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PAST GLOBAL CHANGES

MAGAZINE

PAST LAND USE AND LAND COVER

EDITORS

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and Lucien von Gunten

News

Launch of the PAGES Early-Career Network (ECN)

In February 2018, PAGES continued its commitment to supporting early-career researchers and their careers with the launch of the ECN. Find out more and be involved: <http://pastglobalchanges.org/ecn/intro>

PAGES SSC news

PAGES' Scientific Steering Committee met in Minneapolis, USA, from 21-26 May to discuss the organization's future plans. Extensions to two working groups, PALSEA and VICS, were approved. Fourteen working group, open and educational workshops or conferences were also allocated financial support.

In February, SSC and Executive Committee (EXCOM) members Pascale Braconnot (France) and Darrell Kaufman (USA) were selected for the IPCC Assessment Report 6 Working Group I. Braconnot is Review Editor of Chapter 8 and Kaufman is Lead Author in Chapter Two.

And former SSC member and co-chair Sheri Fritz will receive the International Paleolimnology Association Lifetime Achievement Award in June 2018. PAGES congratulates Sheri on this well-deserved recognition of her contributions to paleolimnology.

Data stewardship

PAGES took another step towards safe and accessible data stewardship by formally signing an agreement in January 2018 with the Neotoma Paleocology Database. Neotoma joins NOAA/NCEI Paleoclimatology and PANGAEA as recommended data repositories.

PAGES 2k Network Phase 3

New projects ARAMATE, CLIM-ARCH-DATE, PALEOLINK and MULTICHRON launched at the start of the year. Read more and be involved: <http://pastglobalchanges.org/ini/wg/2k-network/intro>

Two new working groups

Climate Reconstruction and Impacts from the Archives of Societies (CRIAS) aims to improve the use of society's archives - personal documents, narrative sources, archival materials, early instrumental observations, and artefacts such as flood markers - in reconstructing historical climate variability and human impacts: <http://pastglobalchanges.org/ini/wg/crias/intro>

Cycles of Sea-Ice Dynamics in the Earth system (C-SIDE) aims to reconstruct changes in sea-ice extent in the Southern Ocean for the past 130,000 years, reconstruct how sea-ice cover responded to global cooling as the Earth entered a glacial cycle, and to better understand how sea-ice cover may have influenced nutrient cycling, ocean productivity, air-sea gas exchange, and circulation dynamics: <http://pastglobalchanges.org/ini/wg/c-side/intro>

OC3: Top-10 in AGU Journal

Lead author Andreas Schmittner and the OC3 working group celebrated the announcement that their paper "Calibration of the carbon isotope composition ($\delta^{13}\text{C}$) of benthic foraminifera" in *Paleoceanography* (an AGU publication) was one of the journal's top downloaded articles in recent publication history. At the end of 2017, the article was in the top 10 with 914 downloads - an impressive achievement for the group's first product.

Suggest a new working group or apply for meeting support

Propose a new working group: <http://pastglobalchanges.org/ini/wg/new-wg-proposal> or apply for workshop support by 4 October 2018. This round of workshop support is only open to current PAGES working groups: <http://pastglobalchanges.org/my-pages/meeting-support>

Help us keep PAGES People Database up to date

Have you changed institutions or are you about to move? Please check if your details are current: <http://pastglobalchanges.org/people/people-database/edit-your-profile> If you have problems updating your details, we can help. Contact pages@pages.unibe.ch

Upcoming issue of Past Global Changes Magazine

The next PAGES Magazine focuses on data and data stewardship. Guest editors are SSC member Darrell Kaufman, Alicia Newton (*Nature Geoscience*) and Jack Williams (Neotoma). Although preparations are well underway, if you would like to contribute, please contact Lucien von Gunten: lucien.vongunten@pages.unibe.ch

Calendar

INQUA-PAGES: Impacts of sea-level rise

26-29 August 2018 - Utrecht, The Netherlands

Knowledge for fire and biodiversity policy

4-9 September 2018 - Egham, UK

OC3: Ocean circulation and carbon cycling

6-9 September 2018 - Cambridge, UK

PALSEA2-QUIGS: Climate, ice and sea level

24-27 September 2018 - Galloway, USA

SISAL: Regional patterns in isotope signatures

8-12 October 2018 - Agadir, Morocco

GEOTRACES-PAGES: Trace element and isotope proxies in paleoceanography

3-5 December 2018 - Aix-Marseille, France

www.pastglobalchanges.org/calendar

Featured products

2k Network

Eight new papers were accepted to the 2k phase two synthesis special issue of *Climate of the Past* (2017; no. 841).

Global Paleofire

The Global Paleofire Working Group 2 discusses new opportunities for charcoal-based fire history reconstructions (2018, *Fire* 1).

LandCover6k

Jed Kaplan et al. perform a systematic evaluation of two widely-used ALCC scenarios (KK10 and HYDE3.1) in northern and part of central Europe using an independent, pollen-based reconstruction of Holocene land cover (REVEALS) (2018, *Land* 6).

Rob Marchant et al. explore the cumulative effects of climate and land-use change over millennial timescales in East Africa (2018, *Earth Sci Rev* 178). Behnaz Pirzamanbein et al. constructed a hierarchical model for spatial compositional data to reconstruct past land-cover compositions for five time periods during the past 6000 years over Europe (2018, *Spat Stat* 24).

PALSEA2

Nadine Hallman et al. reconstruct a high-resolution sea-level curve encompassing the last 6000 years of past sea level in French Polynesia, based on a comprehensive study of coral microatolls, which are sensitive low-tide recorders (2018, *Nat Comm* 9).

YSM Special Issue

A paper detailing the first high-resolution Lake Dojran pollen record for the last 12,500 years is the first contribution to a special issue stemming from PAGES 3rd Young Scientists Meeting in 2017 (2018, *Clim Past* 14).

Cover

Typical cultural landscape on the low mountains of the Shandong province in eastern temperate China.

This landscape has kept its ancient structures with crop cultivation on terraces and grazing above the terraces intermingled with woodland. The species-rich flora, characteristic of this agricultural land, is optimal to study the relationship between pollen and vegetation in cultural landscapes (Li et al. 2017, *Veg Hist Arch* 26). Image credit: M.-J. Gaillard.

Past land-use and land-cover change: the challenge of quantification at the subcontinental to global scales

Marie-José Gaillard¹, K.D. Morrison², M. Madella³ and N. Whitehouse⁴

If the effects of past land use on environmental and societal processes and climate are to be quantified, the reconstructions of past land use and related land-cover change have to be more realistic than the model scenarios previously used. Vineyards in Pommard, Burgundy, France. Image credit: M.-J. Gaillard.

Land-use change has influenced, and influences, many aspects of the environment such as pedogenesis, soil erosion, hydrology, vegetation, lakes' and rivers' nutrient status, microclimate and, last – but not least – regional and global climate. It is still a challenge, however, to quantify land-use change in the past and its effect on past environment through time and across space. Such knowledge is necessary for the development of sustainable landscape management and land-use strategies in line with the challenge of climate warming mitigation.

It is widely accepted that plant cover on Earth is part of the climate system and anthropogenic land-cover change (as a consequence of land-use change) may imply a complex combination of biogeochemical and biogeophysical processes. The size and sign (warming or cooling) of the net effect of anthropogenic land-cover change on global and regional climate is, however, still a matter of debate (Strandberg et al. 2014; Gaillard et al. 2015). The first coordinated database of land-cover (basically deforestation) maps, at 50-year intervals, since 1700 CE for climate modeling studies was led by Leemans and collaborators, and discussed for the first time at a workshop organized by PAGES Biome 300 (Leemans et al. 2000). The latter was part of the PAGES HITE working group initiated by Frank Oldfield (Oldfield et al. 2000), the first PAGES activity dealing with the human dimension of climate change. It resulted in the now well-known HYDE Database (History Database of the Global Environment) of past land use and land cover (Klein Goldewijk 2001). Since then, HYDE has been updated and improved regularly to the latest version (3.2; Klein Goldewijk et al. 2017) and has been the most-used database on land use by climate modelers. HYDE's and other scenarios of past land use, however, tend to overlook socio-cultural effects such as technology or diet, which are as important as the physical environment in determining land-use strategies. Improving the records of socio-cultural characteristics behind the diverse approaches of past societies to environmental exploitation will augment our understanding of past, present and future dynamics of our planet.

In this issue, we have gathered contributions that illustrate the challenge of reconstructing past land use and land cover at different spatial scales (from local to global). The PAGES LandCover6k working group's primary goal is to use pollen, archaeological (both material culture and biological remains) and historical data to provide quantitative information on past land cover and land use to evaluate and improve Anthropogenic Land-Cover Change (ALCC) scenarios for paleoclimate modeling. Archaeology and history-based land-use maps with quantifiable attributes at the global scale, plus pollen-based reconstructions of past land cover at a subcontinental and continental scale using the REVEALS model (Sugita 2007) or alternative methods, are major products of the working group. In addition to the need for global modeling studies of the Earth system over past millennia, there is also scope for improved interregional comparisons of land-use history and for data syntheses that will allow better understanding of the interconnected histories of land use and social transformations over time.

The issue opens with papers on the need for realistic reconstructions of past anthropogenic land-use and land-cover change to develop a complete understanding of the Earth system over time (Harrison et al. p.4; Stocker et al. p.6). These are followed by presentations of methods to achieve such reconstructions and their potential in the evaluation of model outputs (Morrison et al. p.8; Woodbridge et al. p.10; Marquer et al. p.12). Eight contributions on various aspects of land-use reconstructions based on archaeological and historical data, and the challenge of upscaling the information to global scale, follow. Lombardo et al. (p.14) provide an example of application of the LandCover6k global land-use classification in Latin America. Case studies from Africa (Boles et al. p.16), Japan (Bell et al. p.22) and Europe (Whitehouse et al. p.24) combine archaeology-based, land-use reconstructions with pollen-based estimates of land cover. Biagetti et al. (p.20) discuss past rain-fed agriculture in hyper-dry regions, and Widgren (p.18) presents maps of past land use in Africa. Antolín et al. (p.26) apply

paleoecological and archaeological methods to reconstruct agricultural decision making in western Europe, Kolář et al. (p.30) use archaeological evidence to reconstruct past population dynamics and land use in central Europe, and Vander Linden et al. (p.28) discuss diffusion of early farming across Europe. The issue closes with examples of transient pollen-based REVEALS reconstructions of land-cover change in eastern China compared with archaeological data (Li et al. p.32), and the first synthesis of REVEALS-based reconstructions for the Northern Hemisphere (Dawson et al. p.34).

We hope this special issue will motivate more palynologists, archaeologists and historians to join the exciting opportunity of synthesizing the wealth of existing information on past land use and land cover in formats that are useful for the wider communities of social, environmental and Earth-system scientists.

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Do we need to include anthropogenic land-use and land-cover changes in paleoclimate simulations?

Sandy P. Harrison¹, B.D. Stocker², K. Klein Goldewijk³, J.O. Kaplan^{4,5} and P. Braconnot⁶

We motivate and describe the minimum set of data required to improve the modeling of feedbacks associated with land-cover and land-use changes on climate over the Holocene.

The paleoclimate modeling community is gearing up for a new set of analyses of past climate change as part of the current phase of the Coupled Model Intercomparison Project (CMIP6). The role of land-surface feedbacks on climate will be a major focus of these analyses. Assessment of the importance of human impacts on land use and land cover (LULC) for climate during the industrial period have been hampered by uncertainties about the nature and size of these changes and by differences in the way LULC changes are implemented in models. The climate impact of LULC changes before the industrial period is also a matter of debate. Here, we examine why we need to include anthropogenic LULC changes in paleoclimate experiments and the key data requirements for doing so.

What is LULC change and how does it affect climate?

Climate-induced changes in land cover during the last century have been small, and largely confined to increased productivity and shifts in growing-season length. However, human activities during the industrial period have profoundly changed terrestrial landscapes, by removing natural vegetation for agriculture and husbandry, and through more subtle changes in structure and composition of the vegetation caused by management practices. Anthropogenic LULC changes affect climate through changes in the carbon cycle resulting from modifications in vegetation and soil carbon storage (biogeochemical feedbacks) and through changes in the surface-energy budget resulting from modifications of surface albedo, evapotranspiration, and canopy structure (biophysical feedbacks). About one third of the total anthropogenic CO₂ emissions during the industrial period have been attributed to LULC changes, while biophysical effects have contributed to cooling extra-tropical regions and warming the tropics (Myhre et al. 2013). However, large differences between reconstructions of the extent of agricultural and grazing land prior to industrialization (Fig. 1) imply significant uncertainty in anthropogenic climate forcing during the historical period (Stocker et al. 2018).

Early agricultural impact on climate?

There is archaeological and palynological evidence from many parts of the world for human-induced landscape changes during the Late Holocene. This raises the issue of

whether the LULC changes associated with the Neolithic agricultural revolution, from ca 10,000 year BP onwards in the Middle East, were large enough to affect climate. The idea that greenhouse gas emissions associated with Neolithic LULC changes were sufficiently large to offset climate cooling (the overdeglaciation hypothesis: Ruddiman 2003) has been challenged on multiple grounds (e.g. EPICA Community Members 2004; Stocker et al. 2017) but a LULC impact on climate in more recent millennia appears more plausible. Model studies have shown that prescribed Holocene LULC changes had detectable impacts on regional temperature and precipitation and even had a significant effect beyond the major agricultural regions (e.g. Smith et al. 2016). However, reconstructions of pre-industrial LULC change (Klein Goldewijk et al. 2011; Kaplan et al. 2011; Klein Goldewijk et al. 2017) are based on estimates of past population and the timing of first agriculture, and simple assumptions about the cropland and pasture area required per person, derived from relatively well-documented regions and extrapolated to the rest of the world. Large uncertainties in all of these factors translate into widely different land-use

reconstructions (Gaillard et al. 2010). Hence, confidence in inferred LULC-related climate impacts is low.

LULC changes: Minimum requirements for paleoclimate modeling

The vegetation module of Earth System Models (ESMs) predicts the natural vegetation response to changes in simulated climate and CO₂. LULC changes are treated as external forcing and used to modify the simulated natural vegetation distribution by specifying the area of each grid cell at each time occupied by crop or pasture plant functional types. Changes in cropland and pasture area involve a redistribution of carbon, nitrogen and water mass between these different areas (or “tiles”) and between product pools within the grid cell. This, and prescribed management (e.g. soil cultivation, implemented by enhancing soil organic matter decomposition rates; removal of material from cropland and pasture (harvest), implemented by diverting a fraction of aboveground biomass into respiration) determine the carbon balance of each grid cell. Typically, cropland management has a stronger impact on reducing soil carbon

Figure 1: Land use in the Middle East (top panels) at 6000 year BP and West Africa (bottom panels) at AD 1500, from the two widely used global historical land-use scenarios HYDE 3.2 (left panels, Klein Goldewijk et al. 2017) and KK10 (right panels, Kaplan et al. 2011), illustrating the large disagreement between LULC scenarios at a regional scale.

Figure 2: Schematic illustration of simulating gross (top row) versus net (bottom row) LULC change within one grid cell (modified from Stocker et al. 2014). The orange area represents abandonment of cropland and the brown area represents conversion of forest to cropland. In the scheme for gross LULC, abandoned cropland is treated as a separate land unit for secondary land ("secd"). In the scheme for net LULC, only the net land-use change (conversion of primary minus abandonment of cropland) is accounted for and no area of secondary regrowth is created. Note that A denotes equal areas. As a result, a smaller grid-cell-area fraction is affected by LULC in the net scheme compared to the gross scheme and biomass stocks are on average smaller in the gross scheme due to younger vegetation on secondary land.

storage than grazing. The treatment of pasture, and particularly whether pasture expansion results from conversion of forests or naturally open vegetation, varies between ESMs, and has strong effects on simulated LULC CO₂ emissions.

LULC changes are bi-directional: land can go from natural vegetation to crop or pasture, but cropland and pasture can also be abandoned and revert to natural vegetation (Fig. 2). This secondary growth (whether forest or openland) does not necessarily have the same characteristics and carbon balance as undisturbed natural vegetation. Accounting for these total (or "gross") LULC changes (e.g. Shevliakova et al. 2009) is particularly important in regions of shifting cultivation and has been shown to increase CO₂ emissions over the past 150 years by ca 10–40% (Arneth et al. 2017). However, accounting for gross LULC changes requires additional information about land turnover rates and the time-varying extent of shifting cultivation.

The productivity of natural vegetation can be affected by management, most importantly wood harvesting for construction or fuel. Wood harvesting further inflates total CO₂ emissions from LULC changes, with effects during the historical period similar in magnitude as those of shifting cultivation (Arneth et

al. 2017). Implementation in models requires additional information on either the area affected by, for example, clear cutting or the amount of biomass removed by grid cell.

Thus, technically, the minimum set of information required to be able to model the impact of LULC changes in paleoclimate experiments is:

- Cropland areal fraction;
- Pasture areal fraction;
- Whether pasture has been converted from natural forest or from open vegetation;
- The fraction of biomass removed each year by crop harvest;
- The fraction of aboveground biomass removed each year by livestock on pastures;
- Land turnover rate under shifting cultivation;
- Time-varying extent of shifting cultivation;
- The amount of biomass removed or area affected each year by wood harvesting.

The PMIP4-CMIP6 experiments

The evaluation of paleoclimate simulations provides an out-of-sample test of the models used to project the future, and paleoclimate experiments are therefore included as part

of the suite of simulations in the current phase of CMIP6. The contribution of the Palaeoclimate Modelling Intercomparison Project (PMIP) to CMIP6 (PMIP4-CMIP6) will focus on a limited number of paleoclimate experiments. One of these simulations, the Last Millennium simulation (*past1000*, 850–1850 CE; Jungclauss et al. 2017), will include prescribed time-varying LULC changes thus ensuring that the LULC forcing will mesh continuously with the LULC forcing being used for the 20th century. The baseline mid-Holocene simulation (*midHolocene*, 6000 year BP; Otto-Bliesner et al. 2017) will not include prescribed changes in vegetation cover or LULC, although some modeling groups will be running with interactive vegetation and thus will be able to examine the feedbacks associated with climate-induced changes in natural vegetation. Additional sensitivity experiments are planned to investigate the likely impact of both climate-induced vegetation changes and LULC changes on the mid-Holocene climate. Robust evidence-based reconstructions of vegetation and LULC changes are therefore an important contribution to the PMIP4-CMIP6 exercise. The challenge for the PAGES LandCover6k Working Group (<http://pastglobalchanges.org/ini/wg/landcover6k>) is to translate the still somewhat patchy observational records into a global gridded dataset in a timely way so that these sensitivity tests are more realistic than previous attempts to investigate LULC changes during the Holocene.

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Contrasting CO₂ emissions from different Holocene land-use reconstructions: Does the carbon budget add up?

Benjamin D. Stocker¹, Z. Yu² and F. Joos^{3,4}

Reliable reconstructions of past land-use change are essential to address key challenges in understanding the role of humans in the Earth's environmental history. Here we discuss how to integrate past carbon cycle changes within constraints of the land carbon budget.

Particular features in the ice-core CO₂ and CH₄ records have been hypothesized to be linked to the rise and fall of agriculture and societies (Ruddiman 2003) and have been used to serve as stratigraphic markers for the Anthropocene (Lewis and Maslin 2015). The trend reversals in atmospheric CO₂ around 7000 years (7 ka) before present (present=1950 CE) and in CH₄ around 5 ka BP, and the continuous increase in their concentrations thereafter, have been linked to the expansion of early agriculture, associated deforestation and CO₂ emissions, and the establishment of wet rice cultivation with high CH₄ emissions. The apparent downturn in atmospheric CO₂ after 1500 CE falls into the period following the arrival of Europeans in the Americas and the subsequent dramatic collapse of native populations. However, these proposed hypotheses, claiming a causal link between the history of civilizations and past greenhouse gas changes, critically rest on the plausibility of land-use and land-cover change (LULC) reconstructions and the magnitude of associated greenhouse gas emissions. Several studies have put these links into question (e.g. Pongratz et al. 2009; Singarayer et al. 2011; Stocker et al. 2011).

