Is yearly rainfall amount a good predictor for agriculture viability in drylands? Modelling traditional cultivation practices of drought-resistant crops: an ethnographic approach for the study of long-term resilience and sustainability

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Abstract

FAO guidelines on water requirements for plant growth in the absence of irrigation, stipulate that cultivation is not viable in areas with less than 450mm of annual rainfall. Indeed, in all maps of agricultural land use, most hyper-arid, arid, and semi-arid drylands are considered unproductive. Yet, modern societies in arid and semi-arid drylands still practice rainfed cultivation under regimes of much lower annual rainfall. This paper presents the results of ethnographic and cross-cultural investigations in the cultivation of Pearl millet, Finger millet and Sorghum, with a global perspective. We use published ethnographic material and novel data collected on the field to build and test models that display the interaction of ecological and geographic variables in explaining agricultural practices. The aim of this research is to show how rainfed agriculture is practised much more often, and in much more suitable areas, than normally reported. This holds the potential for the understanding of how these practices can play a pivotal role for long-term resilience and future sustainability of agricultural systems in drylands.

Keywords: eHRAF; rainfed agriculture; millets; sorghum; Traditional Knowledge; drylands, modelling.

1. Introduction

Finger millet, pearl millet and sorghum are amongst the most important drought tolerant crops in the world. These cereals are cultivated in several ecological regions, but are most common in drylands, where they constitute major food crops (Belton and Taylor 2004, Hadebe et al. 2016, Gupta et al. 2017). Compared to other crops, such as wheat, maize or rice, sorghum and millets require less water input during their growth. Still, they have received comparatively much less attention (see Jones et al. 2016). A minimum of 300 mm/yr for millets and 350/400 mm/yr for sorghum are considered necessary for the development of seeds (ICRISAT and FAO 1996). This entails that in all those areas where annual rainfall is lower than 300 mm, especially during the period of plant growth, it would not be possible to cultivate these crops without irrigation. However, there are ethnographic examples of modern societies that do cultivate these crops extensively, under exclusively rainfed conditions, in areas where annual average precipitation is much lower (Lancelotti et al. 2019). In this paper, we aim at analysing how widespread this practice is, and to derive some decision-making models that could respond to the general questions: (1) how do people engage with a practice that is supposedly not viable but might hold a great potential for drylands? (2) what are the ecological drivers behind the cultivation of sorghum, finger and pearl millet? And (3) what can be done to sustain, improve and amplify these agricultural systems?

We approach these research questions through an ethnographic and cross-cultural modelling perspective. Differently from the yield-oriented models normally developed in agronomic studies (e.g. Misra et al. 2010, Van den Putte et al. 2010, Handschuch and Wollni 2016, Satir and Berberoglu 2016, Adam et al. 2018, Silungwe et al. 2019), we focus on the decision mechanisms behind the choice of growing finger millet, pearl millet and sorghum, as well as on the techniques that have been traditionally applied to cultivate these cereals regardless of production outputs. This information holds incalculable value in the current search towards ecological sustainability (see Lam et al. 2020) and food security (Nolan and Pieroni 2014, and references therein) as it results from extremely resilient social-ecological systems, which have been in place for extended periods of time and are a consequence of long-term processes of ecological adaptation (see Altieri and Nicholls 2017, Singh and Singh 2017, and references therein). As so, we integrate traditional ecological knowledge[1] (TEK)

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[1] Also referred to as local or indigenous ecological knowledge (LEK, IEK). According to the World Agroforestry Centre (ICRAF), local knowledge is defined as a the knowledge of a particular community living in a specific location as a result of traditional, external and contemporary learning; indigenous knowledge refers to culturally embedded explanations of reality; and traditional knowledge contemplates the part of local knowledge that is transmitted through generations (ICRAF 2014).

with academic ecological knowledge[2] (AEK) (see Ludwig and Poliseli 2018) in order to create models that aim to understand how traditional agricultural systems relate to their surrounding environment.

Traditional agricultural practices are the result of long-term adaptation processes (Altieri and Nicholls 2017) mainly determined by the combined effect of plant growth rhythms and the surrounding environment (Lasco et al. 2016). Undoubtedly, agricultural activities can be related to other factors such as market economy, technological implementations or social-cultural tradition, which contribute to the high variability of agricultural systems that we find in human societies. However, we maintain that, under specific environmental conditions, societies can only adopt a finite number of agricultural solutions, independently of their cultural baggage (but see Fraser et al. 2015). In fact, as an ecological or medical reason is often at the basis of food taboos (Meyer-Rochow 2009), which can be seen as an extremisation of food preferences, it is reasonable to assume that this might hold true also for the latter. As so, we designed a model that analyzes the cultivation and farming techniques of communities with non-market economies that practice non-mechanized agriculture (TEK), in relation to crop rhythms and ecological settings in which they are applied (AEK).

For this purpose, we created a database of published and novel ethnographic data on all the known communities that cultivate one or more of the target crops, independently to their environmental, ecological or technological background. Therefore, we included the full spectrum of environmental conditions in the model in order to capture all the variability of conditions in which these three crops are grown. Thus, for example, we recorded instances of sorghum and finger millet cultivation in very humid areas (e.g. the Khasi or the Garo of North-eastern India). However, in humid environments these species represent one of the many that are cultivated and usually have a mere subsidiary role, whereas in drylands, and especially in hyper-arid and arid areas, sorghum and millets are sometimes the only crops available and constitute a staple food. Hence, we will concentrate our discussion in the latter given their primary role in drylands.

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[2] Also referred to as scientific or Western ecological knowledge (SEK, WEK). Ludwig and Poseli (2018) argue for the use of AEK in order to avoid conflicts generated by the concept of what is scientific (SEK would imply that LEK, IEK and AEK have no scientific base) or the provenance of the scientists (WEK suggest that only Western knowledge can be considered academic).

2. Cultivation in drylands

Drylands are generally defined by the scarcity of water, which affects the environment and its natural resources, and therefore determines and drives human economic activities. The United Nations Environment Programme (UNEP) has provided a clear definition of drylands according to an aridity index (AI), expressing the ratio between average annual precipitation and potential evapotranspiration. According to the UNEP, drylands are lands with an AI < 0.65, and can be further divided, into hyper-arid (AI <0.03), arid (0.03-0.2), semi-arid (0.2-0.5) and dry sub-humid (0.5-0.65) lands. Drylands represent 41% of the global land area, and are to be found throughout all continents (Figure 1).

Characterized by patchy and limited resources, often ephemeral and erratic, drylands - especially hyper-arid to arid - are generally seen as ‘marginal’ areas for human settlement and food production. They are fragile ecosystems, where minor shifts in rainfall can trigger heavy changes in the environment, that can in turn ignite episodes of drought, famine, and migrations. Nonetheless drylands have hosted the emergence and the development of many statal entities throughout the last six millennia, like Ancient Egypt, Mesopotamian states and empires, the Indus civilizations, the kingdom of Aksum, the Zimbabwe cultures, or the Mesoamerican states, among others. Contrarily to the large-scale processes (e.g. emergence of state) that often occurred in centres close to rivers or better watered areas, that left monumental and massive evidence, the surrounding drier areas have generally been hosting small scale societies that used flexible, sometimes opportunistic, approaches to develop adaptive strategies to cope with erratic resources, maintaining tight or loose ties with prominent centres, villages, or cities. Those peripheries have often been considered a sort of marginal edges to wetter areas, and only recently have been undergoing a profound re-elaboration, and some authors have begun to see drylands between those centres as active centers of innovations throughout history (e.g. Clarke et al. 2016, Zerboni et al. 2017).

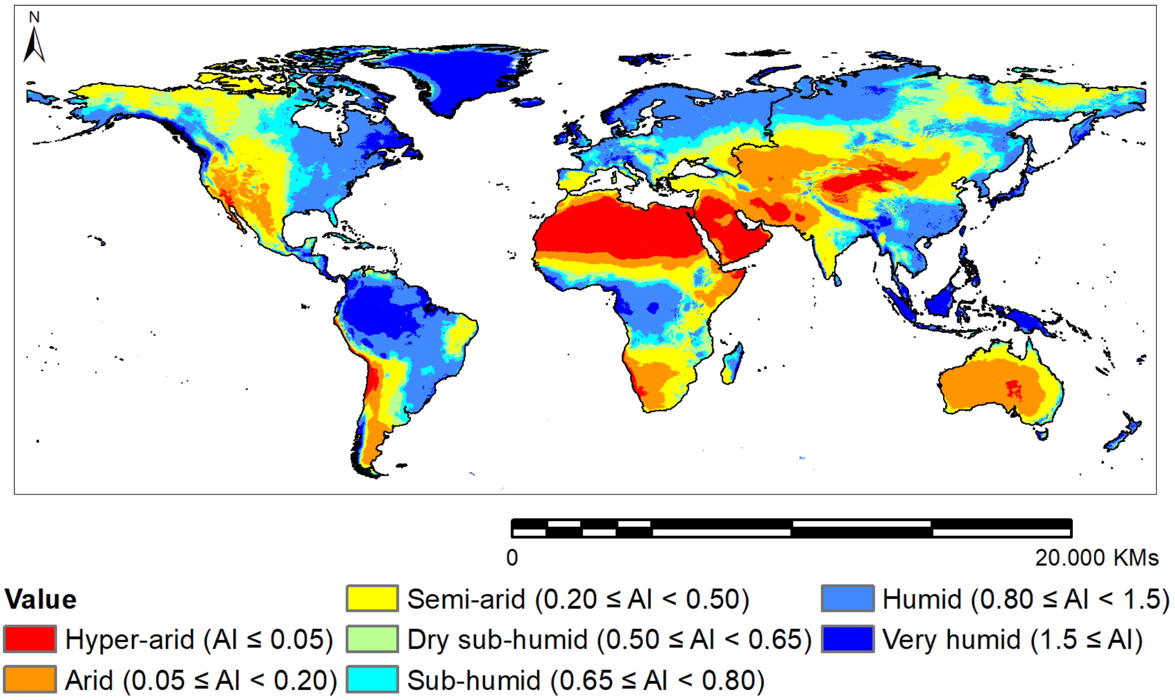


Figure 1: World's regions classification according to Aridity Index values

The legacy of long-term past adaptations in those open spaces set outside of permanent centres is nowadays to be found in the traditional ecological knowledge of current drylands inhabitants, who developed a variety of innovative solutions to produce food under strong environmental constraints. Yet, in many reconstructions of agricultural land use and system productivity, large portions of drylands (hyper-arid and arid, see Figure 1) are considered totally, or mostly, unproductive, under the assumption that below a given rainfall cultivation not viable (e.g: Rockstrom and Falkenmark 2015). This holds true even when we explore maps of rainfed cultivation of drought-resistant and drought-tolerant species, such as millets and sorghum, and both global (e.g. Sebastian 2014) and regional viewpoints (e.g. NLUPP 2010) do not consider arid and hyper-arid lands as suitable areas for cultivation. Most of these maps are produced through satellite imagery with low resolution through the most common indices such as the NDVI, hampering and limiting the remote recording of patchy and dispersed small fields. Only in very recent years, in fact, international space agencies and private enterprises have developed and started using new hyper-resolution sensors (up to few centimetres) that are capable of catching sub-metric scale variation in the Earth land cover These products are becoming accessible to the public through online platforms (e.g. Planet.com) at affordable prices by the end of the present decade, and their impact on global studies of land-use is yet to come.

