Did pastoralism delay the collapse of the green Sahara 6000 years ago?

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Abstract

During the early Holocene, northern Africa was relatively humid and supported a large human population. Around 5,500 years ago (5.5 ka) the regional climate deteriorated and the population declined substantially. Evidence suggests these changes were coeval, but it is unclear whether or not humans influenced this ecological collapse. Using a climate-vegetation model driven by global forcings, we forecast the length of the Holocene African Humid Period (AHP). The model indicates that the system was most likely to collapse between 7-6 ka, which is at least 500 years before the observed collapse. Archaeological and ethnographic evidence from northern Africa, suggests that the shift from hunter-gatherer to pastoralist societies around 7 ka was an effective adaptation to the orbitally-driven regional environmental changes. The pastoralist strategy may even have slowed the deterioration caused by orbital driven climate change. This supports the view that modern pastoralists are beneficial for the management of the world's dryland environments.

1 Introduction

Tipping points are an emotive topic when talking about future climate change Lenton et al (2008), and such pivotal changes may already be happening in sensitive regions such as the Amazon, the Sahel and Antarctica Rignot et al (2014). A common example given for this sort of threshold behaviour in the climate system is the 'Green Sahara' Lenton et al (2008). With the onset of favourable

orbital conditions around 14.7 ka summer rains penetrated much further into northern Africa Otto-Bliesner et al (2014). As a result, humid conditions were established initially at lower latitudes, and progressively later at more northern latitudes Shanahan et al (2015); Tierney et al (2017); Lézine et al (2011). Pollen reconstructions Hély et al (2014) indicate a mix of tropical elements reaching up to 20°N, and Sudanian woodland and Sahelian grasslands extending at least as far as 28°N. These changes supported numerous Sahelian and aquatic animals, such as elephant, crocodile and fish Jousse (2017). Yet, debate is on-going over the rate of climatic deterioration at the end of the African Humid Period (AHP). Both sediment flux records from deep sea cores off the coast of northwest Africa deMenocal et al (2000); McGee et al (2013); Adkins et al (2006) (Fig. 1a) and ΔD_{wax} isotopic values from east and northeast Africa Tierney et al (2017); Tierney and deMenocal (2013) point to a rapid hydroclimatic shift 5500 years ago. Pollen and sedimentological records from Lake Yoa in northern Chad, however, indicate a more gradual decline in precipitation and subsequent progressive drying of the regional ecosystem Kropelin et al (2008); Francus et al (2013) (Fig. 1a). This discrepancy is partly a consequence of differential sensitivity of the various proxies Tierney and deMenocal (2013); Francus et al (2013), but also because the changes in regional hydroclimates were modified by vegetation feedbacks Renssen et al (2006) and local groundwater conditions Lézine et al (2011). A coherent spatial picture of the end of the AHP is emerging, as demonstrated in a recent synthesis of hydrological reconstructions Shanahan et al (2015), revealing a time transgressive termination of humid conditions from north to south.

Human occupation during the humid period is clearly demonstrated in numerous rock engravings and occupation sites, bearing evidence for the development of food production strategies and increasing socio-economic complexity Sereno et al (2008); Cancellieri and di Lernia (2014). Combining regional estimates of relative human population levels Manning and Timpson (2014) (Fig. 1b) with archaeological evidence, several major phases of population expansion and contraction can be identified in the Holocene Sahara. Hunter-Gatherer-Fisherfolk Cancellieri and di Lernia (2014) initially colonised all regions around 10.5 ka with population levels peaking between 8-7.5 ka (Fig. 1b). Over the following millennium, northern Africa underwent a population decline; observable both at the broad spatial scale Manning and Timpson (2014) and in regional occupation Sereno et al (2008) (Fig 1b). This appears to have been driven by a millennial long dry event at 8ka as seen in a recent precipitation reconstruction from leaf wax biomarkers Tierney and deMenocal (2013). After 7 ka, domestic cattle, sheep and goat spread throughout northern Africa. This widespread implementation of pastoralist strategies is followed by a second population boom (Fig. 1b). Whilst domesticates were evidently kept for meat as well as secondary products such as milk Dunne et al (2012), they also played an important role in the ideological landscape of the Sahara in the mid to late Holocene. From around 6.5 ka to 4 ka, tumuli containing the interred remains of domestic cattle suggest the development of a 'cattle cult' di Lernia (2006); di Lernia et al (2013). The second pulse of northern African human occupancy lasted until 5.5

ka, at which point the Sahara underwent a major population collapse, coinciding with the decline in favourable climatic conditions (Fig. 1). But was this climate-human interaction one way - or was the collapse of the Green Sahara an early example of humans interfering with a sensitive environmental system?

1.1 Could Humans trigger a collapse?

Typically, traditional subsistence pastoralists have been seen as agents of environmental degradation through overgrazing, habitat change and resource competition with wildlife. This view was embedded in the environmental doctrine of the 20th Century, partly as a consequence of the historical relationship between colonial administrators and traditional pastoralists Warren (1995). This doctrine has led to a recent suggestion that mid Holocene pastoralists accelerated climatic deterioration in the Sahara Wright (2017), which has significant implications for the way in which modern populations living in marginal environments are perceived, and particularly how modern pastoralism is recognised within local and regional ecological and economic policies. We submit this argument to a more rigorous quantitative assessment, by examining the relationship between mid-Holocene climatic deterioration and the development of African pastoralist strategies.

