current soil. Furthermore, for the whole simulated period, values for precipitation, potential evapotranspiration, temperature, water table depth and type of vegetation must be available. Meteorological data can be generated using climate reconstructions like that of Davis et al. (2003) to obtain annual values for precipitation, evapotranspiration and January and July temperatures. These can be downscaled to daily values using a reference series based on current measurements (Finke & Hutson, 2008). Vegetation types can be reconstructed with local pollen diagrams (Verbruggen, Denys, & Kiden, 1996) and water table depths are coming from the hydrological model. Additionally, the model handles erosion and sedimentation events, which can be derived from point scale reconstructions using the temporal DEM and results from on-site pedological and palaeoecological research.

The reliability of the model outputs needs to be maximized. The underlying hypothesis is that if process rates and final state of the soil are well reproduced by the model, it is a suitable interpolator in time, i.e. it can give a reasonable estimate of soil conditions at different points in time. Model

reliability is therefore maximized by (i) calibrating the model on measured soil data and (ii) by calibrating process rates to reproduce literature values (e.g. Egli & Fitze, 2001). Furthermore, individual model components such as water and chemical flow routines, decalcification speed and C-sequestration need to be calibrated and verified. The above mentioned model components in SoilGen have a good verification status (c.f. Addiscott & Wagenet, 1985; Smith et al., 1997; Jalali & Rowell, 2003; Dann et al., 2006; Jabro, Jabro, & Fox, 2006; Finke & Hutson, 2008). Ideally, the calibrated model is verified at independent test locations in the study area as well. As the runtime for such model for temporal extents in the range of 15000 BP – present may be quite long, the number of geographic data points that can be simulated is limited and obtained values must be spatially interpolated to obtain complete spatial coverage.

Land Evaluation Model

The aim of the land evaluation model is to delineate areas where in a chosen part of the temporal extent, the conditions for concomitant uses of land were optimal. Land evaluation is defined as "the process of collating and interpreting basic inventories of soil, vegetation, climate and other aspects of land in order to identify and make a first comparison of promising land use alternatives in simple socio-economic terms" (Brinkman & Smyth, 1973). Early examples of land evaluation in archaeology were reported by Kamermans, Loving, & Voorrips (1985) and Finke & Sewuster (1987) and focused mostly on the agricultural aspect, but this needs not be the case. Here we take a broad interpretation of land use, i.e. also the use of land for hunting and gathering and as a comfortable place to live. The resulting maps provide a biophysical motivation for occupational patterns and thus can be considered deductive predictive maps.

The first activity in an archaeological land evaluation is careful evaluation of the archaeological and palaeoecological record for evidence of land uses, e.g. pollen, plant macroremains, artefacts, archaeological traces in the soil, et cetera. This should, in combination with knowledge on the socio-economic organization, lead to identification of land use objectives and subsequent definition of land utilization types. The next step is identification and mapping of relevant basic land properties (called "land characteristics", e.g. soil pH) and compound land properties (called "land qualities", e.g. moisture supply capacity). These properties are in our approach largely derived from the models described earlier. The requirements of the land utilization type are then formalized and matched with the land characteristics and –qualities at the considered period to result in maps indicating the suitability for the defined land utilization types. In case a fairly complete overview of possible land utilization types is acquired and reasonable assumptions on the socio-economical system can be made, assessments of the population carrying capacity can be made using the suitability maps. Land evaluation has since the 1970s undergone an evolution from qualitative evaluation approaches towards approaches that quantify crop production with models and use trade-off analysis to define land use systems in detail (Stoorvogel et al., 2004). We consider such analysis as extensions to the proposed approach but do not pursue it in the case study at hand.

The spatial object of land evaluation should correspond to the smallest unit of land use or land management, assuming this management was homogeneous. We consider agricultural fields of 40m x 40m reasonable. A period of one year is considered a reasonable temporal scale as the crop growth, hunting and gathering cycles take one year to complete.

Model Integration at Different Scales

Concepts of Scale

When different models are to be connected for integrated studies such as geoarchaeological studies, it should be realized that the various models in the framework may not have the same spatial or temporal scale and may or may not cover the whole research area or timeframe. In the context of scale, three concepts are of relevance (Bierkens, Finke, & De Willigen, 2000):

(i) the *grain*, being the largest area (or volume) or time interval for which the property of interest is considered homogeneous. For example, in a digital elevation model of 5m x 5m the spatial grain is $25m^2$, and in a calendar the temporal grain is one day. If a model framework contains models with different grains, and these models have to be connected, upscaling or downscaling methods must be applied to obtain results at the target grain;

(ii) the *extent* is the total area or time interval considered in a study. If two or more model components do not have the same extent, then extrapolation (or singling out) is necessary to have results for equal extents;

(iii) the *coverage* is the fraction of the extent for which there are data values (for a chosen grain). If one model operates on a small spatial grain, then many model runs must be done to obtain full coverage. In this case the runtime of the model may be limiting. If the applied models do not have the same coverage then interpolation is necessary to obtain equal coverage. The choice for a grain affects the variability of the target property. At any grain, the within-grain variability is ignored as only the grain-average is considered. At a large spatial grain, less variability can be displayed on a map but we are more certain about the average values. Inversely, a small spatial grain allows displaying variability in detail but we may not be certain at all if these patterns are true. Ideally, the spatial grain is chosen based on an acceptable uncertainty threshold. In practice, choice of spatial grain (and temporal grain as well) is determined by the available data and analysis instruments such as models.

Model Linkage over Different Scales

In this study, we assume that all models must produce their final outputs at full extent (the complete study area), full coverage (no empty areas) and at the spatial and temporal grains of the Land Evaluation Model. These grains are agricultural fields of about 40m x 40m and one year. Fig. 2 shows the intrinsic grain and coverage of the model instruments and displays the actions that must be taken to attain the target grain and coverage of the land evaluation model. This figure is a simplification of reality since the models do not just contribute to the land evaluation model but also to each other, which may involve more upscaling, downscaling and interpolation activities. We refer to Heuvelink & Pebesma (1999) and Bierkens, Finke, & De Willigen (2000) for an extensive review of upscaling and downscaling methods in the context of modelling. The latter publication also gives protocols to choose appropriate scale transfer methods for specific situations.

In the context of upscaling, the choice of a method depends on the question if the model responds linearly to its input parameters. If this is the case, one can upscale (e.g. spatially average) the model inputs and run the model at the coarser grain to directly obtain results at the target grain. Usually, in hydrological and soil genesis models this is not the case. Then the model has to be run at many locations at a fine grain, and the model results have to be upscaled. The latter method has the disadvantage that many more model-runs need to be made, which can be time consuming.

In the context of downscaling one can utilize fine-grain auxiliary information to obtain plausible patterns at the finer grain. The auxiliary information should then be relevant for the process studied. For instance, a DEM can be used to downscale the water table depths produced by a coarse-grain hydrological model, because the water table depth is known to be related to micro-relief.