Contrasting land-use reconstructions

Expansion of agriculture has reduced the land area covered by forest throughout much of the Holocene. Today, about a third of the Earth's land surface area is – more or less intensively – in use for agriculture. This estimate of modern land use is derived from

national statistics and satellite data. However, such precise information is only available for the last few decades. Past vegetation, reconstructed from pollen records in lake sediments or bogs, have only just begun to be used for quantitative land-cover reconstructions (Editorial, this issue). Instead, reconstructions of past LULC are typically based on estimates of historical population size and assumptions on the per-capita requirement of cropland and pasture area over the Holocene. These values are highly uncertain, and the most widely used land-use reconstructions provide conflicting results (see Harrison et al., this issue).

Replacement of forests by agricultural land also affects the energy balance at the land surface, reduces evapotranspiration where trees have been replaced by crops and grasses, or increases evapotranspiration where lands are being irrigated. It further increases the surface albedo, especially in northern latitudes when snow is present. This effect has contributed to a cooling in the mid-latitudes that counteracted LULC-induced warming due to greenhouse-gas emissions in the past, and may have exacerbated cold conditions during the Little Ice Age (Betts et al. 2007). Reducing the large uncertainties in reconstructions of past LULC is therefore important to define a reliable land-surface boundary condition for climate model simulations covering past centuries and millennia, and for other simulations that use preindustrial boundary conditions (e.g. *piControl*,

historical, abrupt-4×CO₂, 1pctCO₂ of CMIP6 model simulations; see Eyring et al. 2016). The boundary between preindustrial and industrial conditions is commonly set at 1850 CE (see also Harrison et al., this issue).

Land conversion also impacts carbon (C) storage in the soil. The long residence time of soil carbon entails legacy effects of past land use on the terrestrial carbon balance, even decades after land conversion. Conflicting land-use reconstructions underpin the ongoing debate about the extent and impact of preindustrial human activities on the carbon cycle and climate. However, there are two constraints that help narrow the range of possible land-use histories in the past (Stocker et al. 2017) and the influence of past LULC on climate and the carbon cycle.

Constraints on LULC histories

First, the present-day state of land use and the biomass density of vegetation across space is relatively well known. The difference between C storage in actual vegetation and in potential natural vegetation is equal to cumulative CO₂ emissions from past LULC since appearance of the first agriculturalists. Hence, cumulative LULC CO₂ emissions are relatively well-constrained, implying that uncertainty in past LULC emissions becomes mainly a problem of distributing their cumulative total through time. More emissions in distant millennia imply that less is left for the more recent past. Emissions have to converge to within the constrained

Figure 1: (A) Time series of global total land area under agricultural land use for HYDE 3.2 (Klein Goldewijk 2016) and KK10 (total of pasture and croplands in HYDE 3.2; Kaplan et al. 2009). The time axis is on a different scale before and after 1700 CE. Total expansion for the two scenarios between 1850 and 1920 CE is illustrated by arrows on the right. **(B)** The terrestrial C budget for the period 1850 to 1920 CE. Cumulative CO₂ emissions from LULC for HYDE 3.2 (purple) match within uncertainties the total terrestrial C stock change inferred from the atmospheric CO₂ record (green), whereas LULC emissions for KK10 (cyan) are much smaller. C uptake by peat (blue) is small. LULC emissions are from simulations with the LPX-Bern Dynamic Global Vegetation Model (Stocker et al. 2017).

range of estimates for cumulative emissions. Quantitatively, Stocker et al. (2017) found relatively small differences in cumulative LULC-induced CO₂ emissions when applying different LULC histories in their model (Fig. 1). However, further research is needed to reduce remaining uncertainty in cumulative emissions and differences between satellite and model-based estimates (Erb et al. 2018).

The second constraint comes from the total C budget of the terrestrial biosphere. Ice-core data on past CO₂ concentrations and carbon-isotopic composition have been successfully used to reconstruct the net C balance of the land biosphere, as well as the C balance of the ocean (Elsig et al. 2009). Knowing all natural contributions to land C inventory changes, we can isolate anthropogenic sources by difference. Despite imperfect knowledge on C sources and sinks from all ecosystems, this approach provides a way to integrate our understanding of past C cycle changes within the budget constraint. Two examples below illustrate this point.

Unprecedented terrestrial C release after 1850 CE: very likely anthropogenic

During the period 1850–1920 CE, ice-core data suggest a substantial terrestrial C source of 45 PgC in total. This is on average 0.64 PgC/yr, or around half the current annual CO₂ emissions from modern LULC and by far the most rapid land-C-balance change ever recorded in all preceding periods of the Holocene. Is this the anthropogenic signal? One reconstruction of past LULC (HYDE 3.2; Klein Goldewijk 2016) suggests that emissions fall right into the same magnitude as this apparent land C source (Fig. 1). The alternative reconstruction (KK10; Kaplan et al. 2009) suggests a much larger land area under use in 1850 CE than HYDE 3.2. This necessarily leaves less room for further land-use expansion after that point in time, and resulting emissions cannot explain the net C source derived from the ice-core data. Additional natural C loss from land in response to the slight warming trend was likely counteracted by the fertilizing effect of slowly rising CO₂ between 1850 and 1920 CE, assuming that our estimates of these feedback strengths are accurate. Taken together, the land C budget suggests that the KK10 scenario, featuring extensive deforestation before 1850 CE, leaves a C source of 31 PgC unexplained and therefore appears less likely than a more moderate extent of pre-1850 CE deforestation as suggested by HYDE 3.2. However, KK10 is more in line with pollen-based quantitative vegetation reconstructions in north-western Europe than HYDE 3.2 (Kaplan et al. 2017). These considerations of the land C budget and timing of emissions illustrate the relevance of improving preindustrial land-use reconstructions to understand terrestrial C sources and sinks and climate-carbon cycle feedbacks also in the most recent decades.

A large terrestrial C source after the Mid-Holocene

The parallel evolution of ice-core CO₂ and its isotopic composition suggests no significant change in terrestrial C storage between 5 and 3 ka BP. Could large anthropogenic

Figure 2: Terrestrial C budget in the period 5–3 ka BP. The total terrestrial net change (green) is derived from ice-core CO₂ and δ¹³C data. The difference between the total net change and peat uptake (blue) provides a top-down constraint on the sum of CO₂ emissions from LULC and other natural sources (grey bars). LULC emissions are estimated based on two alternative scenarios, HYDE 3.2 (purple) and KK10 (turquoise).

emissions have been masked by an equally large and contemporaneous natural C sink? Indeed, the build-up of northern peatlands, initiated after ice-age conditions, was a major C sink at these timescales. Through large-scale data synthesis (Loisel et al. 2014) and global modeling (Stocker et al. 2014), it is now possible to estimate the timing and amount of C sequestration in peatlands throughout the Holocene. This allows subtracting their contribution from the total land C balance and reveals that a large terrestrial non-peatland C source must have contributed to the near-neutral land C balance in that period (Fig. 2). Can anthropogenic emissions close the budget? Probably not. A comparison of the inferred natural non-peatland C source with LULC emission estimates based on available LULC reconstructions suggests that other, still unknown, natural sources must have contributed to C cycle changes during this period.

Other gradual changes in the land C cycle amount to substantial sinks or sources at these long timescales. Examples include permafrost changes, the continuous build-up of soil C after the retreat of ice sheets, biome shifts in response to monsoon weakening in Africa and summer cooling in the boreal zone after the Mid-Holocene. It would be fruitful to specifically target and reduce uncertainties in these less-well-quantified but important components of the land C cycle through multi-model studies, constrained by data from paleoecological archives. This would allow us to isolate additional components of the terrestrial C budget and further narrow the range of possible land-use histories. This range will additionally be reduced by integrating information from pollen-based

vegetation reconstructions and archaeology-based land-use characteristics as produced by PAGES' LandCover6k working group (<http://pastglobalchanges.org/ini/wg/land-cover6k>, see also Editorial and Harrison et al., this issue). The combination of such bottom-up and top-down constraints for the land C budget will improve our understanding of the Earth's environmental history and the role of humans therein.

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Global-scale comparisons of human land use: developing shared terminology for land-use practices for global change

Kathleen D. Morrison¹, E. Hammer², L. Popova³, M. Madella⁴, N. Whitehouse⁵, M-J Gaillard⁶ and LandCover6k Land-Use Group Members*

Although archaeological data are needed to understand the impacts of past human land use on the Earth system, synthesis is hampered by a lack of consistent categories. We develop hierarchical and scalable land-use classifications for use across the globe.

Human land-use practices have been highly variable over the course of the Holocene, a diversity evident in the differentiated effects of human activity on land cover. Historically, agriculture was one of the most significant forms of land use, but even mobile hunter-gatherers transformed land cover through landscape-scale burning (Bliege Bird 2008). Livestock-keeping, plowing, irrigation, and the production of metal, ceramics, and bricks, have also been drivers of historical change. It is important to understand the aggregate effects of anthropic activities on the Earth system, but significant challenges are posed by: (1) the complexity, diversity and mosaic nature of human land use itself (Fig. 1); (2) the need to develop a uniform vocabulary and terminology for land-use practices around the globe and across the span of human history; (3) the sheer quantity of evidence to be analyzed; and (4) the lack of a tradition of global-scale comparisons. Nevertheless, there is a deep reservoir of expertise about land-use and land-cover transitions waiting to be tapped. One goal of LandCover6k is to improve understanding of the relationships between land-use and land-cover changes (Gaillard et al., this issue). By comparing land-use and land-cover trends, we can better disentangle anthropogenic forms of land-cover change from climatic or other drivers.

The LandCover6k land-use classification

Comparison of land-use practices is complicated by regionally- and historically-specific terminologies. Even where the same category is used, there may be disagreement about the applicability of the term. "Agriculture", for example, is subject to multiple interpretations about boundary conditions. In part, classificatory chaos reflects the complexity of land use itself. People typically practice multiple forms of land use simultaneously, and shift strategies as needed. This is not merely a complication but a critical area of research relating to resilience, sustainability and fundamental processes of change. We have sought to retain as much of this important complexity as possible while also making the simplifications necessary for global comparison.

To develop systemic, global-scale comparisons of land-use/land-cover relationships, it

is first necessary to employ a consistent set of categories. Accordingly, and in consultation with scholars from across the globe, we developed a unified set of land-use categories (Fig. 2). The classification is hierarchical and expandable, with the highest level of generality designed to facilitate global analyses (level 1), and lower-order categories for regional studies (levels 2-3). Like all classifications, it simplifies complex systems, but such tradeoffs are offset by the analytical possibilities for large-scale analyses and minimized by the multi-level structure of the classification.

It is important to note that categories refer to *activities* known to have taken place in a particular location and time and do not necessarily reflect specific groups of people. Thus, if we know that both farming and pastoralism took place in the same area, we can include both categories in the database regardless of whether or not pastoralists were socially distinct from farmers. Categories refer to *land* (e.g. animal herding is taking place in this location) rather than to people (people here are herders), with the database designed to allow multiple forms of land use to co-exist.

Land-use types

The most general classification of land-use types was developed during a PAGES-sponsored workshop (Morrison et al. 2016) and refined during several regional workshops and an INQUA-sponsored thematic workshop (HoLa). The term "No evidence of land use" is to be used in cases where archaeologists are reasonably certain that humans were not present. "Minimal or extensive land use" applies to areas which are, for example, crossed by a few roads, but are not otherwise in use. Hunting and gathering encompasses both mobile and sedentary foragers; we presume that tending of wild plants is often a feature of forager land use. Within archaeology, much scholarly effort has been expended on the precise contours of early farming and its differentiation from other forms of land use; we recognize this complexity and have built in levels of detail sufficient for regional-scale studies.

Agriculture is the most internally diverse land-use class, reflecting both its history and significance to landscape transformation. The level 2 classification of agricultural forms (Fig. 2) is therefore the most finely subdivided. Not all croplands are

Figure 1: Land-use systems are often mosaics, incorporating multiple forms of land use simultaneously. In this village in the Philippines, irrigated rice fields are grown near the settlement, while the hillsides are used for swidden farming. This land-use regime would be classified as agriculture in level 1 of the LandCover6k land-use classification (Fig. 2), flooded-field farming and swidden in level 2, and rice paddy/taro pondfield in level 3. Domesticated animals and crops would be coded separately. Image credit: O. Paredes.

equivalent. In the tropics, for example, forms of arboriculture typically mimic the structure of the natural forest in terms of taxonomic diversity and vegetation structure; arboriculture plots may be relatively short-lived, making differentiation between “natural” and anthropogenic vegetation difficult over the long term. In some temperate regions, domesticated grazers, such as cattle, are associated with human-made pastures, a practice uncommon in Africa and Asia. The manipulation of water and of slope are often critical components of agricultural practice; irrigated, ditched and terraced landscapes are found across the globe, associated with a range of cropping practices. Understandings of the aggregate effects of human land use on the Earth system must address this diversity, but also develop modes of comparison that make it possible to aggregate the vast, scattered body of archaeological and historical data.

Pastoralism without farming is sufficiently important in some regions that it was made a global (level 1) category. Where farming accompanies herding, however, our classification places this under the heading of agriculture. Similarly, the category “urban and extractive industries”, which includes land used for cities, mines, and quarries, was included at the global level because of its significant impact on land cover, despite its often-limited spatial extent. More detailed discussions and definitions of the land-use classifications are in preparation.

Land-use variables in the database

Our system allows the comparison of archaeological and historical data from across the globe and throughout the Holocene. It does not, however, provide systemic data on specific land-use practices of interest to climate modelers that may cross-cut categories. For example, mobile hunter-gatherers in Australia and North America who used fire as part of their subsistence strategies changed regional vegetation in ways that mobile hunter-gatherers not practicing landscape burning did not. In this case, a single land-use category masks a significant difference. Similarly, tillage, livestock production, irrigation, and pyrotechnologies may have important land-cover effects that complicate simple categorization. For example, metal production, which uses large quantities of wood (Jouffroy-Bapicot et al. 2007), can occur in diverse farming or urban contexts and is not necessarily linked to a specific land-use regime. Similarly, the same overall land-use regime (e.g. dry farming) may be carried out with either digging sticks or plows, but the choice of technology itself has implications for carbon cycling. Tillage, like burning and irrigation, may impact carbon cycling independently of the crop grown. Accordingly, our classification includes some variables within land-use groups (irrigation and large-animal husbandry are part of level 2 classifications), while others are coded separately.

Building a global land-use database

Although archaeologists and historians have amassed a huge amount of information

Figure 2: The LandCover6k land-use classification matrix.

about past human land use, these data cannot be directly compared or quantified without recourse to a single vocabulary. Working in consultation with climate modelers and keeping in mind the need to better understand the links between land use and land cover, we have developed a simple but capacious classification system for forms of land use and specific land-use activities that can be applied at a global level across the Holocene. We hope this framework - the product of several years of widespread consultation - will allow the important archives of archaeological and historical data to be marshaled to address critical issues of global change.

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European forest cover since the start of Neolithic agriculture: a critical comparison of pollen-based reconstructions

Jessie Woodbridge¹, R.M. Fyfe¹, C.N. Roberts¹, A.K. Trondman², F. Mazier³ and B. Davis⁴

Europe was extensively wooded prior to the arrival of Neolithic agriculture. Forests have since been cleared and fragmented by humans. Here we compare different approaches to transforming fossil pollen data into quantitative past forest cover estimates on a continental scale.

Pollen-based reconstruction of past European vegetation in quantitative terms has been the focus of several research projects in recent years. A comparison of the results of three such efforts gives insights into the accuracy of different methods (Roberts et al. 2018). Here we summarize the methods, outcomes and their implications. The approaches include, firstly, a mechanistic model of the pollen-vegetation relationship (REVEALS; Sugita 2007) taking into account inter-taxonomic differences in pollen morphology, pollen productivity and characteristics of pollen dispersal and deposition. The second dataset derives from a pseudo-biomization (PBM) based approach, which assigns each individual taxon to a "land-cover class" and then allocates each pollen sample to a "biome" (Woodbridge et al. 2014a; Fyfe et al. 2015). The third is a dataset of tree pollen values converted from pollen data using a Plant Functional Type (PFT) approach (Davis et al. 2015; Fig. 1). The reconstructed vegetation datasets that are

used in this comparison are primarily based on the fossil and modern European Pollen Databases (EPD and EMPD; Leydet et al. 2007-2017; Davis et al. 2013), alongside new chronologies produced by Giesecke et al. (2014). The REVEALS approach is the most complex of the three methods and requires pollen productivity values for the major plants involved in the vegetation reconstruction. Here we use the REVEALS reconstructions published by Trondman et al. (2015) for five time windows of the past 6000 years. The PBM and PFT methods are simpler and do not require values of pollen productivity. They can be more easily applied on broad spatial scales to provide time-continuous vegetation reconstructions.

Comparing vegetation reconstructions

For this comparison, Europe has been divided into three broad climatic-ecological zones, namely Mediterranean, northern and mid-latitude Europe, with results presented for the latter two regions (Fig. 1). Estimates

of Holocene vegetation change, using the different approaches, show broadly similar trends for mid-latitude and northern Europe (Fig. 2). The period of maximum forest occurred between approximately 8200 to 6000 BP, followed by a progressive decline in forest cover that accelerated after around 1200 BP (early Medieval times). The PBM, PFT and REVEALS reconstructions show remarkably similar reconstructions for total forest cover in mid-latitude Europe. They reveal that the percentage of forest cover has declined more in mid-latitude than in northern Europe over the last 6000 years, from about 65 to ~38%. The mid-latitude zone was originally dominated by broad-leaf trees, much of which has now been converted to arable and pasture land, but also by late migrating trees such as spruce, fir and beech. However, within this temperate zone, there were marked inter-regional differences in the timing of forest loss. In particular there were contrasting historical trajectories between north-central Europe, where the majority of forests remained intact until Early Medieval times (although records from some areas, such as coastal Poland, show forest loss earlier), and the UK and Ireland, France and Belgium, where most forests had already been cleared in Bronze and Iron Age times (Woodbridge et al., in press). Reconstructions of Holocene forest cover in the northern boreal zone show less consistency between the different pollen-based methods, with the PFT reconstructions systematically higher than those for REVEALS and PBM (Fig. 2). This reflects the weighting applied to open land-cover classes during the PBM process, which was applied after testing the method using modern surface-pollen samples and comparing against remotely-sensed maps (Woodbridge et al. 2014a), and the lower productivity of open vegetation types accounted for in the REVEALS reconstructions. For all regions of Europe, the PBM reconstructions show that the loss of broad-leaf forest has been more pronounced than that of needle-leaf forest (Fig. 2c). This is also shown by the REVEALS reconstructions performed in mid-latitude and northern Europe (e.g. Marquer et al. 2017).

Figure 1: Pollen sites used in the PBM and PFT analyses, and REVEALS estimates for total forest cover percentage. Red dashed lines represent the separate regions analyzed: i.e. northern and mid-latitude Europe.

Numerous factors have contributed to vegetation change and forest loss, including

Figure 2: Pollen-inferred forest cover for: (A) mid-latitude and; (B) northern Europe using the PBM, PFT and REVEALS approaches for the same grid cells; (C) PBM scores for pasture/arable and disturbed land, broad-leaf forest and needle-leaf forest during the last 11,000 years for all regions. (D) UK and Ireland REVEALS estimates for key vegetation types, and; (E) summed probability distributions of normalized archaeological radiocarbon dates in the UK (Woodbridge et al. 2014b).

climatic changes and long-term ecological dynamics, along with forest conversion to agricultural and grazing lands. Early Holocene pasture/arable and disturbed land PBM scores represent natural vegetation dynamics. An increase in pasture, arable and disturbed land (indicated by the PBM scores for these land-cover classes) is evident from 4000 BP, i.e. Bronze Age (Fig. 2c). This accelerates in the most recent 2000 years, and indicates an increase in agricultural land broadly in line with the loss of forest. Focusing on sub-regions can allow exploration of patterns between vegetation and demographic change. Patterns of demographic change in human societies can be inferred from the density of ^{14}C dates from archaeological sites, which is shown here for the UK (Fig. 2e; Woodbridge et al. 2014b), and indicate an increase in human populations after 6000 BP following the appearance of Neolithic farming. This pattern is reflected in the loss of forests and opening of vegetation indicated by REVEALS reconstructions (Fig. 2d).