2 Natural length of the Holocene African Humid Period

Before considering human agents in the context of climatic change, it is first necessary to determine the length of the African Humid Period assuming no anthropogenic influence. Observations alone do not provide sufficient constraint on this. The 'natural' length of the present interglacial has been estimated from observations Tzedakis et al (2012) and potential anthropogenic perturbations highlighted within it Ruddiman (2013). Unfortunately such an approach is not possible in this situation, because of insufficiently accurate relevant chronologies. Mediterranean sapropel deposition is used as an indicator of humid conditions in northern Africa Na et al (2013), because they have some of the best chronologies Ziegler et al (2010) and so highlight the limits of the approach. Short, well-dated records Ziegler et al (2010) suggest the most recent sapropel ended sooner than other instances over the past two glacial cycles (Fig. 3a). However longer records that allow selection of similar orbital configurations Tzedakis et al (2012) cannot detect differences at the sub-millennial timescales required (Fig. 3b). A concerted effort would be required to develop a sufficiently accurate chronology to advance in this direction.

Proxy records of northern African palaeoclimate are derived from a variety of sources. These range from lake-level, dust deposition, pollen and geochemical records. The data used in Fig. 1A and 5A are derived from the database compiled and interpreted by Shanahan et al (2015). For every 500 year interval, the climate state has been subjectively determined Shanahan et al (2015) as either
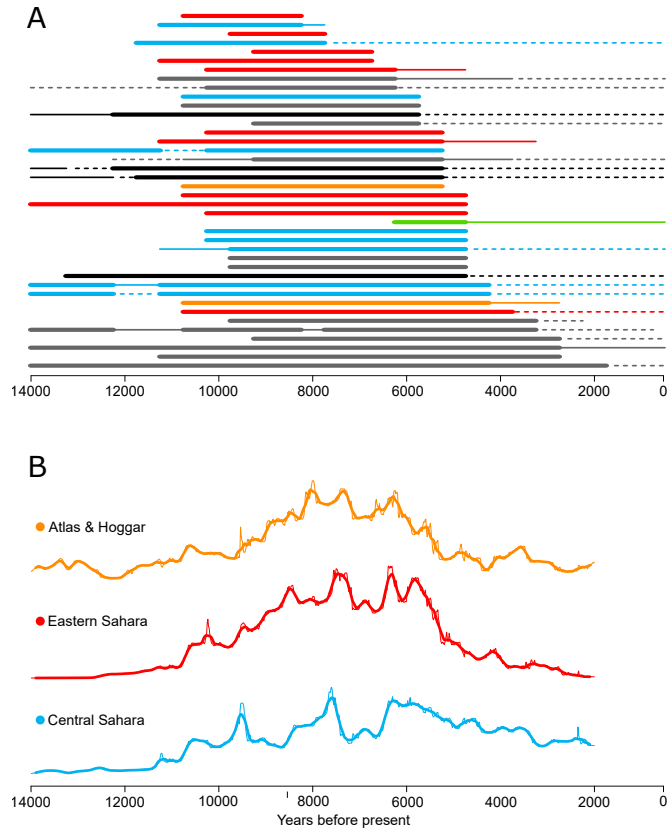
Figure 1: Reconstructions of Holocene northern Africa. (A) Palaeoclimate reconstructions Shanahan et al (2015) showing the existence of humid conditions (thick solid lines), moderate conditions (thin solid) or dry conditions (dashed). The individual reconstructions are colored by region: Central Sahara (Blue), Eastern Sahara (Red), the Atlas & Hoggar Mountains (Orange). The records discussed in the text are Lake Yoa Kropelin et al (2008) (green) and marine cores deMenocal et al (2000); McGee et al (2013) (black), whilst records outside of the population regions are coloured gray. (B) Estimates of relative population evolution for the three regions of northern Africa Manning and Timpson (2014)
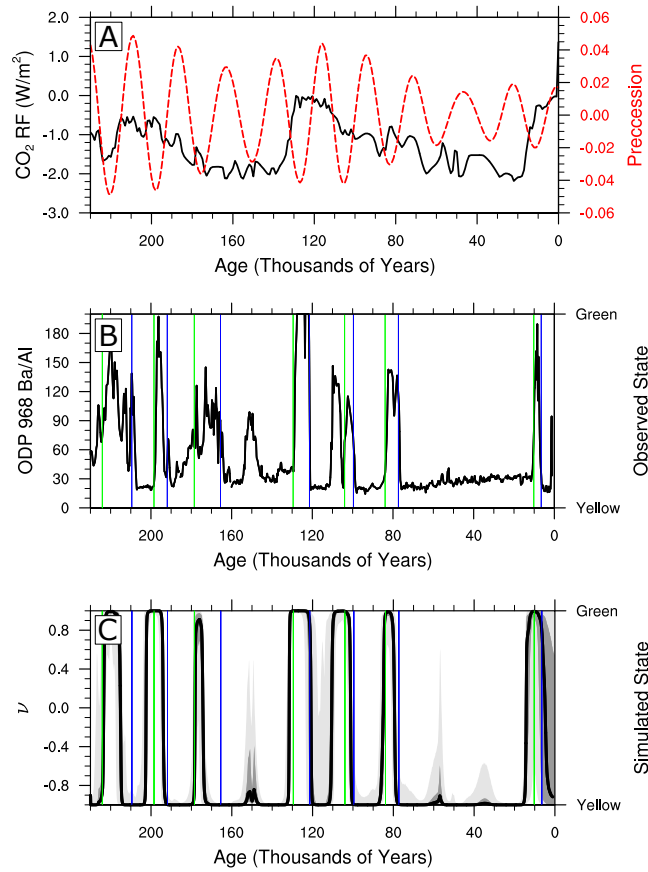
Figure 2: The last two glacial cycles. (A) The input times series of radiative forcing of carbon dioxide changes Lüthi et al (2008) (black) and climatic precession Berger and Loutre (1991) (red). (B) Barium to Aluminium ratio at Ocean Drilling Program site 968 in the Eastern Mediterranean Ziegler et al (2010). (C) The distribution of the roughly 12,000 ensemble members that exhibit seven 'green' events. The median (black), inter-quartile range (dark gray) and 5-95% range (light gray) are shown, along with the sapropel start (green) and end (blue) dates calculated from observations Ziegler et al (2010)
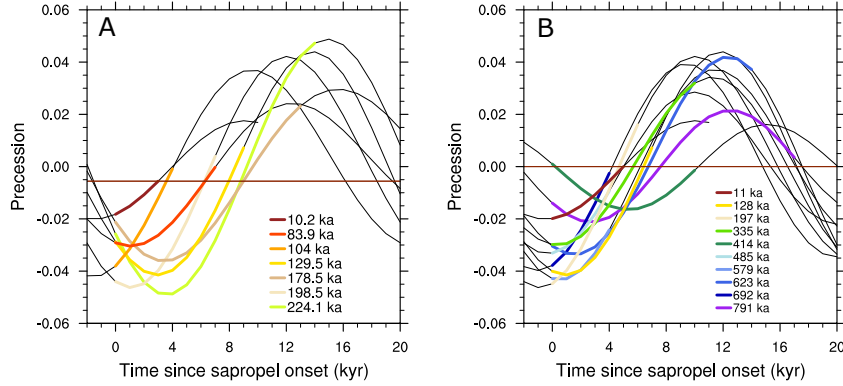
Figure 3: The relationship between sapropel formation and orbital precession using the sapropel chronologies. Precessional curves associated with sapropel formation are aligned to the start of each occurrence according to the respective chronology. The coloured segments of these curves indicate the actual duration of the sapropel. The red horizontal line indicates the precession at the termination of the most recent sapropel. (A) A speleothem-tuned chronology Ziegler et al (2010) provides well-constrained estimates of the onset and termination of sapropels over the past 250,000 years. The use of a geochemical index to identify sapropels (such as the Ba/Al ratio used in Fig. 2B) minimises the impact of post-depositional oxidation Mercone et al (2000) that has been shown to remove the upper-most part of a sapropel Higgs et al (1994). This chronology suggests that the most recent sapropel was of much shorter duration than previous instances, yet only includes one other interglacial sapropel (at 129.5 ka). (B) The past ten interglacial sapropels seen in a Mediterranean Sea level record Rohling et al (2014). This highlights potential issues with the chronology around 400 and 800 ka, rather than suggesting abnormalities in the Holocene instance. These two interglacials have orbital configurations most like the Holocene Tzedakis et al (2012), but appear to show sapropel onsets 90°out of phase with all the other occasions.