RESULTS

Predictive Modelling

The landscape in the study area is dominated by arable lands where intensive ploughing revealed a large amount of archaeological artefacts. More than two decades of intensive archaeological investigations, mainly by means of systematic field surveys and excavations, revealed sites dating from the Final Palaeolithic to the Neolithic. An inventory of the collected data (Sergant, Crombé & Perdaen, 2009) shows a geographical and chronological discontinuous site-distribution, possibly implicating an intermittent population and exploitation of the region during prehistory (Crombé & Verbruggen, 2002; Crombé, Perdaen & Sergant, 2008). As stated above, a mixed approach to predictive modelling (Finke, Meylemans, & Van de Wauw, 2008) was used to test if these observed occupational patterns are confirmed, based on predefined biophysical attractors and present data.

For this study area, we produced filtered (P=0.001) expectation maps for the Final Palaeolithic, the Mesolithic and the Neolithic period, based on a number of respectively 27, 193 and 91 find spots. A total of 151 non-find spots were also taken into account. This information was combined with present-day full-cover auxiliary information on various attributes, such as topography, slope, wetness index, wind exposure, visibility, distance to open water, natural drainage class and texture class. For more and detailed information on the different attributes and the production of these predictor grids, we refer to Finke, Meylemans, & Van de Wauw (2008).

Fig. 3 shows the filtered expectation maps for all three archaeological time periods mentioned above. By using the evidence filter, only those patterns that are strongly supported by field evidence are displayed, while patterns supported by less strong evidence are filtered out. The filtered expectation maps for the Final Palaeolithic, the Meso- and Neolithic only display low probabilities for findings. Given the data at hand however, these appear to be the most reliable. For the Final Palaeolithic (upper part Fig. 3), regions alongside river courses and the borders around the Depression of the Moervaart, are pointed out on the expectation map as certainly being poor in archaeological sites. The map of the Mesolithic (central part Fig. 3) displays certain, but low probabilities for findings in the polder areas in the west and alongside the borders of the Depression of the Moervaart. Previous mentioned expectancy maps differ from the one for the Neolithic (lower part Fig. 3), in which a much broader area of low probabilities is displayed. Topographically higher

lying regions show much higher probabilities on a non-filtered version. However, these appear to be highly uncertain because they are not displayed on the filtered map. This suggests that there was less occupation on these lower-lying parts of the landscape during the Neolithic.

Although the predictive modelling resulted in maps displaying only certain but very low probabilities for archaeological findings, we were given more insight in the state of knowledge at the beginning of the project. The observed site distributions do not match the predictive map based on our knowledge of the current landscape and the chosen biophysical attractors. This motivates an integrated landscape reconstruction.

Model Framework and Component Integration

The proposed general model framework (Fig. 4) connects four models in a sequence, DEM > hydrological model > soil model > land evaluation model, but was actually designed in the reverse order to ascertain that all the needed data by the land evaluation model can be generated with the model instruments earlier in the model chain. The identified model components cannot be directly connected because of scale issues: as the grain sizes of the DEM, hydrological model, soil model and land evaluation model differ, upscaling and downscaling steps must be added to the chain. Furthermore, interpolation is necessary to obtain full coverage with soil properties. Thus, the model framework is integrative in the sense that it combines process knowledge from various disciplines and integrates the result to predictive maps with chosen spatial and temporal grains. From such framework, protocols can be derived that specify data and information flows between involved research groups, which will be of great value when several disciplinary groups cooperate. The model framework is generic in the sense that it is portable to other landscapes, especially in regions with shallow water tables. However, the processes to be included (or not) in the various models partly depend on the geographic setting; for instance the construction of a temporal DEM in a tectonically active area or an area undergoing strong erosion may involve inclusion of additional processes.

Model Components

Elevation Model

The flowchart of activities for reconstruction of the temporal DEM is given in Fig. 5. The generation of a DEM exclusively representing the natural topography was elaborated in the following three filtering steps:

During the first step the LiDAR data were filtered for topographical objects, which is the most critical and difficult step in LiDAR data processing (Liu, 2008), as it creates filtering artefacts and some buildings and vegetation still remain. Also, the artificial features disturbing natural topography are not subject to this filter method, as visible on Fig. 6a.

In order to meet these problems it is crucial to conduct a second filtering of the LiDAR ground point data to remove the filtering artefacts and the missed artificial features, Fig. 6b. This second filtering is conducted automatically using topographical vector-data. As no automated filtering procedure is

completely accurate, additional manual editing was necessary (Chen, 2007) to remove remaining artefacts, which was based on aerial photographs, Fig. 6c. The filtering resulted in masked areas, where new elevation values were created through interpolation using two different methods. Small confined areas were interpolated using surrounding data points with inverse distance weighted interpolation. The elevation for large areas was estimated based from contour lines on historical topographical maps of 1863 showing the landscape before the infrastructures were created.

A third filtering of the elevation data aims to extract small artificial elements in the DEM, such as small drainage ditches, remnants of former ditches bordering fields and convex shaped fields by circular ploughing. These remaining features are too small and too numerous to be removed manually during the second filtering step. The third filtering step implies a slope analysis followed by a removal of the elevation values for which the rate of the maximum change in z-value in a predefined radius of surrounding cells exceeds a defined threshold, Fig. 6d. To avoid the removal of natural slopes, certain confined regions in the study area, exposing natural inclines exceeding this threshold, are assigned an adjusted threshold.

The high resolution DEM derived from the airborne LiDAR-data proved to be useful to detect archaeological and palaeoenvironmental features such as palaeochannels or filled ditches, even when other data sources show no evidence for these features. The DEM is also useful to geophysical and palaeoecological field sampling and archaeological prospection. Combining the high resolution DEM with historical maps and archaeological data enables a detailed interpretation of the natural conditions and the human response during the creation of the landscape.

Hydrological Model

The flowchart of activities needed to run the hydrological model is given in Fig. 5. The study area of the project is divided into three subareas (Fig. 1) because of different orientation of the streamlines throughout the area and large hydrogeological differences related to geomorphologic features in the landscape, such as the Cuesta of Boom. A region of 120 km² to the north of the city of Ghent was selected as the first study area to test and to arrange the hydrological model. The results discussed below are preliminary, because of the ongoing calibration of the model. For the moment, the time window at hand is situated between 1947 and 1976, a 30-year long time frame covering the period in which the soil survey in the area was executed. This took place between 1949 and 1953 (Van Ranst & Sys, 2000).

A steady state flow simulation is performed for this time window with the average value of precipitation and evapotranspiration for the period of 1947 to 1976, calculating groundwater levels for cells of 100m x 100m. This results in a map of the average water table, expressed in m relative to the second general levelling (abbreviated as TAW) (Fig. 6) or, subtracted from the DEM, in m below surface. As an outcome of the transient flow simulation, maps of the groundwater level are given for each month, covering the 30-year time window. For each year, the three months with the highest and with the lowest groundwater levels are selected and their 30-year average is calculated, given two maps of the MHW and MLW.

