ECOSYSTEMS

Spatially Continuous Land-Cover Reconstructions Through the Holocene in Southern Sweden

Robert O'Dwyer,[1] Laurent Marquer,[2,3] Anna-Kari Trondman,[4] and Anna Maria Jönsson[1]*

[1]Department of Physical Geography and Ecosystem Science, Lund University, Lund, Sweden; [2]Research Group for Terrestrial Palaeoclimates, Max Planck Institute for Chemistry, Mainz, Germany; [3]Department of Botany, University of Innsbruck, Innsbruck, Austria; [4]Faculty of Landscape Architecture, Horticulture and Crop Production Science, Swedish University of Agricultural Sciences, Alnarp, Sweden

ABSTRACT

Climate change and human activities influence the development of ecosystems, with human demand of ecosystem services altering both land use and land cover. Fossil pollen records provide time series of vegetation characteristics, and the aim of this study was to create spatially continuous reconstructions of land cover through the Holocene in southern Sweden. The Landscape Reconstruction Algorithm (LRA) was applied to obtain quantitative reconstructions of pollen-based vegetation cover at local scales, accounting for pollen production, dispersal, and deposition mechanisms. Pollen-based local vegetation estimates were produced from 41 fossil pollen records available for the region. A comparison of 17 interpolation methods was made and evaluated by comparing with current land cover. Simple kriging with cokriging using elevation was selected to interpolate the local characteristics of past land cover, to generate more detailed reconstructions of trends and degree of variability in time and space than previous studies based on pollen data representing the regional scale. Since the Mesolithic, two main processes have acted to reshape the land cover of southern Sweden, originally mostly covered by broad-leaved forests. The natural distribution limit of coniferous forest has moved southward during periods with colder climate and retracted northward during warmer periods, and human expansion in the area and agrotechnological developments has led to a gradually more open landscape, reaching maximum openness at the beginning of the 20th century. The recent intensification of agriculture has led to abandonment of less fertile agricultural fields and afforestation with conifer forest.

Key words: Landscape Reconstruction Algorithm; Fossil pollen; Ecosystem services; Land cover; Southern Sweden; Interpolation methods.

HIGHLIGHTS

- South Swedish land cover has changed substantially during the past 7500 years.

- A growing human population and new land use practices induced land cover changes.
- Our land-cover reconstructions provide insight in landscape trends and variability.

INTRODUCTION

Climate change and human land use have played important roles in the development and sustainability of ecosystems over temporal and spatial scales (for example, Berglund and others 2008). In Europe, climate was the main driver of vegetation changes until about 4500 BP when human activities and population growth started to have a large influence at regional and sub-continental scales (Marquer and others 2017; Kuosmanen and others 2018). Societal development and agricultural inventions led to formation of man-made ecosystems, such as grazed forests, pastures, meadows, and crop fields. The dependence on different ecosystem services has changed over time, in relation to changes in human lifestyle, technological advancements, and development of agricultural practice, with more rapid and extensive changes seen during the past 50 years than in any other time in human history (MEA 2005). Today, the climate is also changing due to human activities; these induced changes in temperature and precipitation may affect ecosystem functioning and distribution of species (IPCC 2014). Knowledge about the past is needed for improved model projections about ongoing climate and land use changes.

A long-term perspective of plant ecosystem changes can be obtained by analysing fossil pollen preserved in sedimentary archives. The European Pollen Database (EPD) (Fyfe and others 2009; Giesecke and others 2014) was developed in the early 1990s to provide a structure to archive, exchange, and analyse quaternary pollen data, covering the continent to represent the major aspects of European vegetation history (for example, Fyfe and others 2015; Giesecke and others 2017; Roberts and others 2018; Zanon and others 2018). In Sweden, fossil pollen studies have provided valuable insights in the development of vegetation over time, in relation for example, to changes in Swedish vegetation composition and diversity over the Holocene, as caused by migration of species, climate change, ecological succession of species, and human activities (Berglund and others 1991, 2008; Björkman 1999; Lindbladh 1999, Lindbladh and others 2008; Cui and others 2014; Hultberg and others 2015; Mazier and others 2015; Fredh and others 2012, 2017, 2019; Hannon and others

2018). Lindbladh and others (2000) were the first to use pollen-based mapping of historical land cover in southern Sweden. Since then, new modelling techniques have been developed, and the number of pollen sites available has increased.

The REVEALS model (Regional Estimates of VEgetation Abundance from Large Sites; Sugita 2007a) has been used to create pollen-based maps of past land cover (Nielsen and others 2012; Trondman and others 2015; Pirzamanbein and others 2014, 2018), accounting for inter-taxonomic differences in pollen production, dispersal and deposition mechanisms at regional scales. Such maps provide generalized pictures of regional landscape development, and information from local pollen estimates would enable mapping local variations within the regional vegetation pattern. The Landscape Reconstruction Algorithm (LRA; Sugita 2007b) has been developed to achieve quantitative pollen-based reconstruction of vegetation cover, accounting for inter-taxonomic differences in pollen production, dispersal and deposition mechanisms at local scales. The LRA works by first using the REVEALS model to estimate the regional vegetation coverage based on pollen records from large lakes ($>$ 50 ha). Once the influence of regional vegetation is defined, quantitative reconstruction of local vegetation around smaller sites, lakes, and bogs ($<$ 50 ha) can be obtained by using a second model called LOVE. The LRA provides estimates of local land cover (LOVE estimates) in terms of distance weighted abundance of plant taxa within the RSAP (relevant source area of pollen), the smallest spatial unit for which vegetation abundance can be estimated by modelling fossil pollen data (Sugita 2007b). RSAP corresponds to a specific spatial resolution, from a few metres or kilometres around the site where pollen deposited. LRA modelling has been applied in various environmental contexts (for example, Sugita and others 2010; Cui and others 2014; Poska and others 2014; Hjelle and others 2015; Mazier and others 2015; Abraham and others 2017; Marquer and others 2020a). To create spatially continuous land cover maps based on point data, interpolation methods have to be applied. The most commonly used interpolation methods are inverse distance weighting (IDW), kriging and cokriging, with kriging generally having lower prediction bias compared to other methods (Mirzaei and Sakizadeh 2016). The selection of interpolation method is important, as different methods generate different results, and an ensemble of methods can provide additional insights into trends and uncertainties (Araújo and New 2006).

The aim of this study was to create spatially continuous reconstructions of land cover throughout the Holocene in the southern part of Sweden, to explore the long-term perspective of regional and local vegetation changes. LRA-based vegetation estimates were produced from 41 fossil pollen records available for the region. An ensemble of 17 interpolation methods, which included both deterministic and geostatistical methods (with and without elevation as covariable), was compared to address uncertainties when interpolating over large areas and evaluate the suitability of different methods in comparison with current land cover. One of the best-performing methods was selected for interpolation of 15 past time windows through the Holocene. By applying the interpolated LRA approach to all fossil pollen sites in southern Sweden, this study provides an overview of local variations within a regional context, thus adding an intermediate spatial level to the analysis of pollen data in comparison with earlier studies that focused on specific local conditions (Cui and others 2014; Mazier and others 2015; Fredh and others 2017, 2019) or a large regional scale (Trondman and others 2015; Marquer and others 2014, 2017). The spatial reconstructions depict the increase in human impact on land cover throughout the Holocene. In discussion, the observed trend over time and space was interpreted in terms of human desire for provisioning ecosystem services, such as food and wood, which creates a pressure on the land and lead to altered land use and land cover (Potschin and Haines-Young 2011).