wet, moderate or dry (Fig. 1A). As with the sensitivity metric (eq. 8), we date the collapse as the first time in which humid conditions are not present (Fig. 5). The relative population levels (Fig. 1B & 5B) are a summed probability distribution analysis based on a comprehensive review of the abundance of carbon-14 dated archaeological sites across northern Africa Manning and Timpson (2014). The population estimates can only provide relative time series and the size of populations cannot be compared between the regions shown in Fig. 1B. We exclude African palaeoclimate reconstructions south of 13.42°N from our analysis, as this is the most southerly archaeological site used to reconstruct the population estimates Manning and Timpson (2014).

2.1 Idealised Model Formulation

The simplest model of climate-vegetation interactions consists of the vegetation cover being determined by rainfall, which itself depends on external forcing and vegetation cover Brovkin et al (1998). We adapt the non-dimensionalised model of Lui Liu (2010) that captures inter-annual variability Liu et al (2006) with the modification that the time-invariant background rainfall is now considered a linearised function of precession and carbon dioxide forcing. This idealised model incorporates a vegetation cover, ν, that ranges from shrubland (1; 'green') to desert (-1; 'yellow'). The vegetation cover changes at a rate

$$\frac{d\nu}{dt} = \frac{1}{\tau_\nu}\tanh(R) - \nu \tag{1}$$

where τ_ν is the vegetation timescale (in years) and R is the non-dimensionalised rainfall. R is centred around a sensitive range that spreads from (-1,1). It is given by:

$$R = a + bP + cF + d\nu + N \tag{2}$$

where P is the eccentricity-modulated precession Berger and Loutre (1991), $\varepsilon \sin\varpi$, (Fig. 2A) and F is the radiative forcing with respect to the preindustrial. Here the radiative forcing (Fig. 2A) represents solely carbon dioxide and is calculated as $5.35ln(CO_2/278)$, where CO_2 is the carbon dioxide concentration Lüthi et al (2008) in parts-per-million by volume [278 ppm was the preindustrial concentration]. The feedback of vegetation onto the rainfall is captured by the $d\nu$ term in eq. 2, where d sets the magnitude of the feedback. Previous work Liu (2010) has used d ranging from 0.8-1.2; a wider range is sampled here to encompass a broader spread of uncertainty (see Tab. 1). The red noise term, N, is given by

$$\frac{dN}{dt} = \frac{\sigma\varsigma(t) - N}{\tau_N} \tag{3}$$

where τ_N is soil moisture timescale (in years) and ς is a random sample from a unit normal distribution scaled by a tunable parameter, σ.