Pedogenesis Model

The flowchart of activities needed to run the model for soil reconstruction is given in Fig. 5. Obtaining meteorological input data from general climate evolution data is essential for running the model, as soil genesis is strongly influenced by fluctuations in precipitation, evapotranspiration and temperature. In the figure these data are considered as available input which was the case for the presented model run, but may be laborious in other cases. As an example of the output of the soil model at the 1m x 1m spatial grain and one year temporal grain, Fig. 8 shows the evolution of soil pH in soil depth and time. The effects on soil pH of calcareous aeolian dust additions in the Dryas periods are clearly visible. In deeply drained soils the high Belgian precipitation surplus in combination with acidity produced by organic matter decomposition rapidly decalcifies the soil, especially in the Holocene. In such soils the conditions for agriculture without fertilization in the form of liming were unfavourable already from the start of the Neolithic. This effect is less marked in soils with shallow water tables. Other output data comprise the organic matter content and bulk density which are important to assess the chemical and physical soil fertility in the land evaluation model.

Land Evaluation Model

The land evaluation activities are depicted in Fig. 5. Apart from the procedure, no results from the case study can yet be shown as this model is applied near the end of the model chain when the other model outputs are available. Current emphasis is on evaluation of archaeological and palaeoecological evidence for land use types in the form of pollen, plant macroremains and archaeological artefacts and features. The earliest possible indication for agriculture within the area of Sandy Flanders was found at the site of Doel "Deurganckdok-sector B" (Bastiaens et al., 2005). One charred cereal grain of *Triticum aestivum* (bread wheat) was recovered on the top of a sand dune, underneath a peat layer (Crombé & Vanmontfort, 2007). The beginning of the peat growth was dated around 5050±55BP. Artefacts linked with agricultural land-use activities were discovered at Kluizen and Zele. In Kluizen, three ardshares were reused in the revetment of a well, dated in the Early Iron Age (Laloo et al., 2009), while in Zele, two fragments of an ard were found in a Late Iron Age well (Bourgeois, De Clercq, & Laloo, 2009). At the excavations of Bronze and Iron Age sites at Sint-Gillis-Waas, pollen of *Cerealea* were collected in wells, indicating agricultural activities in the vicinity (Gelorini, 2001).

Intensive multidisciplinary palaeoecological analyses are currently performed in selected areas of Sandy Flanders, such as the late glacial Depression of the Moervaart, palaeochannels and deep archaeological features (e.g. wells and ponds).

CONCLUSIONS

The identification of occupational patterns benefits from landscape reconstructions, since the current landscape often does not provide essential information as may result from evidence-filtered predictive modelling. The development and subsequent application of model instruments provides the tools to interpolate various landscape characteristics in space and time, using process knowledge supplemented by empirical interpolation methods.

As such model instrument for landscape reconstruction we propose to apply and integrate the following model components:

i.   A temporal DEM from a current DEM, historical maps, point reconstructions of palaeosurfaces and interpolation methods;
ii. A hydrological model applied at various time slices to reconstruct the water table dynamics and flooding hazard areas;
iii. A soil genesis model applied at various point locations to reconstruct relevant soil characteristics such as pH, organic matter content, followed by spatial interpolation of the results for time slices;
iv. A land evaluation model to identify areas of land per time slice that provided favourable conditions for the land uses at that time.

All these model components need input data that only palaeooecological, sedimentological and pedological on-site research can provide. Since the model components operate at different spatial and temporal grains and coverages, upscaling and downscaling methods as well as interpolation methods should be part of the integrated instrument.

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FIGURE CAPTIONS

Fig. 1 The study area. A: Localisation of Belgium within Europe. B: Sandy Flanders with localisation of known archaeological sites and the three subregions from the hydrological modelling.

Fig. 2. Spatial (upper figure) and temporal (lower figure) grain versus coverage of model components in this study. Soil=soil model; DEM=Temporal Digital Elevation Model; Hydro=hydrological model; Eval=land evaluation model.

Fig. 3 Maps of the probability of finds of Final-Palaeolithic, Mesolithic and Neolithic origin obtained by Bayesian modelling and filtered so that only probabilities strongly (P=0.001) supported by field evidence are displayed.

Fig. 4 Model framework. Legend and detailed activities are given in Fig. 5.

Fig. 5 Flowcharts for construction of a temporal DEM (a, with legend), the hydrological model (b), the soil genesis model (c) and the land evaluation model (d). Solid lines indicate data flows; dotted lines indicate information flows (for model calibration and verification).

Fig. 6 Removal of topographical objects from a DEM. a: filtering major objects from point LiDAR data; b: filtering by overlay with topographic vector maps; c: manual filtering by comparison with aerial photographs; d: filtering of non-natural relief by slope analysis. White areas are removed during the indicated filtering step. Between c and d and after d interpolations are performed to refill the grid.

Fig. 7 Average water level (mTAW) in the most eastern subregion of the hydrological modelling.

Fig. 8 Simulated soil pH as a function of depth and time in a deeply drained silt loam soil in Flanders.
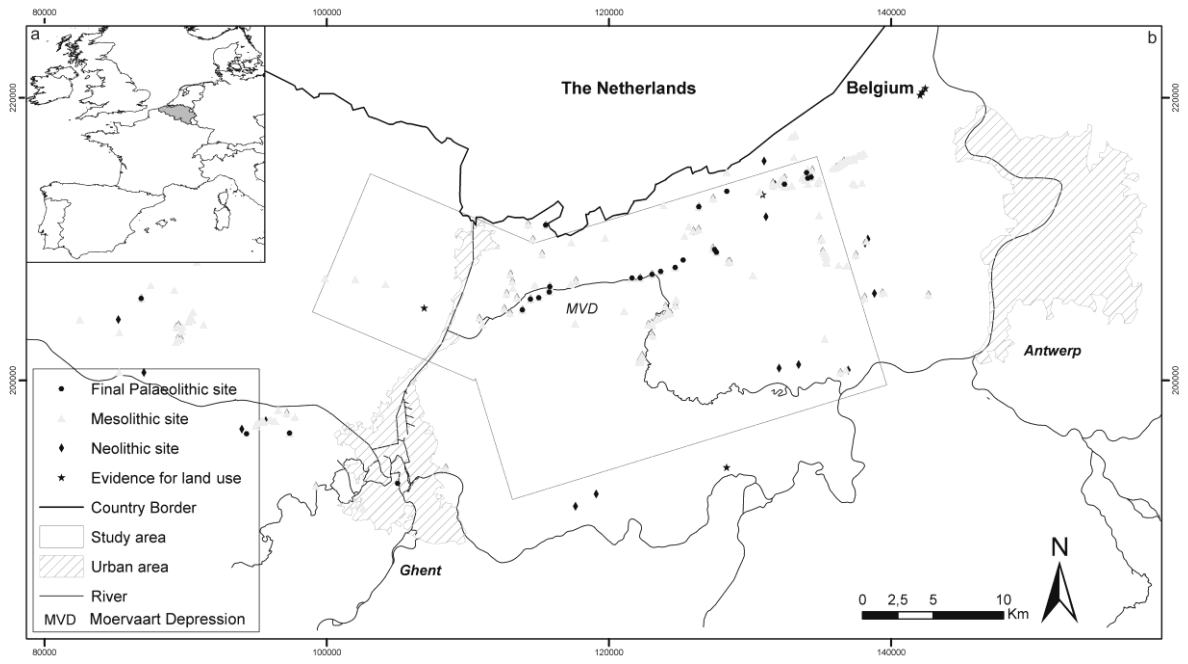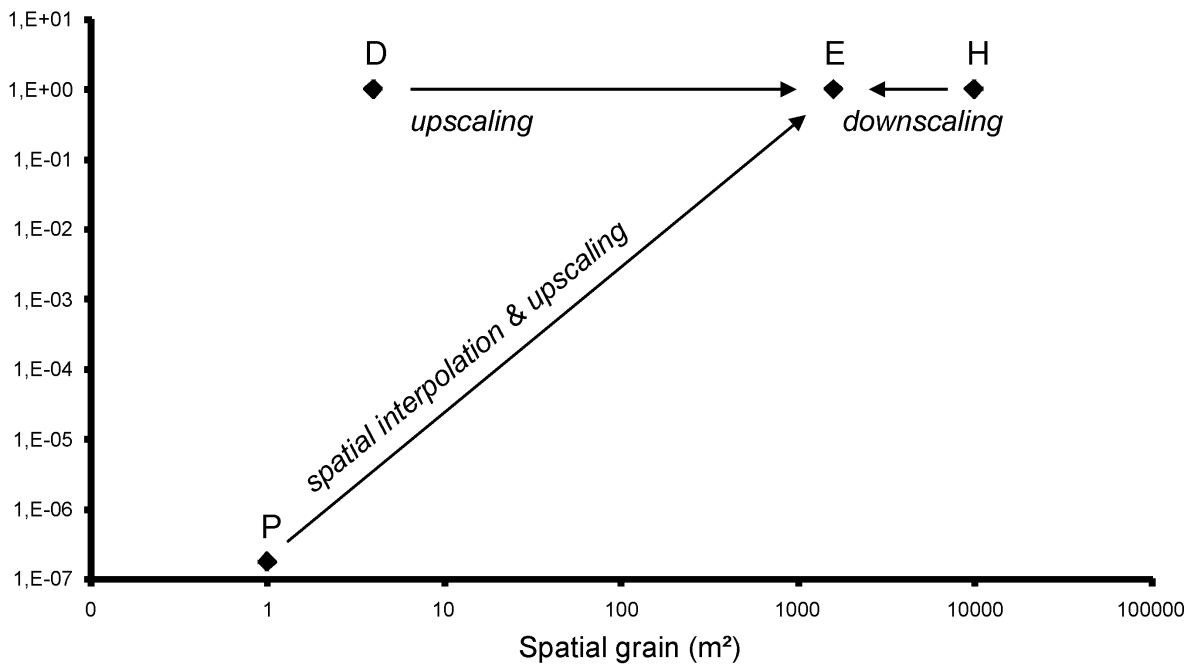
Fig. 1