MATERIAL AND METHOD

Fossil Pollen Data and Quantitative Vegetation Estimates

The LRA approach was used to generate local land-cover reconstructions based on fossil pollen data for southern Sweden. A detailed description of the algorithms of the REVEALS and LOVE models can be found in the appendices of Sugita (2007a, b). All pollen records were retrieved from the LANDCLIM pollen data archive (Trondman and others 2015, 2016; Marquer and others 2014, 2017) and the EPD network (http://www.europeanpollendatabase.net/index.php). For the LRA application, we considered twenty-five pollen types and the relative pollen productivity estimates (RPPs) obtained from various regions in Europe (the LANDCLIM standard 2 dataset of Mazier and others (2012)). These RPPs have been previously applied in regional land-cover reconstructions (for example,

Trondman and others 2015; Marquer and others 2014, 2017; Kuosmanen and others 2018) and recent local reconstructions in the South of Finland (for example, Alenius and others 2020). Tables about RPPs and their standard errors, as well as fall speeds of pollen are provided in Marquer and others (2014, 2017). The LRA results are expressed as percentage cover of plant species with their standard errors; standard errors were obtained by a delta method (Stuart and Ord 1994).

Pollen counts were grouped into time windows (TW). Initially 44 TWs were selected for the model runs which correspond to the best compromise between a high pollen count, a good temporal resolution, and a continuous time scale. Note that the higher the pollen count the smaller the error estimates of LRA will be. The TW's spanned one 60-year period for present time (2010-1950), 50-year periods from 0 to 100 years before present (BP; 0 BP = AD 1950), then 100-year periods from 100 BP back to 3000 BP, and 500-year periods from 3000 to 9000 BP. This does not apply to Krageholmssjön that has been used for REVEALS runs in Skåne for which the TW's spanned one 110-year period for modern time (2010-1900), 150-year periods (50–200 BP), then 200-year intervals from 200 BP back to 3000 BP, and 500-year periods from 3000 to 9000 BP.

We used the REVEALS v.5.0.exe and LOVE v.5.0.exe computer programs (Sugita, unpublished). Neutral atmospheric conditions and a constant (through space and time) wind speed of 3 m s^{-1} are assumed for the model runs, as it has been done in previous studies (for example, Trondman and others 2015; Marquer and others 2014, 2017, 2020a). The Gaussian plume model (GPM) implemented in REVEALS by Sugita (2007a, b) has been used as modelling scheme to describe dispersal and deposition of pollen grains in the air; see Marquer and others (2020b) for recent discussion about the use of the GPM in LRA reconstructions. Zmax, the maximum spatial extent of the regional vegetation from the centre of the study sites, was set to 100 km. The RSAPs were calculated by using an inverse modelling approach including in the LOVE model. Pollen records were grouped into 3 size intervals (0 to < 2 ha, 2–10 ha, > 10 ha) for the LOVE runs to reduce biases related to basin size on the calculation of the RSAP, that is, a large basin size would lead to a large RSAP and then by using all sites together we would artificially increase or decrease the RSAPs for several sites. The RSAPs (mean of all Holocene TWs) for the pollen sites within the size intervals 0 to < 2 ha, 2–10 ha, > 10 ha vary between 250 and

790 m, 370 and 1220 m, and 555 and 2715 m, respectively.

The resulting REVEALS estimates and their standard errors consisted of regional plant species abundances for the southernmost and northernmost areas. The REVEALS estimates used as inputs for regional vegetation abundance in LOVE were based on pollen records from the four largest lakes in southern Sweden: Fiolen, Trummen and Kansjön in Småland and Krageholmssjön in Skåne (Table A1). For the LOVE model, pollen records from 41 small study sites located within the borders of the five counties of southern Sweden (Blekinge, Halland, Jönköping, Kronoberg and Skåne) were used (Figure 1). Pollen records from bog and lake were run separately by using different models of pollen dispersal and deposition for bogs (Prentice 1985) and lakes (Sugita 1993). All the sites that have been used in the present study have robust chronological controls and satisfactory time resolutions of Holocene vegetation changes; information about chronologies of pollen sites is given in Trondman and others (2015, 2016) and Marquer and others (2017). All the chronologies were based on calibrated years before present (BP through the paper). LOVE estimates were expressed as distance weighted plant abundance within the RSAP for each pollen site.

Fifteen TWs of high quality (high number of pollen sites and low uncertainties in LOVE esti-

mates) were selected to cover important steps of land use and societal developments in southern Sweden throughout the Mesolithic period, the Neolithic period, the Bronze Age, the Iron Age, the mediaeval period and the modern period (Table 1). Based on the plant taxa, coverage estimates for five land cover types (LCTs) were calculated with their relative standard errors: Conifer forest, broad-leaved forest, shrubs, open land, and arable land (Table 2).

Spatial Interpolation

Continuous spatial interpolation and mapping were carried out using ArcMap 10, Esri Inc. to compare the outcome of 17 different methods. Four deterministic methods, which create surfaces from the measured points based on the degree of smoothing or extent of similarity, and seven geostatistical methods, which quantify the spatial autocorrelation and account for the spatial configuration of the points around the predicted location, were evaluated in this study. Each method has its own set of parameters that can be customized for different datasets (Table 3). Different kriging methods were included as they differ in terms of assumptions and usability, that is, ordinary kriging assumes that the unknown mean is a constant, simple kriging that the exact mean is known, and universal kriging that the model errors are autocorrelated. Probability kriging estimates the auto-
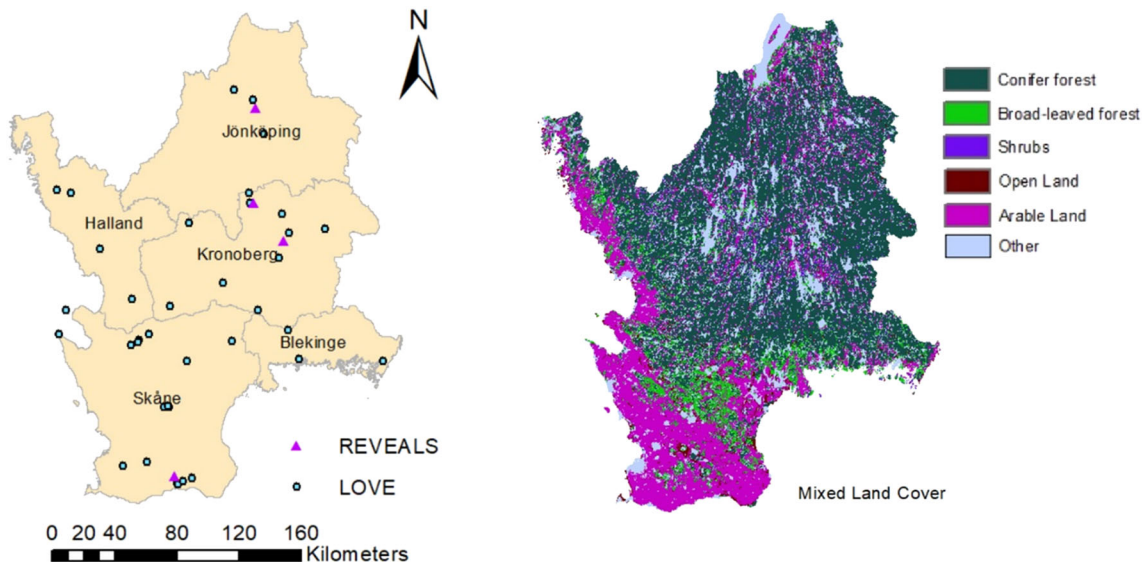
Figure 1. (A) Map of Southern Sweden, showing the 41 sites used for pollen-based LRA modelling (light blue circles) and the four pollen sites for REVEALS runs (purple triangles). The study area included the counties Skåne, Blekinge, Halland and two part of Småland, Jönköping and Kronoberg. Table 2 contains information on the sites from which lake and bog sediment cores had been sampled to provide fossil pollen records. (B) CORINE mixed land cover for the 5 LCTs assessed in this study.

Table 1. The Time Windows (TWs) Selected for this Study Among the 44 TWs Covering the Last 9000 years, the Number of Pollen Records and Pollen Counts Used in the Analyses, the TW's ppanned Periods in cal y BP as Well as CE/BCE, and the Corresponding Cultural Periods of Swedish History.