Future priorities for pollen and land-cover research

The impacts of past human populations in transforming natural vegetation have major significance for understanding long-term forest dynamics and for future conservation and management of such resources. For instance, this allows habitats that could be more resilient or at risk from future environmental change to be identified. Future research needs to focus on developing the links between fossil pollen assemblages and land cover in regions where these relationships are not yet so well understood,

for example, through obtaining values of pollen productivity for major plants in the Mediterranean region. A greater number of reliable pollen datasets with good chronologies are needed to further develop understanding of vegetation, land-cover and land-use changes, especially in areas where current data coverage is poor. Improved spatial coverage would also allow models of anthropogenic land-cover change to be better evaluated. Different approaches to vegetation reconstruction allow testing of the differing abilities of these methods to sense landscapes. REVEALS offers a quantified and spatially-explicit approach, which is valuable to branches of sciences that require detailed information about past land cover, such as climatologists (Gaillard et al. 2010). Advances have been made in quantifying the effects of past land use and climate on European vegetation change (e.g. Marquer et al. 2017) and in producing forest reconstructions based on the Modern Analog Technique (MAT) through coupling modern pollen samples with satellite-based forest cover (Zanon et al. 2018). Furthermore, in diverse heterogeneous landscapes, such as the Mediterranean, the use of cluster analysis can offer useful results for exploring past vegetation change (Fyfe et al. 2018). PBM and PFT-based methods provide descriptive accounts of vegetation and land-use changes, which can provide valuable comparisons with datasets that give information about disturbance in the past, such as paleo-climate records, fire history trends, and shifts in past human populations inferred from archaeological site densities. Such comparisons will be of value in further deciphering the causes of long-term land-cover change.

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Modeling past human-induced vegetation change is a challenge – the case of Europe

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Differences between pollen-based reconstructions and dynamic vegetation simulations of past vegetation change in Europe over the last seven millennia are interpreted as being due primarily to land-use change. Incorporating land use in climate and dynamic vegetation models requires new approaches.

Since the spread of the Neolithic agriculture in northern and central Europe 7–6 ka BP, land use became a potential source of atmospheric greenhouse gases and impact on heat fluxes through biogeochemical and -physical processes between the land surface and the atmosphere. These processes will affect climate (temperatures and precipitations) and their impact can be quantified using dynamic global vegetation models (DGVMs). Such models are based on ecological concepts and are forced by climate data or run interactively with Earth System Models (ESMs). DGVMs simulate potential natural (climate-induced) vegetation cover in equilibrium with climate. In most models, vegetation is expressed as the fractional coverage of “plant functional types” (PFTs) per grid cell with a spatial resolution suitable for climate modeling. PFTs are groups of plants with comparable physiological characteristics and ecological requirements and tolerances. So far, land-use change (deforestation and other anthropogenic land-cover modifications) can only be prescribed in DGVMs.

How can we evaluate vegetation models’ outputs?

Historical observations are insufficient to evaluate DGVMs. To capture the natural variability, reconstruction of land-cover change on millennial timescales is necessary. Fossil pollen grains preserved in lake sediments or peat are a key biological proxy of past vegetation cover. Pollen records consist of dated series of samples in which pollen grains have been identified, counted, and expressed in percentages, or pollen accumulation rates. But pollen records cannot be directly compared to vegetation cover simulated by ESMs or DGVMs, because they do not directly reflect plant abundances due to differences in pollen productivity, dispersal, and deposition between plant species. To overcome these problems, the method of “biomisation” was developed, that groups plant species and pollen types into biomes (e.g. tundra, savanna, boreal forest). These reconstructed biomes can then be compared to biome distributions inferred from ESMs by using the simulated climate as forcing for biome models (e.g. Prentice

et al. 1992; Dallmeyer et al. 2017). A technique to convert the PFT distributions simulated by ESMs or DGVMs directly into biomes is currently being developed (Dallmeyer et al. 2018).

The recent pollen-based quantitative vegetation reconstructions for Europe (e.g. Marquer et al. 2017) using the REVEALS model (Sugita 2007) offer a potential way of evaluating DGVM outputs. The REVEALS model accounts for biases related to interspecific differences in pollen productivity, dispersal and deposition between plant species. Moreover, the spatial scale (100×100 km²) and format (PFT) of REVEALS reconstructions are adequate for comparison with DGVMs’ simulated vegetation. For more details on REVEALS applications, see Woodbridge et al., Li et al., and Dawson et al. in this issue.

A case study from Europe

Marquer et al. (2017) used REVEALS land-cover reconstructions for the entire Holocene from 36 grid cells in Europe (Fig. 1) to evaluate the vegetation change simulated by LPJ-GUESS. LPJ-GUESS (Smith et al. 2001) is a dynamic, process-based

vegetation model optimized for application at a regional spatial scale. It describes landscape and stand-scale heterogeneity and accounts for the biophysical properties that influence regional climate variability. LPJ-GUESS simulates climate-induced vegetation; it does not consider land use unless it is prescribed in model runs. In contrast, the influence of land use on vegetation cover is recorded in pollen records. The results of a comparison between the LPJ-GUESS outputs and the REVEALS estimates of plant cover suggest that they differ during the early part and last three millennia of the Holocene (Fig. 2). These differences are assumed to be due to ecological processes related to, among others, tree migration and soil development in Early Holocene and land-use in Late Holocene. Marquer et al. (2017) also used “indices” describing the degree of change in the vegetation, e.g. “turnover” and “evenness”. “Turnover” is a measure of the degree of change in vegetation composition over time. “Evenness” describes the relative abundance of all plant species/taxa within the studied vegetation, where little difference in abundance between species implies high evenness,

Figure 1: Location of the 36 1°x1° grid cells used in Marquer et al. (2017) for Europe. Gridded pollen-based REVEALS estimates of plant abundance for the last 11.7 ka BP were calculated using all available pollen records in each grid cell.

Figure 2: Differences between vegetation-change indices calculated based on LPJ-GUESS (dynamic vegetation model) simulations and pollen-based REVEALS estimates of past plant cover in Europe (Fig. 1). The differences are expressed by a similarity index ranging from 0 (no similarity) to 1 (total similarity). Left panel: similarity index for “evenness” and “turnover” indices. Right panel: mean of similarity indices for five vegetation-change indices. Marquer et al. (2017) assume that periods with low similarity indicate an impact of land use on vegetation. The four grey zones are major phases of land-use effects on land cover as identified by Marquer et al. (2017).

while large differences in abundance between species implies low evenness. Other indices of vegetation change are “rate of change” and “difference between present and past vegetation” (Marquer et al. 2017 for more details). Differences between REVEALS- and LPJ-GUESS-based indices of vegetation change are not as large as differences between REVEALS-estimated and LPJ-GUESS-simulated plant abundances, particularly in Early Holocene (Fig. 2). It implies that, although LPJ-GUESS does not simulate effectively tree migration and soil development, REVEALS-based and LPJ-GUESS-simulated vegetation are comparable for most of the Holocene, except parts of Mid- and Late Holocene. These differences are assumed to be due to land-use change. Four major phases of land-use change were identified based on all indices of vegetation change (Fig. 2).

Challenges in implementing land use into dynamic vegetation models

While the differences in format and spatial scale between pollen percentage data and DGVM-simulated vegetation can partly be overcome with the REVEALS model, integrating land use into DGVMs is still a great challenge. A preliminary comparison of the transient vegetation simulations performed within the ESM MPI-ESM 1.2 with the REVEALS reconstructions of Marquer et al. (2017) suggests that the prescribed land-use forcing in the ESM is too strong in most European regions (Dallmeyer A, pers. comm.). DGVMs were originally designed to study the interactions between

natural ecosystems and the atmosphere. However, the insight that land use is one of the many forcings of climate has led to several efforts to incorporate land use in DGVMs in past years. So far, land use is prescribed in DGVMs as sequences of land-use maps (e.g. Pongratz et al. 2010) or “transition matrices” of past changes in cropland, pasture, forestry or urban areas (e.g. Reick et al. 2013). Estimates of past land use at the global scale are currently provided by anthropogenic land-cover change (ALCC) scenarios such as KK10 (Kaplan et al. 2009) and HYDE 3.2 (Klein Goldewijk et al. 2017). These scenarios are based on different assumptions on the main drivers of land-use change, which results in large between-scenario discrepancies (e.g. Gaillard et al. 2010). Kaplan et al. (2017) recently showed that the past deforestation scenarios from KK10 are closer to REVEALS estimates of open-land cover than HYDE scenarios. Discrepancies between scenarios introduce uncertainty in DGVM simulations in addition to uncertainty caused by imperfections in (i) modeling certain processes, (ii) choice of model setup (e.g. bioclimatic tolerance of each PFT), and (iii) known biases in climate data used to force DGVMs. Implementing land-use change and land management in DGVMs is a priority in ESMs (Pongratz et al. 2018), but faces a number of major shortcomings for simulations over millennial timescales:

- Difficulties related to the allocation of agricultural areas in a model grid-cell, and the rules used to replace natural

vegetation by expending cropland and pastures; the differences in effect of different allocation rules were shown to be very large (e.g. Reick et al. 2013).

- Quality and comprehensiveness of the land-use change data; past practices in land management are still largely missing in DGVMs, partly due to lack of data for the past. For instance, information on shifting cultivation does not exist except for the time from 800 CE until present (Hurtt GC, pers. comm.). Ignoring shifting cultivation leads to a large underestimation of land-cover change in Europe (Fuchs et al. 2015).

In this respect, the datasets of pollen-based REVEALS land-cover change and archaeology/history-based land-use change currently produced by the PAGES LandCover6k working group, as well as new approaches developed for the implementation of empirical data describing past land-use and land-cover change in DGVMs, have the potential to solve many of the challenges related to modeling past human-induced vegetation change (Gaillard et al. Editorial, this issue).

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Mapping pre-Columbian land use in Amazonia

Umberto Lombardo¹, C. McMichael², E. Kazuo Tamanaha³ and workshops participants

To improve climate models, climatologists need data on the world's past land use. We present the initial results of a multidisciplinary effort, which aims to (i) expand the database of Amazonian archaeological sites and (ii) reconstruct past land use in Amazonia.

Reconstructing pre-Columbian land-use patterns in Amazonia is crucial in assessing the possible influence that pre-contact (i.e. pre-Colonial) deforestation and post-contact reforestation had on global climate. Pre-contact populations of Amazonia are estimated to have been 5–8.4 million, decreasing by 95% due to disease, slavery and war following European conquest (Denevan 2014). This severe population collapse resulted in the abandonment of cultivated areas and re-colonization of those areas by natural vegetation. As Amazonia is one of the largest terrestrial players in the global carbon cycle, the post-contact reforestation is suggested to have sequestered sufficient atmospheric CO₂ to contribute to the onset of the Little Ice Age (Dull et al. 2010). Many ecologists believe, however, that the total deforested area of Amazonia was not large enough to drive such drastic changes in CO₂ (McMichael et al. 2012).

Assessing the extent to which pre-Columbians modified Amazonian ecosystems is one of the most controversial topics in South American paleoecology and archaeology. Some argue that large-scale, pre-Columbian impacts mostly occurred in areas such as riverine forests and that impacts in inter-fluvial forests may have been minimal and

localized (McMichael et al. 2012). Others suggest that large-scale impacts were widespread (Erickson 2008) and left long-lasting legacies in forest biodiversity (Levis et al. 2017).

Mapping pre-Columbian land-use in Amazonia

In light of this lack of consensus regarding the extent of past anthropogenic disturbance of Amazonia's forests and its effect on global climate, it is important to bring together archaeologists, geographers and paleoecologists to develop a common methodology to assess and map how land was used in pre-Columbian Amazonia. With this in mind, we created a PAGES LandCover6k sub-group called "Mapping pre-Columbian land-use in Amazonia". After securing funding from INQUA's Humans and the Biosphere Commission (HabCom) and the Spanish SIMULPAST project, 16 researchers from seven countries met in Barcelona, Spain, in June 2016 to develop a common research methodology. A second workshop in Trinidad, Bolivia, in October 2017, included 15 researchers from six countries. These meetings focused on: (i) how to extrapolate past land-cover changes from a small number of documented archaeological sites to the entire Amazonia; (ii) what

kind of proxies should be used to infer past changes in land use; and (iii) what should be considered as a baseline towards which changes in land cover can be quantified.

Method and datasets

To date, efforts to map pre-Columbian human occupation in Amazonia have been largely based on geospatial models. McMichael et al. (2014, 2017) used locations of known archaeological sites to infer pre-Columbian settlement patterns in Amazonia, and Levis et al. (2017) used 1170 forest plots of the Amazon Tree Diversity Network (ATDN) to infer pre-Columbian legacies in modern vegetation assemblages. The main problem with these approaches is that the number of sites available is very small and often spatially biased. Lack of mapped archaeological sites in a given area within Amazonia could be due to the fact that large areas have never been surveyed, rather than the nonexistence of sites.

The "Mapping pre-Columbian land use in Amazonia" group concluded that two parallel lines of research are required. The first focuses on improving the quality of existing models by increasing the size of the database of pre-Columbian archaeological sites in Amazonia (Fig. 1). Archaeological

Figure 1: Comparison between the number of archaeological sites (pink dots) used in (A) McMichael et al. (2017), and (B) the number of archaeological sites contained in AmazonArch. The green area represents Amazonia in *sensu latissimo* (as in Eva et al. 2005), consisting of a core sub region, Amazonia in *sensu stricto*, plus four peripheral sub regions: Andes, Planalto, Guiana and Gurupí.

Figure 2: Steps in the supervised classification of pre-Columbian land use in Amazonia.

sites are often documented in Spanish or Portuguese books, journals or reports, and sometimes are stored in researchers' personal databases; for these reasons they are often overlooked by English-speaking researchers. Compiling data about these sites can significantly improve the database in a relatively short time and with limited effort. The second goal includes concentrating our efforts on devising a methodology to include and document, with empirical data, more nuanced forms of pre-Columbian land-use than previously modeled.

We started to compile and digitize all the available data about pre-Columbian archaeological sites in Amazonia, including: (i) geographic coordinates and radiocarbon dates associated with each site; (ii) site characteristics – size, type (i.e. lithic, ceramic, rock art, presence of anthropogenic soils, etc.); and (iii) the availability of ecological, ethnobotanical and archaeobotanical studies in the surrounding areas. The result, called AmazonArch (Amazonian Archaeological Sites Network), is a georeferenced database that allows researchers to share data and information about archaeological sites distributed within Amazonia. AmazonArch's main goal is to gather archaeological data that can be used by network members and other researchers under a data-sharing and data-use policy (<https://sites.google.com/view/amazonarch>).

The group is also working to “fill the gaps” by assessing the environmental impact that pre-Columbian populations had at a regional scale in well-known archaeological areas (i.e. the *terra preta* or Amazonian dark earth sites in Brazil or the Monumental Mounds region in Bolivia) and extrapolate the data from these case studies to the rest

of Amazonia using a supervised classification algorithm (Fig. 2). The used algorithm was originally developed to classify land cover in remote sensing imagery (Richards and Jia 1999). Our plan is to use it to classify Amazonia on the basis of several layers of information, where each layer will be treated by the algorithm as if it was a spectral band in a multispectral image. We will use the following “spectral bands”: digital elevation model, climate, soil map, distance to water bodies, water chemistry, and vegetation. The group identified 19 well-known archaeological areas that will serve as “training fields” and seven land-use classes that will be used to classify the whole of Amazonia. The algorithm will take into account the environmental parameters (the “spectral bands”) associated with each well-known archaeological site (the “training set”) and will assign the land-use classes of the well-known archaeological area to each pixel that has a similar “spectrum” (above a given threshold). This is still a work in progress as we address several problems encountered. The first one is the difficulty of estimating land use in the well-known archaeological areas. Only recently have archaeologists started to examine the archaeological evidence outside the habitation sites, where most of the artifacts are found, so we know far more about *terra preta* (the area where people lived) than we know about *terra mulata* (the area that was under cultivation) and less about adjacent agroforest management.

The ultimate goal is to develop a basin-wide model (Fig. 1) with the supervised classification approach that contains more nuanced land-use data. We believe it is of great importance to start tackling the problem and to establish a replicable and robust

methodology that allows the continuous improvement and updating of the pre-Columbian land-use maps as new data become available. We expect the results of these two approaches will, with time, converge towards more accurate and comprehensive reconstructions of land use in pre-Columbian Amazonia.

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Joining the dots of land-use and land-cover change in Eastern Africa

Oliver Boles^{1,2}, C. Courtney-Mustaphi^{1,3}, S. Richer^{1,4} and R. Marchant¹

Past land-cover change in Eastern Africa must be understood with reference to changing economies within complex webs of interacting human populations. Databases of archaeological sites and paleoenvironmental geoarchives help explore interactions of anthropogenic and environmental drivers of landscape evolution.

Eastern Africa is characterized by strong gradients of environmental variability and cultural diversity. Environments range from hot and moist coastal regions to isolated frigid alpine areas with glaciers, and from dry deserts to biodiverse moist montane forests (Fig. 1a-d), a diversity that has persisted throughout the Holocene even while particular landscapes have seen considerable ecological variability. Outside densely populated and fast-growing urban areas, rural livelihood strategies today range from fishing to specialist mobile pastoralism and sedentary agriculture, some of which is highly intensive. The last 6000 years have seen most Eastern African communities make the transition to food production, which has been accompanied by industrial developments like iron technology and the emergence of supra-regional trading networks, fundamentally changing how societies interacted with their environments. Intensification and diversification of resource use and demographic expansion into previously unexploited areas wrought considerable changes to land cover, as landscapes were manipulated and ecosystems responded. However, our knowledge of these processes exists largely in terms of discrete points – as study sites rather than landscapes. Moreover, the distribution of these points is both temporally and spatially inconsistent, and only in rare instances can we draw direct empirical links between the archaeological and paleoenvironmental records. As a consequence, enquiry into historical land-cover and land-use changes in Eastern Africa requires a multidisciplinary approach that combines Quaternary sciences and archaeology with anthropology, history, ethnography and linguistics.

Synthesizing a diverse range of expertise and data necessitates frequent interactions. Over the past two years, there have been LandCover6k-specific workshops (see Editorial, this issue; Marchant and Rucina 2016) and piggybacked meetings at academic conferences with overlapping themes and researchers. Several workshops and meetings had specific relevance to Tropical Africa and have been crucial platforms for the development of ideas and outputs. A PAGES-supported event in October 2015 at the British Institute in Eastern Africa (BIEA), Nairobi, brought together researchers from Congo, Uganda, Tanzania, Kenya, and Europe, and initiated the organization and collation of datasets that ultimately led to the submission of a 40+ multi-author paper published in *Earth-Science Reviews* (Marchant et al. 2018).

More recently, the African Archaeology Research Day (AARD), hosted at University of York, UK, on 25 November 2017, was used to showcase archaeological and paleoenvironmental datasets and new mapping products relating to historical land-cover and land-use changes since 6 ka BP (Fig. 2a-d). This presentation marked the beginning of a mapping approach that uses expert consultation and consensus building, based on the underlying synthesized data. These new phases build upon the efforts of collating datasets from the region to examine key changes in land use and land cover over the past 6000 years.

The transition to food production

Contrary to many other areas of the globe, livestock domestication predates crop cultivation in Africa (Marshall and Hildebrand 2002). From a cradle in the northeastern Sahara, stock-keeping spread south and westwards, reaching northern Kenya some 4500 years ago and likely facilitated by an increasingly drier climate (Gifford-Gonzalez 1998). Advancement into eastern Africa took place within a complex web of interactions crossing ethno-linguistic and economic frontiers; rather than a linear spread, stock-keeping was adopted through a series of expansions and contractions – “fits and starts” (Wright 2013) – as communities experienced and moved through changing social and physical environments. Cultivation,

by contrast, first appeared in the region during the late third millennium BP in the highlands of Rwanda and Burundi (Van Grunerbeek 1992). The emergence of farming in the Great Lakes region is generally packaged with iron technology and the spread of Bantu languages; though the exclusivity of this suite can be questioned (e.g. Crowther et al., in press), the timing of these developments coincides with the appearance of language and phrases relating to “fields” and “land clearance” (Schoenbrun 1993).

