Lessons from the Past: Unfolding the Dynamics among Climate, Balkan Landscapes, and Humans over the Past Millennium

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The Graduate Center, City University of New York
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UNFOLDING THE DYNAMICS AMONG CLIMATE,
BALKAN LANDSCAPES, AND HUMANS
OVER THE PAST MILLENNIUM

by
Charuta Kulkarni

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THE CITY UNIVERSITY OF NEW YORK
Abstract

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Charuta Kulkarni

Adviser: Professor Dr. Rebecca Boger

The primary objective of this doctoral dissertation is to reconstruct the environmental history of the Central Balkans (Serbia) over the past millennium utilizing biological proxies (pollen, spores, and charcoal), geochemical signals through X-ray fluorescence (XRF), statistical analyses, and atomic mass spectrometry (AMS) $^{14}$C chronology. This dissertation establishes the first chronological framework for vegetation-landscape changes in Serbia and discusses the role of humans and climate as underlying processes.

Chapter 1 discusses the background and the nature of the research problem followed by the extensive literature review on the topic of the Holocene climate and paleoecology. The state of Holocene paleoecology in Europe and in the Balkan region are discussed with an emphasis on the last millennium. The Chapter also includes a summary of key socio-ecological studies across Europe and the techniques used to reveal the long-term human-environmental interactions across the Holocene and the Common Era (past 2000 years). The chapter concludes with the significance of the current study.

Chapter 2 presents the first, well-dated, high-resolution record of vegetation and landscape change from Serbia over the past 500 years. Biological proxies (pollen, spores, and charcoal), geochemical analysis through XRF, and a detailed chronology based on AMS $^{14}$C dating from a western Serbian sinkhole core suggest complex woodland-grassland dynamics and strong
erosional signals throughout the Little Ice Age (LIA; c.1500-1850 CE). An open landscape with prominent steppe vegetation (e.g. Poaceae, Chenopodiaceae) and minor woodland exists during 1540-1720 CE (early LIA), while the late LIA (1720-1850 CE) in this record shows higher tree percentages possibly due to increased moisture availability. The post-LIA Era (1850-2012 CE) brings a disturbed type of vegetation with the presence of weedy genera and an increase in regional woodland. Anthropogenic indicators for agricultural, pastoral and fire practices in the region together attest to the dominant role of humans in shaping this Balkan landscape throughout the interval. The changing nature of human interference, potentially as a response to underlying climatic transitions, is evident through large-scale soil depletion resulting from grazing and land clearance during the early LIA and stabilization of arable lands during the late and post-LIA eras.

Chapter 3 describes a well-dated, high-resolution Central Balkan record of vegetation and landscape change over the past 700 years from the Sava Region, Serbia. This timespan includes the LIA (1500-1850 CE) with several centuries before and after this important interval for comparison. Biological proxies (pollen, spores, and charcoal), geochemical analysis through X-ray Fluorescence (XRF), and a detailed chronology based on AMS $^{14}$C dating from the Sava basin sediments delimit the evolution of the Serbian landscape across a warm-stable pre-LIA interval with relatively high tree percentages, modest occurrence of anthropogenic taxa, and relatively stable agriculture supported by grazing. On the contrary, the LIA interval in the region is expressed through opening and closing of the tree canopies and extensive land erosion, perhaps in response to climatic deterioration and human impact largely associated with socio-political changes of the time. The post-LIA interval shows stabilized woodland in the riparian region, establishment of arable lands nearby lakes and selective forest clearance strategies by humans in the wake of the industrial revolution. Establishing correlation with existing Serbian environmental datasets, this
record reveals the transformation of the Central Balkan landscape and its apparent linkages with changing climatic and socio-political regimes.

Chapter 3 also includes a regional comparison between the Sava core and western Serbian lake to capture the nature and impact of the LIA climatic condition and contemporary human societies on the Central Balkan landscapes. During the 15th-19th CE, indigenous tree (e.g. *Quercus*, *Acer*, *Pinus*) and herbaceous (e.g. *Poaceae*, *Chenopodiaceae*, *Artemisia*) pollen from these records demonstrate fluctuations in woodland-grassland dynamics. While tree populations from the Sava region slowly fluctuate between 50 and 70%, the trees of western Serbia vacillate drastically between 30% and 55%. On the other hand, the Sava region grasslands show variations of ~20-43% whereas the western Serbian grass populations exhibit abrupt oscillations between high (59%) and low (32%) percentages. As a proxy for surface erosion and clastic input into the lakes, the 1-cm resolution potassium and titanium counts are in strong agreement with varying herbaceous taxa. While temporal asynchronicity in the AP and NAP signals between the two cores could be attributed to local factors including differing altitude, terrain exposure, and soils that are inherently different on either sides of the Sava channel, continuous oscillations of both communities during the LIA are analogous. This overall pattern indicates that the Central Balkan landscape at-large was going through considerable environmental change throughout the LIA in the form of opening and closing of the tree canopies on both sides of the Sava Basin. High charcoal indicates accelerated land clearance between the 15th and 17th CE, however, towards the beginning of 18th CE, the cultivars (e.g. *Secale*, *Triticum*) peak to suggest improved agriculture in the region. Correlation with the available Serbian environmental records across the LIA reveals the regional dynamics between woodland and grassland under the influence of an unstable and perhaps drier LIA climatic regime (especially in the early LIA) and reforestation of the region during the latter
part of the LIA due to both climatic and socio-political reasons. This correlation enhances our understanding of the nature and spatial variability of the LIA across the Balkans and its interactions with the contemporary societies.

Chapter 4 examines the interactions of environmental and social dynamics in Central Balkans over the past 700 years, a period that experienced the LIA climatic condition and the warm 20th century. Meanwhile, the same period witnessed a complex human history with the emergence-rise-decline of the Ottoman Empire and subsequent socio-political events (e.g. wars, famines, migrations, epidemics). Environmental datasets for this socio-environmental analysis include biological proxies (pollen, spores, and charcoal), geochemical signals, and a detailed AMS $^{14}$C based chronology of two Central Balkan lakes while social datasets include historic population data, land use, records of societal calamities, and critical historic events derived from a review of the literature and local archives. Among the environmental datasets, indigenous tree and herbaceous pollen from the Central Balkans demonstrate fluctuations in woodland-grassland dynamics whereas potassium counts obtained through XRF act as a proxy for surface erosion and clastic input into the lakes. Microscopic charcoal, cereal pollen and subordinate anthropogenic pollen (e.g. cultivated fruits and vegetables) are used to distinguish the nature of human impact over the landscape. These key anthropogenic indicators create a more thorough social component of the analysis in association with other social datasets. After reconstructing the individual time series for each environmental and social dataset and their synthesis using Principal Component Analysis (PCA), the two Central Balkan records are correlated in order to visualize how a region responds to social and environmental stressors. Our approach demonstrates ways to integrate natural and social science systems research.
Acknowledgments

This is perhaps the most difficult chapter I am writing in this dissertation. Saying thank you here, in a way means saying good bye…

I am deeply indebted to my advisor, Dr. Rebecca Boger for giving me the opportunity to work on this exceedingly interesting project, which has helped me to gain knowledge in diverse research fields. Her support and guidance has been exceptional; without which I would not have been able to do much advancement in my research. Countless scientific discussions with her have allowed me to improve my problem solving techniques in every aspect and her critical insights have always motivated me to explore various facets of this doctoral research.

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I sincerely thank Dr. Tom Guilderson from Center for Accelerated Mass Spectrometry, Lawrence Livermore National Laboratory for providing AMS radiocarbon dates in this doctoral dissertation. I am very grateful to Dr. Brett Branco and Dr. Zhongqi Cheng from Department of Earth and Environmental Sciences, Brooklyn College for their generosity in allowing use of their labs for the pollen extraction process. I would also like to thank Jessica Khaimova for her help in XRFing the Zivaca Oxbow core. Sincere thanks goes to Dr. Hermine Huot for her kind help in the translation of some French archival records. I must also thank Dr. Branko Sikoparia and Dr. Predrag Radisic from Laboratory of Palynology, University of Novi Sad, Serbia for providing reference pollen slides, an immensely important resource for microscopic identification of pollen and spores. Hvala puno to all my Serbian colleagues, who directly and indirectly helped me in planning and executing the fieldwork and botanical sampling that was instrumental in this doctoral dissertation.

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of this acknowledgment is my best friend and hubby, Siddharth, who remains the most important driving force in this journey and in my life.

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### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>a.m.s.l.</td>
<td>above mean sea level</td>
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<tr>
<td>AMS</td>
<td>atomic mass spectrometry</td>
</tr>
<tr>
<td>AP</td>
<td>arboreal pollen (tree-shrub pollen)</td>
</tr>
<tr>
<td>BCE</td>
<td>Before Common Era (analogous to BC)</td>
</tr>
<tr>
<td>BP</td>
<td>before present (=1950 CE)</td>
</tr>
<tr>
<td>cal BP</td>
<td>years calibrated before present</td>
</tr>
<tr>
<td>cal CE</td>
<td>calibrated calendar year CE</td>
</tr>
<tr>
<td>CE</td>
<td>Common Era (analogous to AD)</td>
</tr>
<tr>
<td>Kyr BP</td>
<td>thousand years calibrated before present</td>
</tr>
<tr>
<td>LIA</td>
<td>Little Ice Age</td>
</tr>
<tr>
<td>LOI</td>
<td>loss-on-ignition</td>
</tr>
<tr>
<td>MCA/MWP</td>
<td>Medieval Climate Anomaly/Medieval Warm Period</td>
</tr>
<tr>
<td>NAP</td>
<td>non-arboreal pollen (grass-herb pollen)</td>
</tr>
<tr>
<td>PCA</td>
<td>principle components analysis</td>
</tr>
<tr>
<td>XRF</td>
<td>x-ray fluorescence</td>
</tr>
</tbody>
</table>
## Contents

**Abbreviations**  xi

**List of Tables**  xv

**List of Figures**  xvi

1. **Introduction**  1
   1.1. Background and research questions  1
   1.2. Literature review  4
      1.2.1. The Holocene climate  4
      1.2.2. Holocene paleoclimatology in Europe  6
      1.2.3. Holocene paleoclimatology in the Balkans  9
      1.2.4. The past millennium  10
      1.2.5. Human-environmental interactions  13
   1.3. Methodology  17
      1.3.1. Pollen and charcoal analyses  17
      1.3.2. Lithological and geochemical analyses  21
      1.3.3. AMS radiocarbon dating  23
      1.3.4. Correlation among environmental, social and climatic datasets using statistical means  24
   1.4. Significance of the current study  27

2. **Exploring the role of humans and climate over the Balkan landscape:**  29
   500 years of vegetational history in Serbia  29
   Abstract  29
   2.1. Introduction  30
   2.2. Study area  33
   2.3. Materials and methods  35
3. The Little Ice Age and human-environmental interactions in the Central Balkans: insights from a new Serbian paleoenvironmental record

Abstract 59

3.1. Introduction 60

3.2. Study area 62
  3.2.1. Regional setting and study site 62
  3.2.2. Climate 63
  3.2.3. Regional and local vegetation 63
  3.2.4. Historic setting and the context of the LIA 65

3.3. Materials and methods 66
  3.3.1. Core extraction 66
  3.3.2. Lithological and geochemical analyses 66
  3.3.3. Palynological and charcoal analyses 67
  3.3.4. Rarefaction analysis 68
  3.3.5. Chronology 69

3.4. Results 70
  3.4.1. Age model and sedimentation rates 70
| 3.4.2. Lithology and geochemistry            | 73 |
| 3.4.3. Pollen assemblage zones and corresponding ages-lithozones | 75 |
| 3.5. Discussion                             | 78 |
| 3.5.1. Environmental history of the Sava region throughout the last 700 years | 78 |
| 3.5.2. Regional comparison                  | 87 |
| 3.6. Conclusions                            | 94 |

| 4. An examination of long-term environmental-social dynamics in the Balkans | 96 |
| Abstract                                                                 | 96 |
| 4.1. Introduction                                                         | 97 |
| 4.2. Materials and methods                                                | 99 |
| 4.2.1. List of indicators utilized                                       | 99 |
| 4.2.2. Statistical analyses                                               | 105 |
| 4.3. Results and discussion                                               | 106 |
| 4.4. Summary                                                              | 116 |

**Concluding Remarks**  
118

**References**  
122
Table 1.1: Major subdivisions of the Holocene Epoch and their climatic regimes summarized from the literature. *The boundaries between each climatic interval is transitional and regionally constrained (Please see the discussion for details).

Table 2.1: AMS age ranges for 95.4% (2-sigma) enclosed area shown for the range used in calendar age calculation. Relative percent area represented by the calendar range is shown in parentheses (). Selected dates are shown by an asterisk (*) and the selection criterion is discussed in detail in the results section.

Table 3.1: AMS Age ranges for 95.4% (2-sigma) enclosed area shown for the range used in calendar age calculation. Relative percent area represented by the calendar range is shown in parentheses (). Selected dates are shown by an asterisk (*) and the selection criteria are discussed in detail in the results section.

Table 3.2: Lithostratigraphic description of the ZO sequence (the boundaries between the different layers are gradual).

Table 4.1: Location and nature of the study sites providing ecological and certain eco-social indicators in this study.

Table 4.2: List of indicators utilized in this study.
List of Figures

Fig. 1.1: Location of Serbia within the Balkans (Green highlighted region). Black dots represent available late Quaternary-Holocene pollen records from the Balkans (Data source: http://www.europeanpollendatabase.net/data/).

Fig. 1.2: Low-latitude paleoclimate series with a variety of available climate proxies. Green bands represent timing of rapid cooling events, tuned to the high-resolution GISP2 record (Mayewski et al., 2004 and references therein).

Fig. 1.3: Comparisons of simulated and reconstructed northern hemispheric temperature changes over the last millennium (Masson-Delmotte et al., 2013).

Fig. 1.4: Chronological chart showing archaeological periods in different regions of the eastern Mediterranean from the sixth to first millennia BCE (9 to 2 ka BP) along with key climatic trends (Roberts et al. 2011a).

Fig. 1.5: A composite showing evolution of central European forest cover and population (A) together with oak sample replication (B), their historical end dates at decadal resolution (C) in association with reconstructed summer temperature and precipitation (Modified from Buntgen et al., 2011).

Fig. 2.1: (a) Available Quaternary-Holocene pollen records (black dots) from the Balkans (green highlighted region) (Data source: http://www.europeanpollendatabase.net/data/). The location of Serbia (patterned) and the study site (star) are shown. (b) Photograph of the coring site showing the sinkhole under investigation (Photo credit: Charuta Kulkarni). (c) Vegetation classification of western Serbia, Central Balkans after Horvat et al. (1974). The location of the study site is shown with a star.
Fig. 2: AMS Age-depth model for DS core.

Fig. 2.3: Lithology and K, Ti, and Fe counts (ppm) for DS core. The dotted lines represent the respective pollen zones; refer to description and Figs. 2.4-2.5 for details.

Fig. 2.4: Pollen percentage diagram for DS core: selected trees, shrubs, grasses, upland herbs and aquatics (Exaggeration 5%) with LOI and microscopic charcoal/cm$^3$.

Fig. 2.5: Composite diagram of DS core includes total percentages of AP and NAP; percentage curves of Quercus and Acer (most abundant thermophilous Balkan trees), Pinus and Fagus (representative of montane vegetation that are sensitive to precipitation), Juniperus and Chenopodiaceae (drought indicators), key anthropogenic signals - cereals and Juglans (cultivated taxa that favor warm temperatures), Plantago (grazing indicator), and microscopic charcoal concentrations (proxy for burning and land clearance in the catchment). Potassium (K) and Titanium (Ti) suggest erosion and clastic inputs into the lake. Pollen concentration shows pollen preservation in the sediments while pollen richness identifies taxon diversity through time.

Fig. 3.1: (a) Quaternary-Holocene pollen records (black dots) from the Balkans (Green highlighted region) (Data source: http://www.europeanpollendatabase.net/data/). The location of Serbia (Purple) and the study site (star) are shown. (b) Location of the Sava Basin (Dotted region) and the study site (star) within Serbia. The black dot shows the location of only pollen record available from Serbia (after Kulkarni et al. 2016) (c) Google Image of the study area showing the location of the Sava River and the Zivaca oxbow lake under investigation (Data source: www.googleEarth.com). The star shows the exact location of the coring site.
Fig. 3.2: AMS Age-depth model for ZO Core.

Fig. 3.3: Lithology, inorganic and organic content (%), potassium (K), titanium (Ti) and calcium (Ca) counts (ppm) for ZO core. The dotted lines represent the lithozones; refer to description for details.

Fig. 3.4: Pollen percentage diagram for ZO core: AP-NAP, selected trees, shrubs, grasses, upland herbs, wetland and aquatic species (Exaggeration 5%) and microscopic charcoal/cm³.

Fig. 3.5: Correlation between the two Serbian ecological records – Sava Region (this record) and Donja Sipulja (Western Serbia; Kulkarni et al. 2016): AP% (proxy for forest cover), NAP% (proxy for open landscapes), Estimated taxon richness (proxy for plant diversity), Potassium (K) counts (proxy for land erosion), microscopic charcoal concentration (proxy for land clearance), Cereal and Juglans pollen influx (proxies for agriculture). Dark and light colored curves for each proxy represent the Sava Region (ZO) and Western Serbian cores respectively. The blue highlighted region shows the accepted extent of the Little Ice Age (LIA) (1500-1850 CE). The historic timeline is provided with major socio-political events including major wars (gray boxes).

Fig. 4.1: Location and nature of the study sites providing ecological and certain eco-social indicators in this study.

Fig. 4.2: Evolution of Balkan ecological-social-climatic systems over the last 700 years: The extent of the forest cover and open landscapes are shown by AP% (a) and NAP% (b) of the Sava Region and Western Serbian sites while potassium (K) counts (c) exhibit the erosional inputs into the respective lakes. Human impact on the landscape is shown through the magnitude of land clearance through microscopic charcoal concentration (d) and the degree of agriculture (e) and arboriculture (f) as shown by cereal and Juglans...
pollen influx respectively. Modeled deforestation rates that accounts for population history for Europe (P-Model, Pongrats et al. 2008) and Eastern Europe (K-Model; Kaplan et al. 2009) (g). The Balkan population curves (h)) by McEvedy and Jones 1978 (1400-1975 CE) and alternate 1900-2000 CE population series through various datasets (See ‘Historic Population’ Section for further details); the years of reported famines (Vujevic 1931) are displayed at the top. Central European summer temperature and precipitation (i) are shown after Buntgen et al. 2011; annual records of individual-multiple events of extremely cold periods-seasons and droughts are displayed alongside. The historic timeline is provided with political events including major wars (gray boxes). The blue highlighted region shows the accepted extent of the Little Ice Age (LIA) (1500-1850 CE).

Fig. 4.3: Biplots of ecological, eco-social and social indicators from the Sava Region (a) and Western Serbia (b). The color code for each indicator is similar to that from Fig. 4.2.
Chapter 1

Introduction

The content of this chapter also partially appears as a book chapter in “The results of new archaeological research in northwestern Serbia and adjacent territories” (Original Serbian: Rezultati novih arheoloških istraživanja u severozapadnoj Srbiji i susednim teritorijama)” published by Serbian Archaeological Society, Belgrade and Institute for Protection of Cultural Monuments of Valjevo, Valjevo, Serbia in 2013.
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1.1. Background and research objectives

The Holocene Epoch, circa last 11.7 kyr BP (Cohen et al., 2014) is the period during which humans extended their geographic reach to the most remote places on Earth, domesticated hundreds of species of plants and animals, and developed agriculturally based societies and urbanism (Kirch, 2005). The more we learn about the nature and scale of Holocene climatic variability, the more it becomes apparent that the Holocene climatic changes were of great significance as environmental drivers for human and societal evolution since the end of the last glacial period (Hodell et al., 2001). Thus, a close relationship between climatic and societal changes motivates us to document the short- and long-term changes in the Holocene climate in order to better understand the fate of future human societies at the onset of global climate change.

Although the larger part of the Holocene is considered to be warm, several regional climatic fluctuations stand out throughout the period. During the past millennium, there were two noticeable warm and cold climatic intervals, Medieval Climate Anomaly (MCA; 10th to 14th Century CE) and Little Ice Age (LIA; 15th to 19th Century CE) respectively. These two short-term climatic variations imposed significant changes on landscapes across Europe that contemporary societies inhabited and cultivated (Buntgen et al., 2011a; Fagan, 2000; Ljungqvist, 2010). With this background, this doctoral dissertation takes a close look at past 1000 years and explores the
impacts of climate and humans on the European landscape in terms of understanding long-term socio-environmental interactions.

**Fig. 1.1:** Location of Serbia within the Balkans (Green highlighted region). Black dots represent available late Quaternary-Holocene pollen records from the Balkans (Data source: http://www.europeanpollendatabase.net/data/).

The study area is the Republic of Serbia, central part of the Balkan Peninsula and southeastern Europe (Fig. 1.1). This area was selected for the following reasons:

1) **It is an important climatic and ecological zone of Europe.** Located in mid-latitudes, the Balkans are a 'frontier zone' that meets and interacts with the tropical (monsoonal) climatic system of northern Africa and cold polar regions of Europe (Eastwood, 2004; Xoplaki et al., 2004). This area plays a key role as a climatic transition zone between the western and eastern Mediterranean and also between the Mediterranean and Central European meteorology (Qiriazi and Sala, 2000; Xoplaki et al., 2004; Xoplaki and Luterbacher, 2003). This is a region
with complex physical geography, climate interactions, high levels of endemism both in the
terms of flora and fauna, and a number of relict species preserved in natural ecosystems
(Griffiths et al., 2004). It has been called the “European biodiversity hotspot” as it was a
refugium for many species during the past Ice Ages (Petit et al., 2003); the region as a whole
is surpassed in species richness only by the tropics (Mooney, 1988).

2) **There is a long record of cultural history.** All major transformations within the human
cultures including Neolithic, Bronze, Iron, Roman and Medieval Ages, are preserved in the
Balkan landscapes, making it an excellent location for studying cultural history in relationship
with evolving landscapes (Eastwood, 2004; Roberts et al., 2001).

3) **There are limited climatic and socio-ecological studies.** The Balkans (especially Central
Balkans) are among the least studied parts of Europe both in terms of past climatic as well as
environmental studies (Fig. 1.1). As a result, the nature and the magnitude of the MCA and
LIA in the Balkans (and thus their linkages with contemporary societies) is poorly understood.
At the same time, the Balkan landscapes are now part of the most rapidly changing ecological
regions of Europe and are very sensitive to dramatic climate change in terms of varying
precipitation and temperature patterns (Alcamo et al., 2007; EEA, 2004; IPCC, 2014). This
highlights the need for accumulating more high-resolution ecological records particularly
covering the last 2,000 years of environmental history of this region where the responses of
the terrestrial ecosystems to climatic changes under scenarios similar to the present can help
us to better evaluate the interplays and feedbacks of climate variability in the context of human
landscapes and activities (Mercuri and Sadori, 2014).

Given this context for the Balkan region, this study undertakes palynology, geochemistry, and
other supplementary analyses to trace the climatic signals and human interventions during the last
1000 years. The time frames for these changes are Atomic Mass Spectrometry (AMS) radiocarbon dating. The main objectives driving this research are:

I. To reconstruct paleoenvironmental history of the Central Balkans over the past millennium

II. To identify and interpret the role of climate and humans in shaping the Central Balkan landscape during the MCA (or pre-LIA), the LIA and post-LIA periods

III. To demonstrate ways to integrate natural and social science systems research in order to understand how a region responds to social and environmental stressors

1.2. Literature review

1.2.1 The Holocene climate

The climate is determined by both external and internal factors (Bradley, 1999). External factors include Earth-Sun orbital parameters, i.e. eccentricity, obliquity and precession, as well as solar activity. Internal factors include volcanic activity, feedback processes between hydrosphere – atmosphere – lithosphere – biosphere – cryosphere (e.g. albedo, cloud cover, etc.), variations in ice-sheet volume, changes in speed and circulation of ocean currents, changes in atmospheric greenhouse gases (e.g. CO₂, CH₄) and their impact on incoming and outgoing thermal radiation, and anthropogenic forcing (Zerefos et al., 2011). In terms of the Holocene, there are complex climate responses at the global level including long-term and abrupt changes in temperature, precipitation, monsoon dynamics, and the El Niño-Southern Oscillation (ENSO) and several more, pertaining mainly to significant changes in short-term orbital forcing (Alcamo et al., 2007).

Overall, in the context of both climate forcing and response, the Holocene is far better documented in terms of spatial coverage, dating and temporal resolution than previous interglacials (Jansen et al., 2007). A variety of proxy records (e.g. ice cores, marine and lacustrine sediments, peat bogs, tree rings, speleothems) provide detailed temporal and spatial information concerning
Fig. 1.2: Low-latitude paleoclimate series with a variety of available climate proxies. Green bands represent timing of rapid cooling events, tuned to the high-resolution GISP2 record (Mayewski et al., 2004 and references therein).
climate change during the Holocene. For example, Mayewski et al., (2004) in their extensive review of global Holocene proxy records identify six major periods of rapid climate change i.e. cooling events (RCCs) within a generally warm period; these RCCs include 9000–8000, 6000–5000, 4200–3800, 3500–2500, 1200–1000, and 600–150 cal yr BP. A low-latitude paleoclimate series with state of climate proxy noted shows green bands representing timing of RCCs (Fig. 1.2). Based on such studies, various attempts have been made to subdivide the Holocene, usually on the basis of inferred climatic change (Roberts, 2005). Table 1.1 summarizes three major subdivisions of the Holocene that are largely climate-based demarcations based on the review of the literature.