Table 1: Sampling ranges for model parameters

Parameter	Minimum Value	Maximum Value	Value used in Fig. 4
a	-3	3	0
b	-150	0	-100
c	0	5	2
d	0	2	1
τ_ν	1	10	5
τ_N	1	10	5
σ	0	2	1

The impact of a doubling in CO_2 has previously been shown to expand the critical range of rainfall Brovkin et al (1998). However, it is incorporated here as an additive term (expressed as a radiative forcing change from preindustrial in W/m^2) as attempts with a multiplicative factor were unsuccessful in replicating the observed lack of green states during MIS3 (Fig. 2B). The modified background rainfall, $a + bP + cF$, must at times be less than 1 otherwise the system would never leave the green state and is generally less than 0 to prevent the green state becoming the predominant condition.

Iteration is achieved through a forward timestepping approach Liu (2010) with a timestep, Δt, of 1 year.

$$\nu_{k+1} = \nu_k + \frac{\Delta t}{\tau_\nu} \left[\tanh(\frac{a+bP}{cCO_2} + d\nu + N_k) - \nu_k \right] \tag{4}$$

$$N_{k+1} = N_k - \frac{N_k \Delta t}{\tau_N} + \frac{\sqrt{\Delta t}\sigma W_k}{\tau_N} \tag{5}$$

$$\tag{6}$$

Previous work Liu (2010) has shown that this system can exhibit bimodality (switching between two different states) despite being monostable (i.e. having a single potential well, eq. 7). The stochasticity (eq. 3, best thought of as interannual variability in the soil moisture Liu et al (2006); Liu (2010)) combined with the non-linear dependence of vegetation on rainfall (eq. 1) can lead to the simulation often passing through the state with minimum equilibrium potential Liu (2010). The bimodality explored previously in this style of system Liu (2010) occurs with a background rainfall (and hence minimum equilibrium potential) centred on $\nu = 0$. It is under this condition that the system is most responsive to noise. Otherwise (as for the vast majority of the 230 ka simulated here), the stochastic contribution is effectively biased towards either the green or yellow state. This means the model is not exhibiting the canonical form of abrupt collapse (i.e. a bistable system rapidly flipping state). Rather this model represents forced changes overprinted with substantial stochasticity, which leads to shifts between two predominant states that may be abrupt in nature.

The idealised model has seven unknown parameters: three related to the background rainfall (a, b and c); the feedback strength, d; two inherent timescales (τ_ν and τ_N); and the climate noise scaling, σ. These cannot be individually constrained from observations, in part due to their idealised nature. A 100,000-member ensemble is created to explore parameter and internal variability uncertainty. For each ensemble member, the values of the seven parameters are randomly selected from a uniform distribution over the ranges shown in Tab. S1. The remaining subset of 12,099 simulations are considered as 'not implausible'. Interestingly roughly a third (n=3,534) of this subset never leave the green state during the Holocene.

2.2   Calculation of model sensitivity

In the absence of stochastic noise, the equilibrium potential for the idealised model above is

$$U(\nu) = \frac{\nu^2}{2} - \frac{ln\left(cosh\left(a + bP + cCO_2 + d\nu\right)\right)}{d} \tag{7}$$

If the noiseless system were left to reach equilibrium with a given forcing, it would end in the state with the minimum equilibrium potential. The time-varying nature of the forcings mean that even with the addition of noise an individual model simulation can be adequately approximated by its equilibrium state (Fig. 4A). This permits identification of when the system should flip between the green and yellow states. We define a threshold time, t_thres, at which the minimum equilibrium potential changes side of the $\nu = 0$ line (Fig. 4A). Following from eq. 7, the threshold time, t_{thres}, occurs at time k when

$$sgn(a + bP_k + cF_k) \neq sgn(a + bP_{(k-1)} + cF_{(k-1)}) \tag{8}$$

The time varying sensitivity of northern Africa is estimated by the relative frequency of not-implausible ensemble members with that threshold time. Exclusion of ensemble members that do not collapse during the Holocene does not alter the sensitivity time series. This sensitivity shows a definite spike at 14.7ka (Fig. 4B) demonstrating the ability of our approach to capture the onset of the African humid period. Such a consistent signal is not shown for its termination (Fig. 5C).

An alternate approach to sampling the uncertainty contained within the model's tunable parameters would be to only select the ensemble members with a good fit to observations. Selecting just the 1500 ensemble members best correlated (i.e. with the highest R^2 values) to the Ba/Al observations shown in Fig. 2B would lead to a single sole peak in simulated sensitivity at ˜6.5 ka. Given that sapropel S1 is observed to terminate earlier than the compilation in Fig. 5A Ziegler et al (2010); Shanahan et al (2015), it would be hard to conclude an anthropogenic delay from this subset of best-correlated models. Our 'not implausible' approach is only conditioned on sapropel existence rather than timing - removing any circularity.