a

Spatial coverage
(fraction of extent)
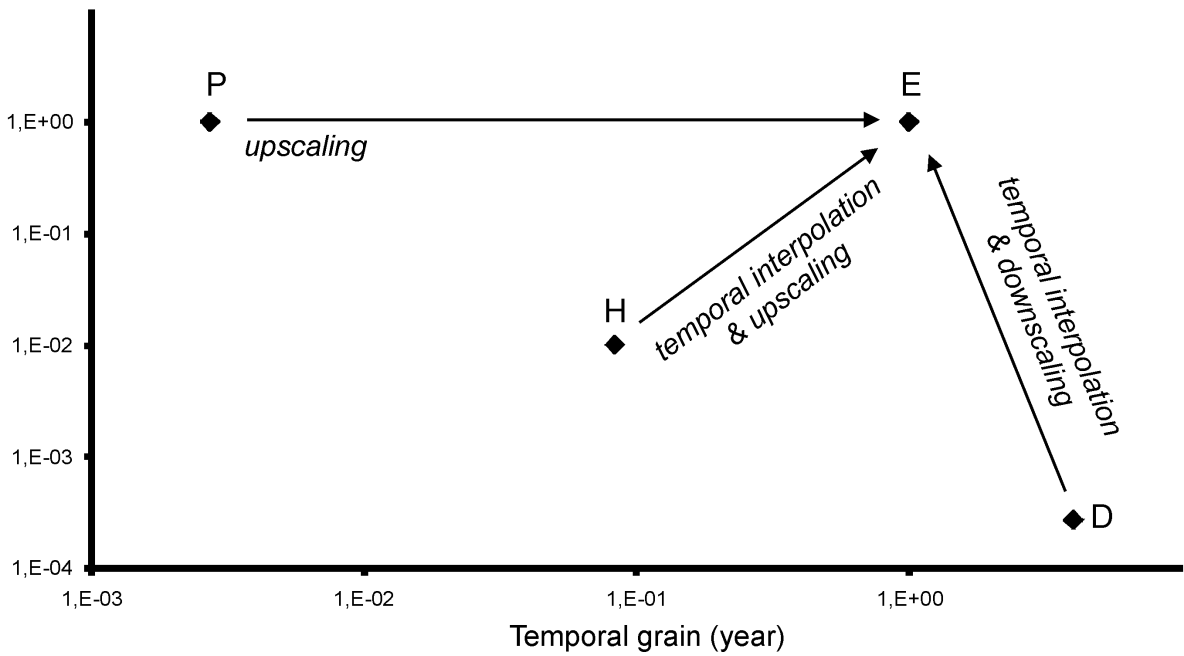

b

Temporal coverage
(fraction of extent)

