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Quantifying the uncertainty of a model-reconstructed soilscape for archaeological land evaluation

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ABSTRACT

Models can serve as temporal interpolators for landscape reconstruction, and geostatistical interpolation can assist in obtaining full-cover maps. Both activities are associated with uncertainty. We applied a hydrological model (MODFLOW), a soil development model (SoilGen) and regression kriging to reconstruct a Middle Bronze Age landscape. This reconstruction comprises maps of a set of land characteristics and is input for a land evaluation meant to explain low occupancy during this period. The land evaluation showed marginal suitability in 81% of the area for Bronze Age land utilization types, which explains the low occupancy. We evaluated the effects of model accuracy and interpolation accuracy on the uncertainty of the land evaluation, assuming no uncertainty about the land evaluation protocol. The effect of model (in)accuracy was assessed by generating 100 perturbations using a variance-covariance error matrix filled using independent measurements from 1953 CE. The effect of spatial interpolation errors was assessed by generating 100 realizations of the land characteristics by Sequential Gaussian Simulation. Results show that uncertainty contributions of the model errors and interpolation errors are similar in terms of entropy H′ between land evaluation maps (fairly low H′ of 0.47 and 0.38 for model and interpolation error respectively). Model-reconstructed land characteristics led to fairly reliable land evaluations. Priority improvements for the model were identified and ranked. Most improvements come at high computational cost.

1. Introduction

The usage of simulation models allows the estimation of system properties at non-sampled locations in space and/or time, but is associated with uncertainty. When combinations of models are applied, and additionally spatial coverage is not continuous, there are contributions to uncertainty expected from the models as well as from the interpolation methods used. Here we report on a study exploring uncertainty contributions from models and spatial interpolation. In the context of a multi-disciplinary study involving geoscientists and archaeologists, explanations were sought for differences in occupancy patterns from the Final Paleolithic to Roman times in a cover sand landscape in Flanders, Belgium. An underrepresentation of Bronze and Iron age remnants was observed when compared to Stone age and Roman age (De Reu et al., 2011) in an area in NW Belgium. It was hypothesized that a paleo-landscape reconstruction might inform on the biophysical causes for the sparse occupancy. Land evaluation is in archaeological studies seen as a tool to explain find patterns and to estimate the area's carrying capacity (Finke et al., 1994; Kamermans, 2000; Van Joolen, 2003), but needs land characteristics for a soilscape representing the period of interest, and a land utilization type. This leads to the working hypothesis, that a reconstructed soilscape can serve as a basis for a land evaluation of a Bronze Age Land Utilization Type (LUT) and that resulting suitability patterns explain occupational patterns or lack of occupation.

For this reason, a modelling study was designed (Zwertvaegher et al., 2010) and carried out (Zwertvaegher et al., 2013ab) to reconstruct a paleo-soilscape for the Bronze Age. The models serve as spatio-temporal interpolators, whereby the lack of data representing the past situation can assumedly be compensated by mechanistic knowledge on the occurring processes, supplemented by geostatistical interpolations when necessary. Here, we report on the usage of such instrument for a paleo-soilscape reconstruction and subsequent land evaluation. Focal point is an assessment of the main sources of

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uncertainty in such reconstruction, given the model instruments, their accuracy and the application of reconstructed paleo-land characteristics in a land evaluation. The research objectives are:

(i) To determine a suitability map for a Bronze Age Land Utilization Type using model-reconstructed soilscapes;
(ii) To quantify the uncertainty associated to such reconstruction, given the application in a land evaluation context, more specifically, to determine:
  a. the effect of model (in-)accuracy on the uncertainty of the land suitability and to identify the simulated soil properties with the largest uncertainty contribution;
  b. the effect of interpolation errors on the uncertainty of the land suitability.
(iii) To formulate consequences for improved approaches in future studies.

2. Materials and methods

2.1. Study area

2.1.1. Geology and soils

The study area (Fig. 1) is located between Antwerp, Ghent and Bruges in Flanders, Belgium, and is bordered by polders of the Scheldt river (East), coastal polders (North) and a hilly area consisting of loess-covered Paleogene and Neogene marine sediments (South and West). The area itself covers 584 km^2 and consists of an East-West (Weichselian) cover sand ridge in the North, Quaternary alluvial sediments of the Scheldt-Lys interfluvium (< 5 to > 20 m thickness) with variable texture in the South and a cuesta in Neogene marine clay sediments, partly covered by aeolian sand, in the Northeast. The geology of the study area has been mapped at 1:50,000 in the 1960 and 1970s (De Moor and van de Velde, 1995; Jacobs et al., 1993, 1996), and was schematized based on its hydrological characteristics (Meyus et al., 2000) for 3-D modelling purposes. A post-medieval Digital Elevation Model (DEM) of the area was constructed by Werbrouck et al. (2011) from high-density airborne LiDAR-data. The soils in the area were mapped at scale 1:20,000 in the early 1950s, and soil profile descriptions and laboratory analyses were done at 390 locations in the study area for 53 variables (*Aardewerk*-database; Van Orshoven et al., 1988). A subset of 97 locations was used in this study because of computational limitations imposed by the soil model. The C-horizons of these soil profiles were used to define the initial conditions (parent material) for the soil model to be used in a later stage for soil reconstruction. Today's soils in the area comprise Podzols, Cambisols and locally Anthrosols (Dondeyne et al., 2012).

