Geoderma 160 (2010) 175–188

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Soil available water capacity interpolation and spatial uncertainty modelling at multiple geographical extents

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ARTICLE INFO

Article history:
Received 3 February 2010
Received in revised form 10 September 2010
Accepted 19 September 2010

Keywords:
GAM
Kriging
Pedotransfer functions
Scotland
Scale

ABSTRACT

Assessment of the spatial distribution of environmental variables and of the associated uncertainty is a key issue in environmental modelling. The water content of soil plays an important role in many ecological and hydrological processes for land suitability evaluation. In this study we present a flexible procedure to interpolate soil-related variables that uses covariates to estimate the spatial trend of the variables and quantifies the uncertainty dealing with non-linear relationships. The procedure further extends approaches based on generalized additive models. The use of Gaussian simulations of the error allows the assessment of spatial uncertainty. The method was applied to available soil water capacity for three different nested extents: national, regional, and catchment. The models fitted have different significant covariates and different estimated values according to the region considered. The results suggest that the estimates from the model fitted at the appropriate extent are the most accurate. Taking into account the uncertainty of the trend, the results provided a realistic estimation of the variability and they are spatially consistent with the geomorphological patterns. Estimating the variability with the proposed procedure is useful for further environmental and land use modelling and it can be integrated with uncertainty from other variables, such as those derived from climate models.

1. Introduction

The water content of soil has a major role in many hydrological processes (Western et al., 2004), such as infiltration and runoff (Bàrdossy and Lehmann, 1998; Herbst et al., 2006), soil erosion and flooding (Fitzjohn et al., 1998; Wang et al., 2001; Nunes et al., 2009). It also plays an important part in pedogenic and geomorphological processes (Beven and Kirkby, 1993).

Available water capacity (AWC) is a general measure of the amount of water that is available in soil for plant growth and it can be a limiting growth factor for vegetation and crops. It therefore influences the productivity of agricultural land and may cause restrictions on land use (Julia et al., 2004). Soil drought can be a serious concern for agricultural and food production and for flood risk (Schindler et al., 2007). Growing attention is also given to the evaluation of soil drought risk due to climate change and projection of further increase in temperatures (Schwärzel et al., 2009).

Spatial variability of soil AWC is therefore important for planning and risk mitigation purposes. AWC can be measured or derived from other soil properties using pedotransfer functions (McBratney et al., 2002) only at defined, sampled sites. In order to obtain values at unsampled locations spatial models such as geostatistical techniques need to be used. To avoid mis-interpretation, it is important to quantify the uncertainty of the predictions obtained with these techniques. Information on uncertainty can then be used in decision-making processes such as the identification of areas at risk of drought or erosion or flooding, which may need land management and conservation practices (Delbari et al., 2009).

Uncertainty is often quantified using stochastic simulations (Goovaerts, 1997), a technique that can predict the values of the target variable and assess both local and spatial variability of the estimates. Recently this has been widely used in soil mapping (e.g. Goovaerts, 2001; Wang et al., 2001; Castrignanò and Buttafuoco, 2004; Bourennane et al., 2007; Delbari et al., 2009). Conditional stochastic simulations are designed to overcome the smoothing effect of the ordinary kriging method (Deutsch and Journel, 1998) that estimates values with less variation than the observed values. These simulations generate a set of equally probable maps of the spatial distribution of the attributes considered, while ordinary kriging produces a map of local best estimates (Castrignanò and Buttafuoco, 2004). The stochastic simulations can reproduce the sample statistics better than kriging, honour sample data at their original locations, and conditional simulated maps can be used to develop a model of local and spatial uncertainty (Goovaerts, 1997).

Methods based on kriging assume stationarity of the mean (Goovaerts, 1997). However this is often not the case for geomorphic variables that present a trend in the values (Lark and Webster, 2006). The combination of interpolation techniques with auxiliary information has proven to be superior to plain geostatistic techniques, providing more detailed results with higher accuracy (Hengl et al.,

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doi:10.1016/j.geoderma.2010.09.015