Fig. 2
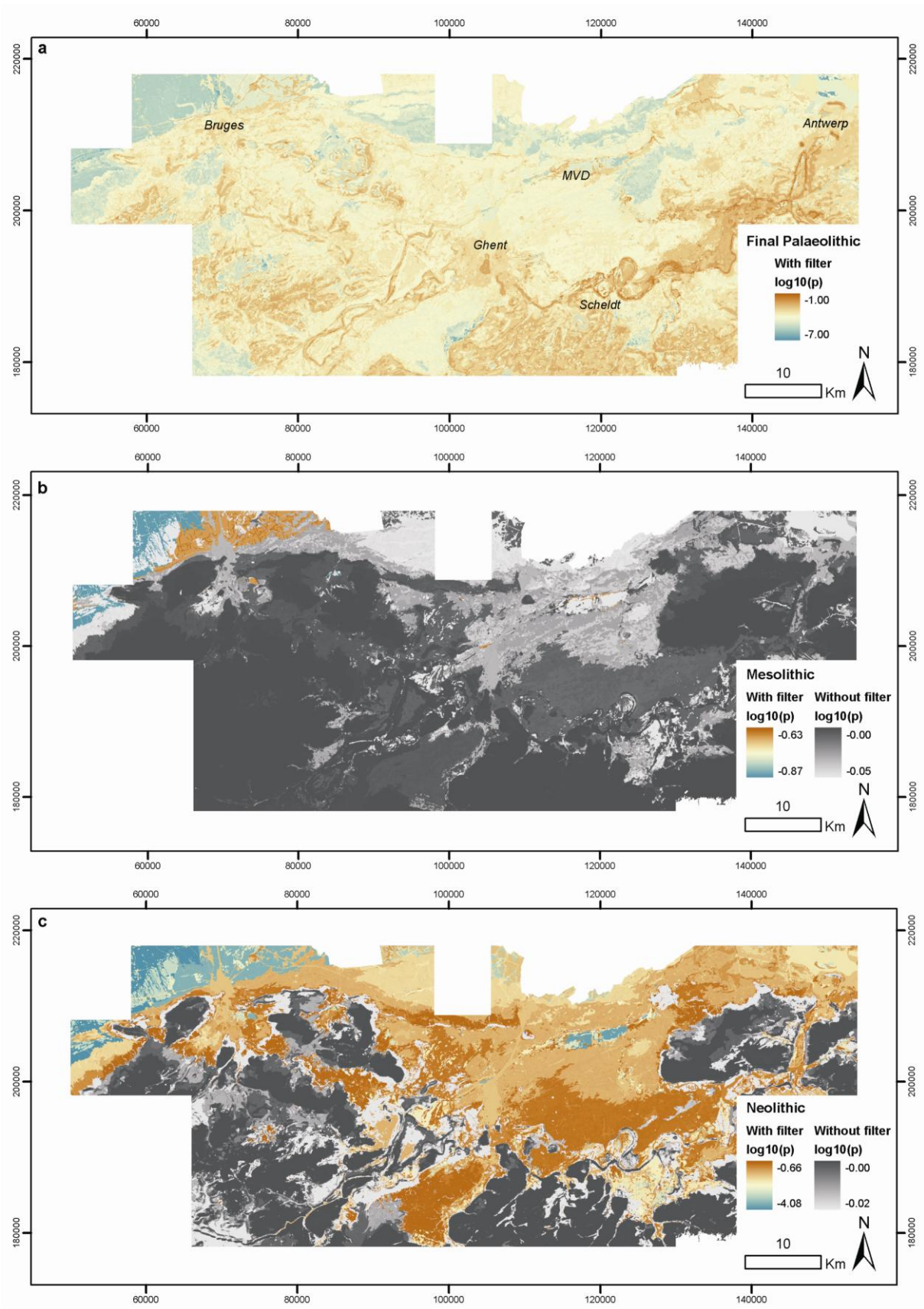
Fig. 3
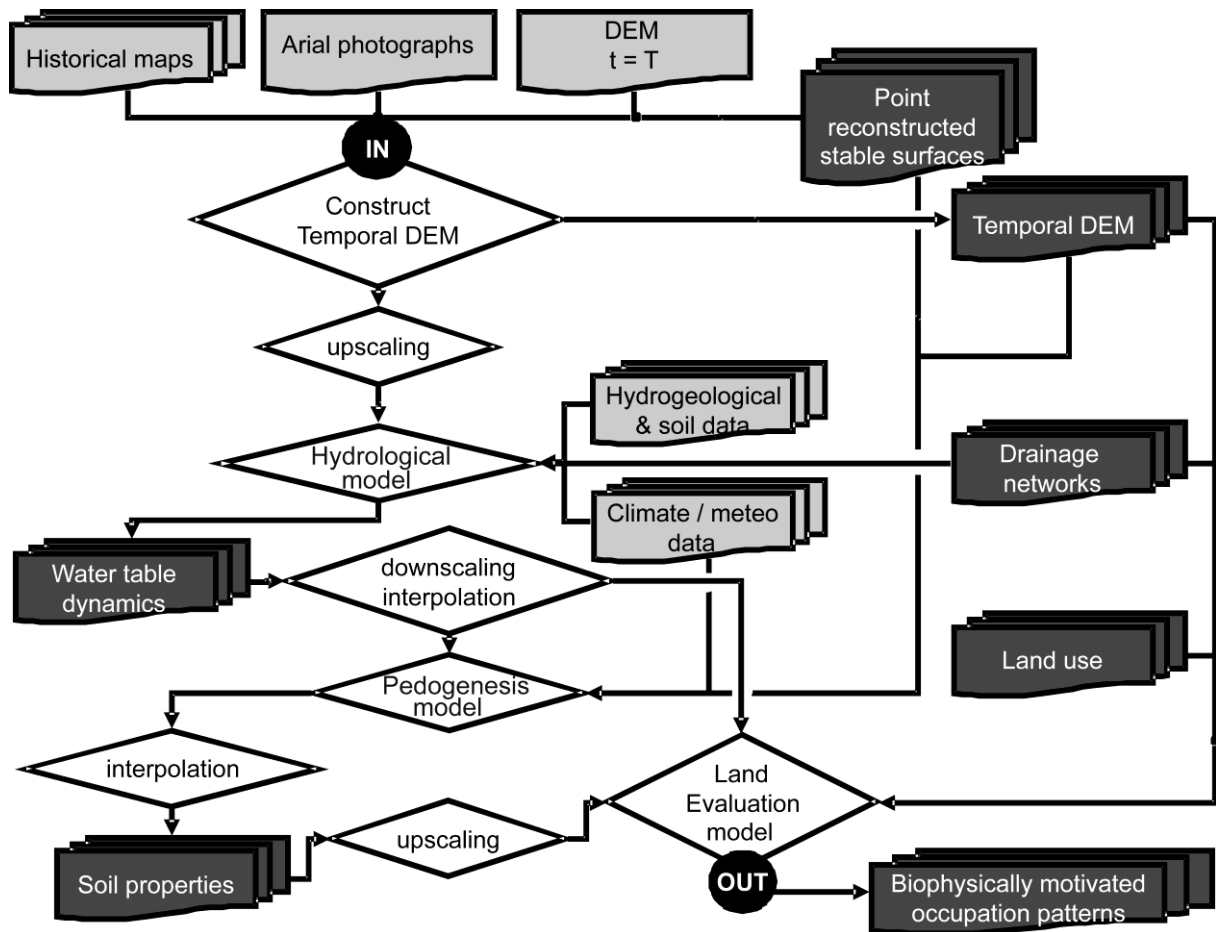
Fig.4