2.3   Constraints from modelling

We develop an idealised model that calculates rainfall and vegetative cover and their feedbacks (Sect. 2.2). Compared to previous models Liu et al (2006); Liu (2010), rainfall responds to imposed orbital precession Berger and Loutre (1991) and past greenhouse gas levels as measured in ice cores Lüthi et al (2008). The model is run over the past two glacial cycles (230-20 ka) using a large ensemble of parameter settings selected at random. Parameter settings that do not exhibit six green episodes during this period are discounted for being inconsistent with the observations. The remaining ensemble members are integrated forward to the present-day (Fig. 2). We find late Pleistocene behaviour alone
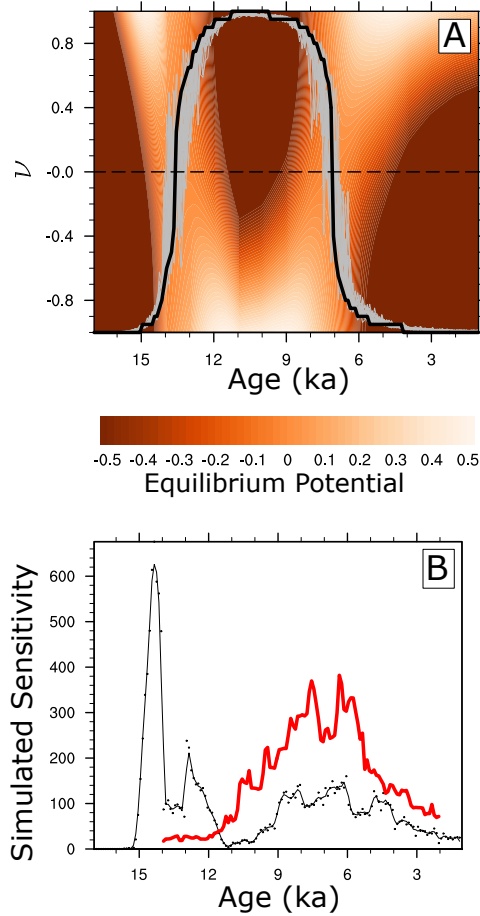
Figure 4: The simulated sensitivity metric. (A) The equilibrium potential, $U(\nu)$, of a particular model instance (see Tab. 1 for parameter settings). The minimum potential in each century (black) is shown along with the results of twenty fully stochastic simulations (gray). The threshold time calculated from eq. 8 coincides when the minimum potential (solid black) crosses the $\nu = 0$ line (dashed) (B) The computed sensitivity of northern Africa diagnosed using the approach outlined in Sect. 2.2 (black dots show the number of ensemble members with a threshold time in each century, black line is a 3 point running average). Also shown is the combined summed probability distribution of the population (red; Manning and Timpson, 2014).

was not sufficient to rule out the continuation of the humid period throughout the Holocene at the 5% significance level (Fig. 2). This failure to accurately predict the passing of a known tipping point - despite having 200,000 years of

observations - should add a cautionary note to our discussion of future climate projections.

A sensitivity metric is devised for the model (Sect. 2.2) to summarise its behaviour and estimate start and end dates for the humid periods. We predict a well-defined start of the AHP (Fig. 4), which corresponds closely with the observed date of 14.5ka Lézine et al (2011); Tierney et al (2017), supporting the validity of this modelling approach. The model shows several times during the Holocene when northern Africa would have been particularly sensitive to interference (Fig. 5C). We treat the model ensemble as multiple plausible instances of a single physical system Liu (2010); Liu et al (2006); Brovkin et al (1998). The sensitivity is therefore interpreted as a single metric for all three regions shown in Fig. 1. An alternate interpretation is that the ensemble members represent different local conditions, implying that the three sensitivity peaks in Fig. 5C each characterise a particular region. However, there is no noticeable regional pattern in the reconstructed collapse dates (Fig. 1A), although more southerly locations in the compilation do show a later response Shanahan et al (2015). However, the majority of observational records showing a collapse between 6-5 ka Shanahan et al (2015) occur at similar latitudes to the archaeological sites used to estimate the human occupancy Manning and Timpson (2014). Therefore a comparison of the sensitivity metric to the palaeoclimate and population reconstructions combined across northern Africa seems appropriate (Fig. 5).

2.4 Collapse delayed

The largest peak in the modelled sensitivity of the Sahara occurs at 7-6 ka (Fig. 5C). This coincides with the second period of population increase between 6.7-6.3 ka (Fig. 5B). The dominant collapse observed for the Holocene AHP (Fig. 5A) occurs 500-1000 years after this peak (Fig. 5C). This implies that humans may have delayed the region's environmental deterioration.