2.1.2. Reconstruction of the past landscape, vegetation and climate

The post-medieval DEM was reconstructed to the early Holocene situation (Vermeer et al., 2013) by mapping the thickness of Holocene sediments, using 72 (OSL and ^{14}C) dated sediment samples, 731 recent profile descriptions and 3288 legacy geological descriptions. The thickness was measured relative to the post-Medieval DEM, but only at locations without human interference. Therefore, we can assume that the same thickness holds relative to the pre-Medieval DEM. The mapped thickness was subtracted from the pre-medieval DEM and -locally- corrected the thickness of some recent fluviatile deposits and removed plaggen topsoils from the DEM. Generally, differences between pre-Medieval and early-Holocene DEMs are small. As the current landscape is strongly drained, and the natural drainage system is disturbed by various canals, the pre-medieval drainage system was reconstructed using the pre-medieval DEM and legacy topographic maps (Zwertvaegher et al., 2013a). This drainage system was used as surface water geometry boundary condition for the hydrological modelling.

Climate and vegetation history was reconstructed using pollen diagrams. Pollen-based anomaly estimations of temperature (Davis et al., 2003) and precipitation (Davis, pers. communication) for the last 12,000 years were used to reconstruct the January and July temperature and the mean annual precipitation, using current climate data from Uccle. Evaporation time series were obtained using the Hargreaves' equation (Hargreaves and Samani, 1985; Finke and Hutson, 2008); Pollen diagrams (Verbruggen et al., 1996) were used to reconstruct vegetation types for the same period. These data (Zwertvaegher et al., 2013a, 2013b) defined the boundary conditions over the Holocene for the models to be used for soil and hydrological reconstructions.

2.2. Land evaluation protocol

The land evaluation follows the classical protocol from FAO (1976, 1985), which means that a Land Utilization Type (LUT) is defined, for which Land Use Requirements are formulated in terms of so-called Land Qualities (LQ) that are based on crop, management and conservation requirements. The over-all suitability for the LUT at a field then follows from the combined judgements on the performance of the local soil for each relevant Land Quality, henceforth called “partial suitability scores”. The land evaluation in this study pertains to the Middle Bronze Age (1331 BCE) for a LUT defined as “Subsistence rainfed cereal farming with no fallow, in a mixed cropping of emmer wheat and spelt wheat. Ox-drawn ards were used to make furrows for the seeds. No manuring.” (Zwertvaegher, 2012, p.150). This LUT was based on archaeological finds of seeds, weed assemblages and remnants of field equipment (de Hingh, 2000). The mixed cropping is applied to reduce yield failure risk because emmer wheat is more sensitive to drought stress than spelt wheat.

In Fig. 2 the protocol is summarized to obtain partial suitability scores from land characteristics (LC) obtained for 1331 BCE by modelling. The threshold values in this protocol are based on Visser (1958), FAO Ecocrop (2012) (http://ecocrop.fao.org/ecocrop/srv/en/home), FAO (1986), Sys et al. (1993), Batjes (1995), Pearson et al. (1995), Gardner et al. (1999) and Guimière et al. (2009), and explained in detail by Zwertvaegher (2012). We assumed that these threshold values are crisp (non-fuzzy). The partial suitability scores were calculated both for emmer and spelt, and for each crop the most limiting land quality score was taken as suitability score. The least limiting of both crop suitability scores was taken as final suitability, which is an ordinal variable taking the value NS, S3, S2 or S1 in order of increasing suitability. This protocol was applied onto grids of 40 × 40 m^2 of the relevant (numerical) LC: Cation Exchange Capacity (CEC, $cmol_c\,kg^{-1}$ soil), Base Saturation (BS, %), Organic Carbon content (OC, %), Mean Water Table depth (MWT, cm), Texture Class (USDA-classes, obtained from Clay, Silt and Sand %), pH, Bulk Density (BD, $kg\,dm^{-3}$), slope (%). These LC must be available for the Middle Bronze Age, and we hypothesized that the spatial patterns of the LC could be reconstructed by process models (next section). Most of these LC were obtained by regression block kriging of model outputs at the 97 locations. MWT simulation results were available at full-cover and were downscaled to 40 × 40 m^2 cells from a 100 × 100 m^2 grid following the method of Sivapalan (1993) and using a detailed MWT-map inside the area to parametrize a mass-conserving downscaling function (Bierkens et al., 2000). Slope class was directly calculated from the reconstructed DEM. The land evaluation procedure was implemented in a Pascal-program available from the first author.

2.3. Reconstructing the Bronze Age soilscape with models

Two models were used to reconstruct the landscape genesis over the Holocene in the area. These model studies were published by Zwertvaegher et al. (2013a, 2013b) and are summarized shortly hereunder.

The hydrological model MOCDENS3D, based on MODFLOW96 (Harbaugh and McDonald, 1996) but extended to simulate the flow of water of different densities (in the presence of salinity gradients), was