Fig. 5a

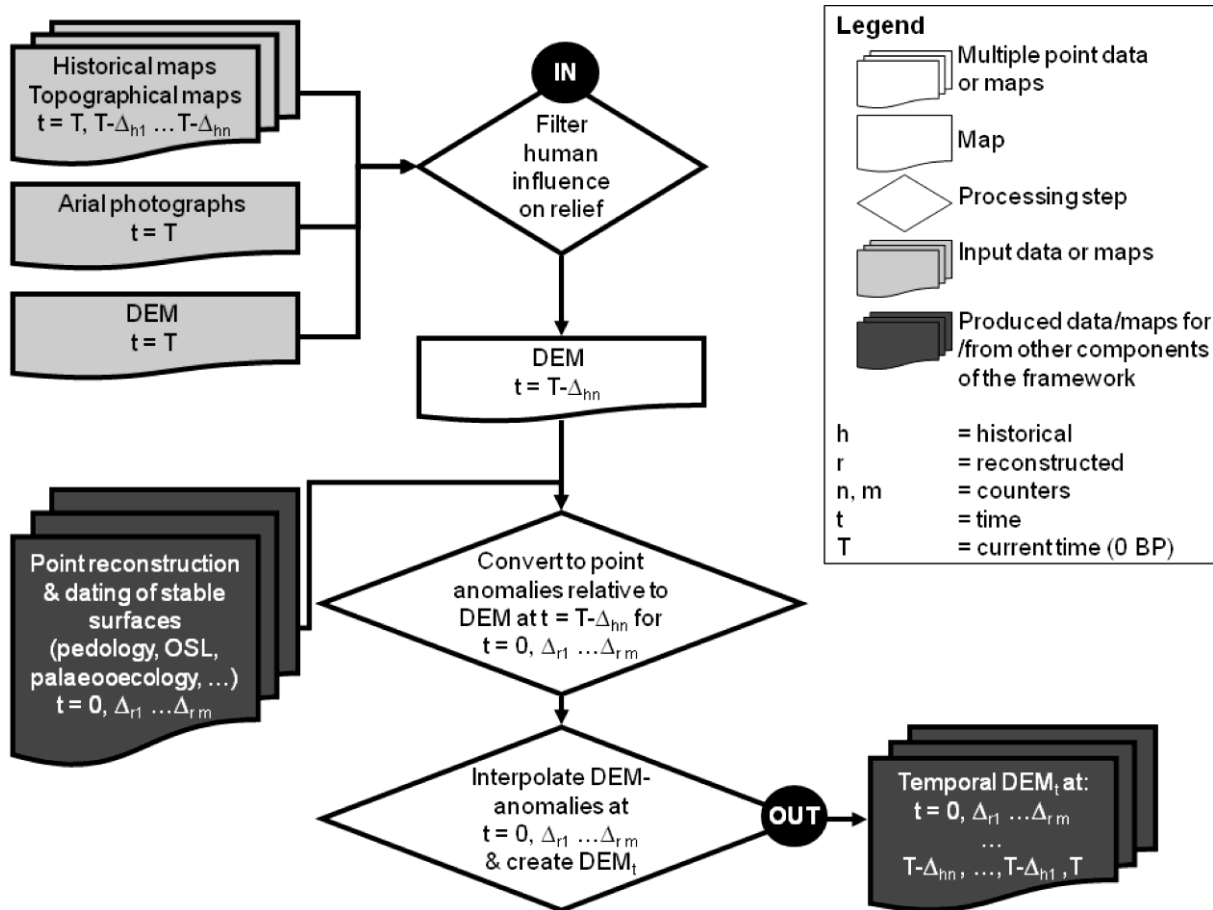**Fig. 5b**

Fig. 5c

Fig. 5d

Fig. 6

Mean Water Table

9,18 mTAW

2,33 mTAW

N

2,5 Km
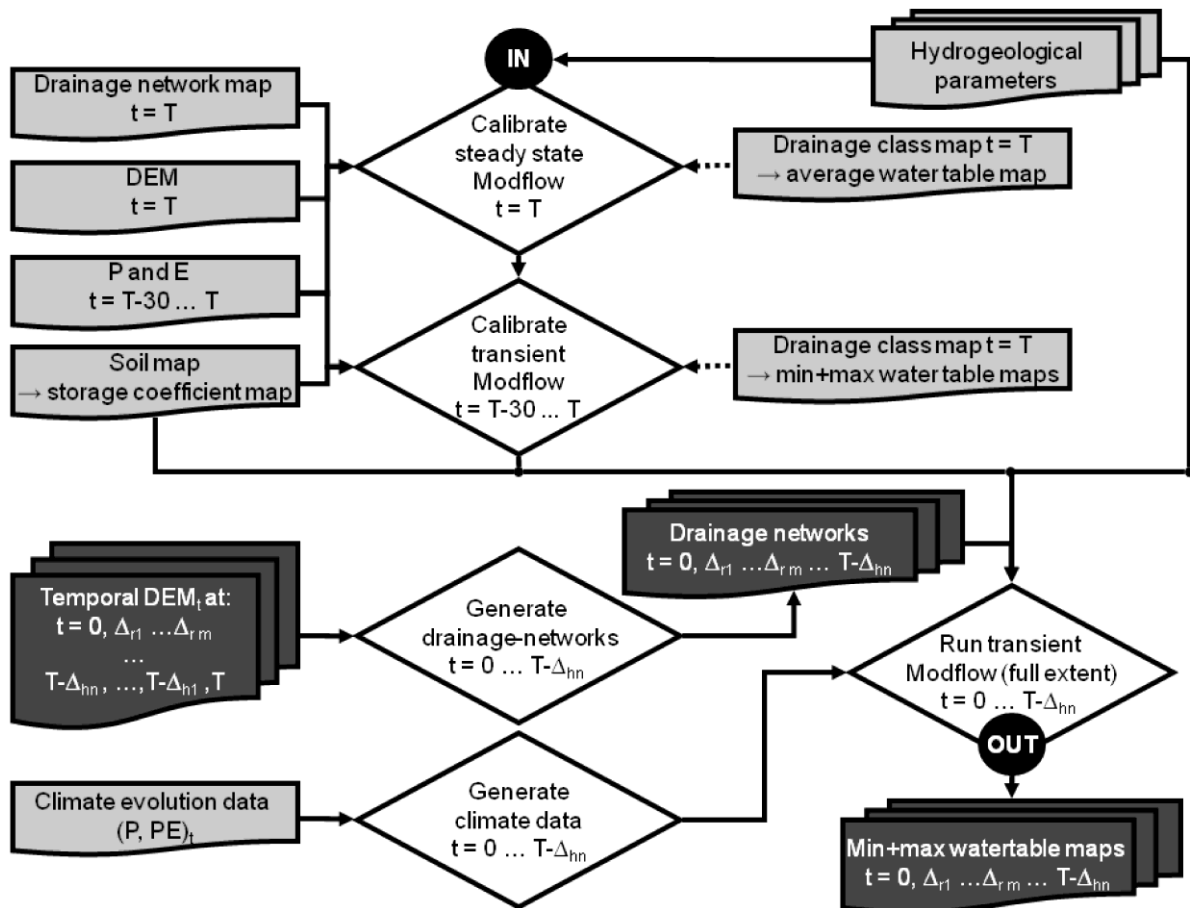