TWs	Number of records used	Total pollen count per time window	Mean pollen count per site (min–max counts)	Cal y BP	CE/BCE	Period
1	27	55,576	2060 (409–4656)	− 60–0	2010–1950	Modern
2	26	39,201	1510 (354–5101)	0–50	1950–1900	
3	29	45,000	1550 (334–7416)	50–100	1900–1850	
4	36	95,541	2655 (356–16,447)	100–200	1850–1750	
8	36	69,998	1945 (327–6032)	500–600	1450–1350	Mediaeval
10	33	70,877	2150 (383–10,082)	700–800	1250–1150	
13	33	46,413	1410 (370–7201)	1000–1100	950–850	Viking
17	32	48,946	1530 (401–11,354)	1400–1500	550–450	Migration
22	28	34,913	1250 (382–5226)	1900–2000	50–50	Roman Iron Age
25	27	33,211	1230 (389–3713)	2200–2300	250–350	Pre-Roman Iron Age
28	23	31,603	1375 (414–3626)	2500–2600	550–650	Bronze Age
33	31	127,991	4130 (432–20,341)	3000–3500	1050–1550	
35	29	107,555	3710 (433–22,847)	4000–4500	2050–2550	Neolithic
37	29	114,428	3945 (487–24,714)	5000–5500	3050–3550	
41	20	82,252	4110 (424–22,469)	7000–7500	5050–5550	Mesolithic

Table 2. The 25 Plant Taxa/Pollen Types Used for the Pollen-Based Land-Cover Modelling, Sorted into 5 Land-Cover Types (LCTs).

Conifer forest	Broad-leaved forest	Shrubs	Open land	Arable land
Abies	*Alnus*	*Juniperus*	*Artemisia*	
Picea	*Betula*	*Salix*	*Calluna vulgaris*	
Pinus	*Carpinus*		*Cerealia-t*	*Cerealia-t*
	Corylus		*Cyperaceae*	
	Fagus		*Filipendula*	
	Fraxinus		*Graminea*	
	Quercus		*Plantago lanceolata*	
	Tilia		*Plantago media*	
	Ulmus		*Plantago montana*	
			Rumex acetosa-t	
			Secale cereale	*Secale cereale*

Note that plant taxa included in Arable land overlap some of those in Open land.

correlation for each variable and their cross-correlation, however, this introduces additional uncertainty. For indicator kriging, every point in the space has an indicator value of either 0 or 1, and disjunctive kriging assumes bivariate normality.

All geostatistical methods (Table 3) were run both with and without cokriging, except EBK that was too computationally demanding. Cokriging is a variant of the kriging method that takes into account a covariable for interpolation. Elevation has been used as a covariable by Pirzamanbein and others (2014, 2018) to create spatially continuous maps of past land cover based on pollen data. In this study, it was selected as a covariable, as the altitudinal variation within the study area (between 0 and 350 m) is linked to both bioclimatic and edaphic conditions, including annual mean temperature, precipitation patterns, soil type and texture (SNV 2011). The kriging interpolations were carried out with and without arcsine transformation of the input data, which can be used for data that are in the form of proportions or percentages (which the LOVE data are).

Table 3. The 17 Interpolation Methods, 4 Deterministic and 7 Geostatistical, Evaluated in this Study.

	Method abbreviation		Method name
	Without cokriging	With cokriging	
Deterministic methods	GPI		Global polynomial interpolation
	LPI		Local polynomial interpolation
	IDW		Inverse distance weighted
	RBF		Radial basis functions
Geostatistical methods	EBK		Empirical bayesian kriging
	DK	DKC	Disjunctive kriging
	IK	IKC	Indicator kriging
	OK	OKC	Ordinary kriging
	PK	PKC	Probability kriging
	SK	SKC	Simple kriging
	UK	UKC	Universal kriging

These methods have been used to interpolate pollen-based modelling estimates and create land cover maps.

Data Analysis and Evaluation

The LOVE-based land cover estimates range from 0 to 1; 0 means the plant species is absent, and 1 the distance weighted plant abundance within the RSAP is 100%. ArcMap cross-validation for TW 1 (2010-1950) was used to determine how well the interpolation methods predicted values at unknown locations. It worked by a process of removing each point estimate one by one and then making a prediction for those points. That is, the sample points were left out one by one in a leave-one-out test. The land cover of the sample point left out was estimated by interpolation and compared with the LOVE data, representing the actual land cover at the sites. The root mean square error (RMSE) obtained after performing each interpolation indicated how well the model predicted values at unknown locations. A cut-off limit of 0.5 is usually set, RMSE values above this indicate poor models and lower RMSE values a more reliable interpolation; c.f. Pirzamanbein and others 2018. In this study, four out of the 17 models (IK, IKC, PK and PKC), fell above an RMSE of 0.45.

For further evaluation of interpolation methods, the TW 1 maps were compared with the 2012 CORINE land cover data, a vector database with a 100 m spatial resolution and a minimum mapping unit of 25 ha, downloaded from the European Environment Agency database (http://www.eea.europa.eu/publications/COR0-landcover). Administrative boundary layers of Sweden were downloaded from the DIVA-GIS website (http://www.diva-gis.org/Data) and used to define the study area in the CORINE land cover dataset. CORINE data have 44 original land cover classes that for our

evaluation purposes were converted into the 5 LCTs calculated based on the LOVE estimates (Figure 1). The relation between CORINE land cover and elevation, used in cokriging, was analysed. Visual comparison was carried out to assess the general spatial patterns of all interpolations, followed by a quantitative comparison of one selected method. The temporal differences between CORINE data from 2012 and TW1 that represented an average of land cover over 60 years was taken into account in the discussion of the results. During this time window, major land cover changes occurred in southern Sweden, associated with afforestation driven by urbanization, agricultural intensification with larger farm units, loss of animal husbandry and the conversion of extensive deciduous forests to even-aged, monoculture conifer forests (SNA 2011), whereas the CORINE 2012 land cover data only provide a snapshot in time, not representative of the entire period in a large part of the landscape, the pollen-based estimates provide an integrated measure.

The simple cokriging with elevation and arcsine transformation of data was found to be among the better interpolation methods (see results section) and therefore applied to create maps for all selected TW's and LCT's. For each TW, five maps were created: one map for each of the 5 LCTs. All interpolated LCT surfaces were converted into raster layers with a pixel size of 500x500m, with the assigned pixel value being based on the cover ranges. Negative values generated by the interpolation were treated as zero. A cover range from 0 to 100% with steps of 5% (20 classes) was used for conifer forest, broad-leaved forest and open land, whereas a cover range from 0 to 20% with steps of

1% (20 classes) was used for shrubs and arable land categories. Different cover ranges were used because shrubs and arable land had lower abundances than conifer forest, broad-leaved forest and open land categories; by using the same cover range for shrubs and arable land as the three other LCTs no variations in shrubs and arable land would have been observed in the maps. Note that a common issue with pollen records is that the further we go back in time, the fewer the number of sites is available. When LCT records were missing for a specific TW at several locations, for example, the arable land for the oldest TWs, no maps were created.

RESULTS

Cross-Validation Based on TW1

The cross-validation (Table 4) results revealed that four of the interpolation methods (Table 3), IK, IKC, PK, and PKC, lacked predictive power (RMSE values ≥ 0.45) and these methods were therefore not analysed further. All 13 remaining interpolation methods had RMSE values < 0.33. The RMSE values did not vary much for conifer forest (RMSE values from 0.23 to 0.27), shrubs (0.06 to 0.08) and arable land (0.03 to 0.04). Slightly larger variation was found for broad-leaved forest (0.25 to 0.34) and open land (0.17 to 0.26). The lowest RMSE values for each of the LCTs are SKC and DKC for

conifer forest (0.23), OK and UK for broad-leaved forest (0.25), SKC, DKC, SK, and DK for shrubs (0.06), UK, SK, OK, and DK for open land (0.17), and SKC for arable land (0.03). SKC was considered as the best method, with top performance (lowest RMSE) for three of five LCTs.