In general, a lack of understanding about dryland social-ecological systems has often led to their undervaluation and demise. Traditional knowledge has often been considered irrational rather than sustainable, under biased perspectives funded on typically western concepts (regular planning, investment and expected return, focus on few crops, intensification of production). As previously stressed (Kratli et al. 2013), development plans have often failed to provide long-term support and rehabilitation to drylands communities in case of drought or famine. As a result, nowadays, overall socioeconomic conditions in drylands are far worse than in other parts of the planet, and not surprisingly World poverty is concentrated in drylands (UNCDD 2011). Recently, a number of papers (e.g. Kratli et. al 2013) have questioned the 'traditional' approach to drylands and are exploring different perspectives. Largely inspired by the principle of the New Ecology (Ellis and Swift 1988, Behnke et al. 1993), and by the adoption of the concept of resilience (as formulated by Holling 1973 and applied with success to drylands, e.g. D'Odorico and Bhattachan 2012, Solh and Van Ginkel 2014, Robinson et al. 2015, Balbo et al. 2016) of social-ecological systems, the study of Traditional Ecological Knowledge (TEK) is being considered a possible way to design sustainable and durable approaches.

3. Materials and Methods

3.1 Ethnographic data: systematic interviews and eHRAF.

Traditional Ecological Knowledge on the cultivation practices of sorghum, pearl millet and finger millet was extracted from both primary and secondary sources. On the one hand, ethnographic fieldwork was carried out in Tigray (Ethiopia), Khartoum State (Sudan) and Sindh (Pakistan) in 2018 and 2019, during which several interviews were conducted with people engaged in traditional agricultural practices. On the other hand, data from existing anthropological studies were obtained from the Human Relation Area Files (eHRAF - http://hraf.yale.edu/) (eHRAF World Cultures, 2020). The objective was to provide a consistent, coherent body of information which allowed for the creation of a robust dataset for cross-cultural comparison on agricultural activities. eHRAF enables researchers to quickly browse across a wide range of cultures, and perform cross-cultural studies (see Ember and Fischer 2017). In the present study, we included all occurrences reporting the cultivation of finger millet (FM), pearl millet (PM) and/or sorghum (SB). The study variables taken into account included: intensity of cultivation (casual, extensive and intensive), watering regimes (rain-fed, *décrue* and irrigation) and the duration of the growing cycle of each crop (Table 1).

Table 1: Variables considered (definitions and references)

Variable	Definition	References
FM Cultivation	Presence of finger millet (*Eleusine coracana* Gaertn.) production	eHRAF
PM Cultivation	Presence of pearl millet (*Pennisetum glaucum* (L.)R.Br.) production	eHRAF
SB Cultivation	Presence of sorghum (*Sorghum bicolor* (L.) Moench) production	eHRAF
Casual Agriculture	Slight or sporadic cultivation of food or other plants incidental to a primary dependence upon other subsistence practice	Murdock 1981: 98
Extensive Agriculture	Or shifting cultivation, as where new fields are cleared annually, cultivated for a year or two, and then allowed to revert to forest or brush for along fallow period	Murdock 1981: 98
Intensive Agriculture	On permanent fields, utilizing fertilization by compost or animal manure, crop rotation, or other techniques so that fallowing is either unnecessary or is confined to relatively short periods	Murdock 1981: 98
Rain-fed Agriculture	Water is provided by rainfall alone (directly or as run-off), cultivation occurs far from any permanent water sources and without any water harvesting	Lancelotti et al. 2019: 1027
Décrue Agriculture	Water is provided by natural inundation, typically from major river systems (floodplain cultivation)	Lancelotti et al. 2019: 1027
Irrigated Agriculture	Water is provided to crops at regular intervals throughout the growing season by human intervention	Lancelotti et al. 2019: 1027
Duration of FM/ PM/SB growing cycle	Mean growing cycle duration and variance	eHRAF

All ethnographic bibliography containing both generic and specific terms referring to the three crops under study was extracted from eHRAF and systematically reviewed (Table 2). Data was separated and organized by community for a total of 66 entries. This preliminary dataset was normalized into a cultures database which included pre-created categories on socio-economic features (e.g. type of subsistence economy, settlement or group mobility) and plant cultivation practices and techniques (e.g. crop importance, cycle duration, land preparation, manuring or watering systems) based on the Standard Cross-Cultural Sample Codebook (Divale 2004). Further eHRAF publications were reviewed in order to complete the dataset, and only the communities with enough information to define all the study variables were retained for analysis, resulting in a final dataset of 57 entries. Finally, as this research concentrates on agricultural techniques rather than on social aspects, the database was organised by growing cycles taking into account that some societies cultivate in each year 2 crops, with different techniques hence reaching a total of 72 entries (Supplementary materials).

Table 2: List of references for eHRAF community

ID	Culture	Region	References	Field dates
1	Amhara	Eastern Africa	Messing 1957, Hoben 1973	1953-1970
2	Azande	Central Africa	Anderson 1911, Larken 1926, Culwick 1950, Baxter and Butt 1953, Schlippe 1956	1900-1953
3	Bagisu	Eastern Africa	Heald 1989	1965-1969
4	Bambara	Western Africa	Paques 1954, Toulmin 1992, Becker 1996, 2000	1945-2000
5	Barundi	Central Africa	Meyer 1959, Albert 1963	1911-1957
6	Bemba	Southern Africa	Richards 1939, 1956, Lagacé and Skoggard 1997	1930-1934
7	Bena	Eastern Africa	Culwick et al. 1935	1931-1933
8	Central Thai	Southeast Asia	Judd 1973	1960-1970
9	Dogon	Western Africa	Paulme and Schützw 1940, Martí 1957, Griaule and Dieterlen 1986, Van Beek 1991, 2002, Griaule 1994	1931-1991
10	Fellahin	Northern Africa	Amraar 1988	1945-1951
11	Fon	Western Africa	Herskovits 1938	1920-1931
12	Ganda	Eastern Africa	Mair 1965	1932-1932
13	Garo	South Asia	Playfair 1909, Burling 1963, Nakane 1967, Majumdar 1978	1908-1965
14	Gikuyu	Eastern Africa	Kenyatta 1953, Routledge and Routledge 1968, Davison 1996	1905-1994
15	Gond	South Asia	Fuchs 1960	1951-1959
16	Gusii	Eastern Africa	Hakansson 1990, 1994	1982-1985
17	Hausa	Western Africa	Forde and Scott 1946, Hill 1972	1940-1967
18	Ila	Southern Africa	Smith and Dale 1920, Jaspan 1953, Fielder 1979	1902-1914
19	Inner Mongolia	Central Asia	Chang 1933, Pasternak and Salaff 1993	1988-1990
20	Iran	Middle East	Hooper et al. 1937	1930-1984
21	Kaffa	Eastern Africa	Adem 2012	No date
22	Kanuri	Western Africa	Cohen 1967, Rosman 1978	1956-1965
23	Kapsiki	Western Africa	Van Beek 1991	1978-1991
24	Katab	Western Africa	Bonat 1989	1980-1984
25	Khasi	South Asia	Gurdon 1907, Nakane 1967	1955-

				1956
26	Konso	Eastern Africa	Hallpike 1970, 2008, 2016	1965-1997
27	Korea	East Asia	Han 1949, Chŏn 1984	1975-1976
28	Lepcha	Central Asia	Gorer and Hutton 1938, Morris 1938, Siiger and Rischel 1967, Foning 1987	1937-1984
29	Lozi	Southern Africa	Gluckman 1941, 1943, 1951, Peters 1960, Beierle 1995	1940-1952
30	Manchu	East Asia	Isett 2007	No date
31	Miao	East Asia	Diamond 1993, 2009	1980-1990
32	Mossi	Western Africa	Tauxier and Brunel 1912, Hammond 1959, Mangin 1959	1908-1956
33	Ngibelai Turkana	Eastern Africa	Gulliver 1951, McCabe and Dyson-Hudson 1985, Bollig 2001, McCabe 2004	1948-1996
34	Ngikebotok Turkana	Eastern Africa	Gulliver 1951, McCabe and Dyson-Hudson 1985, Bollig 2001, McCabe 2004	1948-1996
35	Northern Tuareg	Northern Africa	Lhote 1944, Nicolaisen 1959, 1963	1929-1962
36	Nuba	Eastern Africa	Faris 1989	1966-1980
37	Nuer	Eastern Africa	Evans-Pritchard 1938, 1940, Butt 1952, Howell 1954	1930-1944
38	Nupe	Western Africa	Nadel 1942	1934-1936
39	Nyakyusa	Eastern Africa	G Wilson 1938, MH Wilson 1977, Kalinga 1984	1934-1938
40	Pashtun	Central Asia	Barth 1981	1954-1979
41	Rwandans	Central Africa	Czekanowski 1959, Pagès 1960	1907-1925
42	Santal	South Asia	Biswas 1956	1931-1945
43	Sherpa	Central Asia	Kunwar 1989, Stevens 1990	1979-1987
44	Shilluk	Eastern Africa	Dempsey 1956	1940-1954
45	Shluh	Northern Africa	Berque 1955	1950-1970
46	Shona	Southern Africa	Kuper et al. 1954, Holleman 1969, Bhila 1982	1945-1948
47	Somali	Eastern Africa	Lewis 1962, Galaal 1968, Helander and Beierle 1997, Lewis and Samatar 1999	1955-1970
48	Songhai	Western Africa	Stoller 1989, 2016	1970-1987
49	Southern Tuareg	Northern Africa	Nicolaisen 1959, 1963	1951-1962
50	Tallensi	Western Africa	M Fortes and SL Fortes 1936, M Fortes 1937, 1945	1934-1945
51	Tamil	South Asia	Sivertsen 1963, Nambiar 1965, Haswell 1967, Dumont 1983	1949-1961
52	Teda	Central Africa	Kronenberg 1958, Chapelle 1982	1930-1955
53	Telugu	South Asia	Tapper 1988	1970-1972
54	Tiv	Western Africa	Abraham 1933, East 1939, P Bohannan 1953, 1957,	1916-

			1966, P Bohannan and L Bohannan 1953, 1968	1953
55	Tonga	Southern Africa	Scudder 1962, 1971, 1972, Colson 1986, Reynolds 1968, Cliggett 2005	1949-2004
56	Tsonga	Southern Africa	Junod 1927	1895-1909
57	Wolof	Western Africa	Boilat 1853, Audiger and Moore 1961, Gamble 1967, Venema 1978	1843-1957

Second, a total of 56 semi-structured interviews were systematically completed using a previously created questionnaire as a general guide (Annex). The questions targeted data on agricultural activity related to finger millet, pearl millet and sorghum production, including information about cereal species selection and cultivation, farming methods and techniques, water management practices, growing cycles, land tenure, alimentation and food-security, amongst other topics. Participants were selected through snowball sampling, always under the advice and approval of local authorities and colleagues. Interviewees were majoritarily landowners from rural and semi-rural areas, ranging between 27 and 88 years old and whose main economic activity was farming. They included 47 men and 9 women which had been farmers for the most part of their lives. The total number of interviews performed in each area depended on the availability of participants in a radius of less than 100 km from the base camp and could not be increased to safeguard the security of fieldwork participants. Retrieved information was processed, normalized and added into a separated dataset both as single entries for each interview but also as aggregated data for each of the three cultures: Tigrinya, Sudan Arabs and Sindhs (Supplementary materials).

3.2 Environmental data and spatial distribution.

A total of 58 ecological variables both physio-climatic and edaphological were included, as they are considered to be the principal factors in plant growth and development (Jones et al. 2017). Environmental data were extracted from published GIS data at 30 arc-secs resolution and derived raster files created with ArcGIS 10.6 or QGIS 3.4.15 with GRASS 7.8.2 (Table 3). Mean values ("_m") and variances ("_v") were retrieved for every environmental variable, resulting in a grand total of 116 variables.