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Interval</th>
<th>Climatic regime</th>
<th>Ages* (years BP)</th>
<th>Major climatic forcings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene</td>
<td>Late Holocene</td>
<td>Overall cool and dry (or at least dryer as compared to Early Holocene)</td>
<td>3000-0</td>
<td>Orbital forcings; Ocean dynamics (North-Atlantic Oscillations); anthropogenic impact</td>
</tr>
<tr>
<td></td>
<td>Mid Holocene</td>
<td>Transitional with significant and complex climate responses,</td>
<td>6000-3000</td>
<td>Changes in seasonal insolation</td>
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<tr>
<td></td>
<td></td>
<td>including long-term and abrupt changes in temperature and precipitation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Early Holocene</td>
<td>Warm and moist</td>
<td>9000-6000</td>
<td>Orbital forcings</td>
</tr>
</tbody>
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Table 1.1: Major subdivisions of the Holocene Epoch and their climatic regimes summarized from the literature. *The boundaries between climatic intervals are transitional and regionally constrained.

1.2.2 Holocene paleoclimatology in Europe

Since a large number of seminal Holocene climatic studies have been conducted on the continent of Europe, this section summarizes the nature and extent of Holocene studies in various parts of Europe with a realization that although significant progress has been made in assessing
past climate variations over Europe, most long-term high-resolution reconstructions are restricted to temperature variations at high latitudes. Emphasis is placed on the late Holocene since this is the time period covered in this research.

Observational evidence and numerical models suggest that climatic variability in large parts of Europe is closely linked to changes in the North Atlantic atmospheric and thermohaline circulation (Emeis and Dawson, 2003). As well, change in the solar insolation is considered a climatic forcing for the Holocene climate in Europe. On the basis of macro- and microfossils analysis and radiocarbon dating of raised bog deposits in northern Europe, researchers found a close relationship between a decreased solar activity and fluctuations in radiogenic carbon (Blaauw et al., 2004, 2003, Kilian et al., 2000, 1995). These fluctuations seem to be coeval with major wet shifts ca. 850 BCE, that may have resulted in prominent climatic cooling independently documented and co-relatable in many parts of the Europe, including the North Atlantic Ocean (Bond et al., 2001), the Norwegian Sea (Calvo et al., 2002), Northern Norway (Vorren, 2001), England (Waller et al., 1999), the Czech Republic (Speranza et al., 2002, 2000), central southern Europe (Magny, 2004). The close correspondence between major shifts in δ¹⁴C and precipitation in the late Holocene is also discussed in detail by Mauquoy et al. (2004) implying that changes in solar activity may well have driven these changes during the Bronze Age/Iron Age transition around c. 850 cal. BCE (van Geel et al. 1996; 2000).

Holzhauser et al. (2005) report that the Alpine glaciers in west central Swiss Alps tend to show synchronous advances between 1500 BCE and the recent; these can be tied with millennium-scale climatic oscillations that produced alternating periods of cold-wet and warm-dry conditions in the mid-late Holocene. Many other studies from Europe are in agreement with this observation (e.g. Denton and Karlén, 1973; Magny, 1993; van Geel et al., 1996; Bond et al., 2001). While
studying another Alpine glacier and its correlation with contemporaneous land use phases between 2300 BCE to CE 800, Tinner et al. (2003) report that during the late Bronze Age Optimum from 1350 to 1250 BCE, the Great Aletsch glacier was approximately 1000 m shorter than it is today. According to Tinner et al. (2003), cold-wet phases in the Alpine history can be tied with the Iron/Roman Age Optimum between c. 200 BCE and 50 CE (i.e. the Roman Warm Period).

Assimilating multiple pollen-based proxy climate observations, Davis et al. (2003) presented the first reconstruction of the temperature of Europe during the Holocene. Their results suggest major spatial and seasonal differences in Holocene temperature trends within a remarkably balanced regional and annual energy budget and highlight the need for more detailed, localized datasets in order to provide an accurate climatic picture. According to Davis et al. (2003), Southern Europe and the Mediterranean have undergone an almost linear warming from around 8000 BP, which predates the onset of any major human impact and continues at the same rate through the anthropogenically dominant late-Holocene. They also added that the traditional mid-Holocene thermal maximum was confined to the summers of Northern Europe and this warming was balanced by a mid-Holocene cooling over Southern Europe. While summarizing, Davis et al. (2003) emphasized that the compilation of the climatic-ecological datasets for Southern Europe and their comparison with existing reconstruction is poorly constrained, because there have been relatively few quantitative climate reconstructions, except for the southern parts of France, Italy and parts of Greece.

To sum up, recent global warming and its potential impact on the hydrological cycle and subsequent ecological implications strengthens the need to quantify the degree of past natural climate variability in relation to human impact. This demand becomes even more critical particularly for drought sensitive, densely populated regions with intense agricultural background,
such as most of the Mediterranean basin and circum-Mediterranean regions like Balkans (Luterbacher et al., 2011; Seim et al., 2010).

1.2.3 Holocene paleoclimatology in the Balkans

In the last two decades, increasing number terrestrial and marine sediment records have started investigating the nature of Holocene climate change and human exploitation of the environment in the Circum-Mediterranean region (Roberts et al., 2011). Some major proxies that have been utilized for this region are discussed here.

1.2.3.1 Palynological studies

A large body of palynological data is available from the central and eastern Mediterranean that concentrates on mid to late Holocene reconstructions (Brayshaw et al., 2011; Luterbacher et al., 2011; Mercuri et al., 2011; Roberts et al., 2011a; Sadori et al., 2011). Recent pollen analyses from the Balkan region include studies from Romania (Feurdean, 2005; Feurdean et al., 2015, 2009, 2008; Feurdean and Bennike, 2004; Tantau et al., 2009), Bulgaria (Marinova et al., 2012; Stancheva and Lazarova, 2006; Stefanova et al., 2006; Tonkov, 2003; Tonkov et al., 2002), and Macedonia (Panagiotopoulos et al., 2013; Sadori et al., 2015). Most of these studies are in agreement in their reconstruction of the relatively warm Early Holocene interval (c. 9000-3000 BCE) and comparatively colder Late Holocene interval (c. 3000 BCE to 1900 CE). These studies help in understanding the relationship between local and regional climatic-ecological signals across the Balkans.

1.2.3.2 Speleothem studies

Kacanski et al. (2006) is the only speleothem study from Serbia found which examines the stable isotopic composition of a calcite speleothem that provides a partial late Holocene record of the climate change in the Balkans, and in Serbia specifically. Regression analysis of the
temperature based upon the oxygen isotopic data reveal a generalized downward trend in average
temperature over the past two millennia. However, it is unclear whether the trends are a local
phenomenon or represent regional or global climate conditions. A few Holocene speleothem
records are available from parts of Romania (Constantin et al., 2007; Drăgușin et al., 2014; Onac
et al., 2002; Tămaș et al., 2005) which reveal the regional temperature and precipitation variability
throughout the Holocene.

1.2.3.3 Dendrochronological studies

Dendrochronological studies (e.g. Briffa et al., 1999; Briffa, 2000; Martinelli, 2004)
provide a framework for late Holocene climate trends all over Europe. Of particular interest, there
have been several dendrochronological studies in the Balkans, i.e., Bosnia and Herzegovina
(Poljanšek et al., 2013), Bulgaria (Panayotov et al., 2010), Romania (Popa and Bouriaud, 2014;
Popa and Kern, 2009), Albania (Seim et al., 2010) in recent years. These provide a firm platform
for broader correlations used for the current study. As well, multidisciplinary projects in
environmental history and historical climatology in the proximity of the Balkans (e.g. Switzerland,
Austria, Czech Republic, and Hungary) serve as guidelines for the comparative approach used in
this research.

1.2.4 The past millennium

This dissertation deals with the latest part of the Holocene, the last 1000 years of the history
since 1000 CE (Figs. 1.2 and 1.3). Three major climatic events of this period and their significance
in this study are discussed here:

i. Medieval Climate Anomaly (MCA): The MCA, also known as the ‘Medieval Warm Period’
(~950–1250 CE), is often seen as the most recent global analogue for modern warming and
used as a means of assessing the impacts of natural versus anthropogenic drivers in the climate
system (e.g. Buntgen et al., 2011; Mann et al., 2009). Proxy-based temperature reconstructions for the Northern Hemisphere indicate generally warm conditions during the MCA with maximum warming during 950–1100 CE when temperatures were about 0.6°C higher than the 1960–1990 period (Christiansen and Ljungqvist, 2012). However, it has been also noted that the amplitude of the temperature anomaly varies strongly among regions with many records showing only little or no changes with temporal asynchronities (Luterbacher et al., 2011; Roberts et al., 2012). This picture is particularly true for the eastern Mediterranean-Balkan region, where recent dendrochronological data suggest that there is no evident warming in the region during the MCA (Popa and Bouriaud, 2014; Popa and Kern, 2009). This is consistent with Landrum et al., (2013), whose global simulation shows warmer winters in the region during the MCA, although the summer temperatures show little change compared to the present. The MCA and the transitional period between MCA and LIA is not separately discussed in this dissertation, but referred as the pre-LIA period due to unavailability of pollen data (major climatic proxy utilized in this study) especially between 1000 and 1350 CE.

![Fig. 1.3](image-url): Comparisons of simulated and reconstructed northern hemispheric temperature changes over the last millennium (Masson-Delmotte et al., 2013).
ii. **Little Ice Age (LIA):** The LIA followed the MCA approximately between 1450 and 1850 CE. This was a time when Northern Hemisphere annual temperatures were cooler, and winters were significantly colder with increased snow, compared to modern day winters (Bradley and Jones, 1993a; Jones et al., 1998; Mann et al., 1999, 1998). During this interval, European glaciers reached their greatest extent since the late Pleistocene (Matthews and Briffa, 2005). More importantly, the LIA is considered a regionally asynchronous cooling event that was significant in terms of increased variability of the climate (Mann, 2002; Mann et al., 2009). Many regions of Europe experienced their most dramatic climate extremes with large inter-annual and inter-decadal temperature and precipitation variability interspersed with prolonged multiyear periods of cold (Luterbacher et al., 2004; Pauling et al., 2006; Xoplaki et al., 2005). This variability had a profound effect on contemporary human populations and their strategies to manage the landscape (Pfister, 2005; Pfister and Brázdil, 1999). Although deforestation had begun centuries and millennia prior to the onset of the LIA, it was during the LIA when European land surface changed drastically as people cleared pristine areas and accelerated the rates of land erosion (Kaplan et al., 2009; Ramankutty and Foley, 1999).

The nature and magnitude of the LIA in the Balkans is poorly constrained due to lack of high-resolution hydroclimate studies covering the last few centuries. It is currently described as cold but drier when compared to northern-western European records (Feurdean et al., 2015; Luterbacher et al., 2011; Roberts et al., 2012 and references therein). The distinctive regional differences are considered to be a result of fluctuations in large-scale atmospheric circulation, that determines the relative influence of continental and oceanic air masses (Xoplaki et al., 2001). Hence, while unraveling the paleoenvironmental history of the Central Balkans, it is important to discuss the nature and variability of the LIA across the Balkans and its potential
role in shaping the landscape directly (e.g. changes in temperature and precipitation) or indirectly (e.g. transient weather patterns causing crop failures and humans increasing their deforestation).

iii. **Recent warming:** The 20\textsuperscript{th} century and the early 21\textsuperscript{st} century experienced the warmest period in most of the Northern Hemisphere (Luterbacher et al., 2004; Mann et al., 1998; Xoplaki et al., 2005). This period also shows more stable precipitation compared to the LIA for most parts of Europe with a general declining trend (Buntgen et al., 2011a; Touchan et al., 2005; Xoplaki et al., 2004). Anthropogenic greenhouse gas emissions are considered the main culprit for the changes (Alcamo et al., 2007; Hegerl et al., 2011). Furthermore, human activities (e.g., air pollution) and natural variability and processes in the atmosphere-hydrosphere system have contributed, particularly during the past few decades (IPCC, 2014). As noted by The Geological Society of London in a recent report (November 2010), evidence from the geological record is consistent with the physics that shows that adding large amounts of CO\textsubscript{2} to the atmosphere causes the temperature to rise (‘greenhouse effect’), which in turn leads to higher sea levels, changed patterns of rainfall (Alverson et al., 2003), increased acidity of the oceans (Barker and Elderfield, 2002; Caldeira and Wickett, 2003) and decreased oxygen levels in seawater (Keeling et al., 2010).

1.2.5 **Human-environmental interactions**

With a goal of discerning long-term human-environmental interactions, relatively few studies (e.g. Büntgen et al., 2011; Chapman et al., 2009; Gogou et al., 2016; Roberts et al., 2011a; Sadori et al., 2011; Widlok et al., 2012) have been conducted in parts of Europe. There are fewer studies that explore complex socio-ecological paradigms during the Common Era. This section
describes various approaches to show correlations among climatic, ecological and social datasets. However, identifying causality remains difficult.

While emphasizing the value of pollen research for discussing changing landscapes, Chapman et al., (2009) show that around 1000 BCE, the climate in Central Europe changed considerably toward extremely wet conditions that resulted in substantial deterioration of the environment of Early Iron Age settlers (e.g. seasonal and consistent inundations of arable lands since Late Bronze Age). There are significant social developments such as changes in subsistence strategies from agriculture to pastoralism and invention of a more effective forest clearance technology through iron working that occurred around the same time. Chapman et al. (2009) argue that the timelines for climatic and social changes cannot be merely coincidental and deteriorating agricultural lands under the changing climate might have led the settlers to explore alternative livelihoods and hence, inventing efficient ways to utilize forests as resources. On similar lines, Roberts et al., (2011a, 2011b) indicate that a sharp climatic migration from warm-wet to cold-dry conditions in eastern Mediterranean around 3000-1000 BCE encouraged the contemporary Bronze Age (BA) societies to intensify their land management skills to sustain themselves in the changing surroundings. They superimposed multi-centennial climatic and archaeological records to show that arid phases during the mid-Holocene coincide with major archaeological transitions across the eastern Mediterranean, such as Copper Age to early BA, early BA to middle BA, and late BA to Iron Age (Fig. 1.4). The authors imply that environmental stress or opportunity may have acted as a pacemaker for cultural change and reorganization during these phases, although the interrelationship between such changes and reorganizations might have been truly complex, and thus non-deterministic.
Discussing 2500 years of European climate variability and human susceptibility, Buntgen et al., (2011) provide the nature of climate variations and more viable ways to establish their linkages with agricultural productivity, health risk, and conflict level of preindustrial societies. Their tree ring–based reconstructions of central European summer precipitation-temperature variability during the Common Era show that wet-warm summers occurred during periods of Roman and Medieval prosperity while increased climate variability from ~250 to 600 CE coincided with the demise of the western Roman Empire and the turmoil of the Migration Period (Fig. 1.5). The most important aspect of this study is that they correlated demographic changes with forest dynamics to assess the type and extent of human impact on surrounding landscapes.

Gogou et al., (2016) discuss climate variability and socio-environmental changes in the northern Aegean (NE Mediterranean, south of this doctoral study) during the last 1500 years. Based on sea surface temperature reconstructions from Aegean Sea (NW of Greece) and their comparison with southern Balkan (Macedonia and Bulgaria) pollen sites, they show that the cultivation of temperature-sensitive crops from the region, i.e. walnut, vine and olive, largely co-
Fig. 1.5: A composite showing evolution of central European forest cover and population (A) together with oak sample replication (B), their historical end dates at decadal resolution (C) in association with reconstructed summer temperature and precipitation (Modified from Buntgen et al., 2011).

occurs with stable and warmer temperatures, while cooler temperature regimes are particularly bad for these crops. Gogou et al., 2016 confirm that periods of agricultural growth in Macedonia coincide with periods of warmer and more stable sea-surface temperatures (SSTs) in the Aegean Sea during the LIA. However, in order to establish better causal links for the observed rise in cultivation (i.e. to distinguish the natural and human impacts of the landscape), they incorporate
regional demographics in this analysis. According to them, the Black Death, the 14th century pan-European epidemic, clearly resulted in a decline of anthropogenic pressure that resulted in decreased agricultural activities and increased land erosion due to forest clearance in the subsequent century. As the population increased in the aftermath of Black Death and the tree cover continued to decrease throughout the LIA, there were significant peaks in mountain vegetation (e.g. beech-fir forests) in the southern Balkans, which is somewhat unlikely scenario considering the long history of highland pastoral economy of the Balkan region. Gogou et al., 2016 argue that the increase in the beech-fir forests during 17th and 18th centuries were primarily climate-driven (as shown by SSTs) when herders might have limited their use of high mountain pastures due to the more severe winters and cooler summers. Exploring the role of humans and climate over the Serbian-Central Balkan landscape during the LIA is the central theme of this doctoral dissertation; the above studies provide insights on how to integrate natural and social datasets in order to understand socio-ecological dynamics across the Balkans.

1.3 Methodology

During 2011-2013 field seasons, several sites were identified for extracting samples from different geologic environments including sinkholes, wetlands, and oxbow lakes. Multiple sediment cores were obtained using a modified Livingstone corer (Wright Jr. et al., 1984). After the preliminary examination of each core taken, the two most complete cores were selected and analyzed in detail in this doctoral dissertation.

1.3.1 Pollen and charcoal analyses

Paleoclimatic reconstruction by pollen analysis is possible thanks to four basic attributes of pollen: (1) they possess morphological characteristics that are specific to a particular genus or species of plant; (2) they are produced in vast quantities by wind-pollinated plants, and are
distributed widely from their sources; (3) they are extremely resistant to decay in certain sedimentary environments; and (4) they reflect the natural vegetation at the time of deposition, which (if viewed at the right scale) can yield information about past climatic conditions (Bradley, 1999). Since the plants are always associated with specific climatic zones and ecosystems, their fossil pollen and spores also represent the types of climates in which they existed as well as the nature of habitats – natural or anthropogenic – in which they flourished (Moore et al., 1991). This is particularly helpful for the late Holocene ecological settings that are dealt in this dissertation, where humans have been actively shaping the surrounding vegetation and landscapes.

Another proxy that helps to identify human impact on the late Holocene landscape is microscopic or macroscopic charcoal, which is a product of fire practices that people utilize to increase either agricultural or grazing areas at the expense of woodland in the region and can identify the extent of land clearance in the region (Li et al., 2008). Because charcoal particles can be carried aloft to great heights and transported great distances (Radtke et al., 1991), the source of the charcoal may be from regional (distant) fires, extra-local (nearby but not within the watershed) fires, or local (within the watershed) fires (Whitlock and Larsen, 2001). Hence, the concentrations of microscopic (<100 μm) charcoal fragments are found to indicate the regional nature of fire-land clearance whereas the macroscopic (>100 μm) charcoal is more widely used to reconstruct local fire episodes (e.g. Hallett and Walker, 2000; Long et al., 1998; Millspaugh et al., 2000; Mohr et al., 2000). Considering the regional nature of human-environmental interactions, this study focused on quantification of microscopic charcoal rather than macroscopic charcoal. It is also understood that microscopic charcoal abundance increases during local-natural fires, however, sedimentary records of human use of fire and the natural fire are different as the former is generally accompanied by the occurrence of anthropogenic pollen (e.g. weeds or cereals) (Li et al., 2008).
A careful correlation between pollen and charcoal datasets in this study allowed to shed light on the origin of fires due to human or natural causes.

In order to extract pollen, spores and charcoal from sediments, the samples (e.g. 1-2 cm$^3$) are usually taken at specific intervals (e.g. 8-10 cm) followed by sieving (120 and 7 μm) and a standard chemical procedure involving 10% KOH, 10% HCl, 40% HF, and acetolysis to remove inorganics (Faegri et al., 2000). To enable calculation of pollen, spore and micro-charcoal concentrations (/cm$^3$) and their influx/accumulation rates (/cm$^2$yr), an exotic marker, a *Lycopodium* tablet with a known amount of spores (Stockmarr, 1971) was added to samples before treatment. Biological residues obtained through the above chemical treatment are then dehydrated in alcohols and suspended in silicone oil for microscopic identification and quantification. Identification of pollen and other palynomorphs is based upon the reference slides collected from the study area as well as using relevant keys (Moore et al., 1991; Reille, 1999). “How many pollen to count to make the analysis statistically viable” is the central question in the field of paleopalynology; although the total number of grains counted at each level would depend on the purpose of the study and the source of material being studied, counting at least 200 terrestrial pollen grains has become a customary (Moore et al., 1991; Traverse, 2007). The percentages of arboreal pollen (AP) and non-arboreal pollen (NAP) are based upon the sum of terrestrial pollen (excluding *Cyperaceae* and obligate aquatics) unidentified pollen. Aquatic pollen as well as spores are usually counted in addition to the terrestrial pollen and are presented as a percentage of terrestrial pollen plus aquatics and as a percentage of terrestrial pollen, aquatics, plus spores respectively. Microscopic charcoal pieces are counted for the same slide area as for the pollen. Pollen, charcoal and supportive datasets can be plotted using specialized softwares (e.g. TILIA (Grimm, 1992)).
While the site-specific limitations (and corresponding solutions) have been discussed in Chapter 2 and Chapter 3, overall limitations of pollen analysis in this study are as follows:

1. A major obstacle in pollen analysis remained the low pollen preservation (low pollen concentration) in both the sites under investigation. Due to lack of background data from the region, the cores were selected largely on the basis of the quality of the recovery (almost 100%) and the factors such as organic content, carbonate content could not be tested until the actual analysis was carried out. Both study sites provided highly inorganic and calcareous samples that were inherently alkaline in nature. In general, pollen preservation is enhanced in acidic soils (pH<7) and if pollen does occur in base-rich soils, they occur in low concentrations (Dimbleby, 1957; Dimbleby and Evans, 1974). This might have been a main reason behind low pollen concentrations in both Serbian cores, which made the pollen extraction and counting process quite laborious.

2. The problem of high inorganic content of the sediment samples was partially compensated by utilizing larger volumes of the samples (3-5 cm$^3$) for pollen extraction while extended exposures of the 10%HCl was needed for removal of calcareous inorganics from the samples. These modifications allowed a slightly better recovery of the pollen that were used for quantification.

3. A minimum of 300 terrestrial pollen grains was counted for most depths, however, there were a few samples from each core where this threshold sum could not be achieved due to extremely low (<10,000/cm$^3$) pollen concentrations. Although the most pollen counts were above “a customary threshold” of 200 (Moore et al., 1991; Traverse, 2007), their statistical viability for interpreting vegetation history was tested using two statistical analyses: stratigraphically constrained incremental sum of squares (CONISS) cluster analysis and
rarefaction analysis. The CONISS is applied to actual pollen counts to cluster statistically and stratigraphically close taxa (Grimm, 1987), which helps to create unbiased pollen zonations for further interpretation. Similarly, rarefaction analysis enables a comparison of taxon richness between samples of different size (e.g. pollen sum) by standardizing pollen counts to a single sum (Birks et al., 2016; Birks and Line, 1992) to better document the diversity changes within vegetation units through time (Berglund et al., 2008; Birks and Birks, 2008; Feurdean et al., 2012; Flenely, 2005; Meltsov et al., 2011; Weng et al., 2007; Willis et al., 2007). The robust estimate of taxon richness through this analysis is the expected number of taxa, \( E(S_n) \) (Birks and Line, 1992; Gotelli and Graves, 1996; Heck et al., 1975; Hurlbert, 1971; Sanders, 1968; Simberloff, 1978), whose values were plotted against respective depths and AP and NAP percentages.

1.3.2 Lithological and geochemical analyses

The loss-on-ignition (LOI) procedure is largely used for estimating organic matter within the sediments with the help of loss in the sample weight when heated at a temperature only high enough to burn organic matter. To calculate LOI, the subsamples are weighed before and after overnight drying at 100°C to get rid of initial moisture and are then placed in a muffle furnace at 550°C for 2 hours (Dean, 1974). The remaining residues are inorganic portions of the samples, from which the organic content of the samples could be calculated as percent fractions of their dry weights. The LOI at 550°C has been found to be a robust proxy to summarize many changes in a lake ecosystem, however, it is a percentage, and thus an increase can reflect an absolute increase in organic matter or an absolute decrease in mineral matter, or some combination of both (Birks and Birks, 2006). In addition, organic and mineral matter can both originate in the lake (bioproduction, biogenic silica and carbonate) and/or in the catchment (bioproduction, humus or
mineral in-wash due to catchment instability), thus %LOI is a simple measurement that can have complex interpretations (Shuman, 2003). In this study, the LOI was calculated 8-10 cm intervals (same as that of for the pollen) and were utilized in relation with sedimentological as well as geochemical changes.

The application of X-ray Fluorescence (XRF) technique is widely known for effective elemental analysis of natural and artificial substances. The XRF scans of the sediment core taken at select intervals track geochemical imprint of sediments by providing counts of individual elements including Potassium (K), Titanium (Ti), Iron (Fe), Calcium (Ca), Lead (Pb) and many more that serve as proxy for certain environmental processes (e.g. Arnaud et al., 2012; Aufgebauer et al., 2012; Francke et al., 2013; Hennekam and de Lange, 2012; Hölzer, A. and Hölzer, 1998; Lomas-Clarke and Barber, 2007; Panagiotopoulos et al., 2013; Silva-Sanchez et al., 2015). For example, it has been shown that K and Ti indicate the degree of terrigenous silicate input and soil erosion in the lake settings, hence K and Ti concentrations or K/Ti ratio can act as proxy for physical weathering in the catchment (Arnaud et al., 2012; Aufgebauer et al., 2012; Francke et al., 2013). Thus, sediments with high values of terrigenous abundance and high sedimentation rate tend to show high K and Ti concentrations. Also, the variation in concentrations of certain metal species such as Fe, Ca, and Manganese (Mn) are a result of changes in hydrological processes, climate, and ecology (Boyle, 2001); sedimentary Ca in many lake systems reflects changes from an open to closed basin during wet to dry periods with calcite reaching saturation during dry periods (Cantarero, 2013).