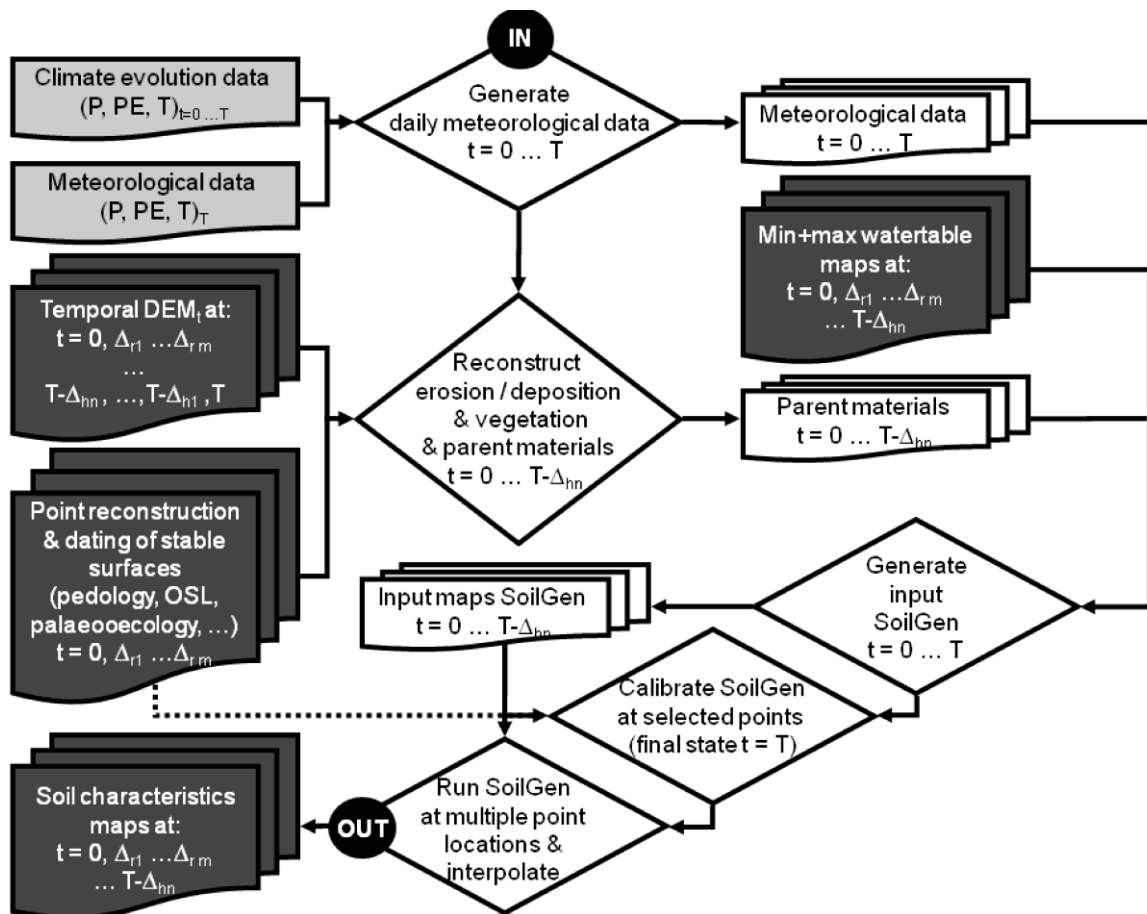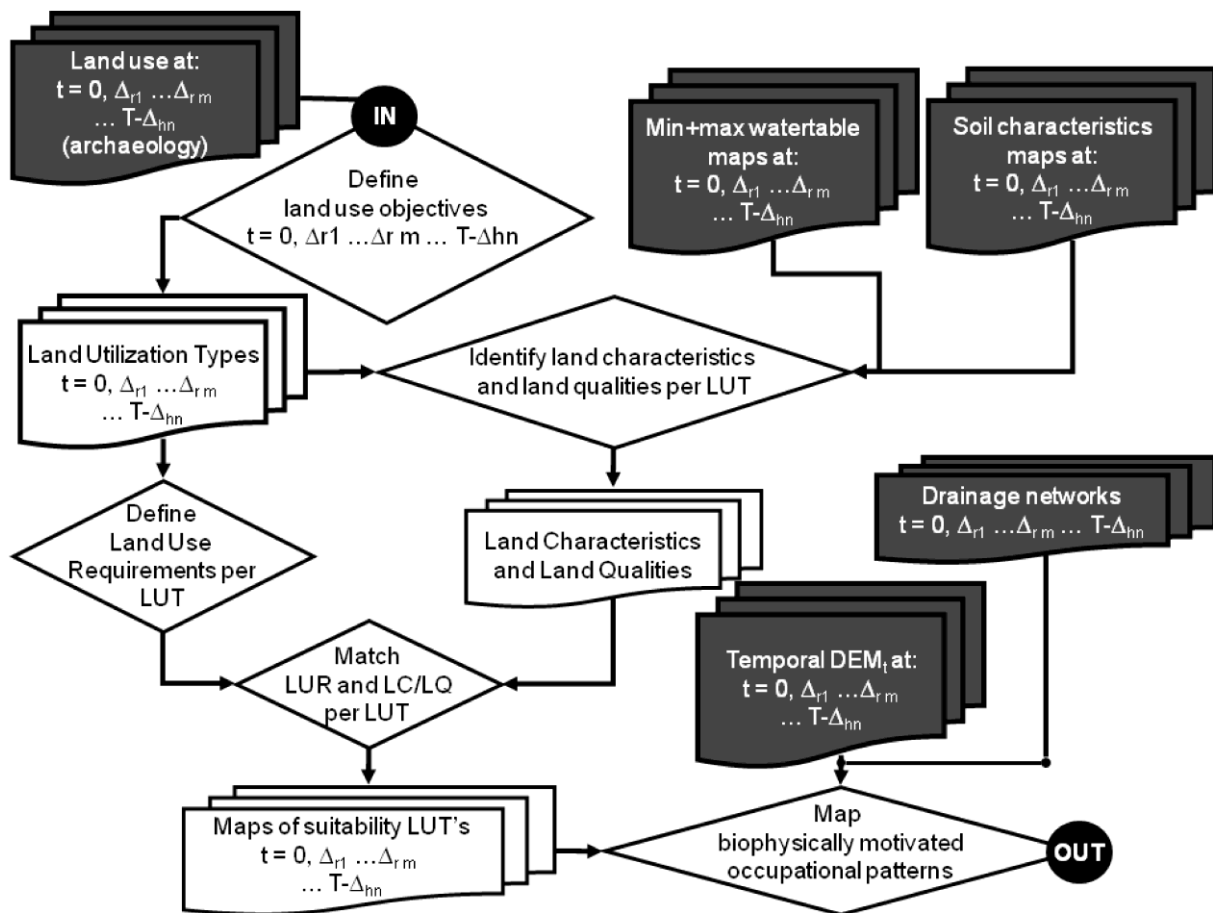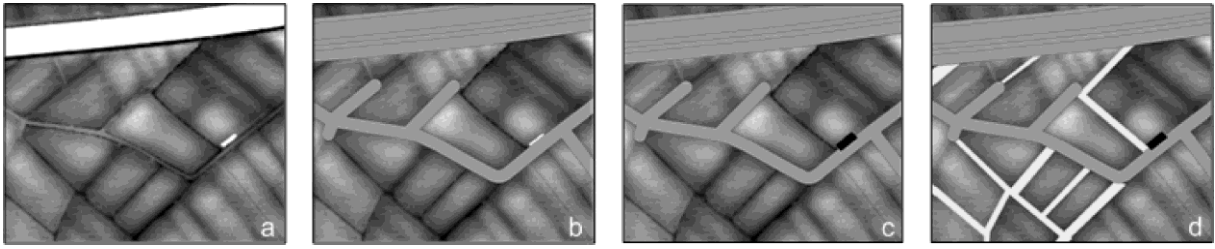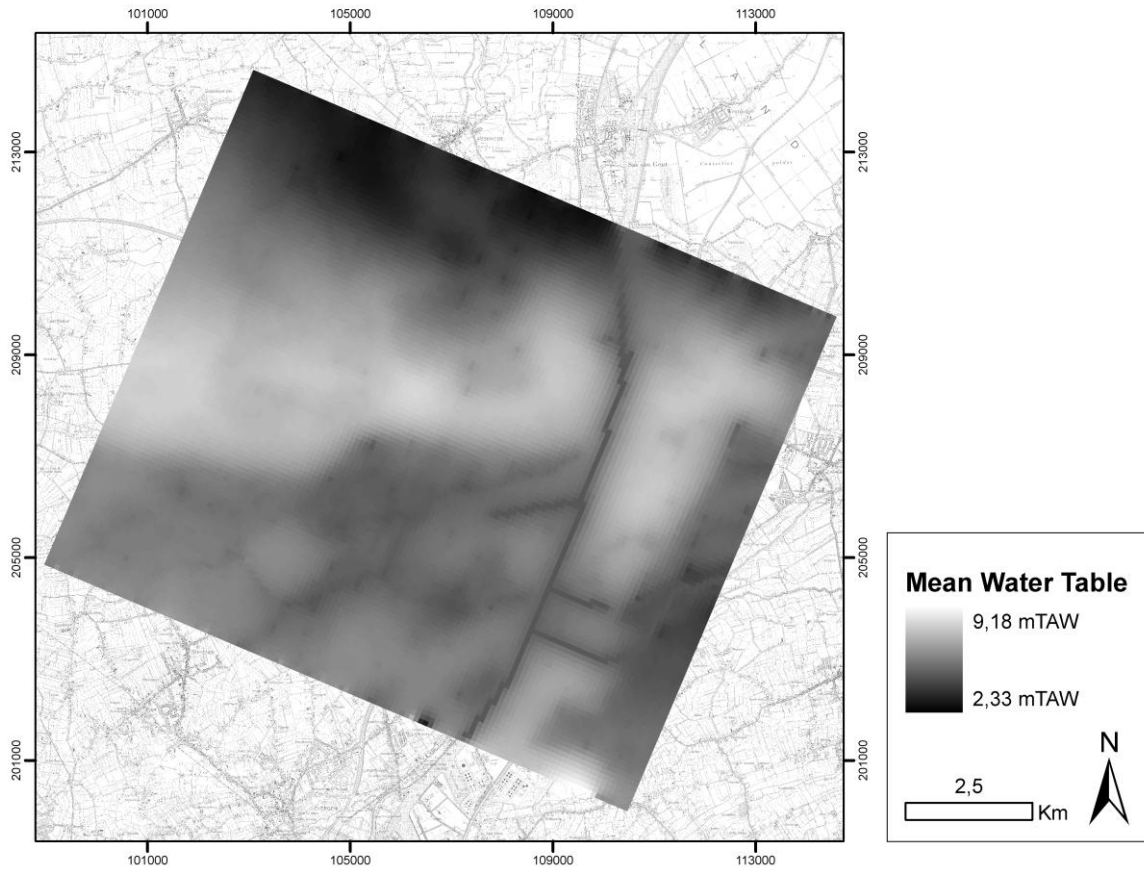
Fig. 7
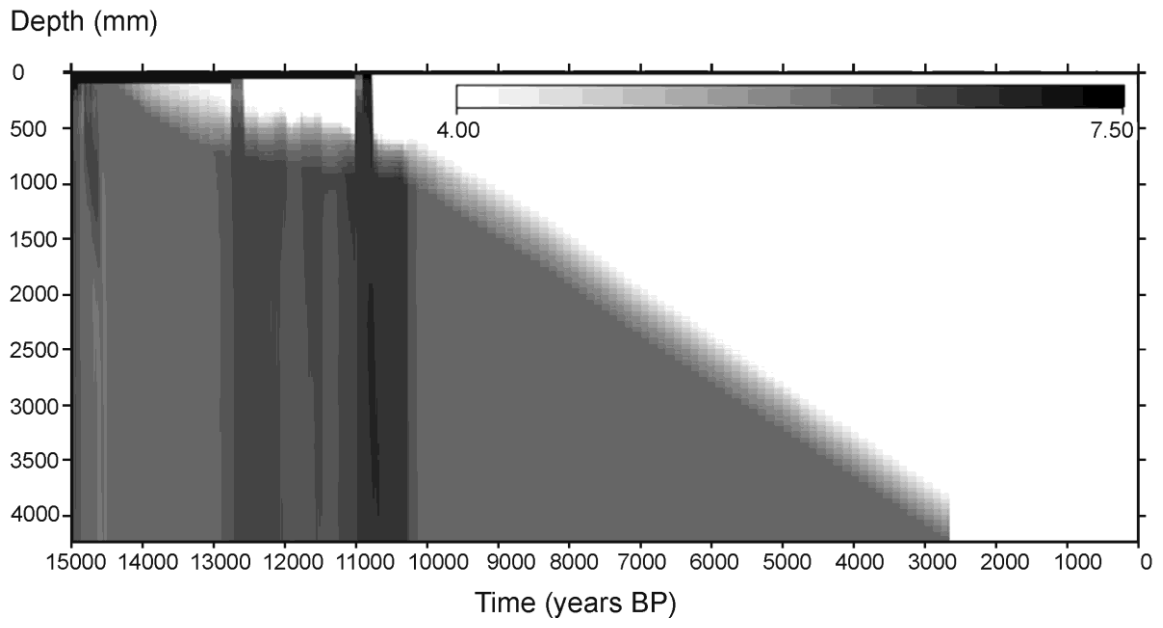
Fig. 8