Table 3: Summary of the environmental variables used in the study. Sources: Global Multi-resolution Terrain Elevation Data (GMTED2010, Danielson and Gesch 2011); Global Solar Atlas (GSA, Estima et al 2013); CIGAR-CSI. Global Aridity and PET database (Zomer at al. 2008); WorldClim (Fick and Hijmans 2017); Global Soil Organic Carbon Map (Hiederer and Köchy 2011); Global Soil Dataset for Earth System Models (Shangguan et al. 2014).

Environmental variables	**Abbreviation**
Altitude	ALT
Slope	SLO
Insolation time	INS
Global Horizontal Irradiance	GHI
Aridity Index	AI
Precipitation Concentration Index	PCI
Annual Mean Temperature	BIO1
Mean Diurnal Range (Mean of monthly (max temp - min temp))	BIO2
Isothermality (BIO2/BIO7) (* 100)	BIO3
Temperature Seasonality (standard deviation *100)	BIO4
Max Temperature of Warmest Month	BIO5
Min Temperature of Coldest Month	BIO6
Temperature Annual Range (BIO5-BIO6)	BIO7
Mean Temperature of Wettest Quarter	BIO8
Mean Temperature of Driest Quarter	BIO9
Mean Temperature of Warmest Quarter	BIO10
Mean Temperature of Coldest Quarter	BIO11
Annual Precipitation	BIO12
Precipitation of Wettest Month	BIO13
Precipitation of Driest Month	BIO14
Precipitation Seasonality (Coefficient of Variation)	BIO15
Precipitation of Wettest Quarter	BIO16
Precipitation of Driest Quarter	BIO17
Precipitation of Warmest Quarter	BIO18
Precipitation of Coldest Quarter	BIO19
Soil Organic Carbon	SOC
Bulk density (Top-soil and subsoil)	BD1 and BD2
Clay content (Top-soil and subsoil)	CLAY1 and CLAY 2
Silt content (Top-soil and subsoil)	SILT1 and SILT2
Sand content (Top-soil and subsoil)	SAND1 and SAND2
Gravel content (Top-soil and subsoil)	GRAV1 and GRAV2
Cation Exchange Capacity (Top-soil and subsoil)	CEC1 and CEC2
Electrical Conductivity (Top-soil and subsoil)	ECE1 and ECE2
pH (H2O) (Top-soil and subsoil)	PH1 and PH2
Organic Carbon (Top-soil and subsoil)	OC1 and OC2
Total Potassium (Top-soil and subsoil)	TK1 and TK2
Total Nitrogen (Top-soil and subsoil)	TN1 and TN2
Total Phosphorus (Top-soil and subsoil)	TP1 and TP2
Total Sulphur (Top-soil and subsoil)	TS1 and TS2
Volumetric water content at -10 kPa (Top-soil and subsoil)	WC11 and WC12
Volumetric water content at -33 kPa (Top-soil and subsoil)	WC21 and WC22
Volumetric water content at - 1500 kPa (Top-soil and subsoil)	WC31 and WC32

Data retrieval was based on previously assigned “areas of activity” (Figure 2): the cultures spatial distribution was obtained from the Geo-Referencing of Ethnic Groups dataset (GREG - Weidman et al. 2010) which employs geographic information systems (GIS) to represent group territories as polygons independently of state boundaries. In case of no data, the location of societies was assigned by using their administrative units as described in eHRAF documents. Territories designated to each culture were not restricted to agriculturally active areas, but included their whole area of activity. Centroids of these polygons were utilized in order to define longitude and latitude for each human community. Furthermore, the geographic location of the ethnographic interviews was established as a 50-kilometer-round area from the GPS location of each subject house. This choice was based on the information about agricultural fields location given during the interviews, which ranged between 0 and 40 kilometers.

3.3 Data analysis and modelling.

The eHRAF data was used as training response variables, whereas the ethnographic dataset was utilized as testing response data.Both datasets were transformed into dummy binary variables and divided into 4 subsets for separate analysis: (1) presence or absence of each study crop (all cases, n = 72); (2) agricultural intensity and watering systems for finger millet (n = 30); (3) for pearl millet (n = 27); and (4) for sorghum (n = 55). Redundancy analysis (RDA) (see Legendre and Legendre 2012: 629-631) was applied in order to analyze each response subset variability in relation to the duration of the plants growing cycle and their surrounding environment. All training response datasets were transformed using Hellinger’s transformation prior to RDAs (see Legendre and Gallagher 2001, Legendre and De Cáceres 2013), whereas the explanatory datasets were standardized (by subtracting the variable mean to each value and then dividing it for the standard deviation) to create comparable scales.

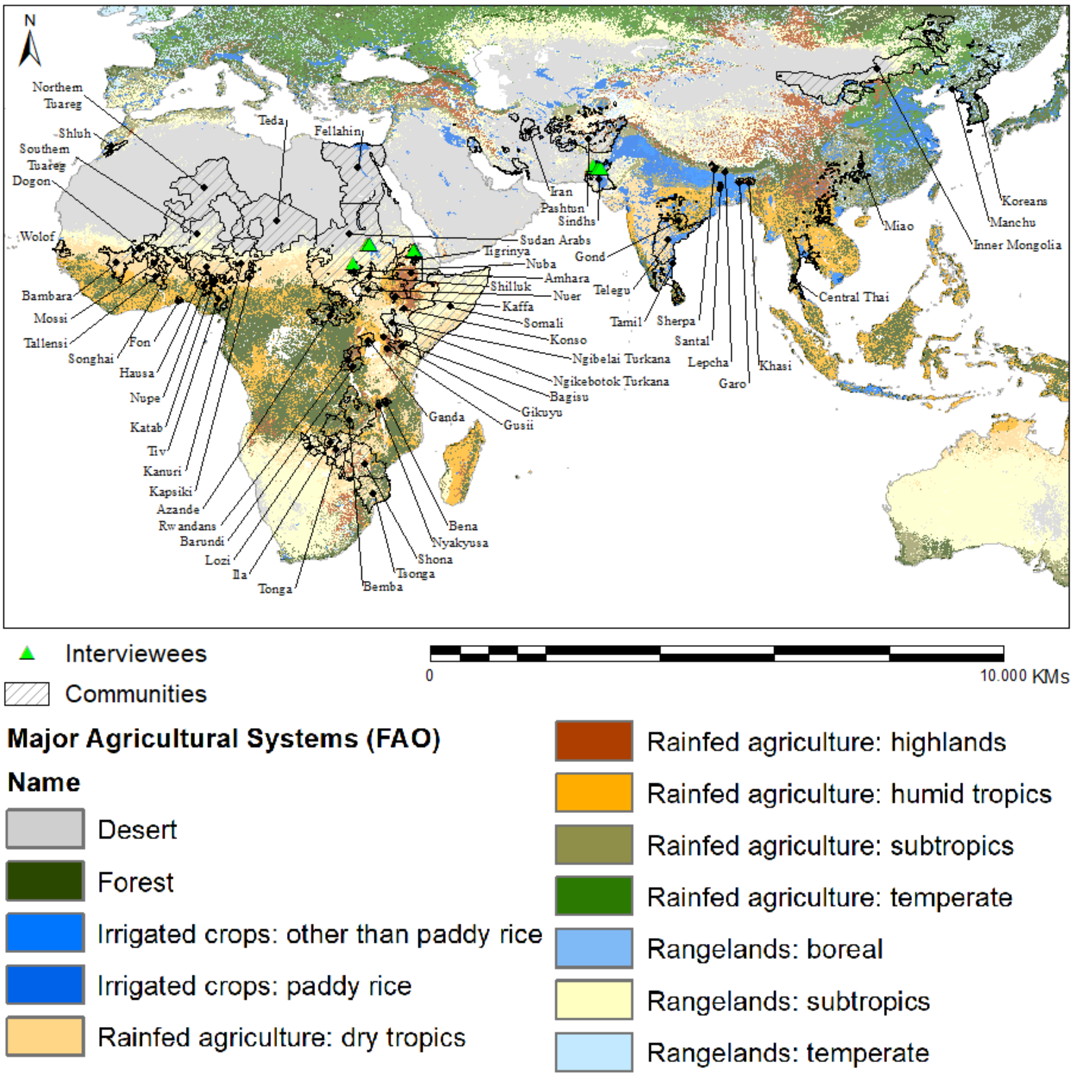


Figure 2: Distribution of major agricultural systems according to FAO (George et al. 2010) and distribution of ethnographic groups (eHRAF), their territorial distribution as indicated by GREG polygons (Weidman et al. 2010), and location of ethnographic interviews.
All operations were performed using R 3.6.2, specifically the rgdal (Bivand et al. 2019), raster (Hijmans 2020), and spatialEco (Evans 2020) packages. Code is available as supplementary materials.

First, global RDAs were performed to explore the overall variability which was accounted for by growing cycle and environmental predictors. The proportion of inertia retained by each of these components was also retrieved as the adjusted coefficient of determination (R^2) (Ezekiel 1930, see Pares-Neto et al. 2006). Permutation tests were used to check for statistical significance of each global RDA (Legendre et al. 2011) and the variance inflation factors of each variable (VIF) (Neter et al. 1996, cited in Legendre and Legendre 2012: 558) were calculated to look for linear dependencies between explanatory variables. Second, adjusted-R^2-based forward selection (FS) (see Blanchet et al. 2008) was used to identify and select significant predictor variables and reduce collinearity - as it can work with supersaturated models (Borcard et al. 2018: 226). A double stopping criterion (R^2 combined with alpha level) was implemented and tested over 1000 permutations (Blanchet et al. 2008: 2630). The resulting reduced models were analyzed as the global RDAs for explained inertia and statistical significance, as were the FS variables for collinearity and statistical relevance. Model coefficients for each FS predictor and ordination scores for both response variables and study cases were calculated in order to understand the effect of each explanatory variable in the response data.

Next, variation partitioning (VP) was performed to test for spatially structured variance (Borcard et al. 1992, Pares-Neto et al. 2006). For this purpose, reduced models were used along with XY coordinates and distance-based Moran's eigenvector maps (dbMEMs) (Borcard and Legendre 2002, Borcard et al. 2004, Legendre et al. 2012; but see Gilbert and Bennett 2010, Smith and Lundholm 2010). Linear trends of each response data subset were analysed by RDA following Borcard et al. (2018: 314). When statistically significant, response data was detrended prior to dbMEM analysis by regressing all response variables on the XY coordinates and retaining the residuals (Legendre and Legendre 2012). The construction of dbMEMs (Borcard and Legendre 2002, see Borcard et al. 2018: 320-327) was carried out using minimum distance between polygon frontiers as geographical distances amongst study cases. RDA was then applied for each response data subset against their dbMEMs. The resulting spatial submodels were tested for statistical significance and FS was applied when confirmed by 1000 permutations. VP analysis (refs., see Borcard et al. 2018: 329-333) was used to decompose the total inertia into independent and shared fractions: that is, the pure fraction of each explanatory dataset; their joint fractions as a result of intercorrelation, and the remaining unexplained variation. Testeable shared fractions were evaluated by simple RDAs, whereas the pure individual fractions of each predictor dataset were tested by means of partial RDA.

Models were evaluated using performance measures: accuracy (correctly classified entries / total number of cases), recall (positive entries correctly classified / total number of positive cases), precision (positive samples that were correctly classified / total number of positive predicted cases) and F1-score (evaluation of the classification performance through calculation of the harmonic mean of precision and recall) (Tharwat 2018). A classification threshold was obtained by using the sensitivity-specificity sum maximization approach on the training data (Cantor et al. 1999, Manel et al. 2001, see Liu et al. 2005, Nenzen and Araujo 2011 for assessments of available methods). The reduced models were then validated by assessing their effectiveness on predicting their training datasets. Next, accuracy and F1-score were measured when predicting the testing response data.