How robust is this delay? The synthesis of observed records Shanahan et al (2015) classifies the hydroclimate state only at 500 year intervals. This choice of interval was motivated by all the chronologies being sufficiently precise to resolve it Shanahan et al (2015). The model inputs are carbon dioxide concentrations Lüthi et al (2008) and orbital parameters Berger and Loutre (1991); both of which have dating uncertainties substantively less than 500 years. Dating of prior humid periods is subject to errors on the order of millennia (hence the failure to constrain the AHP dates observationally). Because of this issue, the valid model parameter settings are determined by matching solely the number of prior instances rather than their timing (Sect. 2.2). We consider the possibility that either a humid period was overlooked or that a sapropel has been laid down without a humid period during the past 230 kyrs to be minimal. To explore the uncertainty in the model output, we replicate the whole experiment a further ten times and see little variation in the temporal structure (Fig. 6). The uncertainty contained within the structure of the idealised model, rather than its parameters, is impossible to quantify. It is worth noting that models which are more complicated are not able to adequately simulate the greening of the
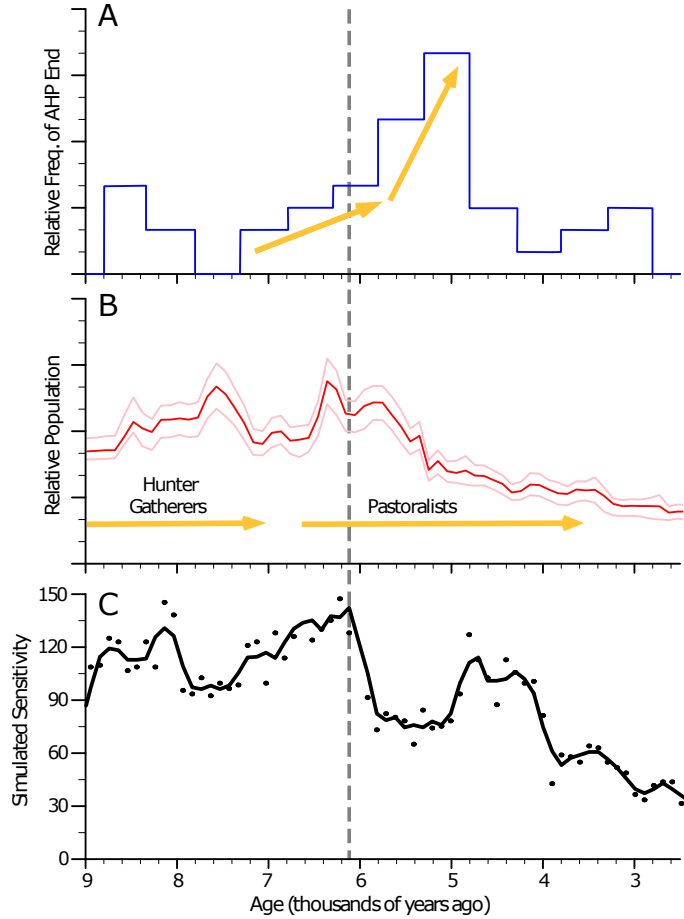
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Figure 5: Potential interaction between humans and the ecosystem during the end of the African Humid Period. (A) Histogram of the number of climate proxies (Fig. 1a) indicating an end of the African Humid Period (AHP) within a 500 year window Shanahan et al (2015). (B) The relative summed population distribution Manning and Timpson (2014) over the same region along with its 5-95% confidence level. (C) The computed sensitivity of northern Africa diagnosed from the model (black dots show the number of not-implausible model settings with threshold time in each century; the black line is a 3 point running average).

Sahara Perez-Sanz et al (2014). In summary, the limiting factor for the precision appears to be the temporal resolution of the compiled observations Shanahan et al (2015), though the delay appears visible despite that (Fig. 5). This refutes the hypothesis that pastoralists were "active agents in landscape denudation" and accelerated the termination of the African Humid Period Wright (2017).
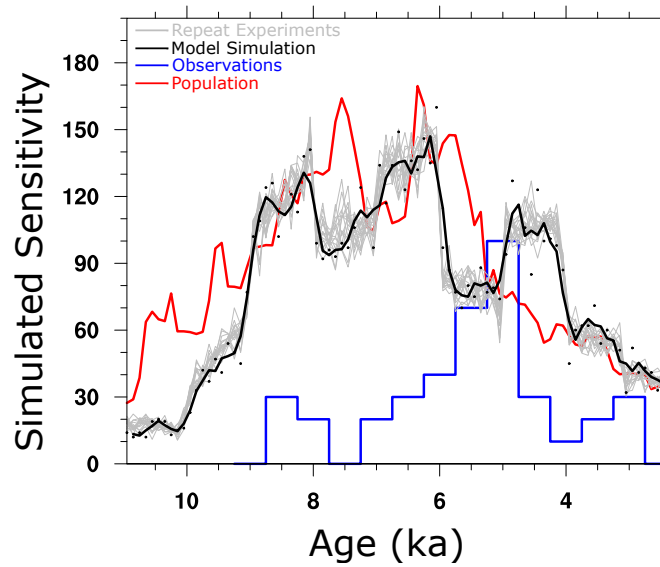

Figure 6: The robustness on the model results. The simulated sensitivity (black), observed frequency of AHP end (blue Shanahan et al, 2015) and reconstructed relative population (red Manning and Timpson, 2014) that are shown in Fig. 3. The whole model experiment was replicated twenty times with different random sampling of the parameter ranges in Table S1. The simulated sensitivities resulting from each of these replicates are shown in gray. They each show a similar temporal pattern with the dominant peak occurring just before 6000 years ago.