Table 1.

Biophysical attractors (in bold) and associated land qualities (in italics)	Parameter																
	Annual precipitation	Annual evapo-transpiration	January temperature	July temperature	Mean lowest water table	Mean highest water table	Soil texture	Bulk density	Stoniness	Calcium-carbonate content	Organic carbon content	Base saturation	pH	Reduced conditions in rooted zone	Surface water presence	Slope	Altitude
Rain-fed agriculture-potential production			X	X													
Moisture availability	X	X			X	X	X										
Oxygen availability	X	X			X	X	X										
Workability								X	X								
Nutrient availability										X	X	X					
Rootability								X	X								
Germination							X	X	X								
Flooding hazard	X	X													X		
Toxicity													X	X			
Erosion hazard																X	
Soil degradation hazard							X			X	X		X				
Hunting, fishing																	
Surface water															X		

Visibility																X	X
Gathering																	
Ecological diversity				X	X	X			X			X		X	X	
Settling																	
Wind exposure																X	X
Wetness					X									X	X	X
Fresh water														X		

Parameter source (model)	RC	RC	RC	RC	H	H	P	P	NR	P	P	P	P	H	H	D	D
Accuracy (units)	<50 mm	<50 mm	2 °C	2 °C	<40 cm	<40 cm	<5 mass%	<0.25 kg/dm^3	NR	<2 mass%	<1 mass%	40%	<1 units	20% of cases	20% of cases	<1%	<0.5 m
Spatial grain (m^2)	10^8	10^8	10^8	10^8	10^4	10^4	1	1	NR	1	1	1	1	10^4	10^4	4	4

Table 2.

Model	Spatial Grain	Spatial Coverage	Temporal Grain	Temporal Coverage
DEM	4 m² (2m x 2m)	100%	4 years	0.027% *n
Hydrological model	10,000 m² (100m x 100m)	100%	1 month	0.2%*n
Pedogenesis model	1 m² (1m x 1m)	0.000017%	1 day	100.00%
Land evaluation model	1,600 m² (40m x 40m)	100%	1 year	100.00%