In this study, the XRF analysis of the sediment cores was performed using an InnovX Olympus Delta DC-4000 multibeam XRF analyzer. Three or more readings were taken continuously at 1-cm intervals with a counting time of 90s and acceleration intensities of 15-40kV.
The values were averaged for each depth and the five-point moving averages were used for final data analysis in order to suppress any noise. Because the sediment matrix is characterized by variable water content and grain size distributions, the count rates obtained for individual elements can be used as semi-quantitative estimates of their relative concentrations (Aufgebauer et al., 2012; Massa et al., 2012); the attention was given to discussing both qualitative as well as quantitative implications of the select geochemical data (e.g. K, Ti, Fe, Ca) in relation with ecological datasets.

### 1.3.3 AMS radiocarbon dating

Radiocarbon dating has transformed our understanding of the timing of events and rates of change in archaeological and environmental proxy records since it was developed in the late 1940s (Libby et al., 1949). $^{14}$C years do not directly equate to calendar years because atmospheric $^{14}$C concentration varies through time due to changes in the production rate, caused by geomagnetic and solar modulation of the cosmic-ray flux, and the carbon cycle (DeVries, 1958; Reimer et al., 2009; Stuiver and Suess, 1966). Calibration is required, which, to be accurate and precise, should ideally be based on an absolutely dated record that has carbon incorporated directly from the atmosphere at the time of formation (Reimer et al., 2013). The age-depth models for both Serbian cores are based on seventeen such absolute-dated and calibrated AMS $^{14}$C chronologies obtained from the Center for Atomic Mass Spectrometry, Lawrence Livermore National Lab, California. All dates were calibrated to calendar years using the CALIB 7.0.0 calibration program (Stuiver et al., 2005) with the INTCAL13 calibration curve (Reimer et al., 2013). A few difficulties that were encountered in the process of creating age-depth models for the study sites are as follows:

1. An unavailability of sufficient dating material remained a major concern due to the highly inorganic nature of the sediments investigated. All available identified macrofossils (seeds, leaf-bark-twig fragments, charcoal fragments, fish bones, freshwater gastropod shells) were sent for
dating in available quantities (at times, ~2 mg). Small sample sizes could result in a low ion current in the AMS system that produces in less reliable dates that are often too young (Jahns, 2005). This may have contributed to a few modern/post-modern and stratigraphically incongruent dates which were excluded from the corresponding age-depth models.

2. Several possible relative age ranges exist for a single date during the last millennium because there are chronological uncertainties due to deviations in \(^{14}\)C production (Kilian et al., 1995; Mauquoy et al., 2004; van Geel et al., 1998). Thus, calendar age ranges selected for the both age models were chosen on the basis of high relative area under the probability distribution within the 95.4\% (2-sigma), which covers maximum possible standard deviation (or uncertainty) making the dates statistically more reliable. Since the cores were extracted in the year 2012, the core tops were set at 2012 CE, which also gave an additional data point for creating the age-depth models. Using a combination of linear extrapolation and linear regression principles, the core top, select AMS dates with 2-sigma ranges allowed to create stratigraphically and statistically sound age-depth models in this study.

1.3.4 Correlation among environmental, social and climatic datasets using statistical means

In this study, environmental datasets (e.g. woodland, grassland, land erosion, land clearance, and agriculture) obtained from the above analyses are correlated with social datasets (e.g. historic population data, land use models, archival records of societal calamities, and critical historic events) derived from a review of the literature and local archives using time series and principal components analyses. To visualize the correlation among the ecology-society-climate datasets across the given temporal frame of reference, time series has been an intuitive and straightforward approach utilized in almost all integrated socio-environmental studies (e.g. Büntgen et al., 2011; Burke et al., 2009; Giosan et al., 2012; Gogou et al., 2016; Kaplan et al.,
2009; Kelley et al., 2015; Roberts et al., 2011b; Widlok et al., 2012). On the other hand, the use of Principal Components Analysis (PCA) is a new approach that has been recently receiving more attention to highlight and summarize major patterns and apparent connections among ecological-social-climatic processes (e.g. Birks and Birks, 2006; Kuneš et al., 2015; Nielsen et al., 2012; Schnitchen et al., 2006; Virah-sawmy et al., 2009). The PCA is basically a data-reduction technique that allows plotting the coefficients in the matrix containing principal components (PCs). The axes in such plots represent the first two or three PCs where each ecological or social indicator is represented as a vector (line) and dots show the actual values of these indicators (Kohler and Luniak, 2005).

In this study, time series for the environmental and social indicators were reconstructed and then became factors in the PCA biplot of the respective Serbian site. Since these indicator values are common for the two approaches, the parallel application of these two statistical means allow the better visualization of the datasets. However, a few problems encountered in the process of integration and correlation are discussed here with their tentative solutions.

1. A major reservation against using the PCA in socio-ecological studies is the varying spatial extents across the datasets; a covariance and thus, correlation could exist between spatially aggregated data (e.g. climate, social) and individual sampling locations (e.g. ecological signals from two Serbian cores). In this study, this was a principal challenge as the environmental-social-climatic datasets posed their individual as well as collective spatial variability and a lack of means to normalize these scales.

a. For environmental datasets, pollen, geochemical, and micro-charcoal records are considered regional in nature since their influxes are dependent on the overall ecological-geological makeup of the catchment as well as regional wind patterns (Dimbleby, 1957; Sugita, 2007).
However, the size of the lake that traps these records needs to be taken into consideration. For example, due to its small size (~230 m²), one of the Serbian lakes seemed to be more locally influenced in terms of receiving pollen influxes from the Central Balkan region. Its pollen zones are discussed as Local Pollen Assemblage Zones (See Chapter 2 for details) and as local variations among the regional vegetation changes shown by another large (~1.27 km²) site under the study (See Chapter 3 for details). Local versus regional variations were kept in mind when discussing the correlations across Serbia-Central Balkans, as well as when examining these datasets with the Eastern European deforestation model (Kaplan et al., 2009) and changes in population and political regimes such as wars that occurred within the realm of the Ottoman Empire in the Balkans.

b. In case of social datasets, it could have been spatially more legitimate to correlate any past Serbian environmental records with the contemporary Serbian (available only as Yugoslavian) population records, but due to the fact that the Ottoman Empire stretched across the Balkans, it is impossible to distinguish the political influence, especially wars, on contemporaneous sub-regional populations in the Balkans. There was no way to normalize the historic population dataset as there is a lack of consensus on the estimates of historical population, especially for times earlier than the 18th century (Pongratz et al., 2008; Zhang et al., 2010).

2. Another important aspect of integrated socio-ecological research is to understand that vegetation and landscape changes across the Common Era are collective artifacts of contemporary climatic and human socio-political impacts (Buntgen et al., 2011a; Cook et al., 2015; Seager et al., 2007). Even if the PCA approach tends to highlight the major patterns of variations through the eigenvalues and not through the original data points, it does not leave
behind the temporal context as the samples are used in the stratigraphic order. While learning apparent connections among ecological-social-climatic processes from the PCA biplots, the time-series remained a principal source of interpretation in this study.

1.4 Significance of the Current Study

In what way does the paleoenvironmental archive from Serbia contribute to our knowledge of spatial and temporal vegetation patterns in the Balkans and eastern Mediterranean region? Is it possible to deduce the nature and extent of short-term climate variations from such paleovegetation records? How can studying fossil pollen grains originating from a remote area of the Balkan Peninsula be relevant to pressing policy issues dealing with the biodiversity and climate change agenda? (Panagiotopoulos, 2013) These key questions highlight a need to put this doctoral research into a broader perspective.

At present, Southeastern Europe as elsewhere around the world is facing impending environmental and social changes. According to IPCC (2014), the Balkan countries are among the most affected regions in terms of changing water cycle due to extreme climatic events such as increased flooding and droughts. The sensitivity of Europe to climate change has a distinct north-south gradient, with many studies indicating that southern Europe will be more severely affected than northern Europe (Alcamo et al., 2007; EEA, 2004). The already hot and semi-arid climate of southern Europe is expected to become warmer and drier, and this will threaten its waterways, agricultural production and timber harvests (e.g., EEA, 2004). In the light of such recent studies, it is evident that parts of Balkans will undoubtedly be affected locally and socially as elsewhere. Particularly, Serbia’s likely entry into the European Union may put a larger stress on Serbian societies, in terms of posing challenges to its economic sectors.
The sustainability of agriculture and its resilience in the face of changing environmental and social conditions is a timely question and could have relevance to political debates both within and outside the country. The importance of generating new high-resolution proxy datasets for this region lies here; they record and explain the nature of responses and interactions of past societies on how they coped with drastic climatic events. This dissertation generates two such independent proxy datasets for Serbia and subsequently integrates them with climatic indicators and available social proxies (e.g., population, deforestation-land use models, records of famines, droughts, crop failures, and critical historic events) to shed light on the interplays and feedbacks of climate variability in the context of human landscapes and activities. This research is the first one undertaken in Serbia and places Serbian palaeoecology on the world map.
Chapter 2

Exploring the role of humans and climate over the Balkan landscape:

500 years of vegetational history of Serbia

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Abstract

This study presents the first, well-dated, high-resolution record of vegetation and landscape change from Serbia, which spans the past 500 years. Biological proxies (pollen, spores, and charcoal), geochemical analysis through X-ray Fluorescence (XRF), and a detailed chronology based on AMS $^{14}$C dating from a western Serbian sinkhole core suggest complex woodland-grassland dynamics and strong erosional signals throughout the Little Ice Age (LIA). An open landscape with prominent steppe vegetation (e.g. Poaceae, Chenopodiaceae) and minor woodland exists during 1540-1720 CE (early LIA), while the late LIA (1720-1850 CE) in this record shows higher tree percentages possibly due to increased moisture availability. The post LIA Era (1850-2012 CE) brings a disturbed type of vegetation with the presence of weedy genera and an increase in regional woodland. Anthropogenic indicators for agricultural, pastoral and fire practices in the region together attest to the dominant role of humans in shaping this Balkan landscape throughout the interval. The changing nature of human interference, potentially as a response to underlying climatic transitions, is evident through large-scale soil depletion resulting from grazing and land clearance during the early LIA and stabilization of arable lands during the late and post-LIA eras.
2.1 Introduction

Situated at the crossroads of three major continents, the Balkan Peninsula (Fig. 2.1a) is a region of diverse climate, complex physical geography, and outstanding levels of floral and faunal endemism (Griffiths et al., 2004). It is called a “European biodiversity hotspot” (Petit et al., 2003) as it served as a refugium for many species during past Ice Ages and the region as a whole is surpassed in species richness only by the tropics (Mooney, 1988). Zolitschka et al. (2000) highlight the importance of paleoecological research in this circum-Mediterranean region across three broad fronts; (1) the potential of obtaining very long records of environmental change from basins that have not been over-ridden by extensive glaciations (unlike northern Europe); (2) the fact that the region is a ‘frontier zone’ where the tropical (monsoonal) climatic system of northern Africa meets and interacts with the North Atlantic climatic system; and (3) the long history of human occupation and civilization in this region (Eastwood, 2004) that makes it a unique setting to study cultural history in relation to evolving landscapes. Moreover, the Balkan landscapes are now part of the most rapidly changing ecological regions of Europe and are very sensitive to dramatic climate change in terms of varying precipitation and temperature patterns (Alcamo et al., 2007; EEA, 2004; IPCC, 2014). This further highlights the need for accumulating more high-resolution ecological records particularly covering the last 2,000 years of environmental history where the responses of the terrestrial ecosystems to climatic changes under scenarios similar to the present can help us to better evaluate the interplays and feedbacks of climate variability in the context of human landscapes and activities (Mercuri and Sadori, 2014). One such proxy-based reconstruction over the last millennium from Serbia, Central part of the Balkans is presented here (Fig 2.1a), which brings important insights for understanding current climate change within a long-term context.
Fig. 2.1: (a) Available Quaternary-Holocene pollen records (black dots) from the Balkans (green highlighted region) (Data source: http://www.europeanpollendatabase.net/data/). The location of Serbia (patterned) and the study site (star) are shown. (b) Photograph of the coring site showing the sinkhole under investigation (Photo credit: Charuta Kulkarni). (c) Vegetation classification of western Serbia, Central Balkans after Horvat et al. (1974). The location of the study site is shown with a star.

The focus of this study is to describe and interpret the environmental history of a Serbian landscape over the past 500 years, including the ‘Little Ice Age’ (LIA), which was a major climatic interval that imposed significant changes on landscapes inhabited and cultivated by contemporary societies. From c. 1500 to 1850 CE, the LIA followed the ‘Medieval Climate Anomaly’, and was a time when Northern Hemisphere annual temperatures were cooler, and winters were significantly colder with increased snow when compared with modern day winters (Bradley and Jones, 1993a; Jones et al., 1998; Mann et al., 1999). During this interval, European glaciers reached their greatest
extent since the late Pleistocene (Matthews and Briffa, 2005). More importantly, this regionally asynchronous cooling is significant in terms of increased variability of the climate (Mann, 2002); many regions of Europe experienced most dramatic climate extremes in terms of large inter-annual as well as inter-decadal temperature and precipitation variability amongst prolonged multiyear periods of cold (Luterbacher et al., 2004; Pauling et al., 2006; Xoplaki et al., 2005). This variability had a profound effect on contemporary human populations and their strategies to manage the landscape (Pfister, 2005; Pfister and Brázdil, 1999). Although deforestation had begun centuries and millennia prior to the onset of the LIA, it was during the LIA when European land surface changed drastically as people cleared pristine areas for agriculture and accelerated the rates of land erosion (Kaplan et al., 2009; Ramankutty and Foley, 1999). Particularly for the Balkans and Serbia, this was a critical period in terms of political, social, economic and demographic changes. After several major conflicts with regional kingdoms in the early 1500s, the Ottoman Empire conquered the Balkans and for almost the next 160-170 years, instituted a number of systems for the management and provisioning of resources for its territories, all the while directing the expansion of the settlement and cultivation across the region (White, 2011a). Both 16th and 17th Century Balkans enjoyed a relatively peaceful period with noteworthy commercial progress and significant increase in population (McEvedy and Jones, 1978). However, by the end of the 17th century, the Ottoman Empire started suffering a major crisis with increasing economic turmoil and social unrest from which it never fully recovered (Fine Jr., 1994; White, 2006). In the 17th-18th centuries during the late Ottoman rule, it was in the war zone of the frequent Habsburg–Ottoman confrontations (1683–99, 1714–18, 1736–39, 1788–92) that forced the outmigration of the inhabitants (Palaiaret, 1997; Stoianovich, 1992). As a result, cultivated lands were abandoned and parts of the Balkans returned to its conventional pastoral economies. Despite their attempts to restore order, the
Ottomans completely lost control over their territories and during 1850-70s, Serbia and other Balkan countries came under independent principalities (Ali, 2012). Subsequently, the withdrawal of Ottomans relaxed the region and a significant demographic rise was seen after 1850s (McEvedy and Jones, 1978; Palairet, 1997). This inward and outward flow of people in Serbia (as well as in every part of the Balkans) has left substantial impacts on the landscape under the changing LIA climatic regimes. The LIA climatic migration coincided with the changing nature of human interference that provides an interesting socio-ecological problem. Here, the first step to unravel this intricate puzzle is undertaken by reconstructing the regional vegetational history of Serbia on a multi-decadal temporal scale.

2.2 Study area

The sediment record is derived from a sinkhole located in western Serbia near a locality called Donja Sipulja (44°30'14.33"N, 19°30'18.46"E) at an elevation of 250 m a. s. l. (Fig. 2.1b). This surficially dry sinkhole is oblate in shape with a surface area of roughly 230 m². While granites and granodiorites dominate the Cer mountains to the north, the late Cretaceous-Tertiary sequences of limestones and dolomites (Dimitrijević, 1997) give this area a typical karstic topography embedded with numerous sinkholes.

Most parts of Serbia enjoy continental climate with moderate sub-Mediterranean influences - cold, relatively dry winters and warm, humid summers. The mean annual air temperature for altitudes lower than 300 m is about 11°C with July maximum temperatures ranging between 37 and 42°C (RHMSS, n.d.). Serbia has a continental precipitation regime with higher rainfall in the warmer part of the year; June is the wettest month with an average of 12 to 13% of total annual precipitation. In low-lying regions such as the study site, annual precipitation is about
540 to 820 mm per year that varies with elevation and exposure. Snow cover is characteristic from November to March, and January has the majority of days with snow cover (RHMSS, n.d.).

Serbia presents an “ecosystem mosaic” composed of forests, shrubs, meadows-pastures, swamps, marshes, and lakes with a mixture of many continental and select sub-Mediterranean plant communities (Radović and Kozomara, 2011). Horvat et al. (1974) provide the detailed vegetation classification of the Balkan region (Fig. 2.1c) characterizing the study area vegetation as part of the deciduous community of Hungarian and Turkey oaks, *Quercus frainetto* and *Quercus cerris*. This oak alliance is extensive in its distribution throughout the region and occurs in several geographic variants; one of them that exists in the study area is a mesophilous community of sessile oak *Quercus petraea*, and hornbeam, very similar to the Illyric *Quercus-Carpinus illyricum* zone (Rakonjac and Nevenic, 2012). The latter occasionally occur with their xerothermic deciduous Submediterranean variants, especially *Carpinus orientalis/Ostrya carpinifolia* in the hilly-mountainous regions. A well-defined and fairly homogeneous submontane-montane community (over 500 m a.m.s.l.) exits throughout Serbia with *Fagus moesiaca* as well as *F. sylvatica* and its associated taxa, *Abies* spp., and *Acer heldreichii*. While sub-alpine coniferous (predominantly *Picea*) belts are rare in this region, some shrubby coniferous taxa exist at tree line above 1800 m.a.s.l. that include *Pinus mugo, Juniperus sibiricae*, and *Vaccinium* varieties (Rakonjac and Nevenic, 2012). The Pannonian forest-steppe zone is also quite uncommon in this region, but may be found as smaller stands of xerothermic oak and maple communities such as *Quercus pubesens, Q. petraea, Acer tataricum* (Tomic et al., 2011).

The modern vegetation at the study site is mainly composed of grasses (Poaceae), herbs (Polygonaceae, Chenopodiaceae, Asteraceae families and the *Plantago* group), sedges, and minor woodland (Fig. 2.1b). Trees and shrubs in the area that are characteristic of the lowland Balkan
deciduous forest include Quercus cerris, Q. frainetto, Carpinus betulus, Acer campestre, Fraxinus excelsior (and/or F. angustifolia and other variants), and minor occurrence of Salix spp. Anthropogenic tree-shrub taxa include Corylus maxima, Juglans regia, and Sambucus ebulus and two Cornus varieties, Cornus mas and C. sanguinea. To a lesser extent, coniferous taxa Pinus nigra and Juniper communis are also found in the surroundings. Herbs include Polygonaceae (Polygonum aviculare and Rumex spp.), Asteraceae family (Asteroideae, Cichorioideae, and Artemisia groups; the Asteroideae includes Anthemis, Carduus and Cirsium types. The Plantago taxa consist of Plantago lanceolata, P. media and possibly P. altissima and/or other Plantago varieties. The wetland species mainly include a variety of Cyperaceae, predominantly Carex and Scirpus.

2.3. Materials and methods

2.3.1. Core extraction

In the summer of 2012, a 2.1 m sediment core (hereafter, DS) was extracted from the center of a sinkhole using a modified Livingstone piston corer (Wright Jr. et al., 1984). After recovery, the core was described in the field and was refrigerated at 2-3°C until further processing.

2.3.2. Lithological and geochemical analyses

The split core was described for lithology and then sampled at 10-cm intervals for loss-on-ignition (LOI), pollen and micro-charcoal analyses. To calculate LOI, the subsamples were weighed before and after overnight drying at 100°C to get rid of initial moisture and then placed in a muffle furnace at 550°C for 2 hours for determining organic/inorganic content (modified after Dean, 1974). XRF analysis of the core was performed at 1-cm intervals using an InnovX Olympus Delta DC-4000 XRF analyzer at the Environmental Sciences Analytical Center, Brooklyn College of CUNY. Three or more readings were taken and the values were then averaged for each depth.
The five-point moving averages were used for final data analysis. Only a selection of elemental data from the XRF scanning is presented here; these include potassium (K), titanium (Ti), and iron (Fe) as they act as a proxy for surface erosion and clastic sediment supply (Arnaud et al., 2012; Francke et al., 2013).

2.3.3. Palynological and charcoal analyses

In order to extract pollen, spores and charcoal from sediments, 3-5 cm$^3$ of samples were sieved (120 and 7 μm) and processed using 10% KOH, 10% HCl, 40% HF, and acetolysis (Faegri et al., 2000). Pollen residues were dehydrated in alcohols and suspended in silicone oil. To enable calculation of pollen, spore and micro-charcoal concentrations, an exotic marker, i.e. *Lycopodium* tablet with a known amount of spores (Stockmarr, 1971) was added to samples before treatment. Identification of pollen and other palynomorphs was based upon the reference slides from the Laboratory of Palynology of the University of Novi Sad and from the Lamont Doherty Earth Observatory (LDEO) as well as using relevant keys (Moore et al., 1991; Reille, 1999). A minimum of 300 terrestrial pollen grains was counted for all depths excluding 120, 130, 160, 190-210 cm due to extremely poor pollen preservation; the terrestrial pollen counts for these depths are slightly lower than 200. The percentages of the selected taxa are based upon the sum of terrestrial pollen (excluding Cyperaceae and obligate aquatics) and unidentified pollen. Aquatic pollen as well as spores were counted in addition to the terrestrial pollen and are presented as a percentage of terrestrial pollen plus aquatics and as a percentage of terrestrial pollen, aquatics, plus spores respectively. Microscopic charcoal pieces >50 μm were counted along with pollen grains. The size criterion was selected to avoid confusion of microscopic charcoal with opaque mineral material, which is typically <50 μm in one dimension (Clark and Patterson III, 1984). All diagrams were plotted using TILIA and TILIA Graph (Grimm, 1992).
2.3.4. Statistical analyses

The total number of different pollen taxa present in a sample and the relative frequencies of different taxa are dependent on various factors including pollen productivity, dispersal mechanisms, basin size, sediment accumulation rate, sampling effort (i.e. pollen sum), and evenness (Odgaard, 1999; Peros and Gajewski, 2008; Seppa, 1998; van der Knaap et al., 2012; C. Weng et al., 2006). In order to elucidate a more impartial vegetational picture, rarefaction analysis is applied to render minimum variance unbiased estimates of the expected number of pollen and spore types that would have been found, if all the samples had the same count size thereby reducing bias in richness caused by different pollen count sizes (Birks et al., 2016; Birks and Line, 1992). This statistical data interpolation technique is widely utilized in palynology as it also enables comparison of richness between samples of different size by standardizing pollen counts to a single sum (Birks et al., 2016). Several long-term palynological studies have attested that palynological richness estimated through rarefaction analysis offers a good understanding of diversity changes within vegetation units through time (Berglund et al., 2008; Birks and Birks, 2008; Feurdean et al., 2012; Flenely, 2005; Meltsov et al., 2011; Weng et al., 2007; Willis et al., 2007). To examine trends in pollen diversity across the western Serbian landscape, a rarefaction analysis was conducted with the help of EstimateS 9.1.0 (Colwell, 2013). All terrestrial pollen were included and the lowest pollen count was used to standardize the size of the pollen counts for each sample. A few pollen-poor samples, which could not meet the threshold sum, were excluded from the analysis. The most robust estimate of richness through rarefaction analysis is the expected number of taxa, E(Sn) (Birks and Line, 1992; Gotelli and Graves, 1996; Heck et al., 1975; Hurlbert, 1971; Sanders, 1968; Simberloff, 1978) whose values were plotted against respective depths with other ecological and geochemical proxies.
2.3.5 Chronology

Plant macrofossils were selected for radiocarbon dating after screening 4-6 grams of sediment with water through screens of 500 and 250 microns. Seeds were identified using the Peteet seed collection at LDEO. The age model for this DS core is based on eight accelerator mass spectrometry (AMS) \(^{14}\text{C}\) dates measured at the Center for Accelerated Mass Spectrometry, Lawrence Livermore National Laboratory. The depths, types of macrofossils dated and associated uncalibrated and calibrated ages are presented in Table 2.1. Radiocarbon dates were calibrated to calendar years using the CALIB 7.0.0 calibration program (Stuiver et al., 2005) with the INTCAL13 calibration curve (Reimer et al., 2013). Due to notable deviations in \(^{14}\text{C}\) production for the time period spanned by this study resulting in chronological uncertainties, several possible relative age ranges exist. Thus, calendar age ranges selected for the age model were deliberately chosen on the basis of high relative area under the probability distribution within the 95.4% (2-sigma) enclosed area. Since the core was extracted in the year 2012, the core top was set at 2012 CE and the age depth model for the DS core was created using this and select AMS dates (Table 2.1; Fig. 2.2) with a combination of linear extrapolation and linear regression principles. Considering the excellent linear correlation among the dates \((r^2 = 0.9908)\), any complex modelling method (e.g. Bacon, OxCal) were not utilized to reconstruct the age-depth model. Sediment accumulation rates were calculated accordingly for each segment in the age-depth model (Fig. 2.2).