Comparison with CORINE Land Cover Data

The visual comparison of TW1 maps produced by different interpolation methods with current land cover (only considering methods with RMSE < 0.45) was carried out to compare the spatial trends of the regional land cover. The deterministic methods indicated the general trends, with GPI and LPI giving a rough regional indication of high and low values for the different land coverages. The geostatistical methods, EBK, OKC and UKC, produced similar patterns (Figure 2). IDW and RBF, among the best methods for broad-leaved forest (Table 4), produced circular areas, strongly influenced by local coverage and gradients between the different sampling sites (Figure 2).

The geostatistical methods, DK, OK, SK and UK, produced mixed combinations of curved lines and circular patterns (Figure 3). More realistic surfaces were produced by DKC and SKC (cokriging with elevation), and for conifer forest and arable land, the pattern resembled these CORINE land cover classes. SKC with arcsine transformed data had

Table 4. RMSE Values of the 17 Interpolation Methods (Table 3) Assessed in This Study.

Interpolation methods		Conifer forest	Broad-leaved forest	Shrubs	Open Land	Arable Land
Deterministic	GPI	0.25	0.34	0.08	0.26	0.04
	LPI	0.25	0.3	0.07	0.22	0.04
	IDW	0.27	0.27	0.07	0.18	0.04
	RBF	0.26	0.27	0.07	0.18	0.04
Geostatistical	EBK	0.25	0.28	0.07	0.19	0.04
	DK	0.24	0.28	**0.06**	**0.17**	0.04
	IK	*0.5*	*0.52*	*0.5*	*0.46*	*0.45*
	OK	0.25	**0.25**	0.07	**0.17**	0.04
	PK	*0.5*	*0.52*	*0.51*	*0.46*	*0.45*
	SK	0.24	0.28	**0.06**	**0.17**	0.04
	UK	0.25	**0.25**	0.07	**0.17**	0.04
	DKC	**0.23**	0.31	**0.06**	0.23	0.04
	IKC	*0.5*	*0.52*	*0.51*	*0.46*	*0.45*
	OKC	0.25	0.33	0.07	0.23	0.04
	PKC	*0.52*	*0.52*	*0.51*	*0.52*	*0.48*
	SKC	**0.23**	0.31	**0.06**	0.23	**0.03**
	UKC	0.25	0.33	0.07	0.23	0.04

For each land cover type, bold numbers indicate the methods providing the lowest RMSE (top performances). Methods for which the RMSE exceeded 0.45 (marked with italics) were not analysed further.
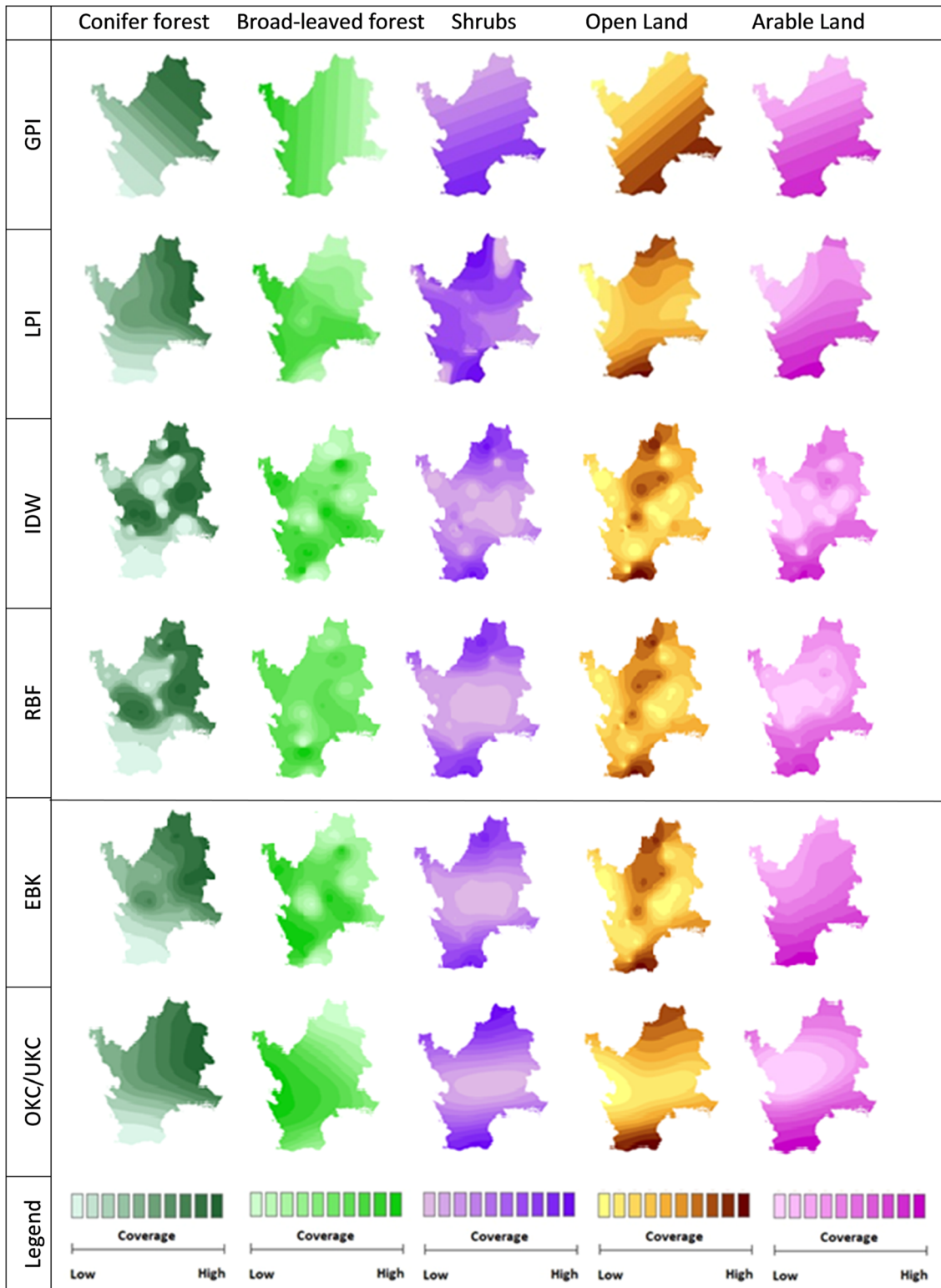
Figure 2. Maps of conifer forest, broad-leaved forest, shrubs, open land and arable land for TW 1 (2010-1950), interpolated using deterministic methods, and two geostatistical methods (EBK, OKC/UKC) producing geometric patterns (Table 3). For detailed legends with scaled bars see appendix (Table A2). For RMSE values see Table 4.

similar, slightly improved RMSE values compared with SKC without transformation, but produced more realistic surfaces for arable land, capturing the fields of the west coast (Figure 3). This interpolation method (denoted SKC arcsine) was therefore also used for the past TWs.

The resulting interpolated maps represent smoothings of complex, mosaic landscapes, in which the land cover class values are linked to the likely occurrence of different land class combinations. Elevation was used for cokriging, and a comparison between elevation and the CORINE land cover classes showed that higher elevation areas (> 100 m) are currently dominated by conifer forest, and low land areas (< 50 m) are predominantly agricultural areas (Figure 4A). The intermediate zone includes a mixture of broad-leaved forest, conifer forest, and agricultural land. A comparison between the SKC arcsine interpolated land cover classes and the CORINE land cover classification showed in general good agreement (Figure 4B). Areas indicated by the SKC arcsine interpolation as having a low cover of conifer forest were predominantly (> 85%) classified in CORINE as having another land cover, and areas indicated as having a high cover of conifer forest were predominately classified as conifer forest (> 80%). The arable land provided a similar picture, interpolated areas having a low cover of arable land were associated with conifer forest, and areas with a high cover of arable land were predominantly classified in CORINE as arable land. For broad-leaved forest, the interpolated cover was substantially higher than shown by the CORINE land cover, whereas for arable land and conifer forest the interpolated covers were lower than observed. The comparison between two data sets indicated the recent time changes, with broad-leaved forest becoming less common in the landscape due to the intensification of agriculture in the south-western part and conversion to conifer forest in the north-eastern part of the study area. Also, shrubs and open land indicated the recent time changes, with plantation of conifer forest on former pasture land.