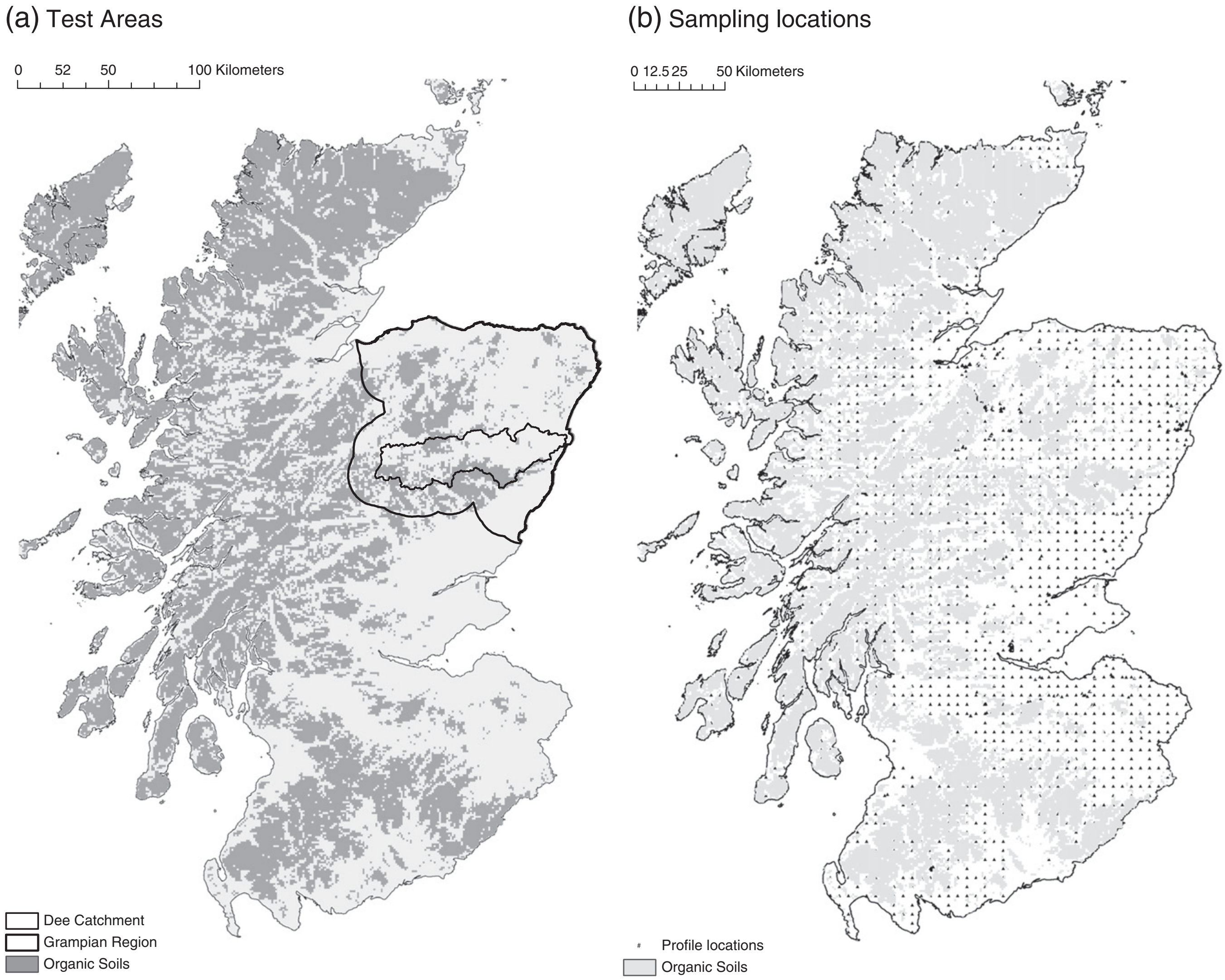

Fig. 1. The three different regions at which the models were fitted: Scotland, Grampian region and Dee catchment (a) with the locations of sampled soil profiles (b).

2004). The two most recognised methods are i) co-kriging (Goovaerts, 1997; Bourennane et al., 2007), and ii) kriging combined with regression (McBratney et al., 2000; Hengl et al., 2004). Bishop and McBratney (2001) compared the prediction results of three methods, namely multiple linear regression, generalized additive model and regression trees, when coupled with traditional geostatistic techniques. Brown et al. (2002) proposed the combination of a generalized additive model (GAM; Hastie and Tibshirani, 1990; Wood, 2004) with geostatistical methods to estimate land use transition probabilities.

Spatial heterogeneity is ubiquitous in nature across all scales, and its formation and interactions with ecological processes are the central issue in spatial modelling. Often model parameters are dependent on the geographical extent at which the models are fitted. There is therefore the need to develop and test models at different extents and levels of complexity, from simpler estimates to more detailed simulations for predictions and land use planning, to understand which processes or variables are prevailing at different spatial extents (Jana et al., 2007; Cheng, 2008; Logsdon et al., 2008).

Many studies suggested the use of terrain-derived indices, such as slope, curvature, topographic wetness index (TWI) and insolation to help predict the spatial pattern of soil moisture and soil water content (e.g. Wilson et al., 2003; Güntner et al., 2004; Western et al., 2004; Baggaley et al., 2009; Dyer, 2009). These different indices have been tested extensively at field or small basin level (Güntner et al., 2004).

Table 1
Geomorphological variables tested and their significance at the different considered areas.

	Dee	Grampian	Scotland
Elevation	0.001	0.001	0.001
Slope			0.001
Aspect			
Curvature			
Profile			0.01
Flow direction			
Flow accumulation		0.1	0.05
Distance from rivers			
Roughness			
Landforms			
Divergent shoulder	0.001	0.001	0.001
Planar shoulder			
Convergent shoulder			
Divergent backslope			
Planar backslope			
Convergent backslope			
Divergent footslope			
Planar footslope		0.05	0.1
Convergent footslope			
Low catchment level			0.1
High catchment level			0.05