The ephemerality of pastoralist sites has frequently hindered archaeological investigation (Boles and Lane 2016) and our understanding is largely based on a small number of key locations and observations of faunal remains at non-herder sites, likely obtained through exchange networks. Mapping the distribution of herding therefore relies on inferences drawn from linguistic reconstruction and traditional histories with consideration of environmental conditions. Pastoralism spread southward through the Rift Valley corridor before expanding zonally, which provides a broad framework that can be extended and refined with details such as the drying climate of the late-second millennium BP that facilitated movement into the grasslands of western Uganda (Robertshaw and Taylor 2000). Currently, archaeological sites in southern Tanzania

Figure 1: Land uses: (A) pastoralism of grazers; (B) a modern boma with acacia branch outer fence occupied with modern buildings and areas for specific activities; (C) urban land-cover mosaics of Nairobi, Kenya; (D) industrial agriculture of sisal (*Agave sisalana* Perrine). Images credit: Rob Marchant.

Figure 2: (A) map of Eastern Africa showing the locations of archaeological sites in the database, base-map ASTER DEM (JPL-NASA, 2018); (B) locations of paleoenvironmental geoarchives; (C) possible distribution of pastoralism at 3000 BP, based on site distribution and first stage of consensus building; (D) agricultural sites in database, basemap showing moisture index (precipitation relative to potential evapotranspiration) AFRICOVER (FAO 2018).

are rare, yet evidence that pastoralism had reached Southern Africa by the early second millennium BP (Marshall and Hildebrand 2002) requires us to consider that area in our distribution models.

Cultivation is perhaps slightly easier to trace, even if direct tangible evidence is often lacking. We can be confident that crop cultivation first appeared in the region when Bantu farming communities moved from the Congo Basin into the Great Lakes Highlands. These communities are tracked by a close association with pottery styles that eventually reached the eastern shore of Lake Victoria and beyond (Lane 2004). In the last 500 years or so, “islands of intensive agriculture” emerged (Widgren and Sutton 2004); locations such as Engaruka in northern Tanzania evidence technological innovations like terracing and irrigation systems (Stump 2009). As well as indigenous African domesticates like finger millet (*Eleusine coracana*) and sorghum (*Sorghum bicolor*), new crops like rice (*Oryza sativa*) and later, corn (*Zea mays*) arrived through trading portals on the Indian Ocean coast and changed the agricultural landscape, enabling farmers to exploit new environmental spaces.

Disentangling land use and land cover

Archaeological research has been spread unevenly across Eastern Africa, with large swathes subject to little or no investigation while other areas - such as the Central Rift

Valley and the Swahili Coast - have been intensively studied. Predictably, this tends to reflect modern population distributions and accessibility. There is, however, reason to suspect that unevenness reflects past population distributions; plotting site locations above a basemap showing modern moisture index (ratio of annual rainfall and potential evapotranspiration; Fig. 2d) suggests past preferences towards the same amenable climatic zones where populations and regional economies are focused today. This is most apparent with respect to sites with evidence of crop cultivation, consistently located in certain zones with more reliable water distribution, such as lake or river basins, or moist highlands. This provides a useful parameter for interpreting between data-points. In conjunction with broader land-cover patterns evidenced in paleoenvironmental records, we can begin to disentangle the probable from the possible spreads of various land-use activities.

Besides the current database of 360+ archaeological sites (see supplementary data in Marchant et al. 2018), we have assembled records from 150+ paleoenvironmental geoarchives that represent the collated evidence of land-cover change over the late Holocene available from lake and marine sediments, swamp and peat deposits, glacial ice, and other sources such as tree-ring and coral growth records. As with the archaeology, the coverage of these records is biased towards

certain areas and eco-climatic contexts. Furthermore, their scale and resolution varies widely: a wetland study of $\delta^{13}\text{C}$ isotopes in the sediments provides information on very local variations in vegetation cover in and around the wetlands, whereas a pollen study from lake sediments can spatially aggregate a vegetation-change signal and include pollen taxa from adjacent mountain ecosystems, riverine forests, savannah, and the wetland itself. The next phase of work for our East Africa working group will explore the spatial coverage of our existing data, and develop land-cover maps for the LandCover6k time intervals (see Editorial, this issue) from which to generate environmental niche reconstructions to delimit land-use classes. We have already begun to record which geoarchives have previously been interpreted as evidencing anthropic influence; we will build on this through Bayesian modelling of radiocarbon dates from the paleoenvironmental and archaeological databases to access patterns of synchronicity in environmental and cultural change. In addition to informing our land-use and land-cover distribution maps, such models will help address questions such as how sedimentation rates might have responded to land-use change. These lines of enquiry will be essential in our assessment of how exactly the landscape of Eastern Africa has been affected by dramatic economic change in the last 6000 years.

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Towards a global history of agricultural systems

Mats Widgren

Maps of past agricultural systems suggest two rapid changes: around 1500 CE, as European colonization led to demographic and agricultural collapse in South America, 1870 to 1920 CE, as industrialization and steam transport resulted in a global division of labor.

Historians, archaeologists and historical geographers have been slow in reacting to the increased interest from climate modelers in past land use. However, the research situation for the Americas in the wake of the 500-year anniversary in 1992 of Columbus's travels did stimulate syntheses on pre-Columbian landscapes (Butzer 1992). Three volumes on the cultivated landscapes of native America were published by Doolittle (2000), Denevan (2001), and Whitmore and Turner (2001). The subsequent dissemination of these syntheses to a broader audience by Mann (2005) should also be mentioned. These studies and publications inspired a cooperative effort by a group of American and Swedish scholars to map the development of global agricultural systems over the last 1000

years under the framework of the project *Mapping Global Agricultural History* (Widgren 2010). Here, we present, as an example, one of the maps created within the project: agricultural systems in Africa around 1800 CE. We based the development of global categories on the previous work of Whittlesey (1936) and Grigg (1974) on global agricultural regions in the 20th century. We are not mapping land cover, per se, or land-use types, but rather a limited set of globally known agricultural systems, i.e. the presence of agriculture and the dominant type of agricultural system. It is not possible to translate the mapped information into areas of different land-cover or land-use types. For example, a single agricultural system, i.e. mixed farming, was dominant in Northern Europe, where the activities

related to crop cultivation and livestock were closely integrated. Land use and land cover could, however, vary widely, from large open fields in the Paris basin to remote farms in northern Scandinavia, where forest was the dominant land cover (Grigg 1974). Presentation of our knowledge on agrarian systems at the global scale in maps nevertheless facilitates comparison with other data and model simulations on land use and land cover.

We have striven to keep the number of categories low in order to increase readability of the maps. On the global scale we defined; (1) Pastoralism and ranching, (2) Husbandry of non-domesticated plants, (3) Extensive or undifferentiated agriculture, (4) Permanent fields, (5) Mixed farming, (6) Intensive systems, and

Figure 1: Agricultural systems in sub-Saharan Africa by 1800 CE. Husbandry of non-domesticated plants (category 2) certainly did exist in Africa, but was practiced in pockets within larger regions of agriculture and has therefore not been mapped. The background data for the map and the GIS-file can be downloaded from Widgren (2017).

Figure 2: Agricultural expansion in Southern Africa CE 1000 to 1800. Based on Maggs (1984) and Christopher (1982). For explanations, see caption of Fig. 1.

(7) Irrigated rice. This classification system is open for discussion and can have advantages or disadvantages depending on different viewpoints and aims. It has proven, however, to work on a global level and make comparisons across and between continents possible. Agricultural systems should preferably be understood on a nominal scale because they are qualitatively different and not immediately possible to translate into an ordinal scale. However, differences in productivity, labor intensity, and in the degree of modification of the land have inspired us to introduce an ordinal scale in the numbering and coloring of the systems. For the continental maps, each category can be further subdivided, as in Figure 1. For a discussion of the global categories and the continental sub-categories for Africa, see Widgren (in press).

In contrast with anthropogenic land-cover change (ALCC) scenarios like those published by Kaplan et al. (2009) or Klein Goldewijk et al. (2017), we can show particularly rapid changes – “leaps” – that were due to global historical and political events. Such a “leap” occurred when the European colonization of South America (ca. 1500 CE) led to a demographic and agricultural collapse, especially in the Amazon. The other most important leap is the expansion of farming in the second half of the 19th century, when the combination of industrialization and steam transport led to a global division of labor on an unprecedented scale. It is in that context that we can see the expansion of the wheat frontier in western USA and eastern Eurasia, and at the same time a rapidly expanding rice frontier in the outer parts of the Asian deltas. Any modeling based on population growth and per capita consumption in different regions becomes increasingly meaningless from this period onwards.

The historical development of farming in Southern Africa exhibits another trajectory that is difficult to model if archaeological and historical data are not taken into account. Archaeologists and historians have known for a long time that the winter rainfall area of Western

Cape cannot sustain the African crops sorghum and millet. The agricultural development of African populations hence came to a definite limit in its expansion towards the southwest. It was only with the introduction of European crops that a Mediterranean type of farming system was established. Nonetheless, European farming had only reached a small area of the Western Cape around 1800 CE (see Maggs 1984 for the archaeological evidence, and Christopher 1982 for the historical evidence of European farming). Recent work based on a large archaeological database for Southern Africa seems to confirm Maggs’ maps of pre-colonial farming communities and provides a strong potential for a more precise mapping of agriculture in Southern Africa (Russell et al. 2014).

The *Mapping Global Agricultural History* project and *PAGES’ LandCover6k* have the goal to provide evidence of land-use change at the global scale based on empirical data. Thanks to those activities, we expect this type of information will become more common. However, it is still a challenge to transparently integrate this empirical knowledge in the model-based back-casting that has so far dominated historical land-cover and land-use studies.

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The unexpected land use: rain-fed agriculture in drylands

Stefano Biagetti^{1,2}, C. Lancelotti¹, A. Zerboni³, D. Usai^{4,5} and M. Madella⁶

Although excluded from most maps of current and past land use, dryland rain-fed (non-irrigated) agriculture has been and is pivotal to enhance resilience of human communities, and understand land-atmosphere interactions and regional climate in many parts of the world.

On a warming Earth, reclaiming traditional knowledge related to low-demanding plant varieties and cultivation techniques that reduce land degradation is a priority. Drylands are generally defined as “challenging” for non-irrigated agriculture (Rockström and Karlberg 2009), since artificial watering is considered necessary to secure regular crop yields. The Sahara and its margins are one of the most emblematic drylands. This region is often considered “inactive” from an agricultural point of view (Rockström and Falkenmark 2015). Land-use models and maps of Africa normally characterize the Sahara as a huge empty area stretching from the northern edge of the Sahel up to the Mediterranean coast and the Atlas Mountains. Similarly, current technical reports and studies on food production in drylands (e.g. UNEMG 2011) tend to consider the Sahara devoid of plant cultivation. The amount and extent of rain-fed agriculture in drylands is also important in terms of biogeochemical and biogeophysical processes between land surface and the atmosphere, therefore impacting on climate both in the past and the future.

Rain-fed agriculture in the Sahara

The perceived dominance of pastoralism, together with the idea that hot deserts are unsuitable for raising crops, seems to have eclipsed the role that cultivation has had over time in these regions. It is therefore not surprising that the extent of rain-fed agriculture in the Sahara is poorly researched. Yet, notes published over the last two centuries suggest the occurrence of this practice in different parts of this desert (Fig. 1). In central Mauritania, in the Moudjeria area, where average rainfall is 170 mm a⁻¹, rain-fed crops were observed in the early 1960s (Toupet 1963) and pastoral communities were reportedly growing cereals without irrigation. In the Ahaggar Mountains (also known as the Hoggar Mountains), where the rainfall varies between 0 and 100 mm a⁻¹, millet (without further specification) was grown in the past (see Duveyrier 1864). Nicolaisens and Nicolaisens (1997) reported the existence of a specific word (“*tawgest*”; de Foucauld 1951) to designate non-irrigated plots of land cultivated by the Tuareg people along the valleys of the Ahaggar. In the Aïr massif,

where average precipitation is 120 mm a⁻¹, Rodd (1926) wrote that “... in certain areas rain-grown crops could be raised most years. In the past a fair amount of cereals seems to have been produced this way...”, obviously hinting at a decrease in this practice. The engagement of nomadic Tuareg with rain-fed farming was reported also in the Tassili n’Ajjér region (now a national park) by the early 1950s (Nicolaisens and Nicolaisens 1997). This practice was further recorded in the Libyan south-west, namely in the Tadrart Acacus (di Lernia et al. 2012), and around the city of Ghat (Bourbon del Monte Santa Maria 1912). These last reports are surprising given the very low (and mostly uneven) rainfall in both those Libyan and Algerian regions, ranging from 0 to 40 mm a⁻¹. In the Tibesti mountain range, close to the Guezendi area, cereal plots were observed in the 1940s (Desio 1942) in areas with less than 50 mm a⁻¹ rainfall. This clearly shows a rain-fed agricultural strategy that complements pastoral and foraged resources. Such strategies have been largely ignored in past and current discourse of resource exploitation in the Sahara.

Figure 1: Aridity Index (AI) from the Consultative Group for International Agricultural Research Consortium for Spatial Information (CGIAR-CSI) and the localities mentioned in the text. Triangles indicate specific locations, while shaded areas and italics names refer to regions with evidence of past (and possibly current) plots of rain-fed agriculture. The AI takes into account the values of precipitation, temperature and potential evapotranspiration. The mentioned cases of rain-fed agriculture in the Sahara fall within the “hyper-arid” or “arid” class, well beyond the threshold for the supposed suitability of rain-fed agriculture.

Figure 2: GoogleEarth™ view of one of the fields recorded at Al Khiday. Imagery taken in September 2012. Rows formed by millet plants, ready to be harvested, are shown.

The case of Al Khiday, Sudan

Recent explorations of the desert in the area of Al Khiday in Central Sudan (Fig. 2) are providing new, extensive and systematized data on rain-fed agriculture. The region today is arid (according to both the Köppen-Geigen and the CGIAR-CSI Aridity Index classifications; Zomer et al. 2008) with a yearly average rainfall of ca 100 mm. Several rain-fed fields between 15 and 30 km west of the White Nile left bank were recently surveyed. The observation of free satellite imagery time series (GoogleEarth™) shows that 70 mm of precipitation in July/August is enough to enable the cultivation of extremely large expanses of land (up to ca. 120 ha per field system; Fig. 2). The cultivated areas are divided in plots owned by different families from neighboring villages, whose people are also engaged in wage labor and may own some small stock. The main crop is pearl millet (*Pennisetum glaucum* L. R.Br.), although in wetter years cash crops, such as karkadé (hibiscus), are also cultivated. After the late spring/early summer rains, the fields are prepared by clearing wild grasses (hoeing) while the soil is still wet. Farmers then walk the fields along parallel lines, making holes for seeds roughly every meter. The sown fields are then left unattended until the harvest in September when farmers use iron sickles to cut the plants just above the ground. Grains are then threshed in the fields and the by-products are left for the domestic stock (goats, sheep, donkeys) to graze.

No data are currently available for productivity of rain-fed agriculture in arid or hyper-arid lands, and a first preliminary evaluation of the productivity of the Al Khiday fields gives a value of ca. 100 kg of millet per hectare. This estimate is based on plant density and average single-plant seed production. This figure is clearly much lower than production from the world's dry

sub-humid and semi-arid regions, where rain-fed agriculture yields vary between 0.5 and 2 t ha⁻¹ (e.g. Wani et al. 2003). In spite of the low yield, local farmers are able to produce double the quantity of millet necessary for the families' annual needs, leaving part of the crop to be sold at local markets after setting aside enough grain for the next planting season. It is astounding that this kind of cultivation not only supplies the families with important dietary carbohydrates, but also supplies some income.

Final remarks

Millet, and specifically pearl millet, are key crops in drylands because of their short growing season and the abundant productivity under aridity and high temperatures. Millets can also be used as fodder, either using the entire plant before grains mature or the by-products from grain processing. They are therefore perfectly suited for mixed agro-pastoral systems. Pearl millet is a critical West African domesticate, and the Sahel zone south of the Sahara is an important area for its domestication (Fuller 2007). However, research on past crops in Africa's drier areas is still limited, and rain-fed practices have never been part of the current discourse on the origin of agriculture, its detection, and extensification/intensification dynamics. Research on ancient rain-fed farming in the Sahara (and other deserts) is urgently needed to address the role of this strategy in enhancing the resilience of human societies in difficult climatic settings. This research, which is in its earliest stages, is proceeding under the framework of PAGES' LandCover6k Land Use group. This working group is producing updated and more realistic assessments of past land use in the light of environmental-human-behavior coupled models. Social science research can greatly enhance the value of this work by connecting present-day adaptive behaviors (traditional ecological

knowledge) to the deep historical record. This work has the potential to revolutionize our understanding of the past, as well as current and future resilience strategies and policy, both at domestic and governmental levels. Furthermore, it will inform current research on the Anthropocene by establishing a deep connection between human behavior and its effects on environmental and landscape modifications.

Archaeology plays a pivotal role in exploring rain-fed agriculture through a long-term perspective, which enables the evaluation of adaptive strategies and the resilience of such practices. Thus, it is urgent to plan new archaeological research that can document rain-fed farming in drylands over the past millennia in order to appreciate its frequency, structure and distribution over time and space. This approach should include new archaeobotanical and experimental techniques that unambiguously identify past water-crop management directly from the cultivated crops recovered from archaeological contexts.

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Simulating vegetation in ancient Japan using HUMPOL: A pollen-based multi-scenario modeling approach

Lauren Bell¹, E. Crema², M.J. Bunting³ and M. Madella⁴

We present a hypothetical vegetation map for the largest Jōmon settlement in Japan (ca. 5900-4100 BP) based on simulated pollen dispersal in the landscape using fossil pollen data. It suggests intentional planting of chestnut groves within the settlement area.

The simulation of vegetation in past landscapes can be important for archaeologists attempting to reconstruct ancient land-use and human-induced land-cover changes. This research focuses on the application of the software HUMPOL (Bunting et al. 2004), a modeling suite based on the “Prentice-Sugita model” from the REVEALS-LOVE algorithm of pollen dispersal and deposition in lakes and bogs – similar to the approach used in POLLANDCAL (Sugita 2007a,b; Sugita 1994; Sugita et al. 1999). However, HUMPOL expands on this by enabling the testing of multiple vegetational hypotheses on known landscape parameters, known as the Multi-Scenario Approach (MSA; Bunting and Middleton 2009). HUMPOL has been used in Europe to determine the extent of human impacts on past vegetational landscapes (e.g. Caseldine and Fyfe 2006; Gaillard et al. 2008). Models can provide insight into patterns otherwise invisible in the archaeological record. They are particularly useful when studying large areas with multiple data sources. HUMPOL is a valuable tool with which the user can test hypotheses on past landscapes by altering multifarious environmental parameters and variables (e.g. degree of vegetational openness) to assess their effect on vegetation cover.

Using HUMPOL for vegetation reconstruction

HUMPOL is most effectively used for vegetation reconstructions at local to sub-regional spatial scales, particularly in projects with

good pollen core coverage and a robust chronology for the relevant time slices. To successfully define landscape parameters for the input map, we must assume the dominant pollen taxa reflect the different vegetation/landscape/land-use types in their ecological system. Pollen dispersal is simulated using this input map.

One major prerequisite for HUMPOL input grid creation is landscape data, most crucially on elevation and hydrology. Geology and soil information can also be included. Unfortunately, as not all spatial data can be placed directly into the HUMPOL software suite, preparation of the data is usually one of the first stages in the modeling process (Fig. 1). The elevation data can be obtained from a high resolution Digital Elevation Model (DEM).