Spatial Changes in Land Cover Types Through Time

The interpolated LOVE estimates depicted the land cover transitions of southern Sweden (Figure 5). The landscape was dominated by broad-leaved forest during the Mesolithic. From 7250 to 75 BP, the coverage of broad-leaved forest was reduced from above 80% to 55–25%, with substantial local variations, followed by a slight general increase

from 25 BP to present time. Currently, nemoral broad-leaved forests are mainly located in the southern part of the study area. Our results showed a temporary decrease during the Bronze Age that might have been caused by the increase in population density and land use at that time. During the modern time period conifer forest became dominant in a large part of the study area. The opening of the land observed from about 2500 BP, accelerated during the Bronze Age and continued until the modern period. Between 0 and 30% of the landscape was open between 7250 and 3250 BP, 35 to 70% of the landscape was open 75 BP, and present time values are 15-25%. Through time, shrubs covered a relatively small fraction of the land. Shrubs decreased in abundance from 5% in 7250 BP to 0–1% in 2250 BP. Peak abundance was indicated for 75 BP, with up to 17% coverage in the north-eastern part, followed by a decrease to 1–5% in present time. The arable land, covering a minor fraction since the Neolithic, expanded in the modern period. Less than 1% of the landscape was arable land in 4250 BP and has since then increased to up to 4% at present in the southernmost part.

The two REVEALS reconstructions (Figure 6) for the southernmost (Skåne) and northernmost (Småland) areas of the study region, supported the general temporal trends of land cover change that was observed in the interpolated LRA estimates, that is, Skåne was subjected to an earlier and more pronounced opening of the landscape than Småland. The REVEALS data also confirm regional differences in forest landscape properties, with Småland having a generally higher proportion of conifer forest than Skåne. Arable land (Figure 7) is recorded earlier (ca. 4500 BP) in Småland than Skåne (ca. 4000 BP), and the extent of arable land is generally larger in Skåne (maximum cover over the Holocene of 34% at ca. 200–400 BP) than in Småland (maximum 4.7% at ca. 400–500 BP).

DISCUSSION

In this study, we explored the spatial and temporal patterns of land cover changes in southern Sweden. Pollen records, transformed by LRA modelling to distance weighted plant abundance throughout Holocene, provided local point estimates of land cover (LOVE data) at 41 locations. A key focus was to evaluate different methods for interpolation of the point estimates to create continuous spatial maps for selected time windows that represent the major cultural periods in southern Sweden. Considering all regions in Europe, southern Sweden
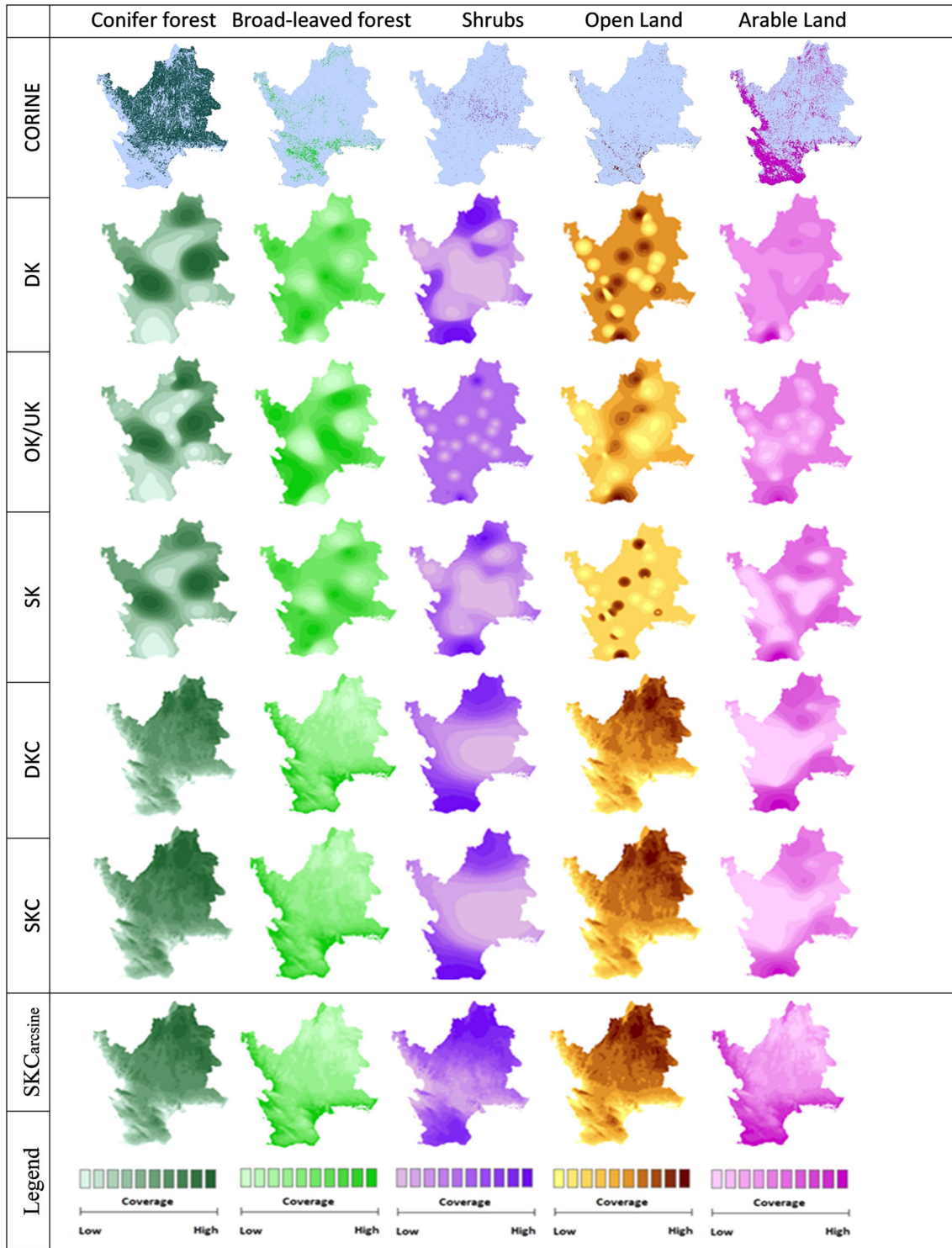
Figure 3. Maps of conifer forest, broad-leaved forest, shrubs, open land and arable land for TW 1 (2010-1950) interpolated using geostatistical methods (Table 3). The top left row represents land cover classes as depicted by the CORINE land cover data for visual evaluation of the interpolation methods. For detailed legends with scaled bars see appendix (Table A2). For RMSE values see Table 4.
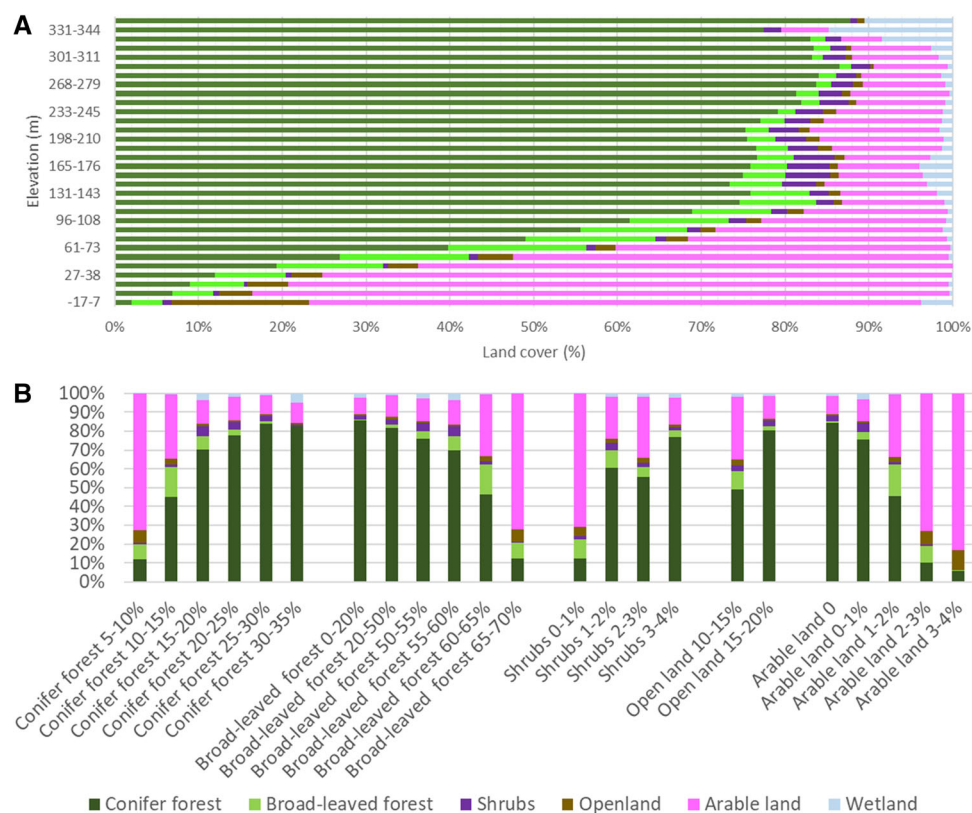
Figure 4. (**A**) Comparison between elevation and CORINE land cover. (**B**) Comparison between the land cover classes (LCT) obtained by SKC arcsine interpolation based on LOVE estimates and the CORINE 2012 land cover classification. The bars represent the proportions of each LCT based on CORINE (y-axis) for classes of LCTs based on SKC arcsine interpolation (x-axis). For details see appendix and Table A2. The correspondence between the LCT and CORINE land cover classes is as follows: Conifer forest = *coniferous forest*; broad-leaved forest = *broad-leaved forest*; shrubs = *moors and heathland + transitional woodland-shrub*; open land = *natural grasslands + pastures + sparsely vegetated areas*; arable land = *non-irrigated arable land + fruit trees and berry plantations + land principally occupied by agriculture + complex cultivation patterns*; wetland = *peat bogs + inland marshes + salt marshes*.