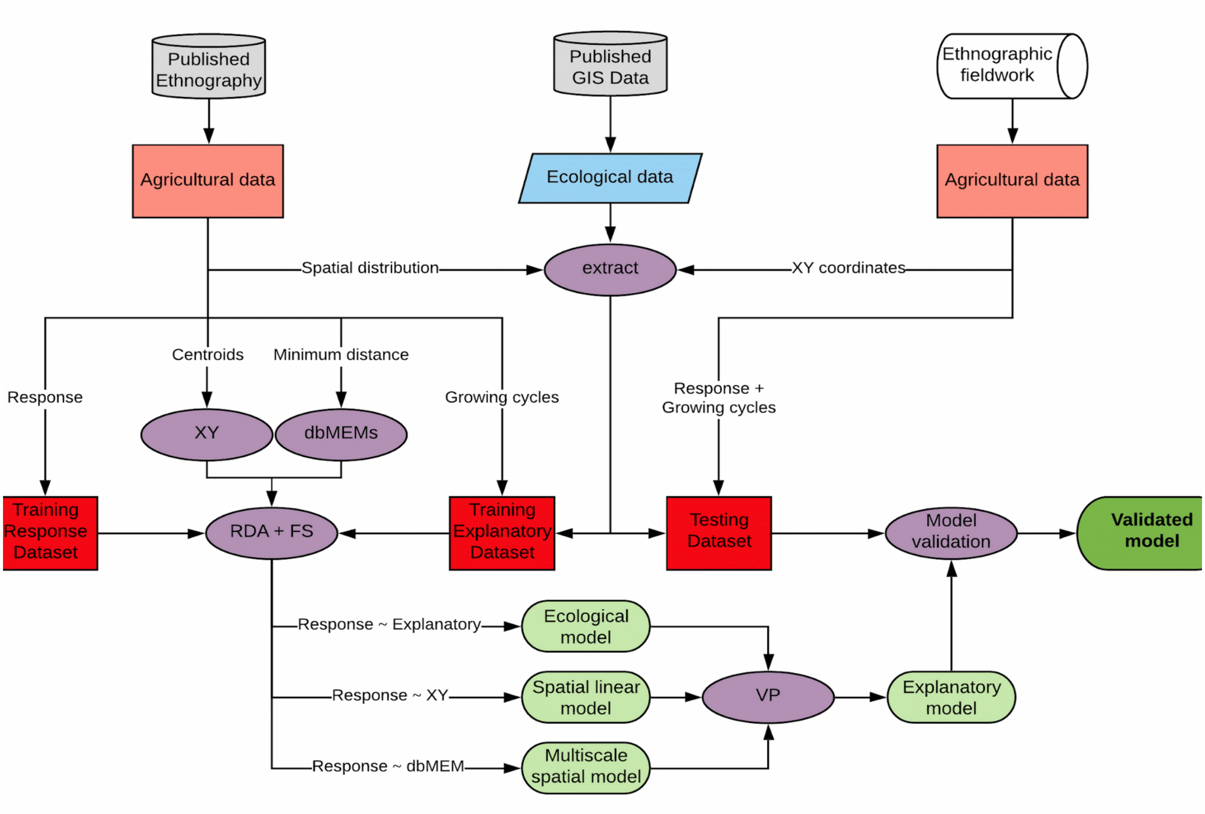


Figure 3: Schematic workflow used in this study (expanded version in supplementary materials). Grey boxes represent online databases. Blue boxes contain spatial data. Red rectangles correspond to datasets. Processing data steps in R are purple ovals. Green boxes represent models.

Figure 3 presents a summary of all the described methods. All statistical analyses were executed using R 3.6.2, specifically the FactoMineR (Le et al. 2008), factoextra (Kassambara and Mundt 2019), vegan (Oksanen et al. 2019), rgeos (Bivand and Rundel 2019), adespatial (Dray et al. 2020) and PresenceAbsence (Freeman and Moisen 2008) packages. The code is available as supplementary materials.

4. Results

Descriptive statistics of crop selection, as well as by finger millet (FM), pearl millet (PM) and sorghum (SB) cultivation training response data (supplementary materials) are presented in Table 4. Amongst the final 72 study cases, finger millet was cultivated by 41.6% pearl millet by 37.5% and sorghum by 76.3%. Entries could be classified in 6 groups according to their crop package: communities that exclusively cultivate finger millet (16.7%), pearl millet (6.9%) or sorghum (30.6%); communities that cultivate both finger millet and sorghum (15.3%);

communities that cultivate both pearl millet and sorghum (20.8%); communities that cultivate all 3 crops (9.7%). Noteworthy, no community showed exclusive cultivation of the two millets alone.

Table 4: Descriptive statistics of training response data

Study crops		**FM**		**PM**		**SB**	
Attribute	n	f	%	f	%	f	%
Crop selection	72	30	41.6	27	37.5	55	76.3
Intensity of cultivation	72	30		27		55	
Casual agriculture (CAS)		0	0.0	0	0.0	4	7.3
Extensive agriculture (EXT)		17	56.7	15	55.6	22	40.0
Intensive agriculture (INT)		13	43.3	12	44.4	29	52.7
Watering regimes	72	30		27		55	
Rainfed agriculture (RF)		28	93.3	23	85.2	46	83.7
Décrue agriculture (DEC)		0	0.0	0	0.0	3	5.4
Irrigated agriculture (IRR)		2	6.7	4	14.8	6	10.9

Regarding cultivation techniques and practices, finger millet seems to be cultivated extensively by slightly more than half the communities (56.7%) and predominantly rainfed (93.3%). Groups were identified by cross tabulation as Extensive-Rainfed (56.6%), Intensive-Rainfed (36.7%) and Intensive-Irrigated agriculture (6.7%). A similar distribution was found for pearl millet cultivation intensity (55.6% extensive and 44.4% intensive) whereas watering practices showed a slightly weaker dominance of rainfed systems (85.2%) versus irrigation (14.8%). The results of cross tabulations for pearl millet cultivation were similar to that of finger millet, but with a higher presence of irrigated systems: 55.6 % entries were classified as Extensive-Rainfed, 29.6% as Intensive-Rainfed and 14.8% as Intensive-Irrigated agriculture. Noteworthy, no cases of casual agriculture or *décrue* watering were identified amongst either finger or pearl millet producers. Finally, sorghum agriculture featured a higher rate of diversity: most farmers engaged in intensive cultivation (52.7%), though 40% still practiced extensive agriculture. Interestingly, 7.3% were classified as casual agriculturalists. Watering practices also were more diverse: even though rainfed regimes were clearly dominant (83.7%), *décrue* and irrigated systems were also encountered in 5.4% and 10.9% respectively. Along with Extensive-Rainfed (40%), Intensive-Rainfed (36.4%) and Intensive-Irrigated (10.9%), 2 additional groups were identified by cross tabulation as Casual-Rainfed (7.3%) and Intensive-*Décrue* (5.4%), in a total of 5 combinations for sorghum cultivation. In no instance, casual agriculture was observed to be combined with *décrue* or irrigated watering regimes, neither was extensive agriculture.

4.1 Modelling the variability.

Global RDAs (Table 5) showed rather high explanatory potential in all cases: adjusted-R^2

values ranged between 56.3% and 100%. However, the models were only statistically significant for crop selection and sorghum cultivation datasets -the statistical significance of pearl millet was not tested as there was no residual fraction. The examination of variance inflation factors showed very high collinearity amongst the predictors included in the global RDAs.

Table 5: Summary of global RDAs by response data subset

Global RDAs	Total Inertia	Constrained Inertia		Adjusted-R²	Unconstrained Inertia		p-value
		Total	Proportion		Total	Proportion	
Crop selection	0.441	0.401	0.908	0.563	0.041	0.092	**0.002**
FM cultivation	0.318	0.303	0.951	0.644	0.0156	0.049	0.057
PM cultivation	0.388	0.388	1	1	0	0	N/A
SB cultivation	0.429	0.413	0.963	0.718	0.016	0.037	**0.004**

As a result of forward selection, the most significant predictors amongst explanatory datasets were identified for each model:

- 6 variables appeared as the most relevant for crop selection (p-values < 0.05), namely: mean top-soil volumetric water content at 15 kPa, mean top-soil pH, variance of mean temperature of the warmest quarter, mean global horizontal irradiance, variance of subsoil clay content and mean precipitation seasonality.
- The most significant variables for finger millet cultivation were: mean subsoil sulphur content, mean precipitation concentration index and top-soil mean phosphorus content.
- For pearl millet cultivation the most important variables were: variance of temperature seasonality, variance of top-soil volumetric water content at 33 kPa, mean subsoil gravel content, mean top-soil clay content, mean duration of the growing cycle, the mean temperature of wettest quarter, variance of top-soil organic carbon content, variance of top-soil silt content and mean temperature during the driest quarter.
- The most important variables for sorghum cultivation were: the mean of growing cycle duration, the variance of both top-soil and subsoil cation exchange capacity and the mean soil organic carbon.

Reduced models using forward selection predictors explained almost as much adjusted proportion of the total variance as global RDAs for crop selection (-1.4%) and finger millet cultivation (-3.7%). However, the constrained variance of pearl millet and sorghum cultivation was reduced by 12.2% and 48.7% respectively. Still, a clear improvement in statistical significance was achieved, as all reduced models passed the 1000 permutation test. Furthermore, all variables were found to be statistically significant and VIF analysis showed them to be independent to one another in all reduced models. The distribution of retained inertia by every RDA and PC axes is presented in Table 7. Models were drawn using triplots representing the 2 first RDA axes (Figure 4). These were always statistically significant except for sorghum cultivation (Table 7), in which the second axis did not pass the permutation test and only the variability retained by the first axis was considered during the analysis even though we show both in Figure 4d.

Table 6: Summary of RDAs of FS variables by response data subset

RDAs by FS variables	Total Inertia	Constrained Inertia		Adjusted-R²	Unconstrained Inertia		p-value
		Total	Proportion		Total	Proportion	
Crop selection	0.441	0.259	0.587	0.549	0.182	0.413	**0.001**
FM cultivation	0.318	0.206	0.648	0.607	0.112	0.352	**0.001**
PM cultivation	0.388	0.356	0.92	0.878	0.031	0.08	**0.001**
SB cultivation	0.429	0.127	0.296	0.24	0.302	0.704	**0.001**

Table 7: Summary of inertia retained by each RDA and PC axes

RDAs by FS variables	Eigenvalues for constrained axes								Eigenvalues for unconstrained axes			
	RDA1	p-val	RDA2	p-val	RDA3	p-val	RDA4	p-val	PC1	PC2	PC3	PC4
Crop selection	0.156	**0.001**	0.098	**0.001**	0.005	0.901	N/A	N/A	0.106	0.063	0.013	N/A
FM cultivation	0.184	**0.001**	0.023	**0.047**	N/A	N/A	N/A	N/A	0.084	0.028	N/A	N/A
PM cultivation	0.28	**0.001**	0.76	**0.001**	N/A	N/A	N/A	N/A	0.022	0.009	N/A	N/A
SB cultivation	0.1	**0.001**	0.019	0.202	0.009	0.458	0	1	0.17	0.074	0.037	0.022

Model coefficients and ordination scores results (supplementary materials) showed the presence of finger millet cultivation to be mainly related to areas with higher values of mean top-soil volumetric water content at low suction pressure and variance of mean temperature of the warmest quarter (Figure 4a). Extensive finger millet cultivation was found to be remarkably related to precipitation concentration index, whereas intensive systems appeared linked to the content of top-soil phosphorus (Figure 4b). The use of irrigation in intensive regimes was shown to be mainly associated with subsoil sulphur content. Next, the choice of pearl millet appeared related to greater irradiance and precipitation seasonality, but also to variance in subsoil clay content in a lesser degree (Figure 4a). Extensive-rainfed systems were associated with longer growing cycles, as well as with higher values of top-soil clay content and variance of top-soil organic carbon content. Intensive agriculture of pearl millet was performed by communities in regions which scored high in subsoil gravel content, mean temperature during the driest quarter and variance of top-soil water content at mid suction pressure. Rainfed regimes amongst intensive systems also depended on the two latter variables, whereas greater values of variance of temperature seasonality, mean temperature of wettest quarter and variance of top-soil silt content appeared in relation with irrigated systems (Figure 4c). Lastly, sorghum cultivation showed its higher limitant to be top-soil mean pH (Figure 4a). As for pearl millet, all rainfed sorghum regimes showed association with extended growing cycles. Casual-rainfed sorghum agriculture was identified in areas featuring elevated variance of cation exchange capacity (both topsoil and subsoil), whereas extensive-rainfed was linked to regions where only the latter was considerable. All intensive systems, regardless of watering regimes, appeared associated with communities inhabiting regions high in top-soil cation exchange capacity but also with higher soil organic carbon content per hectare, the main difference being *décrue* and irrigated agriculture not showing direct association with the duration of the growing cycles (Figure 4d).