2.4. Results

2.4.1. Lithology and age model

The DS core is composed of alternating sequences of clay, silty clay, and silt varying between greyish brown and olive grey hues (Fig. 2.3). The coring site is located at a relatively low
elevation with the nearest stream located ~800 m away at a much lower elevation. While there is always a possibility of minor, ephemeral surface runoff into the sinkhole, the complete absence of coarser grained sediments (e.g. sand) throughout the core is indicative of the lack of major runoff. The sediment accumulation is continuous and the boundaries between sediment sizes are largely gradational.

<table>
<thead>
<tr>
<th>AMS Lab ID</th>
<th>Sample Depth (cm)</th>
<th>Materials used for dating</th>
<th>Uncorrected $^{14}$C age BP</th>
<th>Calibrated 2-sigma age range (cal CE)</th>
<th>Calendar age (cal CE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>163351</td>
<td>28-30</td>
<td>1 unidentified seed</td>
<td>Modern</td>
<td></td>
<td></td>
</tr>
<tr>
<td>164416</td>
<td>46- 48</td>
<td>Woody fragments, charcoal, twig fragments</td>
<td>115±25*</td>
<td>1803-1937 (70%)</td>
<td>1870*</td>
</tr>
<tr>
<td>163352</td>
<td>95-97</td>
<td>Charcoal fragments</td>
<td>190±25*</td>
<td>1731-1808 (60%)</td>
<td>1769*</td>
</tr>
<tr>
<td>164417</td>
<td>139-141</td>
<td>Charcoal and leaf fragments</td>
<td>170±25*</td>
<td>1663-1695 (18%)</td>
<td>1679*</td>
</tr>
<tr>
<td>163353</td>
<td>159-161</td>
<td>1 wood fragment</td>
<td>220±25*</td>
<td>1644-1681 (43%)</td>
<td>1662*</td>
</tr>
<tr>
<td>166829</td>
<td>169-171</td>
<td><em>Sambucus</em> seed, bark fragments</td>
<td>Modern</td>
<td></td>
<td></td>
</tr>
<tr>
<td>164418</td>
<td>191-193</td>
<td>1 bark fragment, twig fragments</td>
<td>Modern</td>
<td></td>
<td></td>
</tr>
<tr>
<td>166830</td>
<td>199-201</td>
<td>1 bark fragment</td>
<td>135±35</td>
<td>1669-1780 (43%)</td>
<td>1724</td>
</tr>
</tbody>
</table>

Table 2.1: AMS Age ranges for 95.4% (2-sigma) enclosed area shown for the range used in calendar age calculation. Relative percent area represented by the calendar range is shown in parentheses ( ). Selected dates are shown by an asterisk (*) and the selection criterion is discussed in detail in the results section.

The AMS dates obtained in this study are greatly constrained due to an extremely low amount of organic matter (<8%) in the core (Fig. 2.4), hence the establishment of a reliable time scale met with some difficulties. Two dates (169-171 cm; 191-193 cm) were modern/post-modern; the bottom date obtained at 199-201 cm was younger than the other samples. These age inconsistencies could be due to the small sample sizes (~4 mg for the first two; ~2 mg for the
bottom date) that can result in a low ion current in the AMS system and thus, in less reliable dates that are often too young (Jahns, 2005). Also, a possible error generated through mixing of different types of macrofossils and probability of surface contamination during core extraction cannot be ruled out. In order to address these discrepancies, the remaining dates were used to construct the age model by combining linear extrapolation and linear regression principles as explained in methods section (Fig. 2.2). An additional chronological control in this age model is established from the arrival dates of common ragweed, *Ambrosia artemisiifolia* in parts of Eastern Europe. It is reported that parts of lower Danubian countries (including Serbia) were first impacted by this invasive species around 1910-1920 CE (Csontos et al., 2010; Makra et al., 2005). This pollen record shows a prominent rise in *Ambrosia* around 30 cm, whose corresponding age in the proposed age model is c. ~1920 CE. This further increases the reliability of the age-depth model. According to this resulting age model, the sedimentation rate of this Serbian core varies from 0.49 cm/yr to 0.33 cm/yr upcore with the base extrapolated to c. 1540 CE.

![Graph showing AMS Age-depth model for DS core.](image)

**Fig. 2.2:** AMS Age-depth model for DS core.
2.4.2. Palynology and geochemistry

Three local pollen assemblage zones (LPAZs) and two subzones are assigned based on visual inspection of the pollen record and supported by stratigraphically constrained incremental sum of squares (CONISS) cluster analysis in TILIA (Grimm, 1987) (Figs. 2.4 and 2.5). Zone numbers and subzone letters are designated from the bottom to top and zone ages were calculated using sediment accumulation rates. The average sample temporal resolution derived from the present chronological model is c. 25 years.

![Graph showing lithology and K, Ti, and Fe counts (ppm) for DS core. The dotted lines represent the respective pollen zones; refer to description and Figs. 2.4-2.5 for details.]

**Fig. 2.3:** Lithology and K, Ti, and Fe counts (ppm) for DS core. The dotted lines represent the respective pollen zones; refer to description and Figs. 2.4-2.5 for details.

**Zone DS-1 (210-120 cm): ~1540-1720 CE**

Zone DS-1 is characterized by comparatively equal percentages of arboreal pollen (AP) and non-arboreal pollen (NAP); the former fluctuates between 30 and 52% while the latter between 32 and 53% (Fig. 2.5). Both K and Ti show particularly high variation across the zone starting
from low to very high values. Microscopic charcoal is extremely high (1800-5500/cm$^3$) throughout the zone. The total pollen concentration is mostly less than 20,000 per cm$^3$ whereas palynological richness shows a steady curve ranging between 50 and 52.

Subzone DS-1a is composed of 44-50% tree pollen with *Quercus* and *Fraxinus* as major trees, each with 8%. These are followed by *Acer* (6%) and *Juniperus* (4%). NAP constitutes the other half of the pollen percentages with Poaceae (11%), Chenopodiaceae (10%) and high percentages (8-11%) of almost all Asteraceae components. The aquatic-wetland component of the landscape is quite dominant. Cyperaceae reach their maximum values (22%) along with another notable wetland species, *Typha latifolia* (7%). A strong anthropogenic signal is seen through a presence of *Ericaceae* (primarily *Erica* and *Vaccinium* type) as high as 10%; other anthropogenic indicators include herbaceous taxa (e.g. *Plantago*, *Polygonum aviculare*, Asteraceae subfamilies). Micro-charcoal reveal extremely high values in this subzone with concentrations as high as 5500/cm$^3$. All geochemical proxies show low concentrations at the base, then abruptly rise between 190 and 180 cm (Figs. 2.3 and 2.5).

In subzone DS-1b, AP, after reaching their maxima (52%) at the base of this subzone, decline to their lowest values (30%) in the spectrum. *Quercus* (10%) and *Betula* (9%) show peaks at 150 cm before declining with other trees. Although with low percentages, continuous curves of *Juniperus* and *Ephedra* emerge throughout this subzone. NAP percentages slowly rise to 49% with Poaceae ascending to 16-19% reaching its maxima (25%) at 140 cm. Chenopodiaceae (13%) and Cichorioideae (8%) remain high throughout the subzone. Wetland taxa Cyperaceae and *Typha* maintain high percentages in this subzone as well. Charcoal and both K and Ti reach their highest concentrations while Fe maintains high values (Fig. 2.3).
**Fig. 2.4:** Pollen percentage diagram for DS core: selected trees, shrubs, grasses, upland herbs and aquatics (Exaggeration 5%) with LOI and microscopic charcoal/cm$^3$. 
Zone DS-2 (120-60 cm): ~1720-1850 CE

Zone DS-2 is marked by maximum NAP percentages (58% with Poaceae (20%) and Chenopodiaceae (12%)), tree taxa dwindling between 30% to 55%, and a significant decline in charcoal (Fig. 2.4). Major AP (e.g. *Quercus*, *Acer*, *Pinus*) is seen with improved percentages (Fig. 2.4). *Acer* exhibits a sharp rise from 4% to 13% before declining at the end of the zone. *Quercus* again expands up to 8% and shows slightly lower values later in the zone. *Pinus* also follows a similar trend reaching its maxima (8%) in the middle of the zone but declines upcore. Two distinctive *Fraxinus* peaks are seen in this zone. *Fagus*, *Abies*, *Betula*, and *Juniperus* retain low but stable values throughout the zone. *Alnus*, *Ulmus*, *Corylus*, and *Tilia* are also present in the spectrum intermittently. The zone shows substantial increase in cereal percentages and another significant cultivated plant, *Juglans*, which first appears and then peaks (Figs. 2.4 and 2.5). Along with Poaceae and Chenopodiaceae, the NAP group is represented by *Plantago* and Asteraceae as both maintain similar percentages as in zone DS-1. *Cyperaceae* and *Typha* both decline markedly. K, Ti, and Fe all maintain very high values throughout the zone (Fig. 2.3). The pollen concentration declines to 10,000/cm³ in this zone and pollen richness slowly decreases from 50 to 46.

Zone DS-3 (60 cm - surface): 1850-2012 CE

In Zone DS-3, AP percentages stabilize reaching their highest percentages (58%) whereas grass and herb pollen decline considerably. *Carpinus betulus* marks the start of the zone with a distinctive peak. *Quercus* expands to its maximum concentration (13%); *Acer* follows with 12%. *Pinus* continues its appearance in this zone, as do *Fagus* and *Betula*. Crop plant pollen (Cerealia, *Juglans*) occur with comparatively stable curves. These trends are accompanied by several weedy types of herbaceous pollen including *Plantago*, *Polygonum aviculare*, and Asteraceae. Another important herb is *Ambrosia* (14%) from its otherwise patchy appearance in previous zones. This
zone is marked by the abrupt increase of *Persicaria amphibia* (or *Polygonum amphibium*) from 50 cm onward (4-30%) and the slight sustained increase in *Myriophyllum*. Microscopic charcoal is negligible in this zone. Ti continues to show a descending trend while K and Fe show constant fluctuations. The pollen concentration in this zone ranges between 4000 and 8000/cm$^3$ increasing upcore to 20,000/cm$^3$. The pollen richness curve shows a sharp decline in Zone DS-3 where the number of pollen taxa decline to 26.

### 2.5. Discussion

The percentages for total NAP are utilized as a proxy for landscape openness (i.e. the amount of non-forested area) as discussed in numerous Balkan (Feurdean et al., 2015, 2013; Filipova-Marinova et al., 2013; Gogou et al., 2016; Panagiotopoulos et al., 2013; Tantau et al., 2009; Tonkov et al., 2015 and many more) as well as European and global Pleistocene-Holocene palynological studies (Giesecke et al., 2011; Traverse, 2007; Tzedakis, 2007; Willis, 1994 and references therein). Moreover, select AP and NAP representing the main ecological groups of pollen and anthropogenic indicators (agriculture, grazing, and fire) are juxtaposed (Fig. 2.5) in order to explicate the localized and regional nature of the Serbian landscape. Select geochemical signals (K and Ti), pollen concentration and richness curves accompany these indicators in order to exhibit a more thorough paleoecological picture of the region.

#### 2.5.1. Ecological changes during 1540-1720 CE (Early LIA)

This interval shows a complexity of woodland-grassland dynamics, significant differences between local and regional vegetation signals and a strong human component of the landscape.

Until the 1640s (Subzone DS-1a in Figs. 2.4-2.5), this Serbian landscape seemed to be open; trees existed in the form of woody patches across grasslands. Among the most significant trees present are *Quercus* and *Fraxinus*. These trees usually occupy stretches along the banks of
streams and lakes due to their ability to tolerate soils that are temporary waterlogged or flooded (Ellenberg, 2009). The accessibility to such land in the vicinity of the low-lying sinkhole (especially in parts of Serbia; please see Horvat et al., 1974 and references therein) is certainly possible which would have allowed these taxa to thrive throughout this period. As the century progressed, environmental conditions do not seem to improve for other dwindling tree populations; they shrunk greatly as grasses and upland herbs took over in the latter part of the 16th century (~1580 CE). Vegetation cover is often reduced before soil erosion ensues, leading to higher amounts of K and Ti into the lake sediments (Widlok et al., 2012); the sudden increase in these two major geochemical proxies as well as Fe into the lake around 1600 CE indicate the decrease in vegetation cover and increased land erosion (Fig. 2.3). Trees partially recover from this weakening for the first half of the 17th century CE; *Betula* accompanies *Quercus* and *Fraxinus* with a distinctive peak around 1660 CE before declining again. Continuous low values of *Juniperus* and *Ephedra* also contribute to AP percentages. Meanwhile grasses and major steppe taxa (e.g. Chenopodiaceae, Asteroideae, Cichorioideae) consistently expand suggesting further opening of the landscape. According to Feurdean et al. (2013), landscape openness represents a significant driver of pollen richness - the greater the landscape openness, the higher the pollen richness. The steady pollen richness curve with highest number of pollen taxa in this period (Fig. 2.5) is consistent with this observation; high (32-53%) NAP percentages (proxy for landscape openness) exhibit a quite open landscape in the early LIA with a large number of pollen taxa in the surroundings.

While the terrestrial pollen component of the landscape indicates dwindling woodland and extensive opening of the landscape that took place in this interval, the area immediately surrounding the study site is dominated by wetland species. The high *Cyperaceae* (15-22%) and
Typha latifolia (3-14%) percentages show a well-developed wetland along the moist sinkhole margins. Availability of water required for these communities could be a product of seasonal fluctuations in the water table (characteristic of karstic terrains), which could possibly be attributed to melting of snow in the late spring (Hughes, 2010).

Fig 2.5: Composite diagram of DS core includes total percentages of AP and NAP; percentage curves of Quercus and Acer (most abundant thermophilous Balkan trees), Pinus and Fagus (representative of montane vegetation that are sensitive to precipitation), Juniperus and Chenopodiaceae (drought indicators), key anthropogenic signals - cereals and Juglans (cultivated taxa that favor warm temperatures), Plantago (grazing indicator), and microscopic charcoal concentrations (proxy for burning and land clearance in the catchment). Potassium (K) and Titanium (Ti) suggest erosion and clastic inputs into the lake. Pollen concentration shows pollen preservation in the sediments while pollen richness identifies taxon diversity through time.

2.5.1.1. Human impact and the potential role of climate

Disentangling the role of climate and people in past environmental changes is often a major conundrum for paleoecologists. In this record, especially during this early LIA interval, human impact certainly had a profound effect on vegetation. However, it could also be speculated that the climate could be playing some role (probably the underlying cause which humans responded to) in shaping the landscape.
The human impact in this period is revealed from shrub populations of Ericaceae, extremely high charcoal concentrations, and the abundance and continuous occurrence of secondary anthropogenic pollen including *Plantago, Polygonum aviculare*, and Asteraceae subfamilies. The presence of Ericaceae is highest (10%) of all AP (Fig. 2.4), brought by two plant genera, *Erica* and *Vaccinium*-type in this record. Most Ericaceae favor soil deterioration (Willis, 1994), grazing as well as burning (Atherden and Hall, 1999; Jahns, 2005) and all these factors were present in this Serbian landscape during this time which would have allowed growth of these two Ericaceae taxa. Moreover, according to Jahns (2005), the spread of *Erica* could be also be attributed to more arid climatic intervals which suggests its growth may have been part of natural vegetation under the influence of changing climate. An increase in grazing pressure during this interval is seen through continuous and abundant occurrence of *Plantago*, mainly *Plantago lanceolata* (Fig. 2.5), a strong indicator of livestock-grazing (Tonkov, 2003; Tonkov et al., 2002). The juxtaposition of extremely high charcoal concentrations and contemporaneous woodland fluctuations during this period indicate that the humans seemed to have used intense fire practices deliberately in association with woodland clearance. However, the major motivation behind this extensive land clearance might have been to increase the grazing area rather than the agricultural area as both cultivation indicators (cereals and *Juglans*) are either completely absent or present in negligible amounts during this time period (Fig. 2.5).

The early LIA was the transitional period for most of eastern Europe when a steep rise in deforestation is visible in independent deforestation models (e.g. Kaplan et al., 2009; Pongratz et al., 2008). The clearance of woodland and associated intense land erosion (seen through increase in all geochemical proxies) in this part of Serbia is consistent within the regional pattern of anthropogenic impact on the landscape. This period coincides with a relatively peaceful, less war-
prone phase of the Ottoman Empire in this region which brought significant commercial expansion
and hence, more people into the region (Fine Jr., 1994; White, 2006). However, based on
normalized McEvedy and Jones (1978) population estimates for Yugoslavia, Kaplan et al. (2009)
argue that the population only moderately increased until the 1750s and was not enough to put
additional pressure on land than previous centuries with low deforestation. This argument leads us
to examine a potential role of climate that might have contributed to reduction of forest cover
directly (e.g. changes in temperature and precipitation) or indirectly (e.g. transient weather patterns
resulting into crop failures and humans increasing their deforestation).

As discussed earlier, this period (1540-1720 CE) coincides with the first half of the LIA
whose imprint varies across the Mediterranean and circum-Mediterranean regions such as the
Balkans. It is evident that the western and eastern Mediterranean records show dissimilar (almost
opposite) trends during the LIA (Cook et al., 2015; Roberts et al., 2012); most of the LIA is
reported to be less cold but drier in the eastern regions than the west (Luterbacher et al., 2011).
The 16th and 17th centuries CE in the greater Mediterranean region are characterized by alternating
wet and dry periods (Touchan et al., 2005) with droughts of greater in intensity and duration than
the wet periods (Nicault et al., 2008). Nicault et al. (2008) highlight at least three well-marked
droughts around 1540–1575, 1620–1640, and 1645–1665 CE.

More specifically for the Balkans, there seems to be a consensus regarding variability of
the early LIA temperature and precipitation in the region. Tree ring records from parts of Romania
(Popa and Bouriaud, 2014; Popa and Kern, 2009) show that on average, lower summer
temperatures during the LIA included the coldest periods between 1430 and 1630 CE (1500–1600
CE), although the amplitude of this temperature decline was smaller than the global average and
the European estimates (Buntgen et al., 2011a; Christiansen and Ljungqvist, 2012). Interestingly,
both these records (Popa and Bouriaud, 2014; Popa and Kern, 2009) also note that the generally cold conditions in the region were disrupted by warmer than average summers between 1640 and 1740 CE. With a slight contrast, a recent dendrochronological record from Bosnia and Herzegovina (Poljanšek et al., 2013) also points out a seasonal temperature variability for the Central Balkans. They show that the above interval (~1640-1740 CE) indicate both less sunny summers (e.g. 1679–1684 CE, 1691–1693 CE) as well as consistent sunny summers (starting between 1694 and 1698 CE). Several multiproxy Balkan records present fluctuating precipitation with an overall drying trend in the region; these include records in Romania (Feurdean, 2005; Feurdean et al., 2015; Schnitchen et al., 2006), Albania (Van Welden et al., 2008; Zanchetta et al., 2012), Macedonia (Francke et al., 2013; Panagiotopoulous, 2013; Wagner et al., 2009 with some confidence), and in some parts of Greece and Turkey (Luterbacher et al., 2011 and references therein). Instrumental-archival data based and/or independent temperature-precipitation modelling efforts highlight several dry periods and coldest springs during the Last Maunder Minimum (1675-1715 CE) throughout the Meridional Balkans (Xoplaki et al., 2001).

The data in this study seem to corroborate drier climatic condition in the Balkans during the early LIA with substantial increase in NAP taxa, increased erosional signals, complete absence of major montane and drought-sensitive species (e.g. *Fagus*), and the continuous presence of *Juniperus, Ephedra* and Chenopodiaceae that are indicators of dry climatic conditions in the Balkans (Filipova-Marinova et al., 2013; Gogou et al., 2016; Kouli, 2012; Sadori et al., 2015; Tantau et al., 2009). Considering these regional scenarios, it could be speculated that in this Serbian record, the limited moisture retained by the sinkhole in late spring, perhaps, from snowmelt enabled sedges and *Typha* to thrive locally while the region as a whole was experiencing
considerable dryness during this interval due to human as well as subordinate/underlying natural forcings.

2.5.2. Ecological changes during 1720-1850 CE (Late LIA)

This interval shows a completely open landscape with slightly increasing woodland, complete eradication of wetland, and development of agriculture in the region.

An extensive grassland with prominent herbaceous steppe communities of Chenopodiaceae, Artemisia, and Asteraceae subfamilies is evident during the late LIA interval. Ephedra disappears while there is a slight increase in Juniperus that continues to appear in the spectrum. This interval signals a gradual expansion of major trees (e.g. Quercus, Acer, Pinus); among which the rise of Acer is striking (3% to 13%). Acer is a natural constituent of the Central Balkan forests and in Serbia that exists either as part of thermophile deciduous forests in the forest-steppe area and/or as part of azonal vegetation (relict) complex scattered in the beech and beech-fir belts at an altitude of about 1000 a.m.s.l. As the increase in both Quercus (8%) and Fagus (4%) (and also in overall forest cover) is seen in this period, it seems both scenarios could have materialized for the unprecedented growth of Acer. The growth in Quercus appears to be the major arboreal constituent in the mixed oak forests with distinctive peaks in Fraxinus excelsior-type and presence of mesophilous taxa including Ulmus, Tilia, and Carpinus betulus. Except for Fraxinus that is perhaps expanding after local disturbances, the presence of these drought-sensitive taxa show evidence of rising temperatures during the growth season and increasing moisture availability (Panagiotopoulos et al., 2013). However, this shift in moisture availability appears to be moderate, and is corroborated by mild fluctuations in herbaceous steppe taxa, notably Chenopodiaceae, and grasses. Significantly high to very high concentrations of all geochemical
proxies account for continued erosion of the landscape and their intermittent fluctuations can be related to changing woodland-grassland dynamics (i.e. closing and opening of the tree canopy).

Overall increased moisture is also reflected in the montane vegetation as two major montane species, *Fagus* and *Abies* are continually present throughout the late LIA (Figs. 2.4 and 2.5). However, their limited presence in the pollen spectrum may reflect their long-distance transport and the low elevation of the site under investigation. Usually an underrepresented montane species, *Pinus* also shows a considerable increase at this time reaching its maxima (8%) and supports the improved moisture situation in the highlands. Nonetheless, *Pinus* is an early-successional tree which sometimes is associated with dry conditions, thus whether the substantial increase of *Pinus* (more than the dominant beech-fir taxa) can be solely attributed to changing climate remains an open question. It might also be attributed to the common practice of planting conifer trees in the highlands as reported elsewhere in Europe (e.g. Lomas-Clarke and Barber, 2007). In the case of Serbia, reforestation is believed to have started as early as the 19th century CE but coniferization of broadleaved forests became a common practice only post World War II (Rakonjac and Nevenic, 2012). From thereon, Austrian pine (*Pinus nigra* L.) is reported to have been favored for both the submontane-montane beech sites in beech coppice forests as well as unforested areas that are characterized by xerothermic conditions and degraded soils (Isajev et al., 2009); *Pinus nigra* L. is present in the vegetation surrounding the study site. Hence, significant growth of *Pinus* in the late LIA period might have both natural (availability of moisture in the montane region) and human intervention as causal factors.

### 2.5.2.1. Human Impact and the potential role of climate

Human impact in the Late LIA (1720-1850 CE) is largely evidenced through the establishment of arable lands with continued pastoral practices in the region. A substantial
expansion of cereals (e.g. *Secale, Triticum*) as well as *Juglans* occurs around ~1720 CE and mainly at the onset of the 19\textsuperscript{th} century (Fig. 2.5). *Juglans* is among temperature-sensitive tree crops that co-occur with stable and warmer temperatures (Gogou et al., 2016; Mercuri et al., 2013), hence its increase during this interval also highlights the presence of less drastic weather patterns as compared to the earlier part of the LIA. Grazing remains part of the Serbian subsistence as *Plantago* maintains its percentage throughout the interval (Fig. 2.5). While *Ericaceae* declines in this interval, the abundance of other taxa including both Asteraceae family members (*Asteroideae* and *Cichorioideae*) and the expansion of trilete fern spores is symptomatic of disturbed or degraded landscapes with a causal relation to anthropogenic activity (Panagiotopoulos et al., 2013). Significant charcoal decline around the same time suggests less wildfire or anthropogenic fires in region (Fig. 2.4). Although a scenario of reduction in land clearance accompanied by establishment of arable lands with persistent grazing across degrading lands appears rather counter-intuitive, one can imagine that the changes in the subsistence strategies across any time period are inherently connected with changing demographics of the region. Throughout the late LIA, Serbia was the war zone of the frequent Habsburg–Ottoman confrontations (1714–18, 1736–39, 1788–92) forcing the continual outmigration of the inhabitants (Palairet, 1997). Hence, the complex scenario of the human impact on the landscape in this record is a collective artifact of these political and economic changes that occurred during LIA climatic transitions.