has one of the highest concentrations of pollen records (c.f. Fyfe and others 2009), and it is thus a suitable region to attempt land cover mapping based on LOVE data to explore the local variability.

Evaluation and Uncertainties of the Spatial Land-Cover Reconstructions

Thirteen of the 17 interpolation methods were able to provide a picture of the current land cover in southern Sweden, thereby allowing for the capturing of variability within the region at a more detailed level than previous regional land-cover reconstructions (c.f. Trondman and others 2015; Marquer and others 2017; Pirzamanbein and others 2018). The resulting maps were influenced by the number, distribution and value ranges of the LOVE data points, in combination with the method-specific characteristics. The relevant source area of

pollen (RSAP, see Sugita 2007b for definition) represents the known vegetation coverage of each data point, corresponding to 41 point estimates of a radius of 250 to 2715 m (mean over the Holocene; RSAP estimates are influenced by the basin size and landscape mosaic. The landscape reconstructions based on local point data were associated with rather high RMSE values in the leave-one-out test, around 0.25 for conifer and broad-leaved forest cover. This is related to the patchiness of a landscape managed by multiple land owners. This means that just next to a grassland there might be a forest, whereas the interpolated maps show gradual spatial changes. The resulting land cover values should be interpreted in relation to the interpolation method used. In general, the interpolation methods with a high degree of smoothing had a smaller range of values than the methods capturing local variability (Table A2), which is in line with the commonly observed differences between point-
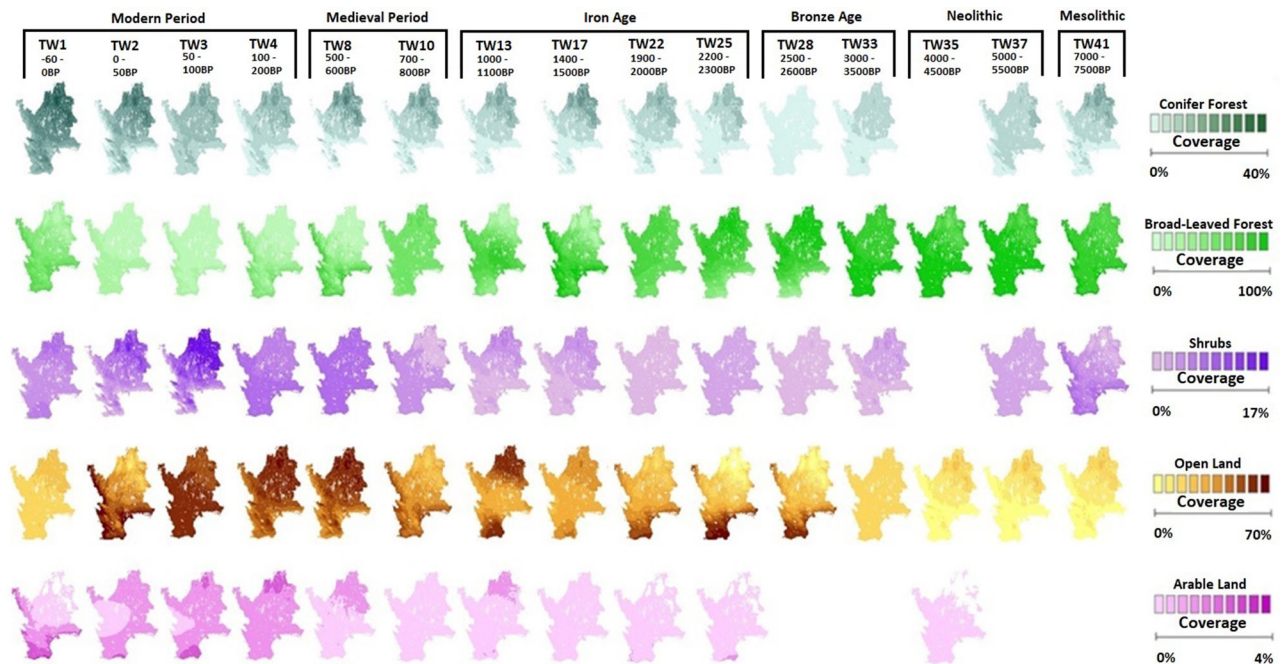
Figure 5. Pollen-based maps of broad-leaved forest, conifer forest, shrubs, open land and arable land produced by simple kriging with cokriging (SKC; altitude as covariable) and arcsine transformation of LOVE estimates. The maps are shown for the selected time windows (see Table 1) and the major cultural periods of southern Sweden.

level data and grid-level (averaged) data in distribution properties and ability to capture extremes (Director and Bornn 2015). The interpolated data were transformed to a raster with 500x500m pixels, enabling the mapping of trends, but as seen from the TW1-maps, the density of data points was not sufficient to provide any details at such a high resolution.

In analogy to ensemble modelling of species distributions (Araújo and New 2006), the use of several interpolation methods can be used and analysed together to obtain information on trends, robust patterns and uncertainties. Our study showed that the different interpolation methods emphasized different aspects of the general landscape coverage, with similar magnitudes of RMSE (Table 4). The geometric patterns produced by the deterministic methods provided an overview of spatial trends, with the GPI maps being sensitive to outliers, and the LPI maps to the chosen neighbourhood distance. The IDW maps depicted both general trends and local patchiness of a landscape managed by humans, as defined by the search neighbourhood. Two geostatistical methods, DKC and SKC, produced more realistic interpretations of the local landscape patterns. That is, cokriging with elevation was found to better capture variability than simple or disjunctive kriging based on LOVE data only. Despite relatively low differences in

altitude (between 0 and 350 m) in southern Sweden, there is a strong relation between elevation and current land cover (Figure 4A). The last glacial period had a major impact on the landscape, with the topography influencing the distribution of different moraine soil types (SNV 2011). Therefore, also the links between elevation and land use through time are strong. Early settlements occurred around the coast and in low land areas, and elevation-dependent edaphic and climatic factors have had a major impact on which parts of the landscape that were explored for settlements and agriculture (Klein Goldewijk and others 2011; Wei and others 2020).