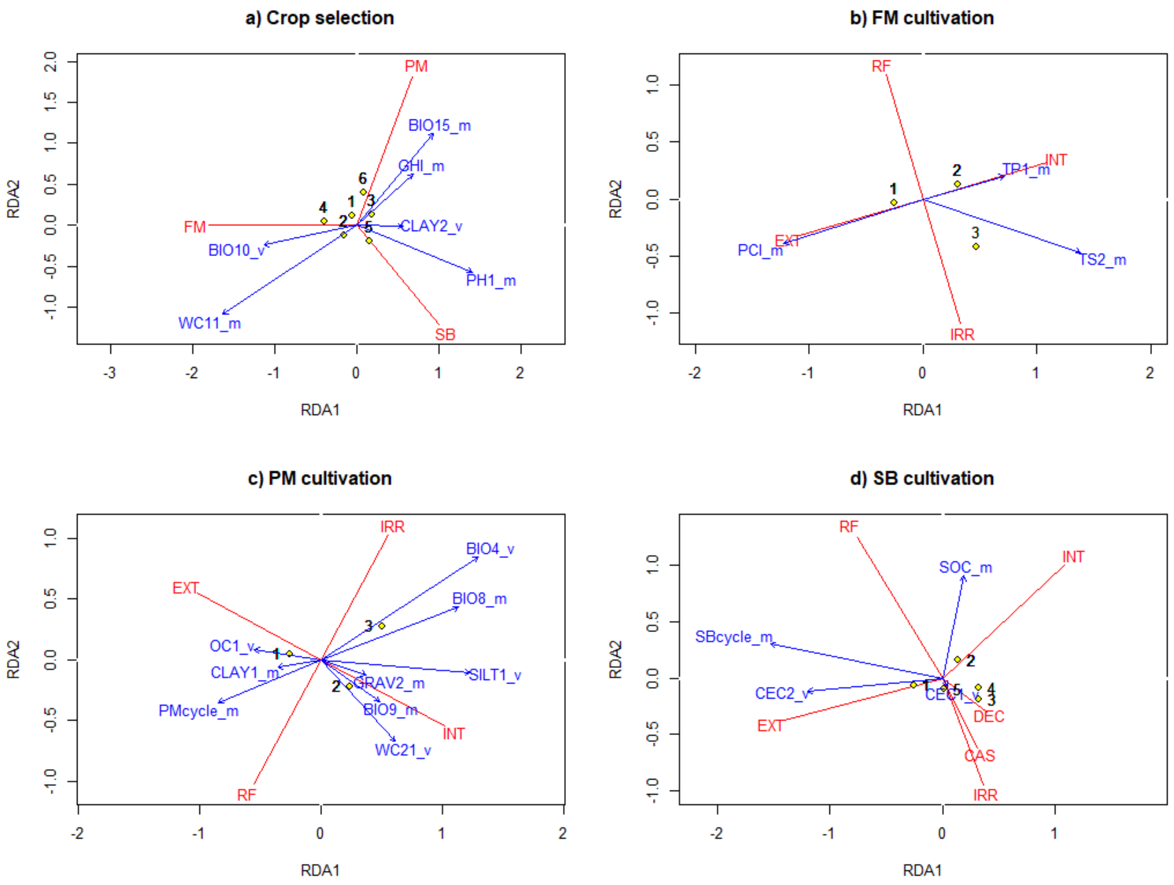


Figure 4: Triplots of RDA by FS variables for: a) Crop selection (1 = FM-PM-SB, 2 = FM-SB, 3 = PM-SB, 4 = FM, 5 = SB, 6 = PM); b) FM cultivation (1 = EXT-RF, 2 = INT-RF, 3 = INT-IRR); c) PM cultivation (1 = EXT-RF, 2 = INT-RF, 3 = INT-IRR); d) SB cultivation (1 = EXT-RF, 2 = INT-RF, 3 = INT-IRR, 4 = INT-DEC, 5 = CAS-RF). For the coding of variables see Table 3.

4.2 Spatial analyses and variation partitioning.

Linear trend analysis by RDA revealed statistically significant models for crop selection and pearl millet cultivation variables, accounting for 15.4% and 25.8% of total variance respectively (Table 8). XY coordinates were not included in the variation partitioning analysis of finger millet and sorghum cultivation as they did not pass the permutation test. None of the RDAs performed with dbMEMs were found to be statistically significant (Table 9), nor was any dbMEM selected by means of FS, hence indicating a total absence of spatial autocorrelation in both finger millet and sorghum cultivation datasets. As a result, dbMEMs were not included in VP analysis.

Table 8: Summary of RDAs by XY coordinates

RDAs by XY coordinates	Total Inertia	Constrained Inertia		Adjusted-R²	Unconstrained Inertia		p-value
		Total	Proportion		Total	Proportion	
Crop selection	0.441	0.078	0.178	0.154	0.363	0.822	**0.001**
FM cultivation	0.318	0.01	0.03	-0.042	0.309	0.97	0.743
PM cultivation	0.388	0.122	0.315	0.258	0.266	0.685	**0.003**
SB cultivation	0.429	0.03	0.07	0.034	0.399	0.93	0.08

Table: Summary of RDAs by dbMEMs

RDAs by dbMEM	Total Inertia	Constrained Inertia		Adjusted-R²	Unconstrained Inertia		p-value
		Total	Proportion		Total	Proportion	
Crop selection (detrended)	0.363	0.065	0.179	-0.06	0.298	0.821	0.808
FM cultivation	0.318	0.056	0.177	-0.038	0.262	0.823	0.634
PM cultivation (detrended)	0.266	0.072	0.273	0.1	0.193	0.727	0.168
SB cultivation	0.429	0.109	0.254	0.017	0.32	0.746	0.368

For crop selection, variation partitioning results (Table 10) showed significant effects of physio-climatic (PC), edaphological (ED) and spatial (XY) components on the variability of the study agricultural package (19.3%, 39.5% and 17.8% of the total inertia). When looking at their unique effects, the explained variance declined to 15.6%, 24.1% and 0.4% respectively. More importantly, the XY pure fraction failed to pass the test for statistical significance, hence pointing to the absence of spatial patterns in the crop selection dataset. By contrast, both physio-climatic and edaphological pure fractions significantly explained a combined 39.7% of the total inertia, and their shared fraction was almost non-existent. It is worth to note that a 12% of the variance retained by edaphological factors was also explained by the spatial component (Figure 5a), thereby pointing to the existence of a linear trend amongst edaphological variables. Also, 4% of the total inertia was shown to be shared by all physio-climatic, edaphological and spatial predictors.

Table 10: Summary of VP analysis results (GC = Growing Cycles, PC = Physio-Climatic, ED = Edaphological, XY = Geographical location)

VP Analysis	Crop selection		FM cultivation		PM cultivation		SB cultivation	
	adj-R^2	p-value	adj-R^2	p-value	adj-R^2	p-value	adj-R^2	p-value
GC	N/A	N/A	N/A	N/A	0.079	**0.047**	0.084	**0.006**
PC	0.193	**0.001**	0.229	**0.003**	0.328	**0.002**	N/A	N/A
ED	0.395	**0.001**	0.461	**0.001**	0.273	**0.015**	0.16	**0.002**
XY	0.178	**0.001**	N/A	N/A	0.258	**0.003**	N/A	N/A
GC+PC	N/A	N/A	N/A	N/A	0.298	**0.006**	N/A	N/A
GC+ED	N/A	N/A	N/A	N/A	0.298	**0.013**	0.24	**0.001**
GC+XY	N/A	N/A	N/A	N/A	0.312	**0.003**	N/A	N/A
PC+ED	0.587	**0.001**	0.749	**0.001**	0.76	**0.001**	N/A	N/A
PC+XY	0.36	**0.001**	N/A	N/A	0.377	**0.001**	N/A	N/A
ED+XY	0.44	**0.001**	N/A	N/A	0.613	**0.001**	N/A	N/A
GC+PC+ED	N/A	N/A	N/A	N/A	0.878	**0.001**	N/A	N/A
GC+PC+XY	N/A	N/A	N/A	N/A	0.354	**0.005**	N/A	N/A
GC+ED+XY	N/A	N/A	N/A	N/A	0.649	**0.001**	N/A	N/A
PC+ED+XY	0.603	**0.001**	N/A	N/A	0.744	**0.001**	N/A	N/A
GC+PC+ED+XY	0.603	**0.001**	N/A	N/A	0.877	**0.001**	N/A	N/A
GC | PC+ED+XY	N/A	N/A	N/A	N/A	0.133	**0.001**	0.08	**0.003**
PC | GC+ED+XY	0.156	**0.001**	0.248	**0.001**	0.228	**0.001**	N/A	N/A
ED | GC+PC+XY	0.241	**0.001**	0.48	**0.001**	0.523	**0.001**	0.16	**0.001**
XY | GC+PC+ED	0.004	0.258	N/A	N/A	-0.001	0.492	N/A	N/A

Next, VP analysis identified the impact of both physio-climatic and edaphological components on finger millet cultivation data to be statistically significant: the former retaining 22.9% of the total variability whereas the latter explained 46.1%. No shared fraction was identified between them (Figure 5b). In the case of pearl millet cultivation, a component related to the duration of the plant growing cycle (GC) was also detected along with the physio-climatic, edaphological and spatial components. Growing cycles explained 7.9% of the total inertia, and was found to be barely relevant statistically (p = 0.047). As for the other components, they retained 32.8%, 27.3% and 25.8% of the variance and all were found to be statistically significant. On the one hand, the unique contribution of the growing cycle, physio-climatic and edaphological components was proved to be statistically meaningful and they accounted for 13.3%, 22.8% and 52.3% respectively. On the other hand, the pure effect of the spatial component was proven to hold no fraction of the total inertia, adding no constrained variance to the model and thereby showing the absence of spatial autocorrelation amongst the pearl millet cultivation dataset. Nonetheless, it featured important shared fractions with the rest of the components (Figure 5c), showing the existence of linear spatial trends amongst them, especially in the physio-climatic fraction

(35.1%). Finally, both growing cycle and edaphological components were found to significantly explain 8.4% and 16% of the total variability in sorghum cultivation, of which 0.4% was found to be shared by both fractions (Figure 5d).