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3 Pastoralist climate adaptations

The view of pastoralism as a detrimental practice dominated early approaches to human ecology Warren (1995), and it was only since the 1980's that anthropologists began systematically collecting data to specifically test that hypothesis. Contrary to the prevailing consensus, these works revealed that in dryland environments, where traditional pastoralist practices were functional, pastoral rangelands were generally observed to be in good conditions Notenbaert et al (2012); Niamir-Fuller (1999). Several mechanisms help explain why pastoralism is sustainable. Mobility, a distinguishing feature of traditional pastoral systems Moore (1987), promotes periodicity and in the intensity of grazing, which plays a major role in grassland health as grasslands can suffer from undergrazing as much as overgrazing Notenbaert et al (2012). This is because grazing ungulates and grasslands have co-evolved from an historical predator-prey relationship, with pack hunting predators keeping large herds of ungulates bunched and moving McNaughton (1997). Healthy grasslands are maintained in precisely this way by pastoralists bunching stock and moving them frequently, fostering a mutually beneficial distribution of dung and urine Moore (1987). Removing grazers from grasslands increases the amount of senescent vegetation, which causes the grasses to cease growing productively Neely et al (2009). Grazing livestock and their preference for the most palatable grasses provide a competitive advantage to the less palatable grasses for water and nutrients, making it important to get the balance correct between overgrazing and over-resting. Traditional pastoralists tend to be acutely aware of these subtle dynamics utilising practices that maximise grassland regeneration McNaughton (1997); Stebbins (1981).

Evidence from long-term studies on herding strategies has also helped to reveal the sensitive dynamic between drought, pasture availability, and herd size. Seasonal and long-term droughts, which are common in areas of pastoral rangeland, as well as disease dynamics, control the growth of herds in a way that means they are unlikely to damage pasture. If longer-term drought starts to restrict pasture, or if herd size increases beyond the carrying capacity of a rangeland, then pastoralists will move on. For example, field research in the Ngorongoro Conservation Area has shown that whilst pastures were being overgrazed in terms of optimal commercial yield, this did not result in environmental degradation Homewood and Rodgers (1984). This is important as it suggests that animal condition deteriorates before they are capable of having a seriously deleterious effect on the environment. It is therefore unlikely that the size of Holocene pastoralist populations, or their herds, would have reached such levels as to surpass carrying capacity. The inherent mobility and customary institutions employed by these populations generates a dynamic state of adaptation, which logically negates over-burdening pastoral rangeland Niamir-Fuller (1999).

Despite these concerted efforts to change the perception of traditional pastoralism Warren (1995); Moore (1987); McNaughton (1997); Homewood and Rodgers (1984), the degree to which that has influenced administrative policy or public perception is still debateable. A recent publication Wright (2017) in

which mid Holocene pastoralists are considered "catalysts in accelerating the pace of devegetation in the Sahara" provides an illustrative example. The historical analogues used in that argument appear inappropriate. For example, Rapa Nui is an island environment, whose inhabitants were primarily farmers and fishermen, not pastoralists. Even so recent research suggests that major environmental degradation on Rapa Nui occurred only after European contact, and that pre-contact changes in land use were a result of environmental constraint, not degradation Rull et al (2013); Mulrooney (2013). Using this type of analogue, one establishes a false premise i.e. where "landscapes with no previous exposure to grazing by domesticated animals have been documented as crossing ecological thresholds shortly after new grazing pressures were introduced" Wright (2017). Northern Africa, however, was becoming a domesticated landscape from the early Holocene onwards (Fig. 1). Pastoralism co-evolved with dryland environments in a context where extant grazing ungulates were in abundance. Moreover recent genetic analyses of modern African cattle indicate considerable introgression from African aurochs, suggesting they underwent a hybridization with local wild stock Decker et al (2014).The introduction of pastoralist strategies, therefore, were based upon natural ecosystem interactions and the functional roles of native wildlife causing little additional burden; potentially allowing positive management of the environment.

3.1 Regional Differences

The division of the entire Saharan population into broad regional sets (Fig. 1B) allows a preliminary look at spatial variation in the timing of population change. The population curves for the Eastern Sahara, the Atlas & Hoggar and Central Sahara start broadly synchronous; showing a rapid population increase after the onset of humid conditions c. 10.5 ka and during the millennial-long population decline between 7.5-6.5 ka (Fig. 1B). At the end of the AHP, however, we observe divergence in the regional demographic response. The eastern Sahara, which is today extremely arid, appears to have undergone a rapid population decline, as occupation shifted towards the Nile Valley, subsequently giving rise to the Pharanoic civilisation Kuper and Kr:opelin (2006). To the north and west, in the Atlas & Hoggar mountain region, population decline appears to have been equally rapid (c. 900 years) and in both regions populations dropped to the same level as in the Late Pleistocene (Fig. 1B). The central Sahara, on the other hand, saw a much more gradual decline in population levels that never reached the pre-Holocene population low (Fig. 1B).