A full ensemble analysis of past time windows was beyond the scope of this study, and the method selected for interpolation of past TWs was SKC arcsine. This method was one of the top performing in terms of RMSE values, and the arcsine transformation of pollen data had the advantage of generating normal distributions with relatively low variance. A quantitative comparison between the CORINE 2012 land cover data and TW1 (''present time'', from 1950 to 2010) showed high agreement in areas dominated by conifer forest and agriculture, respectively. Low correspondence was found for the other land cover categories, that is, areas indicated in TW1 as covered by broad-leaved forest, shrubs and open land were all dominated by con-
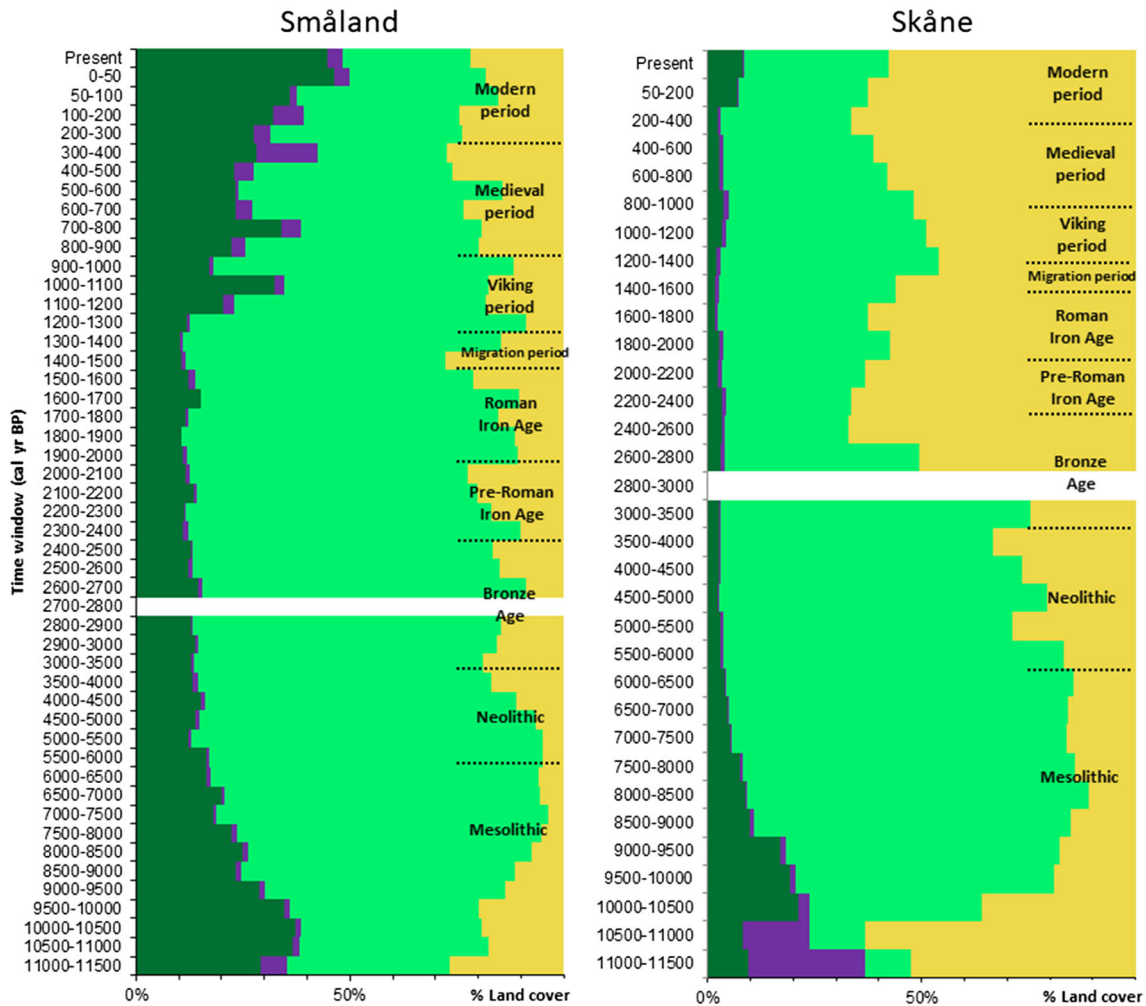
Figure 6. REVEALS estimates for a combination of three large sites (lakes) in Småland and for one large lake in Skåne (Figure 1A), indicating the trend in percentage vegetation cover during the past 11,500 years, including changes in conifer forests (dark green), shrubs (purple), broad-leaved forest (light green) and open land (brown). Arable land (Figure 7) is included in the category open land.

ifer forest and agriculture. That is, this comparison between a snapshot in time (CORINE 2012) and a 60-year time window, was indicative of the substantial land use and land cover changes that has occurred towards modernisation and intensification of forestry and agriculture in southern Sweden (Blennow and Hammarlund 1993; Lindbladh and others 2014; SNV 2011). An additional explanation for low correspondence is that the LOVE estimates of broad-leaved forest were dominated by birch, whereas birch naturally grows in both conifer and broad-leaved forests. That is, birch was considered in both broad-leaved and conifer categories of the CORINE dataset, whereas it was only included in the LCT broad-leaved forest based on LOVE estimates. It should also be noted that the arable land category based on LOVE estimates was based on

two common pollen types only, *Cerealia* and *Secale,* which created an underestimation of arable land. That is, a scale of 0–4% was used for mapping the arable land, however, an average of about 8% of the land area in Sweden is currently arable (SNV 2011). Additional information on pollen grains from other crops and ruderal plants would have contributed to a more complete picture.