When creating the simulated landscapes, each selected pollen taxon and its preferences in terms of landscape parameters will affect where the pollen will be deposited on the grid, and determine its abundance once it reaches the plant’s ideal habitat. For this, the ecological preferences of each plant taxon used in the study need to be known, such as tolerance to slope, facing direction of the slope, and wetness (Fig. 1). To simulate pollen deposition in the pre-defined landscape, HUMPOL also requires pollen productivity estimates (PPE) and fall speed values for each taxon. Pollen productivity differs between plant taxa: for instance, trees generally produce more pollen

than herbs. Furthermore, size and shape differs between pollen-morphological types, which affects their aerodynamics and thus the speed at which they are transported by wind and the distance they travel. PPEs are generally obtained empirically using field data, i.e. datasets of modern pollen assemblages from multiple pollen traps across a specific ecological system (e.g. Mazier et al. 2012). Fall speed is calculated based on measurements of pollen grains for each plant taxon on the basis of Stoke’s Law, which describes fall speed of small particles in the air (see also Dawson et al., this issue). Once pollen assemblages are simulated for the hypothetical landscape, they can be compared to the fossil pollen record (Fig. 1).

HUMPOL at Sannai Maruyama - secondary forest or chestnut gardens?

Sannai Maruyama is situated on a hilltop surrounded by valleys which lead into the Okidate River in modern-day downtown Aomori City in northern Japan (Fig. 2a), and is one of the largest Jōmon settlements known to date. Settled from ca. 5900-4100 BP, Sannai Maruyama displays evidence of pit dwellings, mounds, pottery, clay figurines, and stone implements (Kawahata et al. 2009; Tsuji and Nakamura 2001). Environmental data obtained from waterlogged areas suggest that during occupation there was a prevalence of chestnut trees around the site, a feature rarely seen in Jōmon sites. As chestnut (*Castanea crenata* Siebold & Zucc.) is a sun-loving, insect-pollinated tree,

Figure 1: A workflow for the HUMPOL software suite. *GridIn* converts ASCII-format spatial data into the IDRISI-format grid with a specified cell size. *PolSack* creates unique identifiers and allows input of data for each taxon, community, and pollen core. *CreateLookUp* creates a distance-weighted vegetation lookup table based on abundance and location of each taxon in the landscape using the Prentice-Sugita model. *Script file (.txt)* contains all programmable instructions for the landscape parameters and MSA variables. *LANDPOLFLOW* simulates the dispersal and deposition of pollen in the hypothetical landscape based on data from all the above.

it naturally grows sparsely in valley settings. Human intervention therefore seems the only possibility for expanding its presence (Yoshikawa 2011). The purpose of this research was to test whether climate, passive human presence, or active management of the landscape could be identified as key factors for chestnut's expansion at this time.

Five pollen cores from adjacent valleys were selected due to their reliable dating to around 5100 cal. BP, their spread across the site, and sufficient representation of key dominant taxa. As geology and soil characteristics did not vary enough to have had an effect on vegetation, only a DEM of the area (1.4 km²) and a reconstructed hydrological map were used. PPEs and fall-speed values were acquired from studies in Europe (Mazier et al. 2012) and Japan (Bunting, pers. comm.). To assess the scale of human impact on the vegetation at Sannai Maruyama, two landscape scenarios were created in HUMPOL from two time slices: (1) pristine natural vegetation before the establishment of the settlement; and (2) anthropic vegetation at the time of peak settlement occupation. In the second scenario, three main factors were accounted for. As climate was warming around 5100 cal. BP, the effects of this on the pollen record were explored by increasing the abundance of sun-loving species, *Castanea*, *Juglans* and *Aesculus*. The presence of a secondary forest, as hypothesized by Nishida (1983), was represented in the simulation as a community of taxa associated with human exploitation around the settlement areas. To simulate the effects of intentional fires, variables for landscape openness were used in the settlement areas and in the secondary forest.

The results showed that it is possible to attain a close match to the pollen record at Sannai Maruyama and reproduce some of the expected patterns based on hypothesized anthropic effects on the vegetation (Fig. 2b). Because it was difficult to replicate the values of *Castanea* and *Gramineae*, it can be suggested that Jōmon management methods involved transplanting chestnut trees into the settlement area from saplings collected from the valleys. This disproves Nishida's (1983) hypothesis regarding the layout of the secondary forests. If the modeled hypothetical landscape is correct, it would imply that the areas with pit dwellings were lined with chestnut groves whose produce was shared within the community. However, the HUMPOL software suite is limited in its representation of insect-pollinated plant taxa, such as *Castanea*. This is because the Prentice-Sugita model assumes that all pollen is dispersed by wind; therefore, the simulated pollen assemblages might be misleading. Nevertheless, using HUMPOL for this project has been very useful as an exercise in assessing the effects of potential causes of vegetation changes in the landscape, although further exploration is needed to reach more definitive conclusions. More reliable dates for the other existing pollen records from Sannai Maruyama, for example, would improve the resolution of the models produced. Comparisons to other similar settlements with good pollen-core coverage could also be valuable for furthering this research.

Figure 2: (A) Map of Sannai Maruyama within Aomori Prefecture; (B) The output map from LANDPOLFLOW showing the hypothetical vegetation for the anthropic model (1.4 km²). This map resulted in the simulated pollen assemblages with the best statistical fit for the fossil pollen assemblages from the five pollen records P1, P3, P7, Chikano F6 and SM9 (white dots).

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Prehistoric land-cover and land-use history in Ireland at 6000 BP

Nicki J. Whitehouse¹, M. J. Bunting², M. McClatchie³, P. Barratt¹, R. McLaughlin⁴, R. Schulting⁵ and A. Bogaard⁵

Land cover and use are compared for Neolithic Ireland, revealing complex inter-relationships between land cover and the archaeological record. Land-cover data can be misinterpreted when isolated from the land-use activities that help shape them, while land-cover data complements land-use datasets.

Land-use and land-cover changes have shaped our landscapes and ecological communities. We summarize land-use and land-cover changes for the period 6-4.2 ka BP (4000-2200 cal BCE; the Neolithic period for Ireland) as represented by cereal remains, pollen data, and limited zooarchaeological data (McClatchie et al. 2014, 2016; Whitehouse et al. 2014; McLaughlin et al. 2016). The earliest Neolithic in Ireland is dated to ca. 4000 cal BCE (~6 ka BP), but much of the demonstrably "Neolithic" archaeology dates from about 3750 cal BCE, when we see an abundance of rectangular houses and the first appearance of domesticated animals and plants. Neolithic archaeological material before 3750 cal BCE is limited – although not completely absent (McLaughlin et al. 2016; Schulting et al. 2017) – while the profusion of sites after this date indicates a radical transformation of human society and its associated cultural landscape.

The Neolithic is divided into:

Early Neolithic I (ENI) 4000-3750 cal BCE
Early Neolithic II (ENII) 3750-3600 cal BCE
Middle Neolithic I (MNI) 3600-3400 cal BCE
Middle Neolithic II (MNII) 3400-3000 cal BCE
Late Neolithic (LN) 3000-2500 cal BCE (Whitehouse et al. 2014).

Land use

Archaeobotanical data derive from 52 sites (Fig. 1) assigned to the above time periods, using Bayesian site chronologies (McClatchie et al. 2014). Wheat and barley were being cultivated at many sites by 3750-3600 cal BCE (ENII), including emmer wheat (*Triticum dicoccum* Schübl.), possible einkorn wheat (*Triticum monococcum* L.), naked wheat (*Triticum aestivum/durum/turgidum* L.), naked barley (*Hordeum vulgare* L. var. *nudum*) and hulled barley (*Hordeum vulgare* L.). Flax (*Linum usitatissimum* L.) was also cultivated. Emmer wheat was the dominant cereal, most notably during the ENII and MNI periods. Cereals were present at only a small number of MNII-LN sites and included emmer wheat, naked wheat and indeterminate barley, with increased occurrences of the latter. From 3400 cal BCE (MNII), there is a reduction in archaeobotanical data and reduced human settlement evidence (McLaughlin et al. 2016).

Communities were also making use of locally available wild resources. Most assemblages

contained a range of gathered foods, especially hazelnuts but also apple, bramble and sloe. Hazelnut shell fragments are present at 70-90% of sites, with decreasing levels in the MNII-LN. Fruit remains (e.g. crabapple, bramble) occur at a significant minority of sites, rising to 36% of MNII-LN sites. The regular occurrence of potential wild food-stuffs, as well as cereals, indicates a land use that included many different types of plant resources (McClatchie et al. 2014). Thus, areas devoted to cereal cultivation would have been present alongside the use and potential management of wild resources.

Management of agricultural plots was investigated by analyzing the ecological characteristics of potential arable weeds (Ellenberg et al. 1992; Bogaard 2002). Plants of disturbed places and annuals dominate the arable weeds, and likely indicate highly disturbed, permanently tilled cultivation

plots and that people were not using shifting cultivation practices (McClatchie et al. 2014). This implies intensive management and investment of plots most akin to intensive garden cultivation and cultivation of plots under permanent agriculture.

EN II-MNI sites are distributed on the eastern and southern coastal regions of the island, along many of the river valleys, on prime agricultural soils (Whitehouse, unpublished data), with cultivation fields likely located close to settlements. Pockets of activity are present in the north and west; almost certainly vestiges of wider activities in these areas. There is little evidence for cultivation occurring in central areas of Ireland, today covered by extensive wetlands. During MNII-LN, sites are largely restricted to easterly areas; however, the paucity of evidence may be a reflection of taphonomic biases (McLaughlin et al. 2016).

Figure 1: Distribution of archaeobotanical sites by time slice (note: some periods have been merged due to limited datasets. NEO: indeterminate Neolithic period). Sites follow Whitehouse et al. (2014).

Figure 2: REVEALS reconstructions of land cover for Neolithic Ireland in the six time slices (see text), with oldest at the bottom of the y-axis and most recent at the top. Values on the x-axis represent the proportions of the assigned land-cover type. Circles represent the approximate catchment represented by the REVEALS reconstructions.

Land cover

Pollen land-cover modeling was undertaken using the REVEALS model (Sugita 2007; Woodbridge et al., this issue). Pollen-count data were used covering the archaeological periods of interest; records originated from a single large site (lakes, bogs) or from a minimum of three smaller sites located close together (smaller lakes, mire sites). Age models for the selected sites were developed so we could group results into the relevant archaeological periods. Forest hollows were excluded because of their strong local pollen signal. The spatial scale of REVEALS reconstructions is ~100 x 100 km (Hellman et al. 2008; Trondman et al. 2016).

The reconstruction (Fig. 2) indicates woodland represents 80–90% of land cover, primarily consisting of broadleaf trees, with more pine represented in the west (County Mayo) than in the east. In the east, woodland cover represented ~80–95% of land cover over the Neolithic; on the west coast it declined from 80% to 70%, indicating more open areas than easterly locations. Central locations were almost 100% woodland cover; this actually increased during the Neolithic. This suggests Neolithic people did not generally infiltrate the central districts of the Midlands of Ireland at this time (Whitehouse et al. 2014; Fig. 1).

Hazel was an important component of woodland, making up ~40% of land cover. Although this shows an overall decline over

the course of the Neolithic, hazel land cover increased by about ~10% in the east and west during MNI and MNII, before decreasing again to roughly similar levels. This represents either re-afforestation by hazel or increased hazel pollen production at this time. There is limited heathland and mire cover, despite its importance in the landscape today.

We see a general trend of increasing openness: ~5–30% of the landscape, likely reflecting some regional differences in land-use activities and settlement patterns and subtle differences in vegetation composition. There is, however, no marked clearance event, but rather a gradual process of opening of the landscape. In the west, open values were considerably higher than elsewhere. Early farmers may have taken advantage of already open habitats and increased areas of open land through pastoralism.

Integrating land use and land cover

Land-use data inform us about the archaeological activities at the local spatial scale, while estimated land-cover data provides an understanding at the regional spatial scale. Land cover in ENI and ENII indicates that between 10–20% of land was open in character, likely linked to land use from settlements, cereal cultivation, and animal grazing as well as some naturally open areas. While this is already in evidence during ENI, when open land-cover changes are modest, during ENII these effects became more pronounced,

with clearance of an additional ~5–10% open land.

Land-cover modeling provides important insights into the re-afforestation phase in MNI (in the east) and MNII (in the west), consisting of increases in hazel wood coverage. Several possibilities could explain this: (i) a change in land use due to land abandonment and secondary succession by hazel into previously open areas (e.g. due to population decline), or people becoming more dispersed in the landscape or changing the location of their activities; (ii) increased hazel flower and pollen production due to coppicing for nut production, fencing and hurdle production (Waller et al. 2012) and (iii) post-recovery succession of hazel following burning of woodland to facilitate woodland grazing, as suggested for Neolithic Central Europe (Jacomet et al. 2016). This episode represents a change in land use that is likely associated with human behaviors. Possible climatic changes are unlikely to explain the increases seen in hazel pollen directly because of the uneven responses across the island, although climate may have indirectly driven aspects of land-use change (Whitehouse et al. 2014).

The combination of land-use and land-cover data allows a much fuller and meaningful interpretation of the datasets; both land-use and land-cover interpretations are enriched when combined.

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The AgriChange project: an integrated on-site approach to agricultural and land-use change during the Neolithic in Western Europe

Ferran Antolín, S. Häberle, A. Jesus, H. Martínez-Grau, G. Prats, M. Schäfer and B.L. Steiner

Early farmers were resilient thanks to a small-scale, household-based farming strategy that coped well with climate variability. The AgriChange project is compiling data on crops, local climate variability and risk-reducing strategies to reconstruct agricultural and land-use change in the Neolithic.

Research carried out during the last decades has brought to light a wealth of information on agriculture and wild-plant gathering in Western Europe during the Neolithic period, between 5700 and 2300 BCE (7.65–4.25 cal ka BP). As a result, broad-scale changes in crop types and agricultural practices have been outlined. These changes have the potential to provide insights on the factors that may have influenced agricultural decision making in the past, such as climate change, or land-use change related to technological developments (e.g. the introduction of the plough or new irrigation practices). So far, these aspects have not been assessed in an integrative way and at a large spatial scale. The latter is the main aim of the Swiss National Science Foundation AgriChange project (2018–2021). The geographic focus of the project is the Northwest Mediterranean region up to the Alpine Foreland (Fig. 1). This area witnessed contacts between different farming traditions (the central European one and the Mediterranean one) from the beginning of the Neolithic onwards and is therefore an ideal case study area. The project will thus contribute key data to LandCover6k for a first comprehensive detailed-scale reconstruction of land-use for the study area.

Decision making among smallholders is a complex issue that involves their global socio-economic and spiritual sphere. For this reason, a multi-proxy approach is pertinent. This includes proxies that allow the study of resource diversity over time in the past, spatial variability, exchange, and storage. In addition to this, proxies for paleoclimatic conditions at an adequate temporal resolution are necessary. Data from the northeast of the Iberian Peninsula serves as a useful example of potentials and pitfalls of the project's approach.

The example of the Iberian Peninsula

The northeastern part of the Iberian Peninsula has seen the greatest advances in research during the last few decades and provides a detailed multi-proxy

dataset that includes underground storage capacity, crop types, climate, and summed radiocarbon probability distributions (SRPD) as a proxy for population dynamics (Fig. 2 A–D, respectively). We can see there are two phases with a higher density of SRPD: 5.5–5.0 and 4.0–3.5 ka BCE. These coincide with arid phases and end with a cold and humid phase, respectively.

Naked (free-threshing) wheat tends to prevail during arid phases (5.4–5.2 and 4.2–3.7 ka BCE), while naked barley increased in the latter phase (4.0–3.5 ka BCE). The mean capacity of storage features increased in this phase, but not the median (therefore

some larger storage pits were produced, probably as a response to uncertainty, while keeping the regular sizes in most cases). These changes might have enabled the social developments (population increase, higher settlement nucleation, social stratification and development of regular exchange networks of prestige objects) of the “Sepulcres de Fossa” period (equivalent to other Middle Neolithic cultures in Europe). In contrast, hulled wheats are poorly represented, being mostly found in the arid phases. In the last period (3.2–2.3 ka BCE), hulled barley seems to partly replace naked barley (not separated in Fig. 2), maybe due to higher aridity

Figure 1: Scheme of the local-to-regional-scale analyses performed in the AgriChange project, and location of case studies.

Figure 2: Multi-proxy analysis of agricultural changes during the Neolithic in the northeast of the Iberian Peninsula. **(A)** Storage capacity in liters: Median in light grey, mean in dark grey, temporal resolution marked below the graphs with a thicker black line (Prats 2017); **(B)** Mean percentage of each crop, sites grouped for time slices (Antolín 2016): Barley in yellow, naked wheat in pale green, glume wheats in dark green; **(C)** Paleoclimatic proxies: GISP2 $\delta^{18}\text{O}$ (i) Minorca events (cold phases; Frigola et al. 2007); (ii) Alboran Sea cold events (Cacho et al. 2001); (iii) Sedimentary karst records (arid phases in brown, humid phases in light blue; Bergadà et al. 2017); **(D)** SRPD based on the dates from Morell B (PhD in progress, Autonomous University of Barcelona, Spain).

(hulled barley tolerates drought better than other cereals). During this period, storage features tend to become significantly larger, perhaps to help cope with risk and uncertainty and revealing a focus on increased yields over productivity per land area (i.e. intensification of agricultural land instead of continuing with more small-scale, intensively managed plots).

These results suggest that naked wheat might have been the preferred crop choice over other taxa except during wet phases, when naked barley perhaps was more successful. In response to a progressive climatic aridification during the youngest phases (3.2–2.3 ka BCE), hulled barley might have been a safe choice. This seems to be connected to a change in land use towards more extensive farming systems.

How will the AgriChange project lead us a step further?

Despite recent improvements in the datasets and the novelty of the multi-proxy approach, there are still some important limitations that need to be tackled. These include the restricted number of studied contexts, the poor chronological resolution of the observed agricultural changes, the existing limitations for the identification of the adoption of new landraces (beyond the main crop types), the scarcity of isotopic analyses that help to reconstruct land use changes (Fig. 1), and lack of knowledge on the short-term, local-scale climatic variability.

AgriChange will perform new research in a selected number of key sites and focuses on waterlogged deposits containing cultural layers (Fig. 1). Wetland sites can provide important insights for three reasons:

(i) they offer precisely dated contexts, thanks to the preservation of wood remains datable to a calendar-year scale through dendrochronology, (ii) the cultural layers often present a stratification produced during short periods of time (20–40 years) that may reflect changes during the settlement occupation, and (iii) waterlogged deposits are generally characterized by good preservation conditions of plant and animal remains, which translates into more diverse environmental proxy data than those obtained in most dryland sites. The oldest lakeshore site of the Alpine area, Isolino di Varese (Varese, Italy) is one of the key sites studied in the project. It is a UNESCO World Heritage Site with an initial occupation dated to ca. 5.3 ka BCE with subsequent occupations in younger periods. AgriChange also includes dryland sites both for methodological and ecological reasons, since the distribution of sites with waterlogged deposits is quite restricted (often near lakes).

The project integrates several disciplines and multiple scales of analysis (Fig. 1). Archaeobotanical analyses form the basis of the interpretation and construction of the discourse, since they inform us about what was grown and where. Digital image analysis is used to identify crop types (see Ros et al. 2014; Bonhomme et al. 2017). Single seeds are individually radiocarbon dated (ca. 500 measurements) to identify crop changes over time in each region. AgriChange also uses carbon and nitrogen stable isotopes from cereal grains to infer land-use changes over time (extensive vs. intensive farming methods; Fraser et al. 2013). Carbon stable isotopes are also a valuable on-site proxy for crop water availability in spring (Araus et al. 2003;

Fiorentino et al. 2008) and therefore might reveal short-term climatic changes, otherwise difficult to detect.

Additional proxies (storage features, insect and small animal remains) are investigated to reconstruct and understand crop storage practices and infer storage capacity and crop pests. Although underground storage pits are one of the most common archaeological features found in dry sites, and despite the fact that storage is recognized to be an essential aspect of farming societies (Sigaut 1988), inefficient recording methods and the lack of regional or supra-regional archaeological databases have not yet allowed the study of storage and productivity over time. Recording changes in storage capacity and identification of crop pests in the study area will bring important insights into food security and risk management in the past. Climatic variability is considered at a large spatial scale using global proxies, as well as local to regional scale by compiling several climate proxies such as plant macroremains, insect and small-animal remains and $\delta^{13}\text{C}$ records from cereal remains.