The implication that Holocene populations persisted for longer in some parts of the Sahara either suggests a spatial variation in the rate of aridification or vegetation change, or more intriguingly in the human adaptive strategies. Differential topography across the Sahara is certainly worth considering. Mountains such as the Tibesti, Tassili-n-Ajjer and Ahaggar form a major topographic feature spanning more than 2500km from southern Algeria to northern Chad. These mountains would have acted as important water towers in contrast to the surrounding plains, providing populations living on the windward side with more

persistent rain runoff during periods of increasing aridity. Some of the earliest direct evidence for the exploitation of domestic livestock di Lernia (2006), use of milk products Dunne et al (2012), and the construction of cattle tumuli di Lernia (2006); di Lernia et al (2013), come from the heart of the central Sahara. On the Messak plateau, for example, extensive evidence for rock art depicting livestock scenes and stone monuments with associated domestic animal remains dating to the middle Holocene attest to a highly formalized expression of a wider Saharan 'cattle cult' di Lernia (2006); di Lernia et al (2013). Isotopic analysis of archaeological animal bones from this region also demonstrate seasonal transhumance di Lernia et al (2013), reminiscent of the strategies used by modern traditional pastoralists to ensure the maintenance of healthy pasture. The fact that pastoralists persisted in this region for so long, and invested both economically and ideologically in the local landscape does not support a scenario of over-exploitation. Additionally, the ethnographic record demonstrates how the flexibility inherent in traditional African pastoralist strategies enables them to make the most efficient use of patchy and fragile environments Niamir-Fuller (1999); Notenbaert et al (2012); Moore (1987). It is therefore likely that the origins of such strategies co-evolved with the drying environment in a way that enabled humans to live in an adaptive balance with available pasture.

4   Conclusions

Human-environment interactions can be put into three categories; beneficial, detrimental or neutral/negligible. Until recently, the early anthropogenic footprint in northern Africa was implicitly considered too small to impact the coupled climate-ecosystem. A mechanism has been proposed Wright (2017) for pastoralists to trigger an early collapse of the African Humid Period (Fig. 7A). Neither the comparison between our model and the observed data nor the archaeological and ethnographic evidence discussed above support that hypothesis. Rather the apparent model-data mismatch (Fig. 5) hints that Saharan pastoralists may have delayed the collapse of the green Sahara. The mechanisms by which pastoralists slowed the collapse revolve around the mobility inherent in pastoralism Moore (1987); Niamir-Fuller (1999) and its ability to maximise ecosystem health and resilience Notenbaert et al (2012); McNaughton (1997) as discussed earlier (Fig. 7B).

The possibility that humans could have had a stabilising influence on the environment has significant implications. Naturally there are consequences for our understanding of past climate changes. For example, there is a long-standing discrepancy between observed climate of 6 ka for northern Africa and simulations by global climate models Joussaume et al (1999); Perez-Sanz et al (2014), which currently include no pastoralism. Also the "early Anthropocene" hypothesis Ruddiman (2013) identifies a human-caused perturbation in the carbon cycle around the time of the aridification of northern Africa. Whilst the carbon stored in northern Africa vegetation would have been relatively insignificant, there may have been teleconnected impacts on both tropical wetland methane emissions
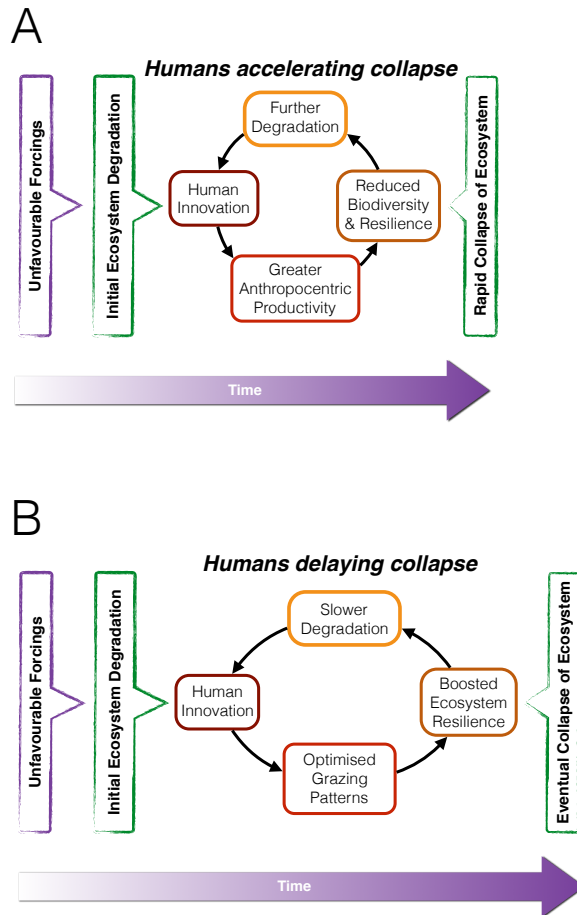
16

Figure 7: Human-Environment Interactions. (A) Schematic of a human population expansion beyond the carrying capacity of the region exacerbating aridification (after Wright, 2017). (B) Schematic of how the technological and cultural advances associated with the pastoralist population could help buffer changes to a fragile ecosystem.

Kirschke et al (2013) and the carbon sequestration in rainforest peatlands Dargie et al (2017).

More broadly, this work presents a positive message about climate adaptation. We contest the common narrative that past human-environment interactions must always be one of over-exploitation and degradation Diamond (2005).

This study shows that increasing human population combined with an intensification of pastoralism did not accelerate aridification and may even have delayed the collapse of the Green Sahara. This finding provides yet more evidence for the sustainability of pastoralism Notenbaert et al (2012). It suggests that traditional, indigenous practices were developed as an adaptation to Holocene climate change in northern Africa. Promoting and enhancing sustainable pastoralism could be a vital adaptation to our current climate challenge.

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