The potential role of climate can largely be found in terms of increased moisture which would have allowed sustained mesophilous (e.g. *Ulmus, Tilia*, and *Carpinus betulus*) and montane (e.g. *Fagus, Abies*) trees throughout the period. Based on detailed monthly and seasonal temperature reconstructions for Europe, Luterbacher et al. (2004) specify higher summer temperatures from ~1750 until the second half of the 19th century, but with a summer cooling
trend (−0.06°C±0.02°C per decade) starting from the hottest summer of the period, 1757 CE. Tree ring data from Romania (Popa and Bouriaud, 2014; Popa and Kern, 2009) partially support this inference indicating lower summer temperatures during this part of the LIA with the one of the coldest periods between 1720–1850 CE with a smaller amplitude. While studying dendrochronological record from Bosnia, Poljanšek et al. (2013) point out sunny summers between 1695–1790 CE with improved moisture content. In Albania, maximum density measurements on pine trees studied for this period indicate a high positive correlation with summer, particularly August temperatures (Seim et al., 2010), however, there is no significant correlation with precipitation. A summer precipitation record from northern Greece (Griggs et al., 2007) states that the frequency of extremes is greatest during the early LIA while May-June temperature between early 18th and mid-19th century CE are moderate to slightly high. This pollen record shows slightly warmer and moist summers, which contributed to the closing and opening of the tree canopy between 1720-1850 CE. This dynamic change in the woodland has significantly impacted the taxon richness as the number of taxa slowly decreases towards the beginning of 19th Century CE (Fig. 2.5). Feurdean et al. (2013) also highlight the decrease in pollen richness across Romania region along the similar time frame. They argue that this is essentially due to cooler/wetter climatic conditions that affected the yield productions resulting in a drastic reduction in agro-pastoral activities, particularly at mountainous sites (Feurdean et al., 2009). This pollen data, on the contrary, implies that people seem to have taken advantage of stable-warmer-moist climatic regimes (as shown by several trees including cultivated Juglans) in re-establishing several arable fields in the Serbian region; this again emphasizes that there are distinctive regional differences within the LIA that resulted from fluctuations in large-scale atmospheric circulation providing the relative influences of continental and oceanic air masses (Gogou et al., 2016; Xoplaki et al., 2001).
2.5.3. Ecological changes during 1850-2012 CE (Post-LIA or Industrial Era)

This post-LIA Era shows significant increase in woodland and further expansion of agriculture with little to no land clearance.

Components of oak-mixed-oak forest and montane habitats contribute 58% of the total pollen, largely at the expense of shrinking grasslands. Peaks of *Acer* (12%) and *Carpinus betulus* (12%) around 1860 CE are among the earliest members of the tree community indicative of changing environmental regimes. *Quercus* continues to rise along with these two taxa and surpasses them after the onset of the 20\textsuperscript{th} century CE. Also, the expansion of montane species is seen in the slightly improved percentages of *Fagus* and *Betula*. Both dry indicators, *Juniperus* and Chenopodiaceae are less abundant than in the preceding interval perhaps pointing towards the arrival of moister climatic regime in the region. The increase in woodland at the expense of grassland results in lowering the taxon richness to 26 (decrease of 43% as compared to the late LIA), the least number of pollen taxa present across all intervals. While *Poaceae* declines, a series of herbaceous taxa and a wetland species partially share the landscape. The sudden appearance of the wetland/aquatic *Persicaria amphibia* and its unexpectedly high concentration (24-30\%) during the first half of the 20\textsuperscript{th} century is particularly interesting. This native Eurasian nitrophilous species is amphibious in nature; it can have both terrestrial as well as aquatic varieties that can grow in damp fields, trenches, slow-flowing rivers and even periodically inundated river banks (Bojňanský and Fargašová, 2007). Thus, a possible but a short-term rise of water table to its original preindustrial levels can be a possible explanation for development of *Persicaria amphibia*. *Cyperaceae* and *Typha* vacillate between low values and absence; they may be outcompeted by *Persicaria amphibia*. However, the terrestrial variety (weed form) of *Persicaria amphibia* is reported as particularly hard to control in European spring crops (Kraehmer and Baur, 2013). Noting a slight increase in the Cereal component, this weedy expansion could also be plausible.
Another important herb that occupies the land roughly around the same time is *Ambrosia* (14%). According to Csontos et al., (2010) and Makra et al., (2005), parts of lower Danubian countries (including Serbia) were first impacted by this invasive species around 1910-1920 CE. This prominent rise in *Ambrosia* during this post-LIA Era agrees with these records about the timing of the inception of this invasive species across the Serbian landscape. Overall, a disturbed type of vegetation emerges with the presence of *Persicaria amphibia* and is supported by the expansion of *Ambrosia*, and the entire ‘disturbance group’ including *Polygonum aviculare*, and Asteraceae.

**2.5.3.1 Human Impact and the potential role of climate**

It is no surprise that almost all parts of Europe including the Balkans experienced the 20\textsuperscript{th} century and the early 21\textsuperscript{st} century as the warmest period (Luterbacher et al., 2004; Mann et al., 1998; Xoplaki et al., 2005) with more stable precipitation (as compared to the LIA) with a general declining trend (Buntgen et al., 2011a; Touchan et al., 2005; Xoplaki et al., 2004). At the same time, the Industrial Revolution, agricultural improvements, and increased trade resulted in a notable population rise in this region that affected landscapes (Kaplan et al., 2009). Most of the above vegetational changes in this Serbian record in this post-LIA period can be attributed to large-scale landscape management where humans continued to modify the landscape. Further development of agriculture in this region is inferred from enhanced and steady concentrations of Cerealia, *Juglans*, and also *Corylus* as a result of stable and warmer temperatures. Meagre amounts of microscopic charcoal indicate deliberate reduction in burning lands as humans found better strategies to manage the landscape while enjoying technological changes as population increased after the withdrawal of Ottomans from the region after the 1850s (Palairo, 1997). This could also explain a significant decline in pastoral practices during this post-LIA Era. Somewhat mixed geochemical signals especially from the beginning of the 20\textsuperscript{th} century CE can also account for
these changing human-landscape dynamics (Fig. 2.5). It is possible that the significant increase in K input could be a product of intense use of artificial fertilizers in the region. This picture fits well in the decoupled “forest-human population relationship” of the Industrial Era; when most countries experienced a “forest transition” – earlier deforestation switching to afforestation – phase concurrent with population growth generally coinciding with industrialization and urbanization (Mather, 1992; Rudel et al., 2005).

2.6. Conclusions

Some major conclusions found in this new high-resolution Central Balkan record from Serbia are –

1) The early LIA (~1540-1720 CE) vegetation shows a complex woodland-grassland dynamics, development of a localized wetland, increasing erosional signals and a strong human component of the landscape. At the local scale, the predominance of wetland communities mark the flooded margins of the sinkhole, plausibly due to snowmelt in the late spring whereas terrestrial vegetation indicates further opening of the landscape from 1640 CE onward. Many of the vegetation changes can be attributed to human impact but evidence exists for linkages between vegetation and LIA climatic variations. The imprint of the LIA (at least this part of LIA) in the Balkans is drier as compared to northern-western Europe and the datasets from this study seem to corroborate this climatic condition leading us to consider the LIA as a likely and perhaps, subordinate contributor in shaping the landscape.

2) The late LIA (1720-1850 CE) in this record shows a completely open landscape with slightly increasing woodland, complete eradication of marginal wetland, and development of stable agriculture in the region. More diverse woodland includes mesophilous (e.g. Ulmus, Tilia, and
Carpinus betulus) and montane trees (e.g. Fagus, Abies) which were possibly a result of increased moisture during this latter part of LIA.

3) The post LIA Era (1850-2012 CE) brings a complex type of vegetation with the presence of the weedy genera including Persicaria amphibia, Ambrosia, Plantago, Polygonum aviculare, and the Asteraceae family and largely increased woodland in Serbia. The occurrence of crop plants (e.g. Cerealia and Juglans) indicates the further development of arable lands in the region as a result of stable and warmer climatic regimes. A large decline in land clearance is visible through extremely low charcoal and decrease in erosional indicators at the wake of industrial revolution-technological change in the region as people found more effective strategies than burning to manage the landscape.
Chapter 3

The Little Ice Age and human-environmental interactions in the Central Balkans:

insights from a new Serbian palaeoenvironmental record

This chapter is in preparation for submission to *Quaternary International*.

Abstract

A well-dated, high-resolution Central Balkan palaeoecological record discusses vegetation and landscape change over the past 700 years. This timespan includes the Little Ice Age (LIA) (1500-1850 CE) with several centuries before and after this important interval for comparison. Biological proxies (pollen, spores, and charcoal), geochemical analysis through X-ray Fluorescence (XRF), and a detailed chronology based on AMS $^{14}$C dating from the Sava basin sediments delimit the evolution of the Serbian landscape across a warm-stable pre-LIA interval with relatively high tree percentages, modest occurrence of anthropogenic taxa, and relatively stable agriculture supported by grazing. On the contrary, the LIA interval in the region is expressed through opening and closing of the tree canopies and extensive land erosion, perhaps in response to climatic deterioration and human impact largely associated with socio-political changes of the time. The post-LIA interval shows stabilized woodland in the riparian region, establishment of arable lands near the lake shores and selective forest clearance strategies by humans in the wake of the industrial revolution. Establishing correlation with existing Serbian environmental datasets, this record reveals the transformation of the Central Balkan landscape and its apparent linkages with changing climatic and socio-political regimes.
3.1 Introduction

Continuing global warming and its potential associated threats to ecosystems and humans present a substantial challenge to modern civilizations that already experience many direct and indirect impacts of anthropogenic climate change (Cook et al., 2010, 2007; Mann et al., 2009). In many regions, increasing temperatures and changing precipitation patterns are altering hydrological and ecological systems thereby influencing water resources, agricultural productivity, human health, and even social conflicts. Furthermore, the degree and intensity of these impacts is likely to increase in the future as human-induced environmental changes continue their substantial imprint on a background of natural climatic variability (Bradley and Jones, 1993b; Buntgen et al., 2011a). The Common Era (the past 2000 years) reveals examples where human influences have increased to the extent that they became capable of strengthening (or at times, attenuating) the results of climatic processes (e.g. intensification/weakening of evaporation) that further influence landscapes and vegetation (Reale and Shukla, 2000). To envision the vulnerability and sustainability of future complex socio-environmental systems, it becomes essential to improve our understanding of the nature of critical climatic episodes in the Common Era (e.g. Little Ice Age (LIA), Medieval Climate Anomaly (MCA)), associated societal responses and environmental changes in terms of elucidating details of climate-humans-ecosystem interactions (Mercuri and Sadori, 2014; PAGES2k Consortium, 2013; Xiao et al., 2015).

This multi-proxy study explores the Balkan vegetation and landscape change in terms of both climatic variability and human impact over the past 700 years. This time interval includes the 14th and 15th centuries CE (transitional period between MCA and LIA; Masson-Delmotte et al., 2013), the full extent of the LIA (1500–1850 CE; Bradley and Jones, 1993, 1992; Lamb, 1965; Mann, 2002), and the post-LIA/Industrial Era. Among these, the LIA is of particular interest as its
nature and magnitude varies across Europe (Bradley and Jones, 1993b, 1992; Ljungqvist, 2010; Mann et al., 2009). Overall, the LIA is identified as a time when Northern Hemisphere annual temperatures were cooler, and winters were significantly colder with increased snow when compared with modern day winters (Bradley and Jones, 1993a; Jones et al., 1998; Mann et al., 1999). However, it is argued that a standard wet-cold picture of the LIA is based on a number of proxy datasets available from northern-western parts of Europe and the imprint of the LIA in the east-south region was perhaps cold but also drier (Cook et al., 2016, 2015; Luterbacher et al., 2011; Roberts et al., 2012). Recent data as well as modeling studies from the Mediterranean region highlight the east-west climate see-saw that has operated between the two Mediterranean regions for the last 1100 years with the eastern Mediterranean region generally drier during the LIA preceded by a wetter MCA (Luterbacher et al., 2011; Roberts et al., 2012). Meanwhile, it is also emphasized that while western Mediterranean aridity/humidity patterns appeared consistent during the MCA/LIA periods, the pattern is less clear in the eastern Mediterranean (Cook et al., 2016, 2015; Gogou et al., 2016; Roberts et al., 2012; Zerefos et al., 2011), largely due to unavailability of high-resolution last-millennium proxy datasets (Gogou et al., 2016; Roberts et al., 2012). The Balkan Peninsula is a key climatic transition zone between the western and eastern Mediterranean, and between the Mediterranean and the Central European region (Qiriazi and Sala, 2000; Xoplaki et al., 2001; Xoplaki and Luterbacher, 2003). Consequently, this new multi-centennial paleoecological record from the understudied Balkan region (Fig. 3.1a) and its correlation with the existing literature advances our understanding of the nature and spatial variability of the LIA across the region while identifying and characterizing its implications and interactions with the contemporary human and environmental systems.
Fig. 3.1: (a) Quaternary-Holocene pollen records (black dots) from the Balkans (Green highlighted region) (Data source: http://www.europeanpollendatabase.net/data/). The location of Serbia (Purple) and the study site (star) are shown. (b) Location of the Sava Basin (Dotted region) and the study site (star) within Serbia. The black dot shows the location of only pollen record available from Serbia (after Kulkarni et al. 2016) (c) Google Image of the study area showing the location of the Sava River and the Zivaca oxbow lake under investigation (Data source: www.googleEarth.com). The star shows the exact location of the coring site.

3.2 Study area

3.2.1 Regional setting and study site

The Republic of Serbia comprises 16% of the Sava Basin (Milačić et al., 2014), its southern-downstream portion west of the Sava-Danube confluence at Belgrade. The northern part (~29,186 km) of the Sava River Basin (ISRBC, 2009) consists of lowlands and is part of the Pannonian Plains (Fig. 3.1b). This area consists of Quaternary alluvial floodplains with gentle
slopes and little relief, except for the Fruska Gora Mountains in the North which are characterized by pre-Miocene metamorphic rock complexes (Toljić et al., 2013). The Drina River Basin is nested within the Sava River catchment area and is located in the southern part of the Sava River Basin. It has an area of ~45,692 km² and a series of Dinaric mountain massifs. The boundaries between the two sub-Basins, the Drina and Sava Basins are Miocene granitoids of Mount Cer and Mount Bukulja in western and central Serbia respectively (Cvetkovic et al., 2007; Koroneos et al., 2011).

The sediment record for this study comes from an oxbow lake Zivaca of the Sava River (44°44'7.41"N, 20°10'57.21"E) at an elevation of 65 a.m.s.l. (Fig. 3.1b-c). The total area of the oxbow is approximately 1.27 km² with a perimeter of ~9 km. It is located in the northern part of the Sava catchment, ~24 km west of the city of Belgrade. The site is protected from large-scale flooding of the Sava main channel through an artificial flood levee structure, however, it is partially waterlogged by groundwater during the spring period (Kitnaes et al., 2009).

3.2.2 Climate

Most parts of Serbia including the Sava region show a continental climatic regime with moderate sub-Mediterranean influences - cold, relatively dry winters and warm, humid summers. The mean annual air temperature for altitudes lower than 300 m is about 11°C with July maximum temperatures ranging between 37 and 42°C (RHMSS, n.d.). Serbia has a continental precipitation pattern with more rainfall in the warmer part of the year; June is the wettest month with an average of 12 to 13% of total annual precipitation (Sekulić et al., 2012). The annual precipitation along the lower elevations is about 600-800 mm per year varying with elevation and exposure (RHMSS, n.d.). Snow cover is characteristic from November to March with January as the snowiest month.

3.2.3 Regional and local vegetation

Horvat et al. (1974) describes the vegetation in the study area as part of the Pannonian forest-steppe zone characterized by stands of deciduous oak and maple communities such as
Quercus pubesens, Q. petraea, and Acer tataricum. These thermophile communities are often accompanied by mesophilous taxa including Carpinus betulus and Fagus mosiacum along shaded cool valleys and cool exposures in the lowlands (Rakonjac and Nevenic, 2012; Vukojičić et al., 2014). The riparian vegetation includes Salix alba, S. amygdaloides, Populus nigra, Acer negundo, with scrub populations of Cornus sanguinea, Corylus avellana, Rubus caesius and occasionally Vitis vinifera, and Humulus lupulus. The stratum of herbaceous plants in these areas is composed of Phalaris arundinacea, Galium palustre, Rorippa amphibia, Carex elata, Iris pseudacorus, Solanum dulcamara, Rumex sanguineus, Polygonum aviculare, P. amphibium (or Persicaria amphibia), P. hydropiper and many more (Karadzić et al., 2015).

Temporary flooded forests in this region include Alnus glutinosa, Quercus robur, Fraxinus angustifolia, Ulmus laevis, U. minor with a shrub stratum of Acer campestre, Salix cinerea, Viburnum opulus, and Sambucus nigra. Dominant herbaceous species in this zone include the Chenopodiaceae family, Carex elongata, C. vesicaria, C. riparia, Hottonia palustris, Glyceria fluitans, Urtica radicans, Mentha aquatica, Asteraceae family (Asteroidae, Cichorioideae, and Artemisia); Plantago can occur as P. altissima (Karadzić et al., 2015). A large-scale aquatic and wetland component include innumerable taxa; the most common communities are Alisma plantago-aquatica, Carex elata, C. rostrata, C. riparia, Cyperus fuscus, Equisetum spp., Iris pseudacorus, Mentha aquatica, Phragmites communis, Sagittaria sagittifolia, Scirpus sylvaticus, Sparganium erectum, Typha angustifolia, T. latifolia, and Veronica anagallis-aquatica (Karadzić et al., 2015).

The modern vegetation around the site contains well-preserved riparian deciduous oak and mixed forests with Salix, Populus, and Fraxinus species in the flooded areas. These are managed
forests, mainly oaks with different age groups (the oldest stand is about 120 years old) accompanied by hornbeam (Kitnaes et al., 2009).

3.2.4. Historic setting and the context of the LIA

In the Middle Ages, the area surrounding the Sava River was called Syrmia which, similar to most parts of the Balkans, witnessed a complex interplay of wars, migrations, epidemics, and famines. For most of the 14th century, this region including Belgrade was under Hungarian rule. While Hungarians held the northern parts of Sava and Danube, the southern parts of the Serbian Empire began to fall apart against the rising Ottomans through a series of raids as well as decisive battles beginning in the 1360s (Fine Jr., 1994). To resist Ottoman invasion and to have a powerful stronghold on the Sava and Danube region, the Hungarians retained their rule through connections with the contemporary Serbian Despotate until the early 15th century (Ali, 2012). This turned out to be one of the periods of noticeable prosperity in terms of economy, culture and agriculture as described by several travelers (Stoianovich, 1992) when the population of Belgrade City and surrounding areas increased to ~40-50,000 inhabitants (City of Belgrade Official Website, n.d.).

The decades between the 1450s and early 1500s witnessed several major conflicts between the Hungarian Empire and the Ottomans, ultimately resulting in the Ottoman conquest of the north in 1521 CE. For almost the next 150-160 years, the Ottoman Empire ruled the region and instituted a number of systems for the management and provisioning of resources for its territories, all the while directing the expansion of the settlement and cultivation across the region (White, 2011a). Both 16th and 17th century Balkans enjoyed a fairly peaceful period with noteworthy commercial progress and significant increase in population (McEvedy and Jones, 1978; Palairet, 1997). However, by the end of the 17th century, the Ottoman Empire started suffering a major crisis with increasing economic turmoil and social unrest from which it could not fully recover (White, 2006).
In the 17th-18th centuries during the late Ottoman rule, this Sava and Danube confluence region was a part of the war zone of the frequent Habsburg–Ottoman confrontations (1683–99, 1714–18, 1736–39, 1788–92) that forced the outmigration of the inhabitants (Mitchell and Kicosev, 1997; Palairet, 1997). This continual inward and outward flow of people as well as internal migrations in the Central Balkans over these three-four centuries resulted in significant social changes such as abandonment of marginal lands, transition from wheat to barley and spelt wheat, and from viticulture to plum growing (Mrgić, 2011 and references therein). During the hardest times, subsistence strategies shifted from agriculture to itinerant animal husbandry-cattle trades (Milojević, 1954).

Despite their attempts to restore order, the Ottomans completely lost control over their territories and during the 1830-50s, Serbia and a few other Balkan countries came under independent principalities (Ali, 2012). Subsequent to the withdrawal of the Ottomans around 1850s, a significant demographic rise was recorded in the region (McEvedy and Jones, 1978; Palairet, 1997).

3.3 Materials and methods

3.3.1. Core extraction

Using the modified Livingstone piston corer (Wright Jr. et al., 1984), a 257 cm sediment core was extracted from the center of the Zivaca oxbow (hereafter, ZO) at a water column depth of 2 m. After recovery, the core was described in the field and was refrigerated at 2-3°C until processing.

3.3.2. Lithological and geochemical analyses

The split core was carefully described for lithology and one core half was sampled at 8-10 cm intervals for loss-on-ignition (LOI), pollen and micro-charcoal analyses. To calculate LOI, the subsamples were weighed before and after overnight drying at 100°C to remove initial moisture
and then placed in a muffle furnace at 550°C for 2 hours to determine organic/inorganic content (Dean, 1974).

Geochemical analysis of the core was performed using an InnovX Olympus Delta DC-4000 multibeam XRF analyzer at the Environmental Sciences Analytical Center, Brooklyn College of CUNY. Three or more XRF readings were taken continuously at 1-cm intervals with a counting time of 90s and acceleration intensities of 15-40kV. The values were averaged for each depth and the five-point moving averages were used for final data analysis in order to suppress any noise. Because the sediment matrix is characterized by variable water content and grain size distributions, the count rates obtained for individual elements can be used as semi-quantitative estimates of their relative concentrations (Aufgebauer et al., 2012; Massa et al., 2012). Only a selection of elemental data from the XRF scanning is presented here, which includes potassium (K), titanium (Ti), and calcium (Ca). While K and Ti indicate the degree of terrigenous silicate input and soil erosion in the lake settings and act as proxy for physical weathering in the catchment (Arnaud et al., 2012; Aufgebauer et al., 2012; Francke et al., 2013), sedimentary Ca reflects changes in hydrological processes, climate (wet or dry periods), and ecology (Boyle, 2001).

### 3.3.3. Palynological and charcoal analyses

In order to extract pollen, spores and charcoal from sediments, 3-4 cm³ of samples were sieved (120 and 7 μm) and processed using 10% KOH, 10% HCl, 40% HF, and acetolysis (Faegri et al., 2000). Pollen residues were dehydrated in alcohols and suspended in silicone oil. To enable calculation of pollen, spore and micro-charcoal concentrations (/cm³) and their influx/accumulation rates (/cm²yr), an exotic marker, Lycopodium, tablet with a known amount of spores (Stockmarr, 1971) was added to samples before treatment. Identification of pollen and other palynomorphs was based upon the reference slides from the Laboratory of Palynology of the
University of Novi Sad and from Lamont Doherty Earth Observatory (LDEO) as well as using relevant keys (Moore et al., 1991; Reille, 1999). A minimum of 300 terrestrial pollen grains was counted for most depths; no pollen was preserved in the bottom segment of the core between 220 and 257 cm. The percentages of arboreal and non-arboreal taxa are based upon the sum of terrestrial pollen (excluding Cyperaceae and obligate aquatics) and unidentified pollen. Aquatic pollen as well as spores were counted in addition to the terrestrial pollen and are presented as a percentage of terrestrial pollen plus aquatics and as a percentage of terrestrial pollen, aquatics, and spores respectively. Microscopic charcoal pieces >50 μm were counted for the same slide area as for the pollen, which is considered to be a proxy for regional fires (Whitlock and Larsen, 2001). The size criterion was selected to avoid confusion of microscopic charcoal with opaque mineral material, which is typically <50 μm in one dimension (Clark and Patterson III, 1984). All diagrams were plotted using TILIA and TILIA Graph (Grimm, 1992).

3.3.4. Rarefaction analysis

In order to examine trends in pollen diversity across the Central Balkan landscape, rarefaction analysis was applied to the pollen dataset. Rarefaction analysis enables a comparison of taxon richness between samples of different size by standardizing pollen counts to a single sum (Birks et al., 2016; Birks and Line, 1992) to better document the diversity changes within vegetation units through time (Berglund et al., 2008; Birks and Birks, 2008; Feurdean et al., 2012; Flenely, 2005; Meltsov et al., 2011; Weng et al., 2007; Willis et al., 2007). It was conducted using EstimateS 9.1.0 (Colwell, 2013). All terrestrial pollen were included and the lowest pollen count was used to standardize the size of the pollen counts for each sample. A few pollen-poor samples that could not meet the threshold sum were excluded from the analysis. The most robust estimate of richness through rarefaction analysis is the expected number of taxa, $E(S_n)$ (Birks and Line,
1992; Gotelli and Graves, 1996; Heck et al., 1975; Hurlbert, 1971; Sanders, 1968; Simberloff, 1978), whose values were plotted against respective depths with other ecological and geochemical proxies.

3.3.5. Chronology

The age model for the ZO core is based on nine accelerator mass spectrometry (AMS) $^{14}$C dates measured at the Center for Accelerated Mass Spectrometry, Lawrence Livermore National Laboratory. A variety of macrofossils were selected for radiocarbon dating after screening 3-4 grams of sediment with water through screens of 500 and 250 microns. Seeds were identified using the Peteet seed collection at LDEO. Due to unavailability of sufficient plant materials towards the bottom of the core, three shell (two freshwater gastropods, one unidentified) samples were also used for dating; two of these samples were picked along the same depths with plant-animal remains. The depths, types of macrofossils dated and associated uncalibrated and calibrated ages are presented in Table 1. All radiocarbon dates were calibrated to calendar years using the CALIB 7.0.0 calibration program (Stuiver et al., 2005) with the INTCAL13 calibration curve (Reimer et al., 2013). Due to the deviations in $^{14}$C production for the time period spanned by this study, results appear in several possible relative age ranges. Calendar age ranges selected for the age model, therefore, were purposefully chosen on the basis of high relative area under the probability distribution within the 95.4% (2-sigma) enclosed area. Since the core was extracted in the year 2012, the core top was set at 2012 CE. A few age reversals as well as age inconsistencies were encountered across the depths, hence the age-depth model was carefully created using selected AMS dates (Table 1; Fig. 3.2) using a combination of linear regression and linear extrapolation. Sediment accumulation rates for each segment were calculated accordingly in the age-depth model (Fig. 3.2).
Table 3.1: AMS Age ranges for 95.4% (2-sigma) enclosed area shown for the range used in calendar age calculation. Relative percent area represented by the calendar range is shown in parentheses (>). Selected dates are shown by an asterisk (*) and the selection criteria are discussed in detail in the results section.