AgriChange integrates multiple proxies to understand long-term agricultural decision making in the past, which will provide valuable lessons for current planning of resilient systems of smallholders in the face of today's multiple challenges such as globalization, liberalization of agricultural land and climate change.

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Comparing and modeling the spread of early farming across Europe

Marc Vander Linden¹ and Fabio Silva^{2,3}

We review modeling approaches and meta-analyses of the archaeology on the introduction of domesticated plants and animals across Europe. Variation in the rates of diffusion, human demography and farming systems suggest complex patterns of land-use and land-cover changes.

The European Early Neolithic is defined by the introduction and subsequent diffusion across Europe of numerous plants and animals originally domesticated in the Levant. We offer here an overview of the archaeological literature focusing on (1) measures of the rate of spread; (2) the demographic background; and (3) the variability of early farming systems. The research strategy benefiting from these various literature reviews aims to, first, analyze large-scale datasets (i.e. meta-analysis) to detect patterns in the archaeological record, and, second, identify the variables responsible for these regularities using models. Particular attention is paid to the interplay between climatic, environmental and human factors.

A question of time, not speed

Seminal work by Ammerman and Cavalli-Sforza (1971) showed a correlation between the local date of introduction of farming across Europe, and the distance from the source of domesticates i.e. older sites in the Near East and gradually younger ones as the spread proceeded through Europe. They also calculated that this progression operated at a mean rate of 1.08 km per year, explained through a model of demic diffusion, wherein the next generation of farmers would move, on average, 25 km away from their birthplace. Ancient DNA studies have recently confirmed that the introduction of domesticates is indeed linked to the dispersal of a new human population, with a limited contribution of the last local foraging communities, though the picture changes regionally (Lazaridis et al. 2016). Several papers have since adjusted Ammerman and Cavalli-Sforza's original estimate, but also pointed to regional variation in this movement estimation. For instance, Bocquet-Appel et al. (2009) showed that, while an average rate of 1.09 km per year can be calculated, it masks considerable variation, concluding that the spread of early farming across Europe was a discontinuous process, with successive episodes of expansion and stasis. Figure 1 illustrates this spatio-temporal structure: early domesticates reached Greece by ca. 8600 ka BP. After a standstill of a few centuries, the spread of early farming occurred

Figure 1: Geostatistical interpolation of radiocarbon dates related to the spread of early farming across the Near East and Europe. Note that the interpolation for Egypt is solely based on a few dates from the Sinai, and therefore should be considered with care for the rest of the region.

along two axes across Europe, firstly along the northern Mediterranean coast and reaching the Iberian Peninsula by the mid 7th millennium before present (7.5 ka BP), and, secondly, along the Rhine-Danube corridor up to the Paris basin by the early 7th millennium before present (7 ka BP). After a long standstill in central and parts of continental NW Europe, the spread resumed once again by the early 6th millennium before present (6 ka BP), when the expansion happened into southern Scandinavia, Britain and Ireland.

Several factors affect these rates of dispersal. For instance, rapid extreme climatic episodes linked to the 8.2 ka BP "cold event" shaped the spread of farming in the southern Balkans (Krauss et al., in press), and Warden et al. (2017) have argued for a relationship between climatic amelioration and the introduction of farming in southern Scandinavia. Another approach lies in comparing radiocarbon dates to computational simulations of the diffusion process and associated parameters, especially the mean spatial dispersal rate, and population growth rate. Such recent models incorporate important geographic

features such as river valleys and coastlines and include the acceleration of the spread along them. These models also take into account the "slowing down" of dispersal related to high elevations and latitudes. The resulting simulations are shown to better match empirical data than simulations from earlier models (Silva and Steele 2014).

Agriculture and demography

The introduction of early farming in Europe is related to the inception of a new human population, and recent work points to the complex demographic history of Neolithic Europe. Fluctuations in population density have been inferred through statistical analyses of radiocarbon dates, assuming that the extent of past populations and their activities is reflected in the number of samples dated by archaeologists. Shennan et al. (2013) identified an apparent recurrent pattern of "boom-bust" (increases and decreases of the number of radiocarbon dates) in several regions of western Europe. The local introduction of farming corresponds to a rise in the radiocarbon record linked to demographic growth assumed from the

Figure 2: (A) Map of the earliest regional Neolithic zooarchaeological assemblages in the Adriatic basin. **(B)** Correspondence analysis for the sites on the map (circle: open air site; triangle: cave site).

introduction of farming; it is followed by a decline in the density of radiocarbon dates interpreted as a depletion of the population. In Britain and Ireland, fluctuations in the radiocarbon record match changes in vegetation cover, where the “boom” is related to deforestation, and the “bust” to woodland regeneration. This sequence occurs during worsening climatic conditions, and is associated with transformations in agricultural regimes, though the precise interplay between all factors is complex (Whitehouse et al. 2014; Woodbridge et al. 2014). It must be stressed that the identification, characterization and interpretation of these fluctuations remain debated. For instance, Silva and Vander Linden (2017) observed that the “bust” in one area sometimes matched the “boom” in the adjacent region during the spread, suggesting that the demographic depletion may also partly correspond to the outgoing migration of a fraction of the local population.

Describing farming variability

Less attention has been paid to land-use patterning in archaeobotanical and zooarchaeological assemblages, due to limited systematic sampling and reporting. Europe sees the introduction of cattle (*Bos taurus*), pigs (*Sus scrofa domesticus*), sheep (*Ovis aries*) and goats (*Capra aegagrus hircus*) and early Neolithic zooarchaeological assemblages present extensive variations in their respective proportions. Cattle and pigs dominate in central, northern and northwestern Europe, and sheep/goats in the Mediterranean (Manning et al. 2013). Multi-linear regression suggests that environmental factors account for 23–30% of the variation in domesticated animals and cultural factors for a further 10%, with the rest of the variation being left unexplained, at least at this scale (Manning et al. 2013). Indeed, these broad patterns mask extensive regional diversity. Figure 2 presents a correspondence analysis of

the earliest regional Neolithic zooarchaeological assemblages across the Adriatic basin. Neolithic sites in southern Italy and Dalmatia are dominated by sheep and goats. Their dominance gradually decreases in central and northern Adriatic in favor of more water-demanding cattle and pigs, mirroring the gradient in precipitation observed across the Adriatic (Gaastra and Vander Linden, in press).

Existing meta-analyses point to a gradual loss of diversity in plant domesticates, especially as farming spreads from the Balkans into Central Europe during the late 7th to early 6th millennium before present (7–6 ka BP; Colledge et al. 2005). As changes in environmental factors alone cannot account for this pattern, two alternative hypotheses are considered: either this narrower crop package corresponds to a cultural preference by early farmers, or is the outcome of neutral drift, a stochastic process linked to what is being transmitted within a small population undergoing expansion. Competing agent-based models indicate that both hypotheses cannot be rejected, leaving open the interpretation of this pattern observable in archaeobotanical data (Conolly et al. 2008; Pérez-Losada and Fort 2011).

Conclusion

The diffusion of early farming across Europe corresponds to the introduction of several plant and animal domesticates, and of a new human population. This process lasted nearly three millennia and comprised cycles of expansion and stasis. Meta-analyses of archaeobotanical and zooarchaeological records demonstrate large variations in the types of cultivars and domesticates in use, shaped by a combination of environmental, climatic, and human factors, which remain difficult to disentangle. This variety of rates of diffusion, associated demographic signals, and crop-domesticated animal packages

suggests likely significant differences in land use across the continent, and associated land-cover changes. Hopefully, future work will address the imbalance between the extensive efforts in analyzing and modeling radiocarbon dates, and the relative scarcity of similar approaches for in-depth analysis of plant and animal remains to improve the understanding of spatial and temporal patterning of animal and crop cultivation practices.

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Using archaeology for population estimates and land-use reconstructions: a perspective from Central Europe

Jan Kolář^{1,2}, M. Macek^{3,4} and P. Szabó¹

Estimation of past population dynamics on a regional scale over thousands of years is a difficult research task. We offer insights based on spatio-temporal modeling and discuss the significance of the archaeological evidence for population and land-use reconstructions.

The size and density of populations are among the most significant factors influencing the character of human-environment interactions, and, in combination with information on subsistence strategies, enable researchers to create a better picture of past land use. However, quantifying or estimating population size and density for the distant past is a challenging task.

Continental-to-global-scale land-use reconstructions based on archaeological data are important because historical land use affected land cover which, in turn, influenced global and regional climate (e.g. de Noblet-Ducoudré et al. 2012; Pongratz et al. 2010; see Editorial, this issue). However, the importance of large-scale archaeological data for paleoscience became widely recognized only recently (e.g. Ellis 2015; Gaillard et al. 2015).

Character of archaeological evidence and population estimates

Archaeology differs from many paleosciences with respect to the nature of the

data it can provide. Archaeologists usually focus on a few sites or specialize in one period, a few specific types of artifacts or methods of analysis. Thus, producing a chronologically long and continuous perspective on population or settlement dynamics presents an unusually complex task.

Several approaches have been used to produce population estimates based on information from archaeological data. One can work with absolute or relative assessments of past populations (Müller 2013). Absolute population estimates usually provide densities (persons per km²) and are related to environmental factors, such as carrying capacity, and ethnographical or archaeological data. Relative population estimates rely on the assumption that the amount of archaeological evidence directly reflects population size and density, although the values are not translated into absolute values. The prevalent technique to produce relative population estimates is the use of summed radiocarbon

probability distributions, which are based on radiocarbon dates of bones, wood or seeds from archaeological contexts (e.g. Bevan et al. 2017; Shennan et al. 2013; Timpson et al. 2014). Although the method is criticized for a diverse range of biases (e.g. financial situation of countries and national research funding agencies allowing for more analyses, research traditions and interests, past mobility and subsistence strategies; see Torfing 2015), it seems capable of providing valuable insights into the long-term history of human activities over large regions. The most important advantage of this approach is that it overcomes the common archaeological focus on specific sites or periods and produces quantified spatio-temporal models easily comparable with paleoenvironmental proxies that may cover thousands of years and large areas (Bevan et al. 2017).

Human activities and land use in the Holocene

The Czech Republic currently does not have sufficient numbers of radiocarbon

Figure 1: Human-activity model for Moravia (26,804 km²; Czech Republic) based on Monte Carlo simulations, classified according to the origin of activity.

dates to use these as the primary estimators of past population, but databases of archaeological sites and excavations are available for the entire area (Kolář et al. 2016a; Kuna et al. 2015). The data in these databases cover most of human history and can be used to model past human activities in both space and time.

Understanding the drivers behind and effects of past population dynamics is of high importance. This can be done only by producing archaeological results which are easily comparable with climatic or paleo-ecological proxies. Our region of interest is Moravia (the eastern part of Czech Republic), from which we collected data on all available archaeological sites and finds dated between 10,000 BCE and 1250 CE.

We analyzed archaeological evidence from 1685 modern civil parishes (basic administrative units), which contain records on 18,736 archaeological components characterized according to basic function (settlement, burial site, hillfort, traces, etc.). Spatial precision differs for all components (precisely located components vs. finds located only to the parish); we thus used the parish as the common spatial denominator. Temporal precision of the archaeological dating also varies. Some components have imprecise dates ("Neolithic-Eneolithic": 5400 BC-2000 BC for most non-diagnostic polished stone artifacts) while others have been dated to the nearest decade.

Adopting the relative approach to understand population dynamics in time, we used several modeling procedures (for details, see Kolář et al. 2016b). Monte Carlo simulations helped us to quantify the uncertainty in the temporal density of components. One thousand potential time series were simulated, where every archaeological component was assigned to a random single year from within its time span. We created a cumulative plot of these simulation runs for each dated component (Fig. 1). In Figure 1, the thickness of the data category envelopes indicates the temporal uncertainty for each category.

We see a rapid increase of archaeological evidence at the beginning of the Neolithic, which was connected with a change in lifestyle and the adoption of agriculture and animal herding. The subsequent period shows a decrease in evidence, which ends during the transition to the Bronze Age. This long-term quantified model of human activities can be readily compared to paleoecological and climatic models, as we showed in Kolář et al. (in press).

The spatial modeling of past human activities is based on parish occupancy likelihood, which is calculated as the proportion of simulation runs in which a parish was considered occupied (for details see Kolář et al. 2016b). These values were later interpolated with the natural neighbor method in a geographic information system (GIS). Land use comprising cereal cultivation and animal herding covered a much larger

Figure 2: Spatial patterns of human activities in Moravia in specific time blocks of Neolithic (5500-5000 BCE), Eneolithic (3500-3000 BCE) and Later Bronze Age (1500-1000 BCE).

extent at the beginning of the Neolithic, around 5500 BCE, than centuries later during the Central European Eneolithic (3500-3000 BCE; Fig. 2). Later in the Bronze Age, especially after 1500 BCE, human activities became much more intense, and human communities settled in most of the available lowlands.

What can archaeology offer?

Population estimates and land-use reconstructions based on archaeological data at a global level depend on the existence of specialized databases of radiocarbon dates or sites. The quality of available datasets varies regionally. The observed dynamics in archaeologically detected human activities most probably reflect population dynamics in general, but possible sources of bias must be acknowledged and addressed. The most significant qualitative and quantitative transformations of anthropogenic remains are caused by pre- and post-depositional taphonomic processes. The way people built their dwellings or buried their dead, the scale of erosion, and intensity of surveys and excavations all have an impact on available datasets. As such, we need to exercise caution in our use of these reconstructions. However, these diverse existing datasets and regional models, including knowledge about past existing social organization and farming technologies, can be incorporated into the assessment of past land use and population dynamics on a global level, enabling the study of relationships between environmental changes and social aspects of past populations.

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What do pollen-based quantitative reconstructions of plant cover tell us about past anthropogenic deforestation in Eastern China?

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Pollen proportions generally underestimate past open land cover in Eastern China. Pollen-based REVEALS reconstructions of plant cover in conjunction with archaeological and historical data provide more realistic descriptions of past anthropogenic deforestation than the scenarios commonly used by climate modelers.

We present here examples of pollen-based REVEALS (Sugita 2007) reconstructions of past regional plant cover in Eastern China (Fig. 1) to demonstrate the potential of such reconstructions to (i) answer questions on past land-use and related land-cover change, and (ii) produce more realistic reconstructions of past anthropogenic land-cover change that can be used in the study of climate-land-use interactions in the past. For instance, the scenarios of past anthropogenic land-cover change commonly used by climate modelers (Klein Goldewijk et al. 2011) were shown to diverge significantly from other ALCC scenarios for several periods of the Holocene and regions of the globe, among other for Eastern China (Gaillard et al. 2010). China is one of the key regions of the globe where agricultural

civilizations already flourished from ca. 7 ka BP and therefore plays an important role in land use-climate interactions over the Holocene. Pollen-based quantitative reconstructions of past land cover can be used to evaluate ALCCs (e.g. Kaplan et al. 2017). The REVEALS reconstructions presented here are part of a larger study within the PAGES' LandCover6k working group, covering temperate and northernmost subtropical China (Li 2016), and will be used to evaluate the existing ALCC scenarios in China.

Li (2016) uses the REVEALS model to estimate past regional plant cover from fossil pollen data with a standardized dataset of relative pollen productivity estimates (RPPs). Li (2016) groups several pollen records from

the same region (e.g. site group 3, 9, etc. in Fig. 2) following the strategy adopted for Europe (Trondman et al. 2015) to increase the reliability of the REVEALS estimates. The time windows follow the standard scheme of the LandCover6k project, i.e. modern (age of the peat or lake-sediment sequence's top) to 0.1 ka BP, 0.1-0.35, 0.35-0.7 ka BP, and continuous 500-year intervals from 0.7 to 11.7 ka BP. REVEALS estimates were calculated for the 31 taxa for which RPPs are available. Some plant taxa were then grouped into plant functional types (PFTs; Fig. 2), i.e. "temperate deciduous trees" (e.g. oak, ash, elm, linden) and "subtropical evergreen trees" (e.g. chinquapin, ring-cupped oak), and "other herbs and cultivated trees". PFT is a concept adopted by ecologists to represent broad groupings of plant species that share similar life forms and physiological mechanisms. In that sense, "other herbs and cultivated trees" is not exactly a PFT, but it rather groups all pollen types/plants that might have been part of human-modified vegetation due to agriculture. One of the dominant pollen types in this group is *Artemisia* (genus including up to 400 species in the world with diverse names such as mugwort, sagewort, wormwood, etc.). Chestnut and walnut are also included in "other herbs and cultivated trees" as species of both genera have long been cultivated in Eastern China, but walnut also grows in the temperate-deciduous woodland zone. The sedge family is included in the reconstruction, although plants from this family often grow locally at the study sites, which might be the case in site groups 9, 13 and 14.

Similar to Europe, herbaceous vegetation is strongly underrepresented in pollen percentages, and pine (*Pinus*) and birch (*Betula*) are overrepresented when compared with broad-leaved trees (Fig. 2). One taxon among herbs, *Artemisia* (see above), is strongly overrepresented by pollen. Therefore, in the cases where *Artemisia* is dominant in "other herbs and cultivated trees", the REVEALS estimated cover of total herbs or "open land" is lower than the pollen percentages, especially in site groups 3, 9 and 10 (Fig. 2).

Do decreases in total tree cover reflect anthropogenic land-use change?

Open land is not necessarily due to human activities and changes in its cover do not need to be human-induced. There are ways

Figure 1: (A) Location of the study region. (B) Location of the site groups used for the pollen-based REVEALS reconstructions presented in this paper (dark red circles). Black circles indicate the additional site groups used in the full study by Li (2016). Dark red stars: location of the archaeological sites mentioned in the text: (a) Hemudu/Tianluoshan; (b) Liangzhu; (c) Shangshan.

Figure 2: Comparison of pollen (left panel in each group of diagrams) with REVEALS estimates of plant cover, i.e. "vegetation cover" (right panel in each group of diagrams) in proportion for six site groups. "Temperate deciduous trees": ash, oak, linden, elm, rose family; "evergreen subtropical trees": chinquapin, ring-cupped oak, oleaster family, coffee family; "other herbs and cultivated trees": *Artemisia* (mugwort, sagewort, wormwood, etc.), hemp (*Cannabis*)/hop, buttercup family, aster/composite family, mustard family, pink family, amaranth/goosefoot families, morning glory family, legume family, mint family, lily family, knotweed/buckwheat family, chestnut tree and walnut tree.

to estimate the percentage of variation in pollen assemblages explained by, for example, climate versus human activities (Marquer et al. 2017), but these methods cannot extract the proportion of human-induced deforestation. Other lines of evidence such as archaeological and historical data syntheses are required to cross-check the interpretation of pollen-based land-cover change.

There is little change in wooded land cover over the Holocene in the southern part of the coniferous-deciduous mixed forest (II: site group 3). It suggests that human impact on the regional vegetation cover was weak except during the last 500 years, which the low number of archaeological evidence from this region also suggests. In the southern part of the temperate steppe zone (VI: site groups 9, 10), the total herb cover or "open land" (Fig. 2) increases at the expense of "woodland" from 6 ka (site group 10) and 4 ka BP (site group 9). Numerous archaeological sites in this region indicate widespread human activity during the Mid Holocene (Hosner et al. 2016), and foxtail millet and broomcorn millet remains suggest that domestication of crops started ca. 7.5 ka BP (Zhao 2014). The distinct increase in open land cover from ca. 6 ka BP can therefore be assigned to large anthropogenic deforestation, with losses of ca. 40% (site group 9) to ca. 70% (site group 10) woodland cover between 6 ka BP and recent time (1500–1800 CE), and ca. 30% (site group 10) to ca. 40% (site group 9) between 4 and 2.5 ka BP. The distinct decrease in total tree cover or "woodland" from ca. 2 ka BP in the coastal area of the temperate-deciduous woodland zone (III: site group 13) probably relates to the first peak in population numbers

at the beginning of the Han dynasty, 2.2–1.98 ka BP (Twitchett and Loewe 1995).