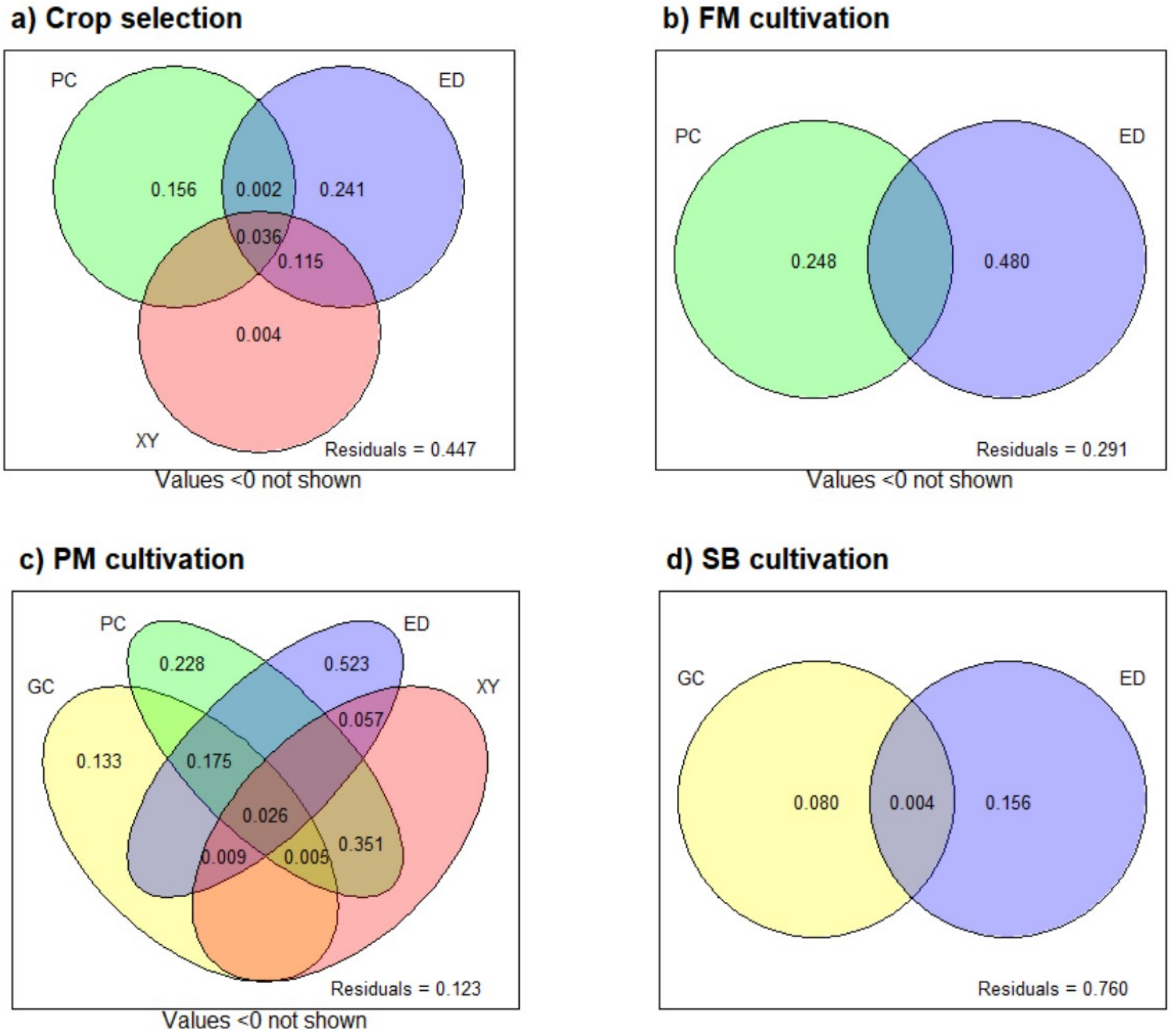


Figure 5: Summary by Venn diagrams of VP analysis of a) Crops selection; b) FM cultivation; c) PM cultivation; and d) SB cultivation.

4.3 Validation of model using ethnographic observations.

All 4 models were found to be capable of predicting their own training response datasets, and hence can be considered as valid models (Figure 6). The crop selection model showed 86.6% accuracy and a F1-score of 0.869, with precision and recall featuring values of 0.88 and 0.857 respectively. 95% accuracy was obtained for the finger millet cultivation model, whereas the prediction of the pearl millet training data was 100% accurate all their performance measures scored 0.95 and 1 respectively. Finally, the modelling of sorghum cultivation practices showed 78.2% accuracy and a F1-score of 0.723. In this case, recall was found to be larger (0.855) than precision (0.627) indicating a higher rate of false positives amongst the predictions.

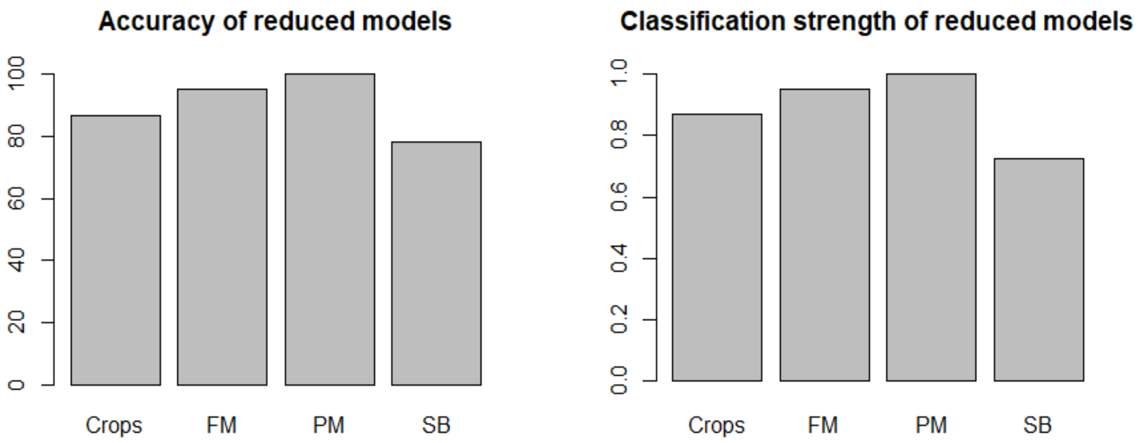


Figure 6: Barcharts of accuracy and classification strength (F1-score) by model

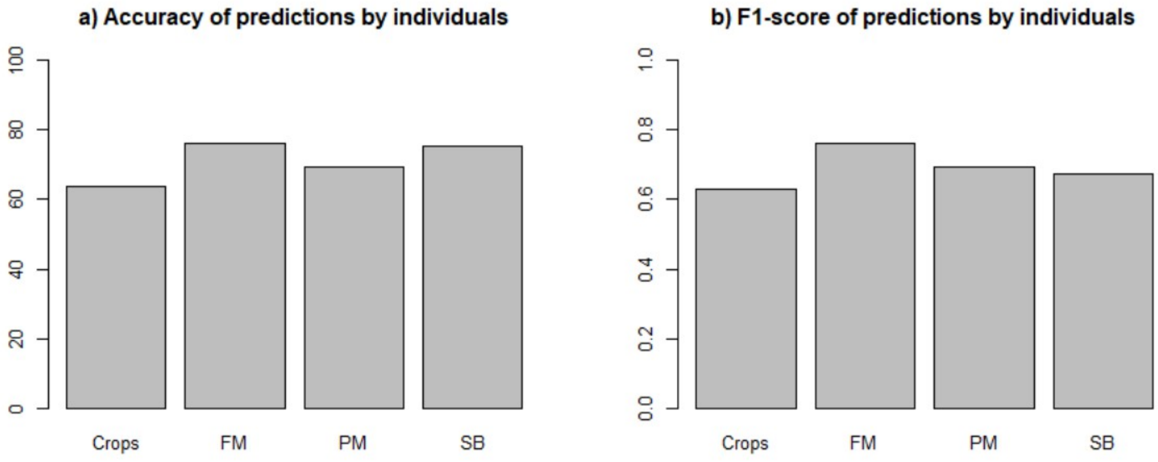
The capacity of the models to correctly predict real data was tested at both individual and cultural levels with the data collected during ethnography (supplementary materials). The modes of each predictor were used in order to create response datasets of the cultivation of all 3 study cereals for the Tigrinya, Sindhs and Sudan Arab as cultures. Descriptive statistics of the testing datasets (supplementary materials) are presented in Table 11.

Table 11: Descriptive statistics of testing response data by interview

Study crops by culture	Tigrinya (n = 27)						Sindhs (n = 16)						Sudan Arabs (n=11)					
	FM		**PM**		**SB**		**FM**		**PM**		**SB**		**FM**		**PM**		**SB**	
Attribute	f	%	f	%	f	%	f	%	f	%	f	%	f	%	f	%	f	%
Crop selection	25	93	0	0	23	85	0	0	8	50	16	100	0	0	5	45	6	55
Intensity of cultivation	25		N/A	N/A	23		N/A	N/A	8		16		N/A	N/A	5		6	
Casual agriculture	0	0	N/A	N/A	0	0	N/A	N/A	0	0	0	0	N/A	N/A	0	0	0	0
Extensive agriculture	0	0	N/A	N/A	0	0	N/A	N/A	0	0	0	0	N/A	N/A	0	0	0	0
Intensive agriculture	25	100	N/A	N/A	23	100	N/A	N/A	8	100	16	100	N/A	N/A	5	100	6	100
Watering regimes	25		N/A	N/A	23		N/A	N/A	8		16		N/A	N/A	5		6	
Rainfed agriculture	24	96	N/A	N/A	22	95.7	N/A	N/A	6	75	6	37.5	N/A	N/A	5	100	0	0
Décrue agriculture	0	0	N/A	N/A	0	0	N/A	N/A	0	0	0	0	N/A	N/A	0	0	6	100
Irrigated agriculture	1	4	N/A	N/A	1	4.3	N/A	N/A	2	25	10	62.5	N/A	N/A	0	0	0	0

Tigrinya people interviewed cultivated finger millet (93%) or sorghum (85%), in all cases as intensive systems (100% of the interviews). No evidence of pearl millet cultivation was obtained. Watering strategies were predominantly rainfed for both cereals (around 96% in both cases). In Sindh we found no evidence of finger millet cultivation but sorghum was planted by all of the people we interviewed, and always under intensive regimes. Watering systems were identified as predominantly irrigated (62.5%) with a third of the interviews reporting rainfed agriculture (37.5%). Furthermore, pearl millet was cultivated by 50% of interviewed Sindhs, all of which featured intensive exploitations. For this crop, however, the predominant watering strategy was found to be rain based (75%), whereas irrigation was performed by the remaining 25%. Finally, during ethnographic fieldwork in Sudan we recorded cultivation of pearl millet in 45% of cases and sorghum in 55%. Once again, no interviewee was found to produce finger millet. Both cereals were intensively cultivated in all cases, pearl millet always under rainfed conditions, while sorghum was watered using the seasonal floods of the Nile as natural irrigation (*décrue* agriculture).

All reduced models scored between 60% and 80% accuracy when predicting individual cases (Figure 7a). Interestingly, the models F1-score (Figure 7b) remained similar to accuracy for crop selection, as well as for finger millet and pearl millet cultivation models. However, the sorghum cultivation model classification strength (F1-score) was lower than its accuracy by 8% due to a higher rate of false positives (0.4) than false negatives (0.233). Regarding the prediction of the testing cases as cultures (individuals mode), the reduced models showed an accuracy of 77.8% for crop selection, 100% for finger millet, 50% for pearl millet and 83.3% for sorghum (Figure 7c). Again, F1-scores (Figure 7d) for crop selection, finger millet and pearl millet cultivation models featured almost no change with respect to accuracy, whereas the sorghum cultivation model also showed lower precision (0.714) than recall (0.833).