3.4. Results

3.4.1. Age model and sedimentation rates

The low amount of organic matter (<7%) and the limited types of materials that were available for dating created challenges when constructing a reliable age-depth from the AMS dates
obtained from the ZO core (Table 1, Fig. 3.2). The bottom date is based on freshwater snail shell fragments, potentially belonging to *Lithoglyphus* (sp. *naticoides*), the most frequent and abundant gastropod species in the lower Sava River channel and freshwater ponds in the Sava-Danube catchment (ICPDR, 2002; Paunović et al., 2012). This detritivorous snail feeds on diatoms and green alga in soft muddy lakes (Lucic et al., 2015; Tomovic et al., 2014).

**Fig. 3.2:** AMS Age-depth model for ZO Core.

There are two parallel dated sequences at 234 cm and 170 cm; each contains one bulk plant-animal organics and one shell sample. For the 234 cm sequence, the shell also belongs to *Lithoglyphus* and has the date of 1334±33 cal yr CE whereas the fish bone remains-plant leaf fragments also at this depth date to 1560±82 cal yr CE. Looking at the freshwater nature of the
shell and overall stratigraphic (regression) trend of the upcore non-shell samples, the age given by the freshwater shell at this depth was a more logical choice.

A somewhat opposite scenario is seen for the 170-cm assemblage; the shell sample at this depth produced an extremely old date of 1115±78 cal yr CE whereas the accompanying organic sample provided a date of 1479±42 cal yr CE. This shell sample was highly fragmented and the species could not be identified; it had a δ¹³C value of 0 ‰, which is not recorded for any other dated samples including the other shell samples. This makes this date incongruent in the sequence and so its non-shell counterpart was used to build a more realistic age-depth scenario.

Moving up the core, the next four dates provide a significant stratigraphic correlation with a regression coefficient (R²) of 0.8181. The topmost date obtained at 13 cm is 1557±83 cal yr CE, has an upper age limit, 1640 cal yr CE and is slightly outside the above regression pattern; if included, the regression coefficient changes from 0.8181 to 0.8202. However, the inclusion of this date produces the sedimentation rates of 0.86 and 0.04 cm/yr for the 234-13 cm and 13-0 cm (core top) segments respectively. Although there are lithological changes around 12 cm (Fig. 3.3), they do not represent such drastic rise in the sedimentation rate. Furthermore, the date was based on a small twig fragment weighing 2.47 mg. Small sample sizes can bring age inconsistencies due to a low ion current in the AMS system, thereby producing less reliable dates (Jahns, 2005). The date obtained at 13 cm, therefore, was removed from the analysis.

To summarize, the proposed age model includes six out of nine AMS dates and is created using a combination of linear regression and linear extrapolation (Table 1; Fig. 3.2). According to this proposed age model, the sedimentation rate of this Central Balkan core varies from 0.1 cm/yr to 0.7 cm/yr to 0.2 cm/yr toward the top of the core; the base is extrapolated to c. 1100 CE. The multi-proxy analyses of the upper 210 cm spanning the last 700 years are presented here.
3.4.2. Lithology and geochemistry

Based on lithological and geochemical variations, the top 210-cm-sediment sequence is subdivided in four lithozones; LZ-1 to LZ-4 (Table 2; Fig. 3.3). LZ-1 (210-170 cm; Fig 3) is a homogenous lithological sequence composed of dark grayish brown silty clay, except for a distinct shell layer at around 170 cm. All elements - K, Ti and Ca - maintain high values, showing a maxima at 173 cm and then declining sharply. LOI is 92-94% indicating minimal organic matter.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Lithological units</th>
<th>Lithozones (LZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-12</td>
<td>Dark olive gray (5Y 3/2) clay</td>
<td>LZ-4</td>
</tr>
<tr>
<td>12-25</td>
<td>Light brownish (2.5Y 6/2) silty clay</td>
<td></td>
</tr>
<tr>
<td>25-35</td>
<td>Olive gray (5Y 4/2) clay</td>
<td>LZ-3</td>
</tr>
<tr>
<td>35-62</td>
<td>Brown (10YR 5/3) silt with an olive gray (5Y 4/2) clay lens at around 50 cm</td>
<td></td>
</tr>
<tr>
<td>62-92</td>
<td>Grayish brown (10YR 3/2) silty clay with a dark olive gray (5Y 3/2) clay lens at around 70 cm</td>
<td></td>
</tr>
<tr>
<td>92-115</td>
<td>Dark olive gray (5Y 3/2) clay</td>
<td>LZ-3</td>
</tr>
<tr>
<td>115-230</td>
<td>Dark grayish brown (10YR 4/2) silty clay interspersed with dark gray (2.5Y 3/2) clay lens; shells present at 170 cm</td>
<td>No zone assigned until 210 cm, LZ-1, LZ-2, LZ-3</td>
</tr>
<tr>
<td>230-257</td>
<td>Olive brown (2.5Y 4/3) silt with a distinct shell zone between 232-244 cm</td>
<td>No pollen zone; lithozone not assigned</td>
</tr>
</tbody>
</table>

Table 3.2: Lithostratigraphic description of the ZO sequence (the boundaries between the different layers are gradual).

LZ-2 (170-140 cm; Fig. 3.3) includes dark grayish brown silty clay interspersed with dark gray clay lens. All geochemical proxies show declining values from 168 cm onwards and remain low throughout the zone. The LOI is stable at 92-93%.

LZ-3 (140-25 cm; Fig. 3.3) has a complex lithology showing alternating sequences of clay, silty clay, and silt. Dark grayish brown silty clay layer and intermittent clay lens mark the bottom of LZ-3, which gradually transitions into a dark olive gray clay layer between 115 and 92 cm. This layer is overlain by greyish brown silty clay (92-62 cm) with a dark olive gray clay lens, which moves upcore into brownish silt (62-35 cm) also embedded with a clay lens. A 10-cm of olive gray
clay layer tops these silt-clay intercalations and subsequently migrates into light brownish silty clay at around 35 cm. The rise in K, Ti, and Ca is seen at the start of this lithozone which maintain high values throughout the zone with a few short term fluctuations. The LOI ranges between 91 and 94%.

Fig. 3.3: Lithology, inorganic and organic content (%), potassium (K), titanium (Ti) and calcium (Ca) counts (ppm) for ZO core. The dotted lines represent the lithozones; refer to description for details.

LZ-4 (25-0 cm; Fig. 3.3) begins at the base of light brownish silty clay that transitions to dark olive gray clay around 12 cm. Both lithological units are fairly homogeneous. Both K and Ti decline in this zone, however, after a minor setback, the Ca values greatly increase reaching its
highest value in the entire record. The LOI shows decreasing inorganic content with as low as 82%.

3.4.3 Pollen assemblage zones and corresponding ages-lithozones

Three major pollen zones are assigned based on visual inspection of the pollen and charcoal record (Fig. 3.4) and are supported by stratigraphically constrained incremental sum of squares cluster analysis in TILIA (CONISS) (Grimm, 1987). Zone numbers and subzone letters are designated from the bottom to top and zone ages were calculated using sediment accumulation rates. The average sample temporal resolution derived from the proposed age model is c. 40 years.

Zone ZO-1 (210-140 cm; ~1370-1470 CE)

Zone ZO-1 is characterized by high percentages of arboreal pollen (AP); they fluctuate between 59 and 68%. Oaks are the most dominant taxa varying between 13 to 24% accompanied by *Acer* (5-12%), *Fagus* (4-6%), *Carpinus* (1-5%) and *Juniperus* (2-7%). *Alnus* and *Fraxinus* are also present throughout the zone, adding up to 2-5% with the former showing a maximum (12%) at 200 cm. At the same depth, *Corylus* starts to increase and shows its maxima (6%) at 190 cm from its otherwise modest appearance throughout the zone. Non-arboreal pollen (NAP) constitutes the remaining share of the pollen percentages with *Poaceae* (12-20%) while minor herb percentages include *Chenopodiaceae* (1-4%), *Asteraceae* (1-4%), and *Plantago* (1-4%). The aquatic-wetland component of the landscape is also visible mainly through *Cyperaceae* percentages between 5 and 13%. All other wetland species (e.g. *Typha* varieties) do not exceed 2%.

An anthropogenic component of the landscape is seen through the presence of minor but continuous curves of cereals (2-6%) and *Juglans* (1-3%) with the former showing a peak at 190 cm. Micro-charcoal show values changing between 0 and 3600/cm³. The charcoal peak at 160 cm
marks the highest value in the sequence. This PAZ includes LZ-1 and LZ-2 with high and low values of all the three elements respectively (Fig. 3.3).

**Zone ZO-2 (140-20 cm; ~1470-1900 CE)**

Zone ZO-2 shows fluctuating tree populations with an overall declining trend; AP oscillate between 50 and 70% throughout the zone (Fig. 3.4). The two most dominant trees from the previous zone, *Quercus* (10-27%) and *Acer* (4-15%) show continuous variations with their maxima at 50 and 110 cm respectively. Although generally declining upcore, both *Alnus* and *Fraxinus* show a series of distinctive peaks throughout this zone. Other trees (e.g. *Fagus, Carpinus*) show diminishing curves; the major exceptions are *Juniperus* (1-10%), *Pinus* (1-8%), and *Ulmus* (1-5%), which maintain slightly higher percentages than ZO-1 punctuated with some of their minimum values. An increase in *Pinus* can be seen at 80 cm.

Meanwhile, there is a significant rise in NAP percentages to 44% especially at the bottom of the zone between 100 and 90 cm. The major NAP contributor is Poaceae (8-29%) with its maximum percentages at 100 cm. This is accompanied by fluctuating curves of almost all herbaceous taxa including Chenopodiaceae, Cichorioideae, Asteroideae, and *Plantago*. Both Asteraceae family members show peaks throughout the zone. The wetland and aquatic taxa show increases in percentages from 12 to 29%; the rise is mainly seen through the increase of Cyperaceae between 50 and 30 cm.

The zone shows substantial decrease in cereal pollen percentages as well as other cultivated crops such as *Juglans* and *Corylus*. The slight rise in Ericaceae accompanies these anthropogenic indicators in ZO-2. Except from 140-90 cm, microscopic charcoal is high (1800-2400/cm³) throughout the zone. This PAZ includes the entire LZ-3 and the bottom part of LZ-4 with consistently high values of K, Ti, and Ca (Fig. 3.3).
Fig. 3.4: Pollen percentage diagram for ZO core: AP-NAP, selected trees, shrubs, grasses, upland herbs, wetland and aquatic species (Exaggeration 5%) and microscopic charcoal/cm³.
**Zone ZO-3 (20-0 cm; 1900-2012 CE)**

In Zone ZO-3, AP percentages stabilize at 62% whereas grass, sedge, and herb pollen considerably decline and fluctuate. *Carpinus betulus* markedly increases at the base of the zone with its distinctive peak (12%) mid-zone along with *Betula* (9%). Both *Quercus* and *Acer* decline in this zone with their minimum percentages in the spectrum, 6 and 4% respectively. *Alnus* declines slightly while *Fraxinus* increases, and other trees including *Ulmus, Fagus* and *Abies* decline upcore. *Juniperus* retains similar values from the previous zone. *Pinus* continues to appear in this zone, but with slightly lower percentages. While Poaceae decreases in ZO-3, Chenopodiaceae increases along with slight rise in some weedy types of herbaceous pollen including *Plantago* and Asteraceae. This zone is characterized marked by declining Cyperaceae percentages and a slight but sustained increase in other wetland taxa, *Typha latifolia* and *Myriophyllum*. Crop plant pollen (Cerealia, *Juglans*) marginally increase in this zone whereas micro-charcoal values are slightly lower than the earlier zone. Zone ZO-3 is part of LZ-4 lithological sequence with a clear descending trend in K and Ti and increase in Ca concentrations.

**3.5. Discussion**

**3.5.1. Environmental history of the Sava region throughout the last 700 years**

**1370-1470 CE: Dominance of woodland and moderate anthropogenic influence**

A densely wooded region throughout the pre-LIA interval is evident by the consistently high AP percentages (Fig. 3.4). Woodland existed largely in the form of riparian thermophiles that includes a variety of deciduous oaks, *Acer, Alnus, Fraxinus*, and *Corylus*. These taxa tend to flourish in overall moist and warm conditions (Ellenberg, 2009; Horvat et al., 1974), hence their presence indicates moist and a fairly stable climatic condition during this interval. These speculations are supported by a modest agricultural component of the landscape; both temperature
and moisture sensitive crop varieties, *Juglans* and cereals (Gogou et al., 2016; Mercuri et al., 2013) are present demonstrating stable cultivation. Historically, this period coincides with a relatively stable Hungarian realm in the region and is considered a time of economic and agricultural prosperity with increased migrants (Fine Jr., 1994; McEvedy and Jones, 1978; Stoianovich, 1992). It seems that in addition to the stable climatic conditions, the overall increase in stability of the regional population also would have provided necessary manpower for sustained agriculture during this period.

The land clearance signal during this interval is quite complicated; among low charcoal concentrations during 1370-1470 CE, two fire episodes around 1430-1440 CE and 1460-1470 CE are apparent. Considering the regional origin of the microscopic charcoal (Whitlock and Larsen, 2001) that is recorded here, it is possible that these two periods correspond with periods of several major conflicts between the Hungarian/Serbian and Ottoman Empires during mid-15th century (Murphey, 1999). These conflicts could have resulted in additional burning of the villages and landscape in the region (Mrgić, 2011). One could assume that these intense land clearance episodes would have left a mark on the local woodland. However, tree cover, especially the riparian vegetation, did not decline in the Sava region. On the contrary, there is a limited presence or absence of most montane-submontane taxa (e.g. *Pinus, Picea, Abies, Betula*) around mid-15th century CE and a concurrent increase in understory shrubs, *Juniperus* and *Cornus* sp. along with a moderate appearance of *Plantago, Pedicularis* and other secondary anthropogenic taxa (e.g. Asteraceae family). *Plantago* and *Pedicularis* are considered as livestock-grazing indicators for high-mountain regions (Marinova et al., 2012; Rull et al., 2011; Tonkov, 2003) whereas *Juniperus* is thought to be an anthropophyte accounting for human impact along the forest borders (Kuneš et al., 2015; Marinova et al., 2012; Tonkov, 2003). Additionally, the presence of *Juniperus* suggests
a drier climate in the Balkans (Atherden and Hall, 1999; Panagiotopoulos et al., 2013). A plausible explanation for this complex ecological signal could be that a few short-term dry climatic spells concomitantly occurred with consistent political conflicts during mid-15\textsuperscript{th} century CE. These concurrent events could have motivated peasants to intensify fires and grazing in the highlands while sparing the riparian vegetation. The textual sources confirm that the Medieval highland pastoral economy of the Central Balkans continued in the later Middle Ages (Popović, 2012). As well, the expansion of grazing practices around this period is also identified for other parts of the Balkans (Gogou et al., 2016; Izdebski et al., 2015).

The likely occurrence of the intermittent dry sequences is also corroborated by the lithological changes along LZ-2, where dark grayish brown silty clay is interspersed with dark gray clay lens between 165 and 140 cm and with high sedimentation rate (Figs. 3.2-3.3, Table 2). Both K and Ti concentrations are in agreement with this conclusion; they show large fluctuations throughout the pre-LIA interval with lower clastic inputs between 1430 and 1470 CE (168-138 cm in Fig. 3.3). Since vegetation cover, riparian or montane, declines before soil erosion ensues (Widlok et al., 2012), the relatively dense forest cover during the late 14\textsuperscript{th} and early 15\textsuperscript{th} centuries CE is likely responsible for these lower clastic inputs into the ZO lake. The decrease in Ca concentration at 168 cm could also be connected to these dry sequences as the decrease in the rainfall and fluvial deposition affect the deposition of sedimentary Ca (Boyle, 2001; Cantarero, 2013). However, the presence of carbonate deposition (shell) layer at 170 cm cannot be overlooked in this case, which could have also saturated the calcium level in this sedimentary sequence (e.g. Aufgebauer et al., 2012). Hence, the decrease in Ca around mid-15\textsuperscript{th} century seems to be a combined product of carbonate crystallization at the lake and decreased hydrological activity in the catchment (Cantarero, 2013; Leng et al., 2013). As grazing increased in the montane region
around 1460 CE onwards (Fig. 3.4), increased concentrations of all the three elements signify increased erosion in the catchment.

In summary, the pre-LIA interval (1370-1470 CE) is characterized by relatively high tree percentages, modest occurrence of anthropogenic taxa and fluctuating geochemical proxies, suggesting dense vegetation, relatively stable agriculture supported by grazing, and fluctuating erosion patterns in the catchment.

1470-1900 CE: Dwindling woodland-grasslands with human impact in the highlands

The LIA interval shows large-scale oscillations in the AP and NAP populations. Starting from the onset of the LIA (c. 1500 CE), trees vacillate between 50 and 70% (Fig. 3.4) with both major thermophilous trees, *Quercus* and *Acer*, repeatedly waxing and waning throughout the LIA. A similar fluctuating pattern is seen in most of the riparian trees such as *Alnus*, *Fraxinus*, and *Ulmus*. The reduction in the tree cover is more extreme during the early and mid-16th century CE which is in accordance with the large increase in grasses and *Artemisia*. This pattern indicates extensive opening of the landscape. The period coincides with the Ottoman conquest of the Sava region and subsequent population influx that lasted to the end of the 17th century (McEvedy and Jones, 1978). Thus, the opening of the landscape during the earlier part of the LIA (1500-1700 CE) could have resulted from these socio-political changes as more food would need to be produced for increased populations. However, based on normalized population estimates for Yugoslavia (McEvedy and Jones 1978), Kaplan et al. (2009) argue that the population only moderately increased until the 1750s and was not enough to put additional pressure on land to cause increased deforestation. If so, climate may have contributed to changes in the forest cover directly (e.g. changes in temperature and precipitation) or indirectly (e.g. transient weather patterns causing crop failures and humans increasing their deforestation for increased timber needs and livestock grazing).
Almost all trees that are present during the early part of the LIA usually occupy temporary waterlogged or flooded banks of streams and lakes (Ellenberg, 2009), hence it is plausible that the unavailability of sufficient soil moisture could be a factor that influenced the frequent fluctuations in the riparian forest cover. Importantly, the LIA especially the early LIA (1500-1700 CE), is considered to be a period of changing precipitation regimes in Serbia (Kulkarni et al., 2016) and in the overall Balkan-Eastern Mediterranean region (Cook et al., 2016; Feurdean et al., 2015; Luterbacher et al., 2011; Xoplaki et al., 2001). Therefore, the insufficient moisture could be due to frequent droughts in the region that affect the sustained growth of the trees. A possibility of such climatic deterioration during the LIA is supported by the negligible and extremely patchy presence of cereals (*Secale, Triticum, Hordeum*) and *Juglans*, major crops from the region that favor stable-warmer temperatures and moist climatic regimes (Gogou et al., 2016; Mercuri et al., 2013).

Nevertheless, establishing a causal relationship between the landscape changes and climatic or human impacts across any time period (and especially across the last millennium) is not straightforward. A reduction in farming could also be a result of socio-political stressors such as internal and external migrations, wars, epidemics, and famines. According to Mrgić, (2011), there was a large-scale depopulation of Northern and Central Serbia during the latter part of the LIA (17th and 18th century CE) when cultivated lands were abandoned, mainly because it was a war zone with frequent Habsburg-Ottoman confrontations (1683–99, 1714–18, 1736–39, and 1788–92). Low population density and the abandonment of agriculture resulted in the dense reforestation of the whole region – which earned it the name of “Sumadija” (literally ‘Woodland’) (Milojević, 1954) –, which can be seen in increased tree populations during the late LIA (Fig. 3.4). Thus, it is plausible that the decrease in agriculture in the region could be a collective artifact of the insufficient moisture as well as adverse socio-political changes.
The Central Balkan region including Serbia was predominantly rural until the end of the 19th century where a major part of the population relied on subsistence farming and highland pastoral economy (Gogou et al., 2016; Palairet, 1997). Since agriculture in the region appears discontinuous for the larger part of the LIA, regardless of its climatic and/or socio-political origin (Fig. 3.4), this could have led people to shift from agriculture to itinerant animal husbandry-cattle trades (e.g. Mrgić, 2011). The extensive and uniform land clearance (from 1550 CE onwards), continuous presence of grazing indicators (e.g. Plantago, Pedicularis), and decrease or absence of most major montane and sub-montane taxa (e.g. Fagus, Abies, Betula, Carpinus) during the LIA, support this interpretation (Fig. 3.4). These montane taxa are highly sensitive to low moisture conditions, which might have affected their growth (e.g. for Macedonia and Bulgaria, See Gogou et al., 2016). Their decline is also indicative of increased highland pastoral practices such as pig rearing on beech forests (Palairet, 1997) by contemporaneous settlers. An additional line of evidence for such environmental change comes from the geochemical datasets from this record; the removal of highland vegetation and absence of stable vegetation/agriculture in the lower catchment would promote higher rates of erosion into the catchment. High K and Ti concentrations throughout the LIA indicate increased clastic inputs into the lake that are found within alternating sequences of clay, silty clay and silt (LZ-3 in Fig. 3.3). These fluctuations in the lithology indicate changes in lake levels, and explains short-term fluctuations in Ca concentrations (Fig. 3.3). However, this speculation does not receive support from the sedimentation rate due to the limitations of the existing age model (Fig. 3.2, Table 1). The sedimentation rate for this part of the core is found to be much lower than the pre-LIA interval (Figs. 3.2-3.3), even though equally high levels of clastic inputs are recorded (Figs. 3.3 and 3.5). It is argued that count rates for individual elements are only semi-quantitative estimates of their relative concentrations in the sediments
(Aufgebauer et al., 2012), thus one cannot expect to find a one-to-one correlation between the changes in the sedimentation rate and the elemental concentrations (Boyle, 2001; Mackereth, 1966). Nevertheless, these observations remain counterintuitive; the availability of more LIA geochemical records with robust chronologies in the future could improve our understanding of the deposition.

Overall reduction in the highland vegetation can also be seen in the understory/sub-montane vegetation. Only sub-montane trees that occur with slightly higher percentages than the earlier interval are Juniperus, and Pinus; Pinus, in particular increases considerably from the 17th century onwards. Unlike its montane counterparts such as beech-fir, Pinus is an early-succession, hardy tree that can thrive in drier and cooler conditions (Panagiotopoulo et al., 2013). Nonetheless, the increase of Pinus (~8%) in this record cannot to be solely ascribed to its resilience towards fluctuating climatic conditions. Looking at the contemporary land clearance in the montane region, the growth of Pinus could be due to human preference for beech-fir over pines in order to exploit timber and feed a large animal population (Palairet, 1997). The expansion of Pinus between 17th and 19th centuries, therefore, could have resulted from both natural (i.e. its ability to withstand unstable climatic regimes) and human intervention. A similar scenario could have materialized for Juniperus; its increase could be attributed to extensive fire episodes throughout the LIA (Fig. 3.4). Some of the fires are likely linked to the Habsburg–Ottoman confrontations from the late 17th through 18th century CE, while others could be a result of the intermittent droughts. The slight rise in Ericaceae shrubs (primarily, Erica) throughout the LIA could also be a result of anthropogenic factors such as soil deterioration (Willis, 1994), grazing and burning (Atherden and Hall, 1999; Jahns, 2005) and/or a dry/arid climatic regime (Jahns, 2005) that were influencing this Serbian landscape.
A substantial rise in the grasses and herbs occurs at the onset of the LIA, but then they dwindle until the end of the interval highlighting a highly unstable landscape throughout the LIA (Fig. 3.4). This increase in grasses followed by a decline - coinciding with the increase in woodland around the Ottoman-Habsburg wars - occurs as herbaceous-steppe taxa including Chenopodiaceae, Cichorioideae, and Artemisia start to share the landscape. While the terrestrial pollen component of the landscape indicates declining woodland-grasslands, the area immediately surrounding the study site shows a development of a wetland along the moist lake margins through the increase of sedges, especially during the latter part of the LIA (1700-1850 CE). The availability of water required for these taxa could be a product of seasonal water table fluctuations, possibly due to melting of snow in the late spring/summer (Bradley and Jones, 1993a). Alternatively, the lake level could have dropped and sedges could have colonized the lower floodplain.

Overall, the LIA interval in the Sava catchment is characterized by the fluctuating extent of forest and large-scale land erosion resulting from frequent droughts in the LIA and/or human impact. The human impact is visible from the evidence of land clearance and grazing in the highlands associated with socio-political changes, perhaps in response to the LIA climatic variability.