In the northern part of the subtropical broadleaved evergreen and deciduous woodland zone (IV: site groups 14, 16), a clear increase in open land occurs from 6.5 and 7.5 ka BP in site groups 14 and 16, respectively. The reconstruction from site group 14 (5 sites) is problematic for the time period 7.5–5.5 ka BP due to differences in timing of land-cover change between the sites or, more likely, problems of chronology for one or several sites. It is not possible, therefore, to date with certainty the age of the first loss in woodland cover (ca. 20–25%) in the area from this reconstruction. The earliest date would be between ca. 7 and 6.5 ka BP and the younger date between ca. 6 and 5.5 ka BP. A woodland-cover loss of ca. 15% occurred between ca. 1.5 and 1 ka BP. The reconstruction from site group 16 shows a woodland-cover loss of ca. 35% between 6 and 4 ka BP and ca. 30% between 3.5 and 3 ka BP. Pollen, charcoal and phytolith evidence at three archaeological sites in the lower Yangtze River region (Fig. 1) suggest that human influence started around 7 ka BP, substantial human impacts occurred at 4.7 ka BP, and widespread human activities expanded around 2.8–2.2 ka BP (Atahan et al. 2008). Site group 14 is located close to the archaeological sites Shangshan (dated to ca. 10 ka BP), Hemudu/Tianluoshan (7.5–6 ka BP), and Liangzhu (5.2–4.3 ka BP) (Fig. 1). Evidences from the Shangshan site suggest the use of rice by humans, but whether it is domesticated or wild rice is not clear. Evidences from the Hemudu and Tianluoshan sites indicate a transition process from domestication ca. 7.5 ka BP to cultivation ca. 6 ka BP, while the

findings at the Liangzhu site suggest a rapid development of rice agriculture around ca. 5 ka BP (Zhao 2010). The latter supports the pollen-based evidence of a significant early deforestation from ca. 6 ka BP (possibly earlier but not older than ca. 7 ka BP) and a subsequent increase of woodland loss over the Mid- and Late-Holocene (from ca. 6–5.5 ka BP).

The examples above demonstrate the potential of pollen-based REVEALS reconstructions of past plant cover in conjunction with archaeological and historical data to quantify woodland loss due to deforestation over the Holocene. These reconstructions show good agreement with syntheses of archaeological studies indicating that humans transformed the landscapes of central-eastern temperate and northern China since ca. 7 ka BP, with substantial increases of the number of archaeological sites recorded after ca. 7 ka BP and between ca. 4.5 and 3 ka BP (e.g. Wagner et al. 2013; Wagner and Tarasov 2014). The REVEALS reconstructions also suggest that the HYDE 3.1 scenarios of Holocene anthropogenic land-cover change (Klein Goldewijk et al. 2011) commonly used in climate modeling strongly underestimate the degree of past anthropogenic deforestation in eastern temperate and northern subtropical China.

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Finding the magnitude of human-induced Northern Hemisphere land-cover transformation between 6 and 0.2 ka BP

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A spatially explicit pollen-based reconstruction of Northern Hemisphere land cover suggests open land increases of 10 to 100% across large parts of the study area over the period 6 and 0.2 ka BP. This change may have influenced past climate.

The quantification of feedbacks and forcings from the terrestrial biosphere onto past and future climate requires Earth system modeling studies that make use of well-constrained descriptions of past vegetation cover (henceforth land cover) and land-use change (Harrison et al.; Gaillard et al., this issue). Most efforts to map past vegetation on a continental to global scale are based on pollen percentages or pollen-based qualitative biome reconstructions. The growing availability of community-supported pollen-data repositories, improved radiometric dating precision, novel age-depth modeling approaches, pollen-vegetation model developments, and new statistical techniques have facilitated the development of highly resolved estimates of hemispheric-scale late Quaternary land-cover change. Spatially explicit regional land-cover reconstructions using pollen preserved in sedimentary archives can be achieved with mechanistic pollen-vegetation models, a kind of proxy system model that describes the processes governing pollen production, transport, and

deposition from vegetation to sedimentary archives.

New generation vegetation reconstructions

The PAGES LandCover6k working group (Gaillard et al., this issue) used established methods and comprehensive pollen and vegetation datasets to develop global Holocene (the last 11.5 millennia) reconstructions of land-use and land-cover change. More specifically, the working group focused on time periods commonly targeted by Earth system modelers (Harrison et al., this issue): e.g. 6 and 0.2 ka BP. Preliminary results for the Northern Hemisphere (NH) demonstrate the potential of pollen-based land-cover products in the assessment of anthropogenic land-cover change scenarios (e.g. KK: Kaplan et al. 2009; HYDE: Klein-Goldewijk et al. 2017), and for quantifying climate forcings due to past land-use change. Figure 1 shows the first hemispheric-scale land-cover reconstruction based on a mechanistic pollen-vegetation model; the

model used here is known as REVEALS (Sugita 2007). These preliminary results precede and guide the publication of a more comprehensive description of methods and results.

REVEALS can account for inter-taxonomic differences in productivity, dispersal, and deposition of pollen taxa in sedimentary basins (Sugita 2007) and estimates plant abundance on a regional spatial scale (2.5–10³ km²) in percentage cover or m²/m² using sedimentary pollen records. REVEALS also provides standard errors (SEs) of plant-cover estimates (Fig. 2). The reported SEs account for component errors within the relative pollen-productivity estimates (RPPs) of the represented pollen taxa and the variation among pollen records used in the reconstruction (Sugita 2007). REVEALS has been validated in several regions of Europe (e.g. Hellman et al. 2008) and North America (Sugita et al. 2010), i.e. pollen-based REVEALS estimates of plant cover based on modern pollen assemblages from surface lake deposits are comparable to plant cover inferred from satellite data, air photographs and vegetation inventories. The REVEALS approach is increasingly used to develop regional-scale land-cover reconstructions, but so far much of that effort has focused on Europe (e.g. Trondman et al. 2015). Land-cover estimates from REVEALS have also been compared to other methods. For example, Roberts et al. (2018) show that REVEALS-based past European land-cover reconstructions differ significantly from those of other pollen-based methods for large parts of the Holocene (Woodbridge et al., this issue). Kaplan et al. (2017) demonstrate that the KK scenarios of European Holocene deforestation are closer to REVEALS estimates of open-land cover than the HYDE scenarios version 3.1.

REVEALS requires several input variables that are not typically needed for other types of paleovegetation reconstructions, including lake or bog size, RPPs, and fall speed of pollen; this information may be missing in legacy data. LandCover6k has led an international effort to gather the relevant knowledge and data for this new generation of land-cover reconstructions. The methodological protocol used follows Mazier et al. (2012) and Trondman et al. (2015). Reconstructions are grid-based (1° × 1° which is the approximate spatial scale of REVEALS reconstructions) and use all appropriate lake- and bog-pollen records available within each grid cell. Pollen records are selected according to criteria

Figure 1: Northern Hemisphere (>40°N) mean fractional land cover for open land, summer-green, and evergreen trees for 6, 0.2ka BP, and the difference between 6 and 0.2 ka BP. Land-cover estimates were generated from site-level pollen records using the REVEALS model and aggregated to 1° × 1° grid cells. The standard errors (SEs) are not shown in this figure for readability (see Fig. 2).

Figure 2: Fractional evergreen cover for 0.2 ka BP (red indicates high cover, see color scale) and reconstruction uncertainty expressed as coefficient of variation (CV; circles; the largest circle corresponds to a $SE \geq \text{mean REVEALS estimates}$, i.e. estimate not different from zero).

including chronology quality, time resolution and pollen-count size. Pollen data was obtained from the European Pollen Database (EPD), Neotoma Paleoeological Database (<http://neotomadb.org>), and other pollen data archives. This synthesis uses multiple RPPs for a total of 45 plant taxa/pollen morphological types. These RPPs are compiled from Calcote (1995), Commerford et al. (2013) and Prentice and Webb (1986) for northern United States, Canada, and Alaska (23 taxa; Dawson et al. unpublished); Mazier et al. (2012; 25 taxa) for Europe; Cao et al. (unpublished; 27 taxa) for Siberia; and Li et al. (2017 and unpublished, 25 taxa) for China. The REVEALS estimates shown here (Fig. 1 and 2) are for the time periods 0.1–0.35 ka BP (0.2 ka, i.e. end of the Little Ice Age, high deforestation) and 5.7–6.2 ka BP (6 ka; low deforestation). The width (i.e. resolution) of the time windows follows Trondman et al. (2015) and ensures that pollen counts are large enough to obtain REVEALS estimates with low SEs. The obtained REVEALS estimates (and their SEs) for the individual plant taxa were grouped into three land-cover types: evergreen trees, summer-green trees, and open land[§].

Land-cover transformation between 6 and 0.2 ka BP

This synthesis of NH land cover at 6 and 0.2 ka BP (Fig. 1) highlights stability (green color, $\pm 10\%$) or regional increases (red colors, $>10\%$) in evergreen trees (ET) in Europe (Finland and Sweden), southern Siberia, western Cordillera, and northeastern regions of North America. However, ET decreased across portions of Siberia, subarctic Canada, and Scandinavia (blue colors, $<-10\%$). Summer-green trees (ST) decreased (blue colors, $<-10\%$) most significantly in Europe; they also occur in other regions of the NH (North America, Canada, Siberia, western China) where either open

land or evergreen trees increased (green, with up to 10%, to red colors). Open land (OL) increases are evident and largest in Europe, and also occur in south-central and eastern Siberia, and northwest China. In North America, OL decreased in the eastern Great Plains, with less pronounced and localized OL increases in both western and eastern North America.

These patterns of OL increases reflect both extrinsic forcing by humans and climate and intrinsic forest processes. Further integration with paleoclimatic and archeological data is needed to disentangle these influences. Regardless of the cause, changes towards more open landscape may have affected both the global and regional climate. For example, climate modeling experiments using a regional climate model in Europe demonstrated biogeophysical forcings on climate from anthropogenic land-cover change between 6 and 0.2 ka BP of ± 0.5 – 1.0°C , with the sign and size of the forcing varying by geographical location and season (Strandberg et al. 2014). Other experiments suggest that early anthropogenic land use in Mesoamerica (ca. Late Classic Maya Period, ca. 1.7–1.05 ka BP) may have decreased summer precipitation by 10 to 20% (Cook et al. 2012).

Improving dynamic vegetation models

The Landcover6k REVEALS syntheses will be of interest to many researchers, but they are primarily designed to support modeling studies of vegetation-atmosphere-anthropogenic feedbacks in the past. The REVEALS estimates will be compared to and integrated with the history-archaeology-based LandCover6k land-use mapping (Gaillard et al., Morrison et al., this issue). These syntheses will be used to evaluate and improve both land-cover and land-use descriptions that are implemented

in Earth system modeling, in particular in the next phases of the PMIP (Paleoclimate Modelling Intercomparison Project; Harrison et al. and Stocker et al., this issue). Current work is focusing on the development of new methods that allow for reconstructions with more complete spatio-temporal coverage and which more explicitly account for uncertainty in the data (e.g. age-depth model uncertainty) and processes (e.g. dispersal and differential production). This explicit treatment of uncertainty, combined with recent advances in data assimilation, allows for the integration of quantitative land-cover estimates and dynamic vegetation models to move towards improved ecological and climate forecasting.

[§]**Evergreen trees:** fir, spruce, pine, hemlock, juniper, other species of the cypress family; **summer-green trees:** larch, alder, birch, hornbeam, hazel, beech, ash, aspen/poplar, oak, linden, elm, chestnut (if growing as forest), willow; **open land:** heather, pink family, chestnut (if growing in cultural landscapes), walnut, amaranth/goosefoot family, ragweed, mugwort, other species of the daisy family, cabbage family, cannabis/hop, bindweed, sedges, legume family, meadow sweet and other species of *Filipendula*, mint family, lily family, grasses, knotweed family, ribwort plantain, hoary plantain, common plantain and other plantain species, buttercup family, rose family, common sorrel/sheep's sorrel and other sorrel species, rye, and other cereals.

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The PAGES Early-Career Network

PAGES ECN Steering Committee¹

PAGES
EARLY-CAREER NETWORK

Early-career researchers (ECRs) bring fresh and novel ideas that have the potential to contribute to existing knowledge and challenge established paradigms. Intense competition in the current job market coupled with challenges such as establishing a professional identity, competing for grants, and choosing an independent career path are leading to a small success rate of ECRs within academia. Therefore, the greater scientific community is missing out on new research ideas, concepts and collaborations when ECRs are lost through the academic bottleneck effect. So how can we maintain a pool of strong-minded ECRs in academia?

One possible answer is establishing a supportive network of researchers that are at the same stages in their careers. So, to facilitate the career of ECRs, the PAGES Early-Career Network (ECN) was created. This idea was first discussed in 2017 at the 3rd Young Scientists Meeting (YSM) in Morillo de Tou, Spain, and resonated with a group of enthusiastic participants. Nested within the PAGES and Future Earth communities (Fig. 1), the goal of the PAGES ECN is to aid in the dissemination of information, establish scientific networks, and foster the development of ideas that can lead to future research collaborations and improved job prospects. Developed by early-career researchers for early-career researchers, the overarching aim of the PAGES ECN is to facilitate the exchange of ideas and skill sets that will provide the tools necessary for researchers to excel in their fields.

The PAGES ECN will achieve this aim by creating a skills database platform where ECRs will be able to meet and share experiences and create ideas for new research and international collaborations. Additionally, the PAGES ECN will foster career development and improve skill sets of ECRs via webinars and training events that will be tailored to the needs of the network participants. The PAGES ECN will promote education and outreach to disseminate scientific ideas to a wider audience and improve the visibility of ECRs in the scientific community by collaborating with other early-career networks.

The interactiveness of the PAGES ECN means any member can participate and work alongside the steering committee, and contribute to the organization of webinars and workshops, as well as participate in outreach events such as the ECN blog and social media platforms. We also seek participation among active members who are interested in acting as regional ECN representatives to facilitate the global integration of ECRs into the wider scientific community. To

Figure 1: Structure of the PAGES ECN within the PAGES and Future Earth communities.

strengthen the position of ECRs within the PAGES community, members of the ECN steering committee will work with PAGES working groups to nominate a liaison person between them.

Visit the PAGES ECN website <http://past-globalchanges.org/ecn>, where you can also sign up to become a member. Also subscribe to the mailing list to keep up to date with our activities. ECRs are encouraged to contribute to The Early Pages blog (<https://theearlypages.blogspot.ch>). You may also contact the PAGES ECN at pages.ecn@gmail.com and follow us on Twitter (@PAGES_ECN) and Facebook (www.facebook.com/PAGES.ECN), and watch our videos on our Youtube channel (https://www.youtube.com/channel/UCnDs_RxOvXZ3nGG6Omm16qA).

Activities

One month after the network's February 2018 launch, the committee organized a pair of webinars entitled 'Welcome to the PAGES ECN' to introduce the group to the PAGES and paleoscience communities. The first

in-person meeting of the PAGES ECN was held at the European Geosciences Union (EGU) meeting in Vienna, Austria, in April 2018. During this splinter meeting, we also introduced the PAGES ECN to interested ECRs. The main goal of this meeting was to exchange directly with other ECRs, get feedback and ideas about this new network, and encourage future collaboration. Future activities will be posted on the website, Twitter and Facebook.

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Phasing of ice-sheet and sea-level responses to past climate change

P A L S E A

Alexandra Skrivane¹, M.R. Sandstrom² and J. Shakun³

Playa del Carmen, Mexico, 6-9 November 2017

The exquisitely exposed Last Interglacial (LIG) fossil coral reefs in the Yucatan Peninsula, Mexico, served as the backdrop for the fifth and final meeting of the PALSEA2 (PALEO constraints on SEA level rise 2) working group (Fig.1). The workshop highlighted current research on ice-sheet and sea-level changes, addressed critical gaps in field observations, and assessed the current knowledge regarding causes, rates, and mechanisms of sea-level and ice-sheet dynamics during past warm periods.

The five-day program (<http://pastglobalchanges.org/ini/wg/palsea2/meetings/127/1715>) included 29 presentations, several group discussions, a poster session, and field excursions to fossil reefs at Xcaret and limestone caves at Rio Secreto. A major theme was the need to combine existing paleo sea-level and ice-sheet databases into a centralized global compilation with a streamlined user interface. Standardizing, interpreting and assessing the quality of field data were discussed as key components for integration and application by the modeling community. For example, participants considered how sample elevation does not necessarily equate to relative paleo sea level, and the need for clear, systematic descriptions explaining interpretations in paleo databases. Talks explored complications of interpreting sea level from fossil reefs, where accretion is often determined by storm deposition of coral rubble.

Participants also examined the quantification of uncertainty due to glacial isostatic adjustment (GIA) on global sea-level signals in order to reconcile peak LIG sea-level reconstructions. Discussions focused on GIA uncertainty stemming from ice-sheet configurations and 3D Earth-model parameters, as well as the need for additional paleo sea-level data. Suggestions included targeting near-to-intermediate field regions sensitive to GIA, such as the Bahamas, to limit possible ice-sheet configurations, developing adjoint framework methods to efficiently estimate GIA-model parameters, and applying 3D GIA Earth models to investigate model error associated with lateral viscosity variations.

Presentations emphasized the importance of understanding glacial ice-sheet volume and spatial extent prior to the last glacial cycle, which determines GIA effects on LIG sites. New cosmogenic nuclide and sediment provenance techniques have the potential to constrain these glacial ice extents over million-year timescales to orbital timescales, respectively.

Dynamic topography due to mantle convection could have significant effects on the elevation of paleo sea-level indicators, but has substantial vertical uncertainty, leading participants to recommend that larger uncertainty bounds be placed on the current assessment of the peak LIG highstand at 6-9 meters above present global sea level (Dutton et al. 2015). This assessment is consistent with a new, far-field LIG peak sea-level reconstruction from fossil reefs exposed in the Seychelles. Resolving sub-millennial sea-level excursions from LIG deposits remains difficult, considering the vertical uncertainties and complex effects of post-depositional alteration on the interpretation of coral ages. The workshop highlighted new developments regarding the potential for stable oxygen-isotope records from polar ice cores to provide additional constraints on the timing and rate of LIG ice-sheet variability.

Pliocene sea level remains a topic of interest as atmospheric CO₂ concentrations were similar to modern values, but constraining global sea level from paleo-shoreline observations and marine geochemical proxies is challenging in light of dynamic topography and diagenesis. Presentations featured a new record of Mid-Pliocene sea-level fluctuations from offshore of New Zealand that offers insight into the pacing and magnitude of ice-sheet variations during this warm period.

Lastly, reconstructions of Holocene ice-sheet stability continue to be refined via multi-proxy

and data-model comparisons as well as the detailed study of coral microatolls. A recent compilation of late-Holocene relative sea-level data and advances in statistical modeling of relative sea-level indicators can support the investigation of factors influencing Holocene sea-level change.

Long-term objectives include improving consistency across the various scientific disciplines in terms of quantifying model accuracy and uncertainty, and endorsing transparency and open-source records for modeling and data acquisitions.

We thank PALSEA2 workshop organizers, namely, Andrea Dutton, Anders Carlson, Glenn Milne, Antony Long and Paul Blanchon, and the supporting organizations: Past Global Changes (PAGES) and the International Union for Quaternary Research (INQUA).

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Figure 1: Last Interglacial fossil reefs at Xcaret, Mexico. Image credit: Alexandra Skrivane¹.

Understanding and modeling space-time Holocene climate variability

Thomas Laepple¹, R.V. Donner² and T. Kunz¹

Potsdam, Germany, 25-27 October 2017

PAGES' Climate Variability Across Scales (CVAS) working group aims to develop a thorough understanding of the mechanisms underlying climate variability across temporal and spatial scales. A specific focus lies on centennial to millennial timescales, where the variability observed in paleoclimate archives cannot be exclusively explained by a linear response to external factors, like solar variability or changes in orbital parameters, but exhibits a rich variability across a broad range of scales. In this context, the first CVAS workshop in fall 2016 (Franzke 2017) identified an existing knowledge gap regarding the scaling regimes of climate variability during the Holocene and the associated differences between tropics, extratropics and polar regions, as well as between land and ocean.