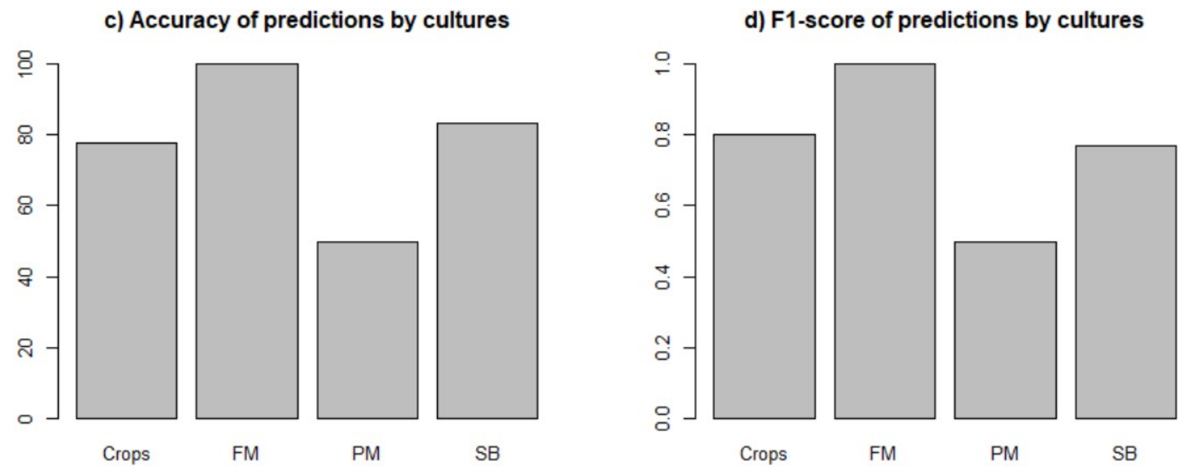


Figure 7: Barcharts of model's predictions accuracy and F1-score by individuals (a, b) and cultures (c, d)

5. Discussion

Traditional agricultural systems have been receiving enhanced attention in the last decade (e.g. Foley et al. 2011, Tittonell 2014, Fraser et al. 2015, Singh and Singh 2017, Altieri and Nicholls 2018, Lam et al. 2020), especially after the introduction of FAO's climate-smart agriculture initiative (FAO 2010). However, most studies have focused on either their theoretical potential as examples to develop sustainable, resilient alternatives to industrial farming (e.g. Altieri and Nicholls 2017, Singh and Singh 2017, Lam et al. 2020); or on the strive for yield improvements by modelling crop responses to critical agronomic factors (e.g. Laux et al. 2010, Handschuch and Wollni 2016, Silungwe et al. 2019). Conversely, there has been far fewer studies addressing the general characterization of traditional agroecosystems, nor the analysis of the driving ecological factors that have shaped the global variability of the existing traditional agrosystems (but see Fraser et al. 2015, Lasco et al. 2016, Peraza-Villareal et al. 2019). As a result, traditional parameters such as the annual rainfall limit (ICRISAT and FAO 1996) are still nowadays used to assess the suitability of given areas for cultivation (e.g. Makadho 1996, Lobell et al. 2008, Knox et al. 2012, Rockström and Falkenmark 2015) determining a general loss of interest in ecoregions such as hyper-arid and arid environments where plant cultivation is usually deemed not possible. Moreover, traditional practices are far from being static, and are constantly hybridizating both with local and global knowledge, thereby hindering the task of creating comprehensive datasets susceptible to ecological analysis.

In this paper, we opted for a cross-cultural approach in order to overcome these problems. Indeed, such an approach allows for the simplification of complex ethnographic data, by reducing intra-cultural variability through generalizations based on the most common practices. For this purpose, we utilized the ethnographic data available in the eHRAF database as our main source of information. Indeed, the eHRAF contains a vast number of documents describing TEK-derived activities from all over the world. Yet, data included in the eHRAF comes from ethnographic studies carried out unevenly across the last two centuries. In spite of the inevitable distortion generated by using data collected under different theoretical and methodological perspectives during more than 150 years of ethnographic research, the eHRAF World Culture database is one of the most effective tools to perform global cross-cultural research (see Ember and Fischer 2017) due to the richness of information it provides. Furthermore, the spatial and temporal heterogeneity of the eHRAF data helps us to overcome the statism and specificity of traditional ethnographic approaches, allowing for a global, more generalistic perspective. Similarly, there is a certain inevitable loss of information in using average and variance values of ecological data across territories (polygons), but it is necessary to create global models that account for the existing ecological variability at both intra- and inter-regional scales. Furthermore, it provides a methodological consistency that allows for the inclusion of a high number of environmental predictors in our models' design but, more importantly, it facilitates the creation of parsimonious models which can be easily validated and analyzed. This is especially relevant when studying social-ecological systems such as traditional agriculture, as they are the result of complex human-environment interactions which are usually not easily to define. In this sense, the resulting models represent a simplification of such relationships, and thereby can be useful in understanding the general underlying social-ecological interactions involved in the development of traditional agricultural systems.

5.1 Is yearly rainfall amount a good predictor for agriculture viability in drylands?

Generally, water scarcity has been established as the main limitant to agricultural production (but see Rurinda et al. 2014). Even for drought-resistant crops such as finger millet, pearl millet and sorghum, mean annual precipitation is still considered the critical factor that defines agroecological systems. However, our model on crop selection portrays a different picture: the importance of yearly rainfall might not be as critical as previously thought. Indeed, differences in mean annual precipitation only explained 8.3% of the overall variance when used as the only predictor in the crop selection model. Even though rainfall obviously impacts crop selection - especially of millets - our first model showed that it is not the total amount of rainfall, but how each crop can exploit the water that is available to them.

First, finger millet was shown to be preferred by groups inhabiting areas where soils feature an enhanced capacity to retain water (e.g. Shilluk, Gusii, Bagisu), whereas pearl millet was chosen by communities such as Fellahin, Wolof or Dogon, who live in areas with higher seasonal precipitation concentration. More importantly, water availability is not the only driving factor in either case. On the one hand, the selection of finger millet is also associated with areas with higher regional variance of summer temperature (e.g. Pashtun, Sherpa, Amhara), hence indicating its capacity to resist greater intra-regional temperature ranges which makes it a suitable species for dryland agriculture. Noteworthy, finger millet has been recognized as a high-temperature tolerant species, with documented landraces resisting temperatures over 40°C (see Yogeesh et al. 2016). On the other hand, enhanced solar irradiance determines the choice of pearl millet as an agricultural product by communities such as Teda, Kanuri or southern Tuareg. This is fundamental for arid ecosystems, and can be explained by pearl millet high efficiency in converting solar radiation into dry matter, especially in comparison with C3 crops (see Begue et al. 1991). This makes the pearl millet the most suitable species for cultivation in areas with high insolation, such as the Sahara and its edges. Finally, the inclusion of sorghum in traditional agrosystems appears to be unrelated to water availability but is associated with relatively higher soil water pH, present in areas such as Inner Mongolia, Somalia or the Turkana region. Indeed, soil acidity has been found to significantly reduce sorghum yields (see Butchee et al. 2012). Furthermore, recent research has proven that pH increases with aridity and temperature (see Jiao et al. 2016), hence making sorghum a good candidate for dryland cultivation. Overall, our model indicates that crop selection in traditional agricultural systems is highly influenced by ecological conditions. Moreover, the identified environmental driving factors agree with previous ecological models, showing the outstanding capacity of TEK holders to identify driving ecological factors and adapt to their surrounding ecosystems.

5.2 Defining the driving ecological factors involved in finger millet, pearl millet and sorghum traditional cultivation techniques.

With regards to the intensity of cultivation and watering practices used in traditional agriculture, finger millet, pearl millet and sorghum were found to be almost completely independent from any rainfall-related predictor. Nonetheless, the models still explained a significant part of the total variability, especially for finger and pearl millet cultivation. In this sense, all three models also performed well when cross-validated against our first-hand ethnographic data. This is especially notable if we consider the impact of current technological implementations such as tractor agriculture or water-pumping techniques and the effects of statal policies on land tenure and availability, but also social factors such as globalization influence on individuals preferences or beliefs about agricultural productivity.

Precipitation concentration throughout the year was found to be associated with extensive-rainfed regimes of finger millet cultivation, as those are types of agrosystems developed traditionally by human communities occupying regions with high rainfall seasonality, both in sub-humid to very humid areas (e.g. Azande, Khasi or Garo) and drylands with AI < 0.40 (e.g. Nuba, Shilluk or Tonga). Noteworthy, this was the only rain predictor to have a significant impact in all three models. The implementation of intensive-rainfed systems by finger millet producers appeared in connection with regions characterized by high topsoil phosphorus content. Interestingly, plant-available soil phosphorus has been identified as a crucial factor for sorghum development and growth in West African landraces (see Adam et al. 2018), where its impact on agricultural yields has been proven to be much higher than climatic variability. As such, communities occupying areas with high phosphorus concentration (e.g. Konso, Nyakyusa, Kaffa) should have also been able to develop finger millet intensive-rainfed agrosystems since both crops have been shown to perform similarly under analogous fertilizing regimes (see Rurinda et al. 2014). Finally, high subsoil sulfur concentrations seem to be a driver for irrigation as the only two instances of recorded irrigated finger millet (e.g. Pashtun and Tamil) are strongly related to this variable. To our knowledge, no study has yet investigated the relation of sulfur and finger millet watering practices. Again, intensive-rainfed systems were independent of aridity, appearing in regions with an AI ranging from 0.30 to 1.07 (semi-arid to humid), while intensive-irrigated agriculture appeared to be restricted to AI < 0.54 contexts (arid to dry sub-humid).

By contrast, pearl millet cultivation systems featured growing cycle, edaphological and temperature-related predictors as their significant ecological driving factors. Previous studies have argued for water stress as the main limitation to pearl millet cultivation (see Begue et al. 1991, Rockström and de Rouw 1997, Winkel et al. 1997, Marteau et al. 2011) despite having identify the importance of other factors such as soil nutrient availability (e.g. Rockström et al. 1999). According to our model, extensive-rainfed cultivation was preferred by peoples planting slow-growing pearl millet varieties in lands with high top-soil clay content (e. g. Fon, Ila, Shona), which would have allowed for better water retention regardless of aridity (AI ranging from 0.14 to 1.04). By contrast, communities such as the Mossi, Nupe or Songhai developed intensive-rainfed systems in arid to dry sub-humid areas where plant-available soil water was much more irregularly distributed as a result of enhanced soil water loss - due to increased evaporation and drainage. Irrigated agrosystems were developed in both hyper-arid (e.g. southern Tuareg, Teda) and semi-arid (e.g. Telugu) environments where soil water evaporation processes were even more significant; but also more irregularly distributed at a intra-regional scale.

Rainfall was not found to play a direct role in traditional techniques applied to sorghum cultivation either. Instead, our results indicate that the most crucial factors were related to the duration of the growing cycles as well as to soil fertility variables, in accordance with previous reports (see ICRISAT and FAO 1996). In our results, extended growing cycles appeared in relation to rainfed cultivation regimes developed by communities such as the Azande, Santal or Tiv, the main limitant to intensive cultivation being soil fertility regardless of aridity (AI between 0.14 to 1.04 for extensive-rainfed cultivation, and 0.16 to 1.07 for intensive-rainfed agriculturalists). Certainly, higher concentrations of soil organic matter allowed for the implementation of intensive cultivation systems (e.g. Koreans, Rwandans, Gikuyu), whereas communities in less fertile regions such as the Hausa, Bambara or Wolof would have been forced to introduce extensive or land-shifting regimes. Noteworthy, communities living in hyper-arid to arid areas which fertility is unevenly distributed such as the Fellahin, Shluh or southern Tuareg people showed *décrue* and irrigated watering practices, as their agricultural activity is usually confined around water sources where soil organic carbon content is elevated. Still, communities living in more humid areas such as Central Thai and Tamil peoples were also found to use irrigation. By contrast, casual-rainfed sorghum production appeared restricted to hyper-arid to arid regions where reduced soil organic matter paired with higher intra-regional variability of top-soil cation exchange capacity (e.g. the areas around water sources), and in association to predominantly pastoral communities such as the Somali or northern Tuareg people.