20th and 21st centuries: Reforestation with less human impact

During the post-LIA Era, increased components of oak-mixed-oak forest and montane habitats indicate the expansion of the tree cover in the region at the expense of shrinking grasslands. While two dominant thermophiles in the region, Quercus and Acer, markedly decline in this interval, several riparian taxa including Alnus, and Salix maintain low but stable populations during the 20th century CE with increased Fraxinus. A significant rise in Carpinus betulus and Betula, representative of montane-submontane tree community, indicates changing environmental
regimes at the onset of the 20\textsuperscript{th} century CE. Similar to the LIA, both \textit{Pinus} and \textit{Juniperus} retain their presence in this post-LIA era along with the minor presence of montane taxa (e.g. \textit{Fagus}, \textit{Abies}) (Fig. 3.4). As previously discussed, this contrast could be a product of a combination of several human activities: first, although slightly lower than the LIA interval, micro-charcoal concentrations and the persistent presence of \textit{Plantago} indicate the continued selective forest clearance practices as well as grazing in the montane region. Secondly, the coniferization of broadleaved forests became a common practice post-World War II (Rakonjac and Nevenic, 2012). From thereon, Austrian pine (\textit{Pinus nigra} L.) is reported to have been favored for both the submontane and montane beech sites in beech coppice forests (Tomic et al., 2011). Consequently, a continued growth of \textit{Pinus} and \textit{Juniperus} during 20\textsuperscript{th} and early 21\textsuperscript{st} Centuries CE could be a result of human landscape management and human/fire induced secondary vegetation along the forest borders respectively.

In addition to the clearing of forests, human impact in this era is evidenced mainly through an expanded agriculture as shown by Cerealia and \textit{Juglans}, which suggests the onset of stable-warmer climatic regime after the drier and more variable LIA conditions (Fig. 3.4). People continued to use fires to increase more arable lands in the lower catchment. As well, people could have increased grazing areas in the montane region as population increased after the withdrawal of Ottomans from the region after the 1850s (McEvedy and Jones, 1978; Palairet, 1997). This argument is supported by decreased clastic inputs into the lake from 1900 CE onwards (Fig. 3.3); although the decrease in the montane vegetation would have led to substantial erosion resulting in increased clastic inputs, the riparian vegetation as well as farms in the vicinity of the lake may have restrained these erosion inputs going into the lake (Fig. 3.3). It seems that even though agriculture in the Sava region expanded as a result of more stable climate as well as political
settings, highland pastoralism remained part of the Serbian subsistence during the post-LIA interval (Palairet, 1997).

Along the lake margins, the reduction in grassland is accompanied by declining sedges along the lake margins with a simultaneous increase in shallow water vegetation (e.g. *Typha* varieties and *Myriophyllum*). This suggests a higher water table in the littoral zone. The significant increase in Ca concentrations could be a product of improved lake level as well as the intense use of artificial fertilizers in the Sava region (Ogrinc et al., 2015).

Overall, the post-LIA interval shows stabilized woodland in the riparian region, establishment of arable lands near the lake and selective forest clearance strategies by humans in the wake of the industrial revolution.

### 3.5.2. Regional comparison

In order to differentiate the local and regional components of the Central Balkan vegetation-landscape and the potential role the LIA climate had in shaping them, the ZO ecological and geochemical datasets are correlated with the last millennium environmental record within Serbia by Kulkarni et al. (2016). This record comes from a small Western Serbian sinkhole lake located near Donja Sipulja in the southern sub-basin of the Sava, ~60 km southwest of the ZO study site (Fig. 3.1b). Although there are certain inherent differences in geology on the sides of the Sava River (see study area section), the vegetation characterized by the deciduous oak forests (Horvat et al., 1974; Rakonjac and Nevenic, 2012) and the nature of agriculture (cultivation of cereals and *Juglans*) remains the common components of the Central Balkan landscape. A series of ecological and anthropogenic proxies are utilized to compare and contrast the sites; the description and significance of each proxy in the LIA correlation follow:
(1) **Woodland-grassland changes:** The percentages for total AP and NAP from the two records act as a proxy for forest cover and landscape openness (i.e. the amount of non-forested area) respectively (Fig. 3.5a-b). This approach is utilized in numerous Pleistocene-Holocene palynological studies from the Balkans (e.g., Feurdean et al., 2015, 2013; Filipova-Marinova et al., 2013; Gogou et al., 2016; Panagiotopoulos et al., 2013; Tantau et al., 2009; Tonkov et al., 2015) and across the globe (e.g., Giesecke et al., 2011; Traverse, 2007; Tzedakis, 2007; Willis, 1994).

(2) **Temporal and spatial plant diversity patterns:** The palynological richness is utilized with the AP and NAP percentages as it documents diversity changes within vegetation units across time (Birks et al., 2016; Birks and Line, 1992; C. Y. Weng et al., 2006). Since pollen-based estimates of past plant diversity are a mix of taxonomic resolutions (family, genus, species) (Feurdean et al., 2013), the expected number of taxa, E(S_n) estimated through the rarefaction analyses of the cores (See Methods section, this paper) provides the taxon richness across the LIA (Fig. 3.5c).

(3) **The extent of land erosion:** Potassium (K) count is chosen to identify the extent of land erosion and clastic inputs (Aufgebauer et al., 2012; Francke et al., 2013) into the respective lakes across the LIA (Fig. 3.5d). Ti could also be used since it is almost analogous in both Serbian records.

(4) **Human impact through fire in land clearance:** Microscopic charcoal concentrations (/cm³) are utilized to reveal the nature of land clearance deforestation in the Central Balkans (Fig. 3.5e).

(5) **Landscape management through agriculture:** The pollen influx of two major agricultural indicators from the region, cereals and walnut (*Juglans*) (Fig. 3.5f-g), show a positive relationship with both vegetation distribution and abundance on the inter-annual to multi decadal scales (Birks and Birks, 1980; Davis et al., 1972). Since both of these crop plants favor
stable and moist climate (Gogou et al., 2016; Mercuri et al., 2013), they are used to indicate the climate of the region. Furthermore, agriculture is also associated with the stability of a workable population in agro-pastoral societies of the pre-Industrial Era (Zhang et al., 2010). The historic timeline for the Sava region is also provided with critical socio-political events to identify potential human stressors (Fig. 3.5h).

**Human-environmental interactions in the Central Balkans across the LIA**

During the LIA (1500-1850 CE), both Serbian AP and NAP percentages demonstrate fluctuations in woodland-grassland dynamics. While tree populations from the Sava region slowly fluctuate between 50 and 70%, the trees of western Serbia vacillate drastically between 30% and 55% (Fig. 3.5a). On the other hand, the Sava region grasslands show variations of ~20-43% whereas the western Serbian grass populations exhibit abrupt oscillations between high (59%) and low (32%) percentages (Fig. 3.5b). While temporal asynchronicity in the AP and NAP signals between the two cores (Fig. 3.5a-b) could be attributed to local factors including differing altitude, terrain exposure, and soils that are inherently different on either sides of the Sava channel, continuous oscillations of both communities during the LIA are analogous. This overall pattern indicates that the Central Balkan landscape at-large was going through considerable environmental change throughout the LIA in the form of opening and closing of the tree canopies on both sides of the Sava Basin.

**Early LIA (1500-1700 CE)**

The earliest part of the LIA shows a sharp reduction in the regional forest (~1550-1580 CE), which corresponds with the high clastic inputs into the respective lakes from 1600 CE onwards (Fig. 3.5d). This change in the ecology is also reflected in the palynological richness in
Fig. 3.5: Correlation between the two Serbian ecological records – Sava Region (this record) and Donja Sipulja (Western Serbia; Kulkarni et al. 2016): AP% (proxy for forest cover), NAP% (proxy for open landscapes), Estimated taxon richness (proxy for plant diversity), Potassium (K) counts (proxy for land erosion), microscopic charcoal concentration (proxy for land clearance), Cereal
and *Juglans* pollen influx (proxies for agriculture). Dark and light colored curves for each proxy represent the Sava Region (ZO) and Western Serbian cores respectively. The blue highlighted region shows the accepted extent of the Little Ice Age (LIA) (1500-1850 CE). The historic timeline is provided with major socio-political events including major wars (gray boxes).

Both records across the LIA; the taxon richness in the Sava region does not decline and rather maintains its pre-LIA values at least until the mid-16th century CE. According to Feurdean et al., (2013), landscape openness represents a significant driver of pollen richness - the greater the landscape openness, the higher the pollen richness. This short-term, multi-decadal expansion of regional grasslands between 1530 and 1550 CE, therefore, could have been the main factor that maintained the diversity of the Central Balkan landscape.

The increase in charcoal concentrations around 1550 CE (Fig. 3.5e) suggests that the contemporary societies used fire practices deliberately to clear woodlands. Independent deforestation models (e.g. Kaplan et al., 2009; Pongratz et al., 2008) show a rise in deforestation across Eastern Europe, thus loss of woodland and associated land erosion in the Central Balkans is consistent within the regional pattern of anthropogenic impact on the landscape. However, based on the presence of grazing indicators (e.g. *Plantago*) in both of the cores (Fig. 3.4; Figs. 4-5 in Kulkarni et al. 2016) during the early LIA interval, land clearance might have been used primarily to increase the grazing area (especially in the montane region) rather than agricultural area as both cultivation indicators, cereals and *Juglans*, are either absent or negligible during the 16th and 17th Centuries (Fig. 5f-g).

Historically, this was a relatively peaceful, less war-prone phase of the Ottoman Empire in Serbia (Fig. 3.5h) when there was a large influx of the people into the region (Fine Jr., 1994; White, 2006). Since most of Central Balkans maintained a low population density throughout the middle ages, this rise in population did not put undue stress on the region and thus, a large fraction of usable land for crops and pastures remained there until the end of the 17th century CE (Kaplan et
al., 2009). Hence, the negligible presence of major crops (cereals and Juglans) that favor stable-warmer temperatures and moist climatic regimes and intermittent but significant recoveries of the tree populations between 1500 and 1700 CE (Fig. 3.5a) rather point towards the quite unstable and perhaps drier conditions and colder temperature regime of the LIA across the Central Balkans. This interpretation is consistent with our current knowledge of the eastern Mediterranean paleoclimatology as the 16th and 17th centuries CE in the greater Mediterranean region were characterized by alternating wet and dry periods (Touchan et al., 2005) with droughts of greater intensity and duration than the wet periods (Luterbacher et al., 2011; Nicault et al., 2008; Roberts et al., 2012). While instrumental-archival data based and/or independent temperature-precipitation modeling efforts highlight several dry periods and coldest Spring seasons through the end of the Last Maunder Minimum (1675-1715 CE) throughout the Balkans (Xoplaki et al., 2001), several multiproxy records from the Balkan region show fluctuating precipitation with an overall drying trend in the region (Atherden and Hall, 1999; Feurdean, 2005; Feurdean et al., 2015; Francke et al., 2013; Panagiotopoulos, 2013; Schnitchen et al., 2006; Van Welden et al., 2008; Zanchetta et al., 2012). This supports the conclusion that the Central Balkan woodland and agriculture seems to have been largely influenced by the LIA climatic stress, which might have further been affected by short-term socio-political instabilities of the time.

*Late LIA (1700-1850 CE)*

During the latter part of the LIA, the Central Balkan woodlands and grasslands continued to compete for the landscape (Fig. 3.5a-b) while the tree canopies steadily started to close from ~1750 CE onwards. Gradually declining taxon richness curves for both Serbian records are in accordance with stabilizing tree cover across the Central Balkans (Fig. 3.5c); the closing of the tree canopies could have been the main factor in the reduction in the diversity (Feurdean et al.,
Studies of the local archives (Milojević, 1954; Stoianovich, 1992) record the dense woodlands in the Central Balkan region from the early-18th through mid-19th centuries CE, which agrees with pollen data from both Serbian records (Fig. 3.5a). This phase of reforestation is correlated with a large-scale depopulation in the Central Balkan region (Kaplan et al., 2009; McEvedy and Jones, 1978; Palaiaret, 1997) as a result of major political conflicts of the time (Fig. 3.5h). Nevertheless, this latter part of the LIA has also been recognized as less severe in temperature and perhaps a time of increased moisture as compared to the earlier part of the LIA (Luterbacher et al., 2004; Poljanšek et al., 2013; Popa and Bouriaud, 2014; Popa and Kern, 2009). Between 1750 and 1850 CE, this part of Europe showed higher summer temperatures with some of the hottest summers with an overall summer cooling trend as shown by dendrochronological studies (Popa and Bouriaud, 2014; Popa and Kern, 2009) as well as paleoclimate models (Luterbacher et al., 2016, 2004). A localized tree ring record from the Central Balkans (Bosnia; Poljanšek et al., 2013) also infers sunny summers between 1695–1790 CE with improved moisture content. Furthermore, other Balkan records (e.g. Albania, (Seim et al., 2010), and northern Greece (Griggs et al., 2007)) confirm stable temperatures during the growing season between early 18th and mid-19th century CE. Following this reasoning, the increase in the Central Balkan woodland during the late LIA seems to be a combined product of improved weather patterns and lower stress on the landscape due to depopulation.

Despite better climatic regimes as compared to the early LIA, agriculture in the region did not improve much during the later part of the LIA, except for a few local variations in the cereal (c.1680-1720 CE, ~1820 CE) and Juglans (c. ~1780 CE) crops seen only in the Western Serbian record (Fig. 3.5g; Kulkarni et al., 2016). Because *Juglans* thrives with stable warmer temperatures (Gogou et al., 2016; Mercuri et al., 2013), the above short-term periods of sustained agriculture
could tentatively be attributed to intermittent calmer weather patterns with sufficient moisture during the late LIA. However, the socio-political situation of the time could have been a critical factor that did not promote agriculture since depopulation in the Sava region was more extensive than other parts of the Balkans (Milojević, 1954; Mrgić, 2011). This extensive emigration in the Central Balkans could have adversely affected the agriculture of the Central Balkans by reducing the number of farmers and agricultural workers in the completely agro-pastoral economy of the Balkan region (Mrgić, 2011; Palairet, 1997). Additionally, army provisions and the requisitioning of men, food and animals could have affected both food production and the population while brigandage and wartime pillage may have destroyed agricultural areas and settlements (Mrgić, 2011). The overall process could have motivated people to at least temporarily shift to pastoralism, perhaps nomadic in nature, as shown by continuous Plantago curves in both records (Kulkarni et al., 2016; Fig. 3.4), especially in the highlands where the availability of forest pastures for pig rearing was readily present (Kaplan et al., 2009; Palairet, 1997). Consistently high and uniform land clearance pattern and large-scale land erosion in the Sava region (Fig. 3.5d-e) support this interpretation.

3.6 Conclusions

Major conclusions from this new high-resolution Central Balkan record from the Sava region are –

1) The pre-LIA interval (1370-1470 CE) in the Sava Basin is characterized by relatively high tree percentages, modest occurrence of anthropogenic taxa and very low geochemical proxies, suggesting dense vegetation, relatively stable agriculture supported by grazing, and fluctuating erosion in the catchment as result of a stable and warmer climate and a comparatively stable socio-political regime.
2) The LIA interval (1470-1900 CE) in the Sava Basin shows consistent opening and closing of the tree canopies, extensive land erosion as a result of the LIA climatic deterioration (in terms of droughts and/or drastic precipitation regime especially until 1700 CE) and human impact (land clearance-grazing in the highlands associated with socio-political changes), perhaps in response to the LIA climatic variability.

3) The post-LIA/Industrial Era in the Sava region brings a stabilized woodland in the riparian region, establishment of arable lands near the lake shores and selective forest clearance strategies by humans in the wake of the industrial revolution.

4) Correlation with the available Serbian environmental records across the LIA reveals the regional dynamics between woodland and grassland under the influence of an unstable and perhaps drier LIA climatic regime, especially in the early LIA, and reforestation of the region during the latter part of the LIA due to both climatic and socio-political reasons.
Chapter 4
An examination of long-term environmental-social dynamics
in the Balkans

This chapter is in preparation for submission to a scientific journal.

Abstract
This study examines the interactions of environmental and social dynamics in Central Balkans over the past 700 years, a period that experienced the LIA climatic condition and the warm 20th century. Meanwhile, the same period witnessed a complex human history with the emergence-rise-decline of the Ottoman Empire and subsequent socio-political events (e.g. wars, famines, migrations, epidemics). Environmental datasets for this socio-environmental analysis include biological proxies (pollen, spores, and charcoal), geochemical signals, and a detailed AMS $^{14}$C based chronology of two Central Balkan lakes while social datasets include historic population data, land use, records of societal calamities, and critical historic events derived from a review of the literature and local archives. Among the environmental datasets, indigenous tree and herbaceous pollen from the Central Balkans demonstrate fluctuations in woodland-grassland dynamics whereas potassium counts obtained through XRF act as a proxy for surface erosion and clastic input into the lakes. Microscopic charcoal, cereal pollen and subordinate anthropogenic pollen (e.g. cultivated fruits and vegetables) are used to distinguish the nature of human impact over the landscape. These key anthropogenic indicators create a more thorough social component of the analysis in association with other social datasets. After reconstructing the individual time series for each environmental and social dataset and their synthesis using Principal Component Analysis (PCA), the two Central Balkan records are correlated in order to visualize how a region...
responds to social and environmental stressors. Our approach demonstrates ways to integrate natural and social science systems research.

4.1 Introduction

Global warming and its associated impacts on ecosystems and social systems present a substantial challenge to modern civilizations that already experience many direct and indirect impacts of anthropogenically-induced climate change (Cook et al., 2015; Jansen et al., 2007; Mann et al., 2009). An assessment of the human-climate-ecosystem interactions of the past can provide insights for present and future global challenges. Multi-proxy reconstructions of climate change impacts and social responses, and the comparative study across the distinct climatic episodes form an effective tool for elucidating the mechanisms of the interactions (Xiao et al., 2015). One such attempt has been made in this study, which examines the environmental-climatic-social dynamics in the Balkans over the past 700 years; the period includes the Little Ice Age (LIA; 1500-1850 CE), a cold climatic interval that imposed significant changes on landscapes that contemporary societies inhabited and cultivated (Fagan, 2000; Grove, 2001; Pfister, 2005). Meanwhile, the same period witnessed a complex human history with the emergence-rise-decline of the Ottoman Empire and antecedent-subsequent socio-political events (e.g. wars, famines, migrations) in the region. This diverse blend of socio-ecological-climatic stressors and their impact on the predominantly agro-pastoral Balkan subsistence provide a unique opportunity for examining human-climate-ecosystem interactions.

Using time-series and Principal Components analyses, ecological datasets (e.g. woodland, grassland, land erosion, land clearance, agriculture etc.) available from pollen, charcoal, and geochemical analyses are integrated and correlated with multiple social datasets that include historic population, deforestation-land use models, annual records of famines, droughts, and
Figure/Table 4.1: Location and nature of the study sites providing ecological and certain eco-social indicators in this study.

critical historic events derived from a review of the literature and local archives. Among the environmental datasets, indigenous tree and herbaceous pollen from two Central Balkans (Serbian) records (Table-Fig. 4.1) demonstrate fluctuations in woodland-grassland dynamics on the regional scale whereas potassium counts act as a proxy for surface erosion and lithogenic inputs in the catchment. Two fundamental aspects of human impact over the landscape – land clearance and cultivation – are distinguished using varying abundances of microscopic charcoal and two prime cultivation indicators in the Balkans, cereals and walnut respectively. These key geochemical and
pollen anthropogenic indicators along with contemporary social datasets together create a more detailed social reconstruction of the past. Time series for each environmental and social dataset are reconstructed and then become factors in a Principal Component Analysis (PCA) technique. PCA helps reveal environmental and social homogeneity and heterogeneity patterns within the Balkans and their likely linkages with the LIA climatic regime. Results provide insights on how a region responds to social and environmental stressors and demonstrates a way to integrate natural and social science systems research.

4.2 Materials and methods

4.2.1 List of indicators utilized

This research is designed to assess and integrate the long-term ecological-climatic-social dynamics of the Balkans. In order to do this, care was taken in selecting datasets that have the potential to provide temporal as well as spatial variations from annual to multi-centennial scale. Three categories of indicators – ecological, social and climatic – are utilized in this study. The description of each indicator within each category is discussed below and summarized in Table 4.2:

I. Ecological and eco-social indicators – Biological and geochemical analyses of two sites located in western (DS) and central (ZO) Serbia, provide both local and regional environmental imprints that are used to develop these indicators. Table 4.1 shows the details for each Serbian site while their analytical details will be found in Kulkarni et al., (2016) and Kulkarni et al. in prep. Ecological indicators from the two sites include:

i. Woodland and grassland: The absolute percentages of arboreal pollen (AP) and non-arboreal pollen (NAP) act as proxies for forested areas and open landscape respectively. Moreover, both AP and NAP are largely wind transported, and so mainly provide a regional
vegetation picture with local vegetation niches. Both datasets are used widely in pollen studies across the globe to describe local as well as regional vegetation patterns during the late Pleistocene and Holocene (e.g., Birks and Birks, 2006; Giesecke et al., 2011; Tzedakis, 2007; Willis, 1994). Percentages of AP and NAP were chosen, therefore, to represent the regional Balkan vegetation framework (ZO site) with some local vegetation insights (DS site) through time.

ii. **Land erosion**: Soil erosion and associated sediment deposition in basins ensues after vegetation cover is reduced. This results in increased amounts of certain elements (e.g. potassium (K), titanium (Ti), iron (Fe)) in the lake sediments (Aufgebauer et al., 2012; Widlok et al., 2012). This coupled relationship provides important information on the environmental processes occurring in the region that could be a product of natural or human impacts on the landscape. Potassium counts were selected since it is a principal weathering product of a variety of crystalline igneous and lithic sedimentary rocks (Cohen, 2003; Francke et al., 2013) that dominate Serbian highlands (Koroneos et al., 2011; Toljić et al., 2013). Potassium is often presented alongside Ti, which can also provide erosion signals from similar geological background (Panagiotopoulos et al., 2013; Wagner et al., 2010). However, the changes in K and Ti at both Serbian sites are completely analogous across respective temporal scales, and so either geochemical proxies could represent land erosion in this study.

iii. **Land clearance**: Since the first agricultural societies in Europe in the mid-Holocene, humans have substantially altered the European landscape (Kaplan et al., 2009). This key eco-social aspect of the Balkan landscape is explored through the extent of land clearance as seen from the varying microscopic charcoal contents in the two sites. Microscopic charcoal
concentrations assist in the examination of the regional fire history as fires are used to clear land (Whitlock and Larsen, 2001). It is understood that microscopic charcoal abundance increases during local-natural fires, however, sedimentary records of human use of fire and the natural fire are different as the former is generally accompanied by the occurrence of anthropogenic pollen (e.g. weeds or cereals) (Li et al., 2008). The pollen-based eco-social proxies (e.g. cereals, walnut) that are purposefully utilized in this study help to differentiate between human and natural fires. Temporal variations in charcoal concentration represent anthropogenic land cover and land use changes, in particular, clearing of forests and woodlands for cropland and pasture, source of fuel, and construction materials (Hughes and Thirwood, 1982).

iv. Agriculture and arboriculture: Cultivation is explored using two main crop types in the Balkans, cereals (e.g. rye, wheat, sorghum) and walnut (Juglans). Although the occurrence and abundance of cereals is adequate to render presence and absence of agriculture in the region (Mercuri et al., 2013), the nature of Juglans is closely examined in order to understand the sensitivity of these cultivars with respect to changing past climate. For the southern Balkans and Mediterranean region, either OJC (Olea, Juglans, Castanea) or OJV (Olea, Juglans, Vitis) group is usually employed to show arboricultural changes with respect to climate as both these groups are only accustomed to stable and warm temperature and highly susceptible to cooler temperatures (Gogou et al., 2016; Mercuri and Sadori, 2014). Except for Juglans, the above taxa are poorly preserved and highly underrepresented (<1%) in both Serbian records, and are thus statistically insignificant for interpretation. This makes Juglans the only major cultivated tree viable to identify any major changes in cultivation strategy as well as its linkages with the LIA climate.
Table 4.2: List of indicators utilized in this study. *See Materials and Methods Section for details.

II. Social indicators – Another vital element of assessing long-term environmental-social dynamics comes from three distinct social indicators gathered from a review of literature and archival records from the Balkans.

i. Historic deforestation: Historic deforestation data generated by two independent models, Pongratz et al., (2008) and Kaplan et al., (2009) (hereafter, P- and K-Model respectively) are used to compare the overall deforestation trend in Europe. Both models discuss the reduction in forest cover on semi-continental scales incorporating national populations. The P-Model
describes deforestation in Europe as a whole in comparison with other continents whereas the K-Model probes into each part of Europe including Eastern Europe where all Balkan nations are modeled both as one region and as individual nations. Although these models have distinct model-building approaches, this study uses the estimates from both models in order to compare historic deforestation trends and their linkages with the Balkan vegetation and land clearance datasets.

ii. **Historic population**: A review of the literature reveals a lack of consensus on the estimates of historical population, especially for times earlier than the 18th century (Pongratz et al., 2008; Zhang et al., 2010). The historic population dataset predominantly used in this study is based on the charts and density estimates provided by McEvedy and Jones (1978). This is a widely accepted demographic study in recent literature and has high spatial and temporal resolutions (See Kaplan et al., 2009; Klein Goldewijk et al., 2011; Pei et al., 2014; Pongratz et al., 2008; Reale and Shukla, 2000; Zhang et al., 2010). In order to reconfirm the consistency of the Balkan population estimates by McEvedy and Jones (1978), an alternate population dataset for 1900-2000 CE was created using various census datasets of the populations for Yugoslavia (Serbia, Montenegro, Bosnia, Croatia) and for the rest of the Balkans (Bulgaria, Romania, Macedonia, Albania, Greece) from several demographic repositories, including the World Bank Database (1960-2000), Developed Institut national d'études démographiques Developed Countries Database (1950-2000), Institute for Statistics of Federation of Bosnia and Herzegovina (1879–1991), and Mitchell (1975) for the early 1900s.

iii. **Archival record on societal calamities**: A dataset of multi-annual records of famines, droughts, and extremely cold periods, along with specific seasonal details whenever
available (e.g. cold summer) was created through a careful examination of the archival records from Yugoslavian and other Balkan countries. The primary resource is Vujevic (1931) which has amassed more than three hundred eyewitness accounts from various Yugoslav, Bulgarian, and Greek archives between the years 1358 and 1864 CE, from which Vujevic (1931) could identify regional hydroclimatic conditions resolved to the year or better with as many as three records per year. Each record is either in a direct relationship with meteorological events (e.g. severe or mild winter) or is related in an indirect way as the eyewitnesses comment on phenomena such as floods, famine, and plague epidemics. The Vujevic (1931) dataset was enhanced with some additional data from White (2006) and Xoplaki et al., (2001) who collected their data from several other archives especially from the Southern Balkans. The historic timeline is provided to recognize the political frame of reference for these societal calamities.