The purpose of the second CVAS workshop, held at the Potsdam Institute for Climate Impact Research, was to specifically address these aspects to characterize Holocene climate variability in both space and time (Fig. 1). With relatively stable climate conditions similar to present-day, the Holocene constitutes a unique reference period for studying temporal scaling properties based upon a variety of paleoclimate archives, together with

reconstructions of key climate forcing factors like solar irradiation and volcanic activity.

With generous financial support from PAGES, the Alfred Wegener Institute Helmholtz Center for Polar and Marine Research, and the German Federal Ministry for Education and Research, the meeting brought together 41 scientists, including 25 early-career researchers, working on Holocene climate variability from three distinct perspectives: data acquisition and interpretation, development and application of time-series analysis methods, and theoretical climatology and climate modeling.

The first day comprised plenary talks introducing the state of the art along with key open challenges in the field. These overview presentations and accompanying panel discussions set the stage for forming three breakout groups:

Data - how to select the best archives to quantify climate variability and understand their caveats

The data group summarized key properties of the major climate archives concerning potential time-scale dependencies in the proxy-to-climate relationship and the time-scale

dependencies of non-climatic effects on the recorded signal. It further identified key areas and datasets that provide good starting points to characterize the spatial and temporal scaling of climate variability.

Analysis tools - from paleo-observations to robust and reproducible variability estimates

The subgroup on analysis tools identified a suite of traditional as well as unconventional methods for studying temporal and spatial scaling in paleoclimate archives and discussed conceptual and practical limits of the existing methods. Particular attention was paid to the challenge of unevenly sampled and "gappy" data and possible ways to overcome existing methodological limitations, triggering some joint research efforts among different members of this subgroup.

Models and theory - origins and interpretation of the space-time structure of Holocene climate variability

The model and theory subgroup discussed possible mechanisms that may generate centennial to millennial scale variability and shape its temporal and spatial structure, summarized existing theoretical concepts to describe and understand such fluctuations, and then formulated working hypotheses in order to focus ongoing research efforts. The subgroup also emphasized the necessity to communicate to the data subgroup the specific data requirements for testing and selecting different theoretical hypotheses.

Following the discussions within the subgroups and in the panel, initiatives have been started to systematically summarize the current state of the art in upcoming review papers. Another outcome of these discussions was a dedicated CVAS session and short course at the General Assembly of the European Geosciences Union in Vienna, Austria, in April 2018.

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Figure 1: Space-time spectrum of simulated Holocene temperature variability. Global 2 m temperature anomaly fields from the last 7000 years of the TraCE-21ka paleoclimate model simulation (Liu et al. 2009) have been decomposed into spherical harmonics; the annual cycle has been removed. The power spectral density generally increases towards longer spatial and temporal scales.

Enhancing global monsoon research in ocean drilling

Pinxian Wang

IODP-PAGES Workshop, Shanghai, China, 7-9 September 2017

Between 2013 and 2016, seven deep-ocean drilling expeditions were completed by the International Ocean Discovery Program (IODP) to explore the Cenozoic history of the Indian, East Asian and Australian monsoons. If the former Ocean Drilling Program (ODP; 1983-2003) cruises are included, the drilling activities covered the African and American monsoons regions as well (Fig.1). To further promote paleo-monsoon researches, 48 scientists from 12 countries attended the IODP-PAGES workshop on "Global Monsoon in Long-term Records". Co-chief scientists of the IODP/ODP monsoon-related expeditions presented their scientific findings, discussed the research directions and made recommendations for the future IODP science program.

The workshop started with presentations given by members of the former PAGES Global Monsoon working group. Traditionally, the variability of the monsoon has been studied almost exclusively on regional scales. With the application of remote sensing and other new techniques since the last decade, the concept of the Global Monsoon has been introduced as a global-scale seasonal reversal of the monsoon circulation associated with the Inter-Tropical Convergence Zone (ITCZ) migration. PAGES established the "Global Monsoon and Low-Latitude Processes: Evolution and Variability" working group in 2007. The working group conducted two successive symposia in 2008 (Wang et al. 2009) and 2010 (Wang et al. 2011), published a special issue in *Climate Dynamics* (Wang et al. 2012) and two synthesis papers (Wang et al. 2014, 2017).

A number of questions were discussed during the workshop, such as the applicability of the Global Monsoon concept at geological time

scales, monsoon response to external forcing and internal feedback, initiation of the current monsoon systems, the use and misuse of monsoon proxies, and the role of monsoon in global climate system. After extensive discussions, workshop participants recommended that global monsoon and its role in the hydrological cycle should be incorporated in the IODP Science Plan beyond 2023.

Although monsoon precipitation accounts only for one third of the modern global total rainfall, its spatial-temporal variation is the most mutable component in the global hydrological cycle. Together with ENSO and trade winds, global monsoon comprises a major low-latitude component of the world climate system, and thus may provide a key to understanding the controlling factors of the hydrological cycle.

The workshop stressed the value of *deep-time monsoon in high resolution records*. Despite prominent progress in generating high-quality records over the past decade, the majority of high-resolution paleo-monsoon records remains restricted to the late Quaternary, with only a limited number of sediment sequences at several IODP sites tracing back beyond the Pliocene. A much longer time coverage is urgently needed to reveal the monsoon changes at the Hot- to Ice-House transition, and the tectonic background of when and how the modern monsoon systems established.

Another topic of discussion was *monsoon proxies*. Chemical and isotopic proxies have been extensively and successfully used in paleo-monsoon reconstructions, but opinions on their interpretation are divergent. Scientific debates call for further calibration of the

current proxies and for development of new proxies, especially those indicative of the global monsoon. As many scientists working in monsoon regions tend to interpret all variance in the context of monsoon circulation, it is essential to discriminate the component of climate changes related from those unrelated to monsoon variations.

Workshop attendees also called for an *extension of the geographic coverage of ocean drilling*. The existing deep-sea monsoon records are heavily biased towards the Northern Hemisphere. High-resolution pre-Quaternary records from the Southern Hemisphere, including monsoon areas off South America, Australia and South Africa, are urgently needed. It is also expected that future targets of paleo-monsoon studies will continue to have a strong focus on margin environments, requiring improvements of international political relationships required to gain access to these regions.

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Figure 1: Map showing all IODP/ODP monsoon-expedition coring sites.

Paleofire knowledge for current and future ecosystem management

Olivier Blarquez¹, P. Grondin² and the GPWG2

Montreal, Canada, 10-14 October 2017

In the past year, fires raged in different places around the world and their impacts on human lives, livelihoods and infrastructures were unprecedented. The long-anticipated effects of ongoing global changes on fire dynamics are now a reality, and have consequences on the functioning of ecosystems themselves, including, among others, loss of resilience, exceeding known range of fire regime variability and burning of ecosystems for which fire was supposedly absent. For example, the length of the California (USA) fire season in 2017 almost doubled, with fires blazing as late as December, and large fires developed in the Greenland tundra where they are unprecedented. Those unusual events modified the global carbon cycle and aerosol emissions, threatened human lives and infrastructures and, associated with climate change, may decrease ecosystem resilience (Stevens-Rumann et al. 2017). In this context, researchers, landscape managers and decision-makers from across the planet are being challenged to reintegrate natural disturbance processes into ecosystem management plans.

PAGES' Global Paleofire Working Group 2 (GPWG2) organized a workshop which aimed to gather paleofire experts and stakeholders, including governmental agencies, in order to assess the use of long-term fire history for future fire and ecosystem management. Twenty-three participants from 10 countries at all career stages presented their research and worked together on strengthening the links between management and paleofire research.

Before the workshop, each participant was asked to contact a stakeholder, manager or decision-maker from their country of origin to survey their knowledge and interest in paleofire research using a questionnaire that was prepared by the workshop organizers. Several challenges in engaging stakeholders and interesting them in paleofire research emerged from the questionnaire answers and were discussed. Although the use of paleofire records for future ecosystem management has been the topic of several recent studies (e.g. Gillson and Marchant 2014; Girardin et al. 2013), paleofire knowledge is rarely translated into effective management tools and tends to remain a purely theoretical discipline.

Better communication between paleoecologists and managers thus appeared to be the first goal to achieve - but several challenges remain, such as avoiding the use of jargon

Figure 1: Lac Geai (Canada) surface sediment sampling with an Eckman sampler used to take the first sample for the Global Modern Charcoal Dataset (GMCD) initiative (Hawthorne et al., in press). Image credit: Katarzyna Marcisz.

and using a common vocabulary. These points crucially require the calibration of paleoecological data that could translate past ecological processes into more measurable units (Hawthorne et al., in press). Currently the Global Charcoal Database (GCD, <http://paleofire.org>) and associated R paleofire package (Blarquez et al. 2014) only gather information on raw charcoal data, which are not directly useful to stakeholders. The development of new products associated with the GCD, such as a database of fire return intervals or other fire regime metrics calculated upon raw GCD data, has the potential to increase paleofire data use for management and will enhance the visibility of the discipline.

While necessary, this is, however, probably not sufficient and the questionnaire highlighted the need for strengthening partnerships between stakeholders and scientists. Co-design of research is starting to emerge in the geoscience field (Vano et al. 2017) and should contribute to make science more useful for communities and future ecosystem management. Several outcomes and products of the Montreal workshop will help paleofire science to follow that trend. There will be (i) the edition of a glossary that will merge terminologies used in paleofire science,

ecosystem management and decision-making, and (ii) an updated questionnaire, which will be shared more broadly, to enable scientists to more effectively communicate with local actors and start new partnerships. The development of new methodological tools, such as improved calibration and interpreted past fire metrics from the GCD, will permit (iii) a better communication of paleofire knowledge via open source tools and data (See <http://paleofire.org> for details).

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Understanding the roles of fuels, climate and people in predicting fire: taking the long view

Robert D. Field^{1,2}, K. Fernandes³, K.C. Glover⁴, W.D. Hansen⁵, J. Rabinowicz⁶ and A.P. Williams⁷

New York, USA, 23-25 October 2017

The Conference on Fire Prediction Across Scales was held at Columbia University in New York, drawing over 120 attendees from academia, government and the private sector. Input from fire managers enhanced awareness among the fire modeling and paleo communities of the real-world importance of better understanding the drivers of changes in fire activity for safety and land management. The meeting was unique in connecting researchers studying fire prediction at all scales, from the behavior of a flame, to a single wildfire, to changes in global fire patterns from year to year. And, necessarily, to changes in fire over centuries and millennia. The paleofire aspects of the meeting covered advances made in obtaining, synthesizing and interpreting charcoal records from lake sediment and burn scars in tree rings.

David Bowman (U. Tasmania, Australia) described the recent fire-driven loss of *Athrotaxis* in Tasmania after a dry spring. In trying to understand the degree to which anthropogenic climate change was a factor, Bowman noted that Tasmania's highly variable fire climate makes climate-change attribution particularly challenging. The paleoecological record provides considerable insight, however, indicating strong El Niño-driven *Athrotaxis* losses during the late Holocene, serving as a long-term analogue for interpreting current fire regime changes. In New Zealand, Jed Kaplan (U. Oxford, UK) described simulations of vegetation cover over the past thousand years, suggesting Maori arrival as a likely explanation for fire-driven forest loss

evidenced in charcoal and pollen records. Further work is needed to consider the climatic influence, given that the Maori arrival was preceded by a possibly confounding Medieval Warm period signal over New Zealand.

In the southwestern US, Rachel Loehman (USGS, USA) examined impacts of human activity on fire regimes over 1200-1900 CE in the Jemez region of New Mexico. Using process-based modeling, Loehman explained how high population densities, intensive agriculture, and fuelwood harvesting could contribute to a 25-fold increase in fire activity, but offset by smaller individual fires on a more fragmented, shrub-dominated landscape. Katherine Glover provided the longest time-scale perspective of the conference, presenting charcoal and pollen data from the San Bernardino Mountains in southern California over 120,000 years from two lake cores. These data are unique in their potential to understand interactions between climate, fire and vegetation cover before the arrival of people.

Jennifer Marlon (Yale U., USA) provided a global perspective, updating on recent activity from the PAGES Global Paleofire Working Group, including the latest (v4) Global Charcoal Database (Fig. 1). Marlon emphasized that, globally, there are pronounced relationships between climate and fire, which can be decoupled by human intervention. Over the western US, for example, a 100-year history of aggressive fire suppression has led to a decrease

in fire activity relative to that expected from observed climate records. This has resulted in a "fire deficit" that has enhanced the response of fire activity to intensified fire weather in recent decades.

Attendees identified important areas where progress can be made. There is a need for more data over under-sampled regions, namely Africa and eastern Eurasia. Glover and Marlon identified a specific need for short cores sampled at high resolution to improve comparisons between paleo and contemporary fire records. Interpreting the paleofire record will also benefit from progress made in regional climate reconstructions such as those from the PAGES 2k Network (pastglobalchanges.org/ini/wg/2k-network), and from longer-term climate simulations, such as the Last Millennium Ensemble from the Community Earth System Model (CESM) Paleoclimate Working Group (www.cesm.ucar.edu/working_groups/Paleo).

Overall, conference attendees working mainly on contemporary fire issues were provided a window into the potential for using the paleofire record to provide context for the contemporary record, take the "long-view" in fire management planning, and to make predictions of future fire activity. The full program and presentation abstracts can be found at the Columbia University Initiative on Extreme Weather and Climate website (<http://extremeweather.columbia.edu/events/past-events/2017-conference-on-fire-prediction-across-scales>).

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Figure 1: Distribution of charcoal records for successive versions of the Global Charcoal Database (courtesy of Patrick Bartlein and Jennifer Marlon). Data are available from the PAGES Global Paleofire Working Group at www.paleofire.org.

Climate change in Africa: Evidence, mechanisms and impacts - Past and present

Rachid Cheddadi¹, I. Bouimetarhan², M. Carré³, A. Rhoujjati⁴, A. Benkaddour⁴ and M. Nourelbait¹

Marrakesh, Morocco, 6-11 November 2017

Climate changes in Africa have a tremendous impact on ecosystems and human societies. Climate change-related risks are aggravated in Africa by the deficient data availability and research efforts which create major knowledge gaps and uncertainties.

In an attempt to build synergy and promote climate change research in Africa, the multi-disciplinary conference CCA2017 (Climate Change in Africa, vulpesproject.wix.com/workshop) was organized at the Cadi Ayyad University of Marrakesh.

The primary goal was to gather scientists from complementary disciplines including Earth sciences, (paleo-)oceanography, (paleo-)climatology, climate modeling, ecology, and archaeology, for a multidisciplinary assessment of the latest results and to start discussions related to climate change and its

impacts, from past natural variability to modern changes and future projections.

CCA2017 was attended by 80 delegates from 20 countries including eight African countries (Algeria, Benin, Cameroon, Congo, Morocco, Senegal, South Africa and Tunisia). Travel support was offered by PAGES for three African early-career scientists who presented their work in both posters and oral presentations. The conference consisted of five sessions: (1) on climate change mechanisms in Africa including links between orbital forcing and inter-annual rainfall variability, extreme precipitation over Africa, dust fluctuations during the African Humid Period, predicting the Sahel summer rainfall, and the variability of the West African monsoon; (2) dedicated to the climate impacts on eco- and agro-systems. This session gathered presentations on the cultural resilience of the

NE Sahara facing problems of surface water storage, the sustainability and resilience in the Congo Basin, the conditions under which forests grow in Central Africa, the impacts on ecosystem functions and services in Sub-Saharan Africa, the history of mountain forests in central Africa, and finally the use of plant DNA to explore the imprints left by past climate changes in Tropical flora; (3) on tropical teleconnections and monsoon systems, which showcased talks on precipitation responses during recent El Niño events, the teleconnection patterns during the last millennium in NW Africa, the trends, rhythms and transitions in East Africa, and the anthropogenic impact on the Sahel climate; (4) dedicated to the Mediterranean region presenting the past droughts and flooding in the Levant, the climate conditions around the Red Sea and Dead Sea during the Last Interglacial, the timings and mechanisms of Holocene environmental changes in Morocco (Fig. 1) and Tunisia, the role of microclimates in preserving plant species in microrefugia, as well as how to predict plant species, future range using vegetation modeling; (5) focused on land-ocean links including oceanic variability in the southern Benguela upwelling system and their implications for increased Agulhas leakage during the late Holocene, the seasonal sea surface temperatures off South Africa, climate variability and its driving forces in southern Africa, and the vegetation dynamics during the Holocene in Benin.

The three-day meeting was followed by a two-day field excursion into the Moroccan desert in which 35 delegates took part. This was a fantastic opportunity to pursue scientific discussions while experiencing one of the most extreme environments on Earth.

The group strongly felt that although climate mechanisms and impacts can be partially studied by the international community without ever being in Africa, all climate change studies ultimately rely on field data. We therefore call for an increased international scientific effort toward field science involving institutional cooperation with local scientists.

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Figure 1: Will the ongoing climate change in Africa lead to an extinction of some endemic species (Cheddadi et al. 2017)?

Decades of quaternary research in Eastern Africa: Implications for sustainable future

Julius B. Lejju and Andama Morgan

5th EAQUA Workshop, Mukono, Uganda, 4-7 July 2017

The 5th East African Quaternary Research Association (EAQUA) workshop was themed “Decades of Quaternary Research in Eastern Africa: Implications for Sustainable Future”. It was intended to foster ways of integrating the long-term scientific information of various paleo studies in eastern Africa from the last six decades to address future environmental challenges in the region. In addition, the workshop was meant to integrate the rich paleo information into practical applications to address the social and environmental challenges affecting the region.

The workshop was attended by over 60 research scientists from Eastern Africa, Ethiopia, Malawi, West Africa, Southern Africa, Europe and USA. More than 40 research papers were presented under several sub-themes that addressed the rich Quaternary environments of eastern Africa. The sub-themes included Regional Climate Dynamics for Eastern Africa; Quaternary Human-Environment interactions in Eastern Africa; Anthropology, Archaeology and Paleontology in Eastern Africa; Natural and Cultural Heritage in Eastern Africa; and Paleoscience in other regions of Africa. The keynote papers reviewed the long-term environmental dynamics of the region, and presented the output of 30 years of paleontological research in Eastern Africa, in particular from the Napak region in Uganda, which yields immense paleo information with significant deposits of fossil records spanning the last 20 Ma. While the region is

covered by Savanna nowadays, geological studies have revealed evidence of patchily distributed flowing rivers and streams, including swamps 20 Ma ago. Furthermore, the discovery of remains of the extinct genus of hominoid primate *Ugandapithecus* and the assemblages of land snails indicate the presence of a tropical rainforest. Aquatic fossil remains suggest the presence of fresh water bodies.

East Africa is believed to be the origin place of humankind, as most of the early hominid fossils were found in this region. When East Africa became drier in the Late Miocene, animals already adapted to a drier environment in the South dispersed to East Africa. The development of the Cenozoic East African Rift System, which greatly re-shaped the landscape of the region, triggered the early hominin evolution and also led to the formation of isolated rift lakes and development of amplifier lakes (Trauth et al. 2010) in the basins three million years ago. The tectonic activity significantly contributed to the exceptional sensitivity of Eastern Africa to climate change, compared to other parts of the African continent. Thus, the last two Ma in East Africa are characterized by variable climate conditions with high fluctuating lake levels (Fig. 1) and complete desiccation of Lake Victoria during the late Pleistocene. The West Nile sector of the Albertine Rift contains fossiliferous Mio-Pliocene deposits, similar in age to parts of the succession

in Kenya, where early evidence of bipedal hominids was discovered.

Climate change in the past and the consequential ecosystems changes have been seen to play a critical role in shaping the evolution trajectories in East Africa. Recent climatic variations in the region at decadal and centennial scales are characterized by strong rainfall seasonality resulting from the annual migration of the Intertropical Convergence Zone. This interannual variability is also linked to other mechanisms such as sea-surface temperature anomalies attributed to the Indian Ocean Dipole and El Niño/Southern Oscillation. The East African region is also known for the existence of rock art sites coupled with lithic fragments and pottery - an indication of the presence of hunter-gatherer systems.

The paleo data of this workshop will be integrated in the assessment of future issues in the region and the proceedings of this workshop will be published as a special issue in a peer-reviewed journal.

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Figure 1: Source of the Nile at Jinja, Uganda.

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