Spatial and Temporal Changes in Holocene Land Cover in Southern Sweden

In the following part, we used the spatially continuous reconstructions of land cover throughout the Holocene to explore vegetation changes. Since the Mesolithic, two main processes have acted to reshape the land cover of southern Sweden, origi-
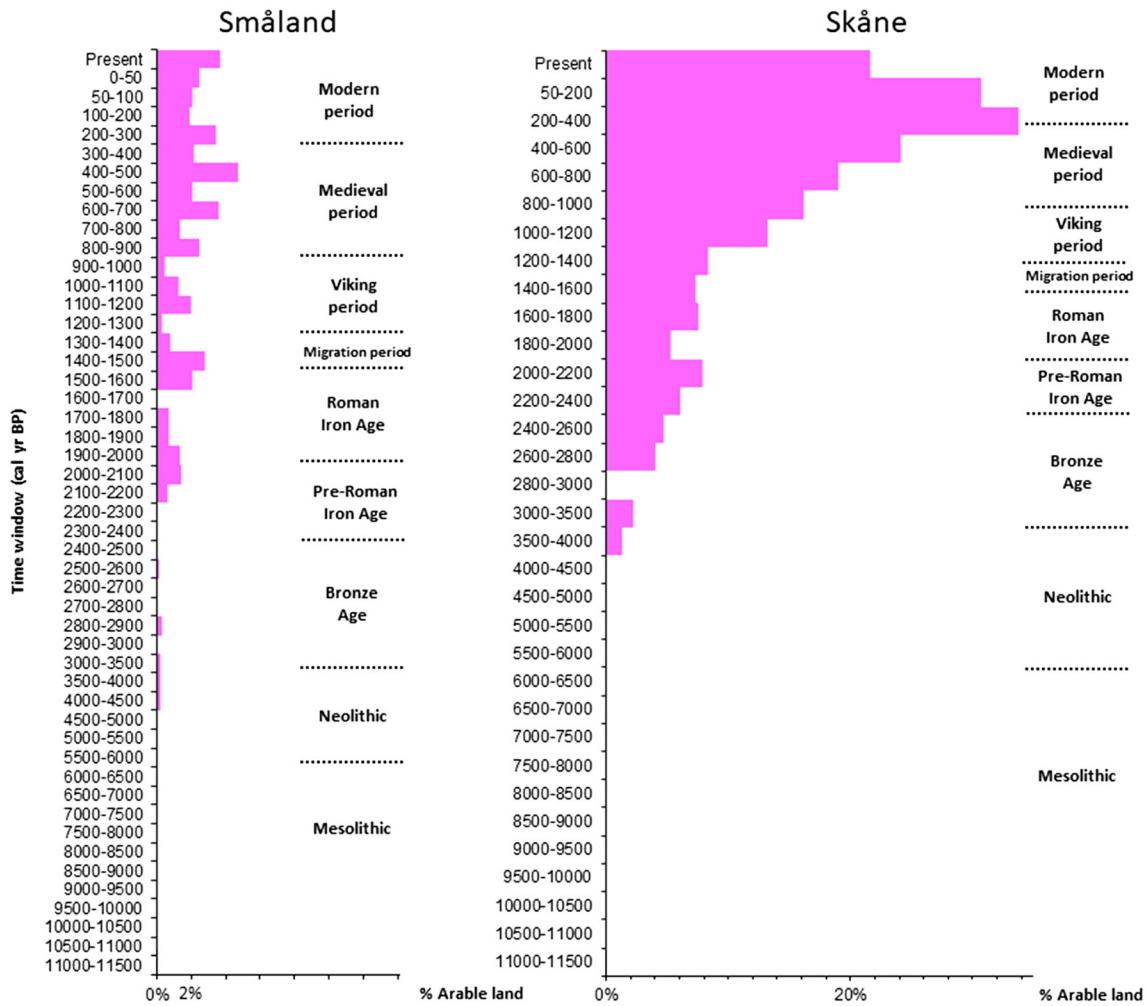
Figure 7. REVEALS estimates for a combination of three large sites (lakes) in Småland and for one large lake in Skåne (Figure 1A), indicating the trend in percentage cover of arable land during the past 11,500 years.

nally covered by broad-leaved forests. Since the last glaciation, the natural distribution of Norway spruce forest has expanded from the north-eastern part of Scandinavia and moved southward (Giesecke and Bennett 2004), and the arable land was developed stepwise by technological interventions and the periodic growth and decline of human population (Berglund 2003; Eriksson and Cousins 2014). Lowest forest cover and maximum open land were reached at the beginning of the 20th century (Li and others 2013; Wei and others 2020).

The Mesolithic landscape was mainly covered by natural vegetation, in south Sweden dominated by nemoral broad-leaved forest, in the north-eastern part in a mix with about 20% boreal coniferous forest. The high forest cover is in line with the low human impact around the Baltic catchment at that time (Fyfe and others 2015; Kuosmanen and others 2018; Marquer and others 2014, 2017). Also, the

Neolithic landscape was dominated by broad-leaved forest, covering 85–100% in all of southern Sweden. The pollen-based LCT maps indicate that 5–15% of the land was open, and that conifer forest was on retreat in the north-eastern part, likely due to climate related disturbances (storms, insect outbreaks, and/or forest fires) rather than human impact. Little to no arable land was indicated for the northeast part, and below 1% of the rest of southern Sweden was arable. The climate cooling from about 6000 BP (Imbrie and others 1992) was contemporaneous with the start of human-induced opening of the landscape.

The Bronze Age maps indicated up to 55% forest cover in the south-eastern part and above 70% in other parts of southern Sweden. This pattern is in agreement with earlier studies, which found that forest cover around 3000 BP was dominated by mixed deciduous forest (Björkman and Bradshaw

1996), and that forest cover was below 40% in the southernmost part of Sweden (Eriksson and Cousins 2014). In the Bronze Age, southern Skåne and coastal areas of Halland and Blekinge were converted into open land (Berglund 1988, 2003), first to improve grazing for livestock and over time to create arable land for cultivation of crops (Lindbladh 1999; Hannon and others 2018), with manure being used as a fertiliser from around 2500 BP (Eriksson and Cousins 2014).

The pre-Roman Iron Age (earliest part of the Iron Age in Scandinavia) brought with it a new practice of stabling livestock for overwintering (Eriksson and Cousins 2014). The growing need of grasslands for hay-making is seen in the maps of the Iron Age as an expansion of open land, up to 70% in the south. The inland was still covered by nemoral broad-leaved forest. During the Roman Iron Age, only limited areas in the south were covered by forest, in line with the management practice of burning to keep the landscape open for pasture and grazing (Blennow and Hammarlund 1993; Cui and others 2014). After the collapse of the Roman Empire and the start of the Migration period, open land was abandoned (reduced to about 40%) and overgrown by broad-leaved forest in the south, and conifer forest expanded to 10–25% in central and northern parts of southern Sweden.

The maps of the Viking period indicated increased arable land cover. Open land increased from about 35% to more than 50% in most parts, and also the northern area opened up at the expense of forest cover. The period is associated with an intensification of agriculture, with infields being used for cereal cultivation and outfields for forest grazing and slash-and-burn agriculture (Lindbladh 1999; Fredh and others 2017). The Mediaeval maps did not indicate the decline of pastures and meadows that have been reported in association with the Black Death pandemic that struck Sweden during 500–600 BP and the colder climate conditions (Little Ice Age) leading to the mid-Mediaeval agrarian crisis (Björkman and Bradshaw 1996; Berglund 2003; Fredh and others 2017). However, the maps showed increased broad-leaved forest in the south and along the coasts, and a general expansion of shrub cover from 2–3% to 3–4% by the mid to late Mediaeval Period, and an expansion of conifer forest to 10-30% of central and northern southern Sweden, likely linked to the reduction of open land. The trend was reversed in the first part of modern period.

The second part of the modern period was associated with a peak in both open land (up to 65%) and an abundance of shrub cover (in general 4–5%, up to 17% in the north-eastern part) and the lowest cover of broad-leaved forest (around 25%). The onset of the agricultural revolution was linked to a general increase in arable land, with broad-leaved forests being cleared and lakes and wetlands drained (Eriksson and Cousins 2014). Presently, arable land (3–4%) is once more found in confined areas such as Skåne and along the coastal regions (Fredh and others 2017). Forest covers 70% of the land and is dominated by planted conifer forest (> 40%) in all of southern Sweden (Cui and others 2014; Lindbladh 1999).

CONCLUSION

In this study, we explored the potential to use LOVE-based interpolations of local land cover to provide insights in spatial trends and degree of variability within a larger landscape. The use of multiple interpolation methods were found to provide complementary aspects, with deterministic methods indicating general, large-scale trends, and geostatistical methods capturing local variations. A complete ensemble analysis, comparing the results of different interpolation methods covering different time windows was not feasible to carry out. For the study region, cokriging with elevation was found useful, due to a strong correlation between elevation and edaphic factors, having an influence on land use suitability through Holocene. The method selected for mapping of the 15 time windows, simple kriging with cokriging using arcsine transformed data enabled the generation of a more detailed picture of the previously known trends in land cover and land use change of the study region. Mapping land cover from regional to local scales provides insights into landscape patterns. This is a new opportunity for the research communities related to palaeoecology, archaeology, and history as well as landscape management and ecology. In particular, such approaches can be used for landscape spatial pattern analysis for studying landscape changes over a long-term perspective, to get a better understanding of the status, trends, and possible future changes of land cover and ecosystem in general.

Department of Physical Geography and Ecosystem Science, Lund University.

DATA AVAILABILITY

Detailed information on the data used in this study and references to sources can be found in the appendix. Table A1. Metadata of the 45 fossil pollen records (41 for LOVE & 4 for REVEALS), spread over South Sweden by location (site name), with site label, coordinates, elevation, area of site, radius of site, and basin type. For the details about the sources of the pollen data, see Trondman and others (2015, 2016) and Marquer and others (2017).

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