III. Climatic indicators –

Climatic conditions and various types of activities by human populations are considered to be important factors shaping vegetation and maintaining open land (Feurdean et al., 2015; Mercuri et al., 2011). Generally speaking, pollen from trees are particularly suitable to highlight climatic events in high resolution, while pollen related to human activities, largely from herbaceous taxa, is considered to mirror land use and economy (Mercuri et al., 2013). However, interpretations are made more complicated by the fact that climate can trigger land use changes and economy shifts, and reactions or adaptation of human societies to climate oscillations produce complex effects on the environment (Buntgen et al., 2011a; Weninger et al., 2009). In order to explore this facet of environmental-climatic-social dynamics, Buntgen et al., (2011b) net summer (AMJ) precipitation and JJA temperature anomalies (w. r. t. 1901–2000 CE)
reconstructions from the past millennium were included. Although these reconstructions are the composite records from Central European trees, a high degree of correlation with other parts of Europe has been established in the same study based on previous pan-European and independent dendrochronological studies (Buntgen et al., 2011a) as well as in subsequent studies that involved Balkan datasets (Cook et al., 2016, 2015; Luterbacher et al., 2016). This substantiates a basis to correlate this dataset with the Balkan eco-social dynamics of the past millennium.

4.2.2. Statistical analyses

In this study, time series and PCA analyses are used to examine patterns within the datasets. Time-series is used to visualize the correlation among the ecology-society-climate datasets across the given temporal frame of reference whereas PCA is a data-reduction technique that highlights the major patterns of variation in these temporal changes while illustrating and summarizing apparent connections among ecological-social-climatic processes (Birks and Birks, 2006). Each indicator series was plotted in Microsoft Excel and the final time series was compiled using Adobe Illustrator. PCA was performed using MatLab R2015b (MathWorks Inc., Natick, MA, USA) where a biplot of the coefficients in the matrix containing principal components (PCs) was created using the function, *pca*. The axes in the biplot represent the first two PCs; each ecological and social indicator is represented as a vector (line) whereas dots show the actual values of these indicators. The significance of the biplot technique is that it imposes a sign convention, forcing the element with largest magnitude in each column of coefficients to be positive and eventually flips some of the vectors in coefficients to the opposite direction (MatLab R2015b). This makes the plot easier to identify the magnitude and sign of each variable's contribution to the first two (or three) PCs. Interpretation of the plot remains unaffected, because changing the sign of a coefficient vector does not change its meaning.
Overall, the interpretation of the vectors in the biplot is based on three relationships among the variables:

1. Positively correlated variables are grouped together;
2. Negatively correlated variables are positioned in the opposite quadrants (Quinn and Keough, 2002);
3. The distance between variables and the origin measures the quality of the variables; longer the vector, the higher is the variance (Kohler and Luniak, 2005).

4.3. Results and discussion

In this study, the time series (Fig. 4.2) and PCA biplots (Fig. 4.3a-b for the Sava Region and Western Serbia respectively) show the correlation among the ecological-social-climate indicators across the past 700 years. Fig. 4.2 reveals the temporal correlations among the indicators while Fig. 4.3a-b reveals the indicator groupings for each site along the first two PCs where the maximum variance is provided by the first PC. For example, since both K- and P-models describe the changes, which is largely a decrease, in the regional forest cover throughout the period, their vectors have their covariance in the PC1 (Fig. 4.3a and b in upper and lower right quadrants respectively). The Balkan population lies in the exact opposite quadrants of the deforestation models; this explains the inverse relationship between population and the forest cover as shown in lower and upper left quadrants respectively of Fig. 4.3a and b. Similarly, the Sava Region and Western Serbian woodlands and grasslands occur in the opposite quadrants of the respective biplots showing their inverse relationship. Since land erosion, land clearance, agriculture and arboriculture do not clearly co-vary with any particular climatic and/or social variable, hence each of them could be considered as collective artifacts of climatic, social and ecological indicators.
across the time. The following discussion reveals several interesting correlations and some possible causes in the long-term environmental-social dynamics in the Balkans.

**Stable/warm pre-LIA interval (1370-1500 CE) with lower population pressure on the landscape**

European summer temperature and precipitation bring somewhat stable-warm and wet conditions during most of pre-LIA interval until c. 1450 CE (Buntgen et al., 2011) and the local archival records are in agreement with these climatic simulations with unusually cold seasons (Fig. 4.2i). This period coincides with the largely stable Hungarian realm in the Central Balkans while the southern parts of the Balkans were struggling with the Ottomans (Ali, 2012; Fine Jr., 1994) in the aftermath of the Black Death. Repeated plague outbreaks of the Black Death between 1347 and 1353 decimated the human population in Europe (Schmid et al., 2015). Between 1350 and early 1400 CE, the Balkans lost one-third of its population to this plague outbreak (McEvedy and Jones, 1978; Fig. 4.2h). The societal situation was further worsened by two major famines and wars in the late 14th century CE (Ali, 2012; Vujevic, 1931; Fig. 4.2h). The first significant decline in the cultivation (Fig. 4.2e-f) and the negligible land clearance (Fig. 4.2d) around this time may be a result of the drastic decrease in population and the unstable political situation in the region. Another likely environmental consequence of this socially difficult period is the increased land erosion between 1390 and 1430 CE (Fig. 4.2c). The Balkans are known for their long-term highland pastoral economy where highland meadows are maintained for livestock-grazing (Gogou et al., 2016; Palairet, 1997). The deterioration of these pasture and possibly some crop lands located on hills and terraces in river valleys of the Central Balkans would tend to increase loss of soil due to lack of human care (Geyer, 1986), perhaps initially before natural vegetation could be re-established in the region. A similar scenario is discussed for Macedonian and Bulgarian
highlands (Gogou et al., 2016), which also support the tentative causation between lower anthropogenic pressures and landscape changes across the Balkans during this period.

At the onset of the 15th century CE and continuing to the end of the century, tree cover increased (Fig. 4.2a) and the Central Balkans remain densely wooded at least along the riparian zone (Kulkarni et al. in prep). This agrees with the estimates of both regional deforestation models, especially the K-model which highlights a moderate increase in the forest cover across Eastern Europe in the early 1500s (Fig. 4.2g). The increase in the vegetation would lesson erosion and associated sediment inputs as interpreted from the Sava Region core around 1440 CE (Fig. 4.2c). This interpretation of increased vegetation – less erosion is supported by an inverse correlation (least covariance) in the PCA (Fig. 4.3) where land clearance and land erosion often co-vary (Fig. 4.3a).

The extent of the Central Balkan land clearance around mid-15th century CE is quite limited except two short-term episodes around 1430-1440 CE and 1460-1470 CE. By mid-15th century, although the regional population had gradually reached the pre-Black Death numbers (Fig. 4.2h and Fig.4.3), the population density for most of Eastern Europe remained very low and there was not undue stress on the landscape (Kaplan et al., 2009; McEvedy and Jones, 1978; White, 2011b). Several conflicts between the Ottomans and the regional kingdoms (e.g. Hungarian realm in the Central Balkans) occurred during this time period. These political conflicts could have resulted in burning villages and the landscape in the Central Balkan region (e.g. Mrgić, 2011). According to pollen data from this region (Kulkarni et al., 2016; Kulkarni et al. in prep), these burning episodes did not affect the lowland vegetation, however, most montane-submontane taxa show a limited presence around mid-15th century CE as well as a moderate occurrence of livestock-grazing indicators, especially Plantago. This indicates the reestablishment of highland grazing in the
Figure 4.2: Evolution of Balkan ecological-social-climatic systems over the last 700 years: The extent of the forest cover and open landscapes are shown by AP% (a) and NAP% (b) of the Sava Region and Western Serbian sites while potassium (K) counts (c) exhibit the erosional inputs into
the respective lakes. Human impact on the landscape is shown through the magnitude of land clearance through microscopic charcoal concentration (d) and the degree of agriculture (e) and arboriculture (f) as shown by cereal and *Juglans* pollen influx respectively. Modeled deforestation rates that accounts for population history for Europe (P-Model, Pongrats et al. 2008) and Eastern Europe (K-Model; Kaplan et al. 2009) (g). The Balkan population curves (h)) by McEvedy and Jones 1978 (1400-1975 CE) and alternate 1900-2000 CE population series through various datasets (See ‘Historic Population’ Section for further details); the years of reported famines (Vujevic 1931) are displayed at the top. Central European summer temperature and precipitation (i) are shown after Buntgen et al. 2011; annual records of individual-multiple events of extremely cold periods-seasons and droughts are displayed alongside. The historic timeline is provided with political events including major wars (gray boxes). The blue highlighted region shows the accepted extent of the Little Ice Age (LIA) (1500-1850 CE).

region during mid-15th century CE while the agriculture and arboriculture was moderately improving in the region (Fig. 4.2e-f). The overall decreases in summer temperature and precipitation that occurred during the same time (Buntgen et al., 2011, Fig. 4.2i) seem to have affected agricultural practices, as shown by the intermittent fluctuations in temperature-sensitive *Juglans* in Fig. 4.3f. This might have motivated peasants to expand grazing areas in the mountains, as found for other parts of the Balkans during the 15th century (Gogou et al., 2016). The increase in grazing in the highlands and somewhat unstable lowland agriculture with a slight increase in grassland at the end of the 15th century CE (Fig. 4.2b) could account for increasing land erosion from 1470 CE onwards.

**LIA climatic variations and its impact on Balkan societies under changing political regimes**

By the early 1500s, the Ottoman Empire took charge of entire Balkan region. For the next 150-160 years of their rule, they instituted a number of systems for the management and provisioning of resources for its territories, all the while directing the expansion of the settlement and cultivation across the Balkan region (White, 2011a). People living in the Balkans during 16th and 17th centuries enjoyed a fairly peaceful period with commercial progress and increased population (Stoianovich, 1992). However, by the end of the 17th century, the Ottoman Empire
started suffering a major crisis with increasing economic turmoil and social unrest from which it never fully recovered (White, 2006). During the late Ottoman rule (17th-18th centuries CE), various parts of the Balkans including Central Balkans was a part of the war zone of the frequent Habsburg–Ottoman confrontations that forced the outmigration of the inhabitants (Palaiarret, 1997; Stoianovich, 1992). Despite their attempts to restore order, the Ottomans completely lost control over their territories and during 1830-50s, parts of Balkans came under independent principalities (Ali, 2012). Subsequent to the withdrawal of the Ottomans around 1850s, a significant demographic rise was recorded in the region (McEvedy and Jones, 1978; Palaiarret, 1997). This continual inward and outward flow of people as well internal migrations within the Balkans over three-four centuries and the exit of the Ottomans around 1850 CE i.e. towards the very end of the LIA does not seem to be a mere coincidence (White, 2011a) and Fig. 4.2 and 4.3 in this study shed light on probable climatic influences for these socio-political transitions.

Until 1560 CE, the climate seemed to be stable and warm (Fig. 4.2h), however from thereon, summer temperatures sharply decline and remain lower throughout the LIA with repeated fluctuations (Buntgen et al., 2011b, Fig. 4.2i). According to Luterbacher et al., (2004), European winters were generally colder than those of the 20th century with the coldest multi-decadal winter periods during the late 16th century and during the last decades of the 17th century, except for two short periods around 1530 and 1730 CE. Local archival records are in agreement with these model simulations; the number of eyewitness records increased during these centuries that reported cold years with extremely cold winters throughout the LIA and a large number of cold summers between 1700 and 1850 CE. Furthermore, the summer precipitation patterns in the LIA are more drastic than temperature variations - the earlier part of the LIA (1500-1700 CE) received less precipitation during the summer as compared to the later part of the LIA (1700-1850 CE) (Buntgen
et al., 2011b, Fig. 4.2i) with dry spells throughout the LIA and several droughts during the latter part of the LIA (Vujevic, 1931; Fig. 4.2h-i).

Although growth season precipitation promotes favorable conditions for agriculture, extreme storm and hail events can result in crop. Several hail storm events are reported in Vujevic (1931, p.8). The coexistence of comparatively higher summer precipitation (Fig. 4.2i) and very low agricultural and arboricultural activities (Fig. 4.2e-f) during the late LIA in the Central Balkans may have resulted from severe winter storms. The existence of droughts, especially during the wettest summer simulated during 1750-1850 CE (Fig. 4.2i) indicates a skewed seasonal distribution of rainfall in the region with a direct effect on society.

While agriculture-arboriculture remained low throughout the LIA apart from some local exceptions (as shown by the Western Serbian site) around mid to late-17th century (Fig. 4.2e-f), the Balkan population increased (Fig. 4.2h). A visible impact of the increased population on the Balkan landscape can be seen through extensive land clearance (Fig. 4.2d), perhaps as a response to a more conducive climate as well as transitioning political realms. Considering the regional origin of microscopic charcoal utilized in this study, contemporary societies across the Balkans could have used intense fire practices deliberately in association with woodland clearance, particularly for the earlier part of the LIA, and grazing especially in the montane regions (Kulkarni et al. 2016; Kulkarni et al in prep).

The phases of extensive deforestation are demonstrated in both Central Balkan lakes in the form of repeated fluctuations in woodland-grassland populations at both local and regional levels (Fig. 4.2a-b). The removal of tree populations especially in the montane areas (Kulkarni et al. 2016; Kulkarni et al. in prep) is also reflected in the enhanced erosion rates across the Central Balkan region (Fig. 4.2c). As land erosion and land clearance go hand-in-hand throughout the LIA
Fig. 4.3: Biplots of ecological, eco-social and social indicators from the Sava Region (a) and Western Serbia (b). The color code for each indicator is similar to that from Fig. 4.2.
(Fig. 4.2c-d), they also concur with the regional P-Model and K-Model deforestation estimates (Fig. 4.3). The reduction in the tree cover is more drastic in the early and mid-16th century CE that coincided with the comparatively peaceful period of the Ottoman conquest of the Central Balkan region and subsequent population influx from the other parts of the Balkans until the end of 17th century (McEvedy and Jones, 1978). However, the large number of famines (Fig. 4.2h) co-occurred with this population influx, which could have impacted the comparatively stable political-social regimes.

Thus, the opening of the Balkan landscape during the earlier part of the LIA (1500-1700 CE) seems to be a combined product of socio-political changes as well as of the drier LIA climatic regime; both tree cover and agriculture could not sustain due to lower precipitation regime in the early LIA (See Kulkarni et al. 2016 and Kulkarni et al. *in prep*) which could have motivated people to clear the pristine areas across the Balkans. It is also plausible that through extensive land clearance (Fig. 4.2d), the pastoral Balkan communities could have contributed to dryness of the landscape thereby encouraging loss of fertile soils and further affecting the agriculture of this region. This climatic-ecological-human interactions loop in the early LIA could have given rise to more droughts and famines that are recorded for the later part of the LIA (1700-1850 CE) (Fig. 4.2h-i) when the overall cultivation was hindered by (except some local deviations; Fig. 4.2e-f) the irregular summer precipitation and overall variability of the LIA climate (Luterbacher et al., 2004; Xoplaki et al., 2001; Zerefos et al., 2011).

A large part of the 18th century witnessed severe Habsburg–Ottoman confrontations (1714–18, 1736–39, 1788–92) that forced the outmigration and constant internal migrations of the Balkan inhabitants (Mrgić, 2011; Palairet, 1997). These socio-political changes could have reduced the number of sedentary farmers and agricultural workers in rural areas of the Balkans (Gogou et al.,
which could have adversely affected the cultivation in the region. The process of depopulation seems to have resulted in partial stabilization of the Central Balkan woodlands especially in the Sava Region (Fig. 4.2a), which might have encouraged local and regional pastoralism (even, fully or semi-nomadic pastoralism), eventually bolstering communities to resist against the already weakened-aging Ottoman Empire (Ali, 2012; White, 2011a, 2006). Starting from the onset of the 19th century CE, several minor and major uprisings took place in various parts of the Balkans (Milojević, 1954; Mrgić, 2011) and the Ottomans could not restore order and completely lost control over their territories starting from 1830 CE (Ali, 2012).

**Stable-warm climate of the post-LIA Era and industrialization of the Balkans**

Subsequent to the withdrawal of the Ottomans, a significant demographic rise was recorded in the region (McEvedy and Jones, 1978; Palairet, 1997; Fig. 4.2h). This demographic change co-occurred with the warmer temperature and stable precipitation regime of the 20th century (Buntgen et al., 2011a; Luterbacher et al., 2016) and the introduction of technological changes in the many Balkan countries (Palairet, 1997). This allowed people to more efficiently manage the landscapes in comparison with their medieval strategies, as shown by the large reduction of land erosion and land clearance (Fig. 4.2c-d). The post-LIA Era is also characterized by the stabilization of the regional woodlands (Fig. 4.2a), which fits well in the decoupled “forest-human population relationship” of the Industrial Era as most countries experienced a “forest transition” – earlier deforestation switching to afforestation – phase concurrent with population growth generally coinciding with industrialization and urbanization (Mather, 1992; Rudel et al., 2005). Both climatic stability and increased population with technological advances seemed to have partially helped the improvement of the agriculture in the region (Fig. 4.2e-f).
4.4. Summary

Using time series and PCA techniques, the study examines the long-term environmental-climatic-social dynamics in the Balkans over the past 700 years including LIA climatic conditions that coincided with the emergence-rise-decline of the Ottoman Empire and antecedent-subsequent socio-political events in the region. This diverse blend of socio-ecological-climatic stressors and their impact on the predominantly agro-pastoral Balkan subsistence provide a unique opportunity for examining human-climate-ecosystem interactions. The key findings in this study are –

1) The Sava Region shows subtle variations for most ecological and eco-social proxies, whereas the Western Serbian record shows many short-term fluctuations across the LIA.

2) A cold and overall dry picture of the LIA, especially for the early LIA, with multi-decadal variability for Central Balkan, supported by the analysis of both Serbian sites, the climatic models, and local archival records. Archival records report high numbers of cold years including extremely cold winters and summers throughout the LIA, as well, large numbers of droughts coinciding with colder seasons.

3) Precipitation in growth seasons promotes favorable conditions for agriculture, although extreme storm events can result in crop failures. The coexistence of extremely high summer precipitation and low production in the region supports this interpretation.

4) Famines and population changes do not correlate well in the region. Famine may be due to the unavailability of food due to short-term climatic changes and other ecological factors; political conflicts and wars during the later part of the LIA could have been a major factor behind the occurrence of famines in this region.

5) Large-scale human impact on the landscape, perhaps as a response to the LIA climatic variations, is evident largely through extensive land clearance while agricultural activities
remain low during/because of LIA conditions. It is also possible that people could have contributed to dryness of the landscape in this region.

6) Population and local-regional forest cover are inversely proportional until the end of the LIA; land erosion and land clearance coincide with regional deforestation with a few exceptions across LIA. The relationship decouples during the Industrial Era.
Concluding Remarks

Based on the utilization of pollen-charcoal-geochemical-chronological and other supplementary analyses of two Serbian sediment cores, this doctoral dissertation reconstructs the palaeoenvironmental history of the Central Balkan region over the past millennium. These are the first paleoecological records from Serbia, which discuss the vegetation and landscape changes during a transitional period between the Medieval Climate Anomaly and the Little Ice Age (before 1500 CE), spanning the Little Ice Age (LIA; 1500-1850 CE) and through the post-LIA/Industrial Era. Both the role of humans and climate responsible for these changes are explored at the multi-decadal scale.

A key contribution of this doctoral research includes the discussion on the nature and variability of the LIA which is not well-understood for the Balkan region. According to the Sava Basin record in this doctoral study (Chapter 3), the LIA interval is characterized by the fluctuating extent of forest and negligible presence of temperature-moisture sensitive crops, and large-scale land erosion in the catchment. For the Western Serbian record (Chapter 2), the early LIA (~1500-1700 CE) shows complex woodland-grassland dynamics with an overall opening of the landscape and increasing erosional signals, while the late LIA (~1700-1850 CE) reveals a completely open landscape with slightly increasing woodland and development of stable agriculture in the region. While temporal asynchronicity in woodland-grassland dynamics as well as agricultural changes between the two Serbian cores could be attributed to some local factors, continuous oscillations of both forested and non-forested fractions during the LIA are analogous. This overall pattern indicates that the Central Balkan landscape at-large was going through considerable environmental change throughout the LIA in the form of opening and closing of the tree canopies on both sides.
of the Sava Basin with the phases of reforestation and increased agriculture in the later part of the LIA. Steadily declining palynological richness curves for both Serbian records are in accordance these ecological changes; the decrease in the taxon diversity is expected with the increased woodland as observed for the later part of the LIA. Both Serbian records individually and collectively reveal a slightly cooler and drier imprint of the LIA (especially for the early LIA) in the Central Balkan region with discernible local variations.

Although more records are needed to understand the magnitude of the LIA, the drier nature of this interval compared to the pre- and post-LIA periods in Serbia and the Central Balkans is in agreement with our current knowledge of the eastern Mediterranean proxy and modeling data and supports the possibility of an east-west climate seesaw that seems to have operated between the two Mediterranean sub-basins over the past millennium (Roberts et al., 2012). This doctoral research contributes towards our understanding of the LIA climatic variability across Europe and becomes part of an increasing body of paleoclimate literature that challenges the “wet and cool” picture of the LIA as painted by western-northern European proxy records (Bradley and Jones, 1993b; Ljungqvist, 2010; Mann, 2002; Matthews and Briffa, 2005).

The past millennium timeframe of this dissertation also allowed the examination of the long-term environmental-climatic-social dynamics in the Balkans as the LIA climatic conditions coincided with the emergence-rise-decline of the Ottoman Empire and antecedent-subsequent socio-political events in the region. A collective use of time series and principal components analyses of ecological-social-climatic datasets obtained from two Serbian cores and from a review of the literature provides insights on how the landscapes responded to climatic as well as socio-political stressors of the time (Chapter 4).
Overall, adverse effects of the LIA climatic variability on the contemporary Balkan societies was observed in addition to constantly changing socio-political regimes. Climatic and archival records (Buntgen et al., 2011b; Vujevic, 1931) reported a high number of cold years throughout the LIA accompanied by a large number of droughts. These climatic variations seem to have impinged on major temperature-sensitive crops (e.g. cereals, walnut) from the Central Balkans that remained quite low throughout the interval, especially for the early LIA. Concurrently, a comparatively stable socio-political regime in the Central Balkan region could have allowed the availability of workable populations for agricultural activities.

In contrast, large-scale human impact on the landscape is evident largely through extensive land clearance as evidenced from repeated fluctuations in woodland-grassland populations. The removal of trees was mainly implicated for the montane areas for increased grazing practices, which led to enhanced erosion across the Central Balkan region. This interpretation of the data supports the existing regional deforestation models (Kaplan et al., 2009; Pongratz et al., 2008). It seems plausible that through extensive land clearance, the pastoral Balkan communities could have contributed to dryness of the landscape thereby encouraging loss of fertile soils and further affecting the agriculture of this region. This climatic-ecological-human interactions loop in the early LIA could have given rise to more droughts and famines that are recorded for the later part of the LIA (1700-1850 CE) when the overall cultivation was hindered by the irregular summer precipitation and overall variability of the LIA climate (Luterbacher et al., 2004; Xoplaki et al., 2001; Zerefos et al., 2011).

A diverse blend of socio-ecological-climatic stressors and their impact on the predominantly agro-pastoral Balkan subsistence during the past millennium provide a unique opportunity for examining human-climate-ecosystem interactions. An assessment of such human-
climate-ecosystem interactions of the past can provide insights for present and future global challenges. At present, Southeastern Europe as elsewhere around the world is facing impending environmental and social changes. According to IPCC (2014), the Balkan countries are among the most affected regions in terms of a changing water cycle due to extreme climatic events such as increased flooding and droughts. The already hot and semi-arid climate of southern Europe is expected to become warmer and drier, and this will threaten its waterways, agricultural production and timber harvests (e.g., EEA, 2004). In the light of such recent studies, it is evident that parts of the Balkans will undoubtedly be affected locally and socially as elsewhere. In particular, Serbia’s likely entry into the European Union may put a larger stress on Serbian societies, in terms of posing challenges to its economic sectors. The sustainability of agriculture and its resilience in the face of changing environmental and social conditions is a timely question and could have relevance to political debates both within and outside the country. Although the picture is yet far from complete and more paleoecological work is needed to elucidate the interplays and feedbacks of climate variability in the context of human landscapes and activities from the Balkan region, two independent proxy records from Serbia that are produced in this dissertation help to record and explain the nature of responses and interactions of past societies on how they coped with drastic climatic events.
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