Overall, our models reveal the existence of important ecological patterns in the ways that traditional agricultural systems adapt to their surrounding environment, most of which showed no direct relationship with annual rainfall nor aridity levels. Noteworthy, variation partitioning analysis detected no variability exclusively driven by geographical location or distance between communities. As so, we argue that processes of cultural transmission would have not played a significant role in the shaping of the studied agrosystems, which were a result of local processes of adaptation instead (see also Ahedo et al. 2019). In this sense, the existing similarities can be considered as a product of cultural convergence, as several communities reached similar agroecological solutions when faced with similar social-ecological problems independently of cultural divergences. As so, traditional agricultural knowledge appears as a type of TEK resulting from long-term adaptation processes which allowed for the development of sustainable, resilient agroecosystems. Interestingly, most of the main driving ecological factors described in the present study were found to be in agreement with previous academic ecological knowledge (AEK), thereby highlighting TEK-holders capacity to properly identify agroecological dynamics and to act in consequence regardless of cultural justifications or even if it is done unconsciously.

6. Concluding Remarks

The ecological modelling of traditional agricultural systems has revealed that the relationship between annual precipitation and agricultural viability is not as strong as previously considered. By contrast, other factors such as growing cycles duration, soil fertility and water holding capacity appear to be much more determinant in shaping traditional agroecosystems. In this sense, our paper shows that profound understanding of the social-ecological dynamics that underlie traditional agricultural systems is still lacking. Further research is needed if we aim to understand how human communities have developed sustainable, resilient agricultural strategies that have been in place for prolonged periods of time. This is especially significant in the current context of climatic instability and increasing population which calls for immediate action.

The value of TEK has been only recently recognized (for a review see Agrawal 1995, Ludwig and Poliseli 2018 and references therein). Often dismissed as naive and non-scientific, TEK has been overlooked by policy-makers in all areas until a few years ago. For agriculture, this has meant the state-driven promotion of AEK-based large-scale strategies focused on yield improvement such as the so-called wheat belt in Ethiopia (IEG Review Team 2018) as well as on fossil water extraction from non renewable aquifers like the North Western Sahara Aquifer System (Tunisia, Algeria, Libya), the Nubian Sandstone Aquifer System (Egypt) and The Jwaneng Northern Wellfield (Botswana), and the fossil water from the Arabian Shield in Saudi Arabia (Foster and Loucks 2006). These kinds of initiatives have usually considered traditional small-holder agriculture as less commercially profitable systems, despite the proven fact that they are generally more productive than large-scale farming (see Stifel 1989, Bridge 1996, Kuivanen et al. 2016, cited in Singh and Singh 2017). In this sense, the scientific community has progressively become aware of TEK holistic value, and recent studies have started to incorporate TEK into AEK (e.g. Fraser et al. 2015, Pearce et al. 2015, Berkes 2018, Hill et al. 2019) as the limitations of exclusively mechanistic approaches have been recognized (see Woodward 2013, Halina 2017; cited in Ludwig and Poliseli 2018). Nonetheless, the number of agronomic studies that include TEK in the development of future agroecological systems is still limited (see Lam et al. 2020).

With this paper, we aim to join other academics in encouraging both scientists and policy-makers to embrace TEK as a crucial part of designing sustainable agricultural systems (see The Montpellier Panel 2013). This is even more important for traditionally neglected areas such as drylands where long-term resilience is of the utmost importance, more so when we consider current changing climatic dynamics and population growth. Despite being at the margin of the current globalized economic system, drylands are inhabited by over 2 billion of the world's population (White and Nackoney 2003), and the numbers keep increasing in relation to global tendency towards the expansion of arid ecosystems. Besides, an in parallel to, the improvement of crops to increase drought tolerance, this situation calls for the development of agricultural strategies suited to these environmental conditions; that is, for the implementation of sustainable agrosystems which can exploit their latent potential and ensure food security without depleting the limited water resources or the optimal soil conditions. In this sense, the present study has reaffirmed the potential of finger millet, pearl millet and sorghum as drought-resistant crops, highly suited for dryland cultivation, even in areas previously considered to be agriculturally unproductive. As stated above, they have received much less attention than other staple crops, such as wheat, berley, maize or rice, mainly as a consequence of their lower productivity. However, they have shown remarkable ecological resilience, as well as the capacity to offer meaningful yields despite environmental constraints. Indeed, our models demonstrated that they can be grown in a wide range of ecological settings, that is not completely dependent on annual precipitation or aridity conditions.

On the other hand, global climate change is fostering fresh research on the effects on agricultural systems worldwide that refers to local practices and knowledge. For example, a recent study by Rurinda et al. (2014) has shown that, under increasing aridity, even though sorghum will perform over 25% better than maize in southern Africa by 2030 (Lobell et al. 2008), the yields of both crops will decrease by 33% as a result of soil impoverishment (Chipansi et al. 2003). Consequently, the authors argue that "*the extent of the impacts of the changing climate on crop production will vary with location depending on other factors particularly soil fertility"* (Rurinda et al. 2014: 29), hence highlighting the major role played by local environmental conditions in crop productivity. In this sense, TEK offers a highly relevant source of information, as it encompasses the exploitation of locally available resources and it is the result of long-term processes of adaptation to the surrounding environment. By contrast, supra-national institutions have often opted for short-term, generalized solutions such as the so-called improvement of the seed market with high-yielding hybrids or the promotion of agrochemicals in economically less developed regions (ICRISAT and FAO 1996). Despite their relatively positive short-term effect on crop yields, these solutions are based on finite resources, and have caused significant damage to both cereal biodiversity and soil conservation, hence burdening natural ecosystems (see Folberth et al. 2020) and, at the same time, endangering the long-term survival of agroecological systems all over the world. Instead, traditional practices rely mainly on renewable resources and they have been considered as the only way to increase productivity and minimize crop failure without sacrificing sustainability and resilience on the long term scale (see Altieri and Nicholls 2018 and references therein).

Lastly, we are not advocating for a defense of unchanged traditional agricultural systems. Conversely, we argue that sustainable policies should incorporate elements of TEK-based practices and combine them with AEK rather than substitute traditional systems for large-scale farming based on Western industrial agriculture. For example, instead of concentrating all the efforts for arid drylands mainly, if not exclusively, in capturing more water (e.g wells and tanks for irrigation but also varieties of seeds that grow with less water) policies should include other factors such as the promotion of local cereal varieties or the introduction of mechanical tools that can assist and boost traditional practices (e.g. by enhancing the maintenance and improvement of soil conditions). Overall, the study of TEK and related practices represents a unique opportunity in the search for resilient agricultural systems that can be implemented in a wide range of ecological settings, including areas previously deemed agriculturally unproductive such as arid and hyper-arid drylands. In this perspective, this paper represents a step toward tearing down the barrier between TEK the AEK, recognizing the vital contribution of local practices to global wellbeing and moving towards a sustainable future, where rather than extracting resources and applying techniques developed in the Western World, local-oriented policies will support and enhance best-adapted practices.

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Ethic statement

The RAINDROPS project has received ethical approval both from CIREP, the Universitat Pompeu Fabra Institutional Committee for Ethical Review of Projects, as well as from the Ethics Committee of the European Research Council Executive Agency.

Author statement

CL and SB conceived the research idea; CL, SB and AR conducted ethnographic fieldwork; AR processed and analysed data; all authors contributed to writing and discussion; CL is PI of RAINDROPS.

Literature cited

Abraham, R. C. 1933. *The Tiv People*. The Government Printer, Lagos.

Adam, M., K. A. Dzotsi, G. Hoogenboom, P. C. S. Traoré, C. H. Porter, H. F. W. Rattunde, B. Nebie, W. L. Leiser, E. Weltzien, and J. W. Jones. 2018. Modelling varietal differences in response to phosphorus in West African sorghum. *European Journal of Agronomy* 100:35–43.

Adem, T. A. 2012. *Culture summary: Kaffa*. Human Relations Area Files, New Haven.

Agrawal, A. 1995. Dismantling the divide between indigenous and scientific knowledge. *Development and Change* 25(3):413–439.

Ahedo, V., J. Caro, E. Bortolini, D. Zurro, M. Madella, and J. Manuel Galán. 2019. Quantifying the relationship between food sharing practices and socio-ecological variables in small-scale societies: A cross cultural multi-methodological approach. *PLoS ONE* 14(5): e0216302.

Albert, E. 1963. Women of Burundi: A Study of Social Values. Pages 179–217 *in* D. Paulme, editor. *Women of Tropical Africa*. Routledge and Kegan Paul, London.

Altieri, M. A., and C. I. Nicholls. 2017. The adaptation and mitigation potential of traditional agriculture in a changing climate. *Climatic Change* 140(1):33–45.

Amraar, H. 1988. *An Egyptian Village Growing Up: Silwa, the Governorate of Aswa.* Doctoral dissertation, University of Florida, Gainesville.

Anderson, R. G. 1911. *Some tribal customs in their relation to medicine and morals of the nyam-nyam and gour people inhabiting the eastern bahr-el-ghazal*. Bailier, Tindall and Cox, London.

Audiger, J., and G. W. Moore. 1961. Wolof of the Bas-Ferlo. L'Institut de Géographie de la Faculté des Lettres de Bordeaux, Bordeaux.

Balbo, A. L., E. Gómez-Baggethun, M. Salpeteur, A. Puy, S. Biagetti, and J. Scheffran. 2016. Resilience of small-scale societies: a view from drylands. *Ecology and Society* 21(2).

Barth, F. 1981. *Features of person and society in Swat: Collected essays on Pathans*. Routledge, London.

Baxter, P. T. W., and A. Butt. 1953. *The Azande and Related Peoples of the Anglo-Egyptian Sudan and Belgian Congo*. London.

Becker, L. C. 1996. Access to labor in rural Mali. *Human Organization* 55(3):279-288.

Becker, L. C. 2000. Garden money buys grain: food procurement patterns in a Malian village. *Human Ecology 28*(2):219-250.

Begue, A., J. F. Desprat, J. Imbernon, and F. Baret. 1991. Radiation use efficiency of pearl millet in the Sahelian zone. *Agricultural and Forest Meteorology* 56(1–2):93–110.

Beierle, J. 1995. *Culture summary: Lozi*. Human Relations Area Files, New Haven.

Behnke R.H., I. Scoones, and C. Kerven. 1993. *Range Ecology at Disequilibrium: New Models of Natural Variability and Pastoral Adaptation in African Savannahs*. Overseas Development Institute, London.

Belton, P. S., and J. R. N. Taylor. 2004. Sorghum and millets: Protein sources for Africa. *Trends in Food Science and Technology* 15(2):94–98.

Berkes, F. 2018. *Sacred ecology*. Routledge, New York.

Berque, J. 1955. *Social structures of the High Atlas*. Presses Universitaires de France, Paris.

Bhila, H. H. 1982. *Trade and Politics in a Shona Kingdom: the Manyika and their African and Portuguese neighbours, 1575-1902.* Longman, London.

Biswas, P. C. 1956*. Santals of the Santal Parganas*. Bharatiya Adimjati Sevak Sangh, Delhi.

Bivand, R., T. Keitt, and B. Rowlingson. 2019*. rgdal: Bindings for the 'Geospatial' Data Abstraction Library*. R package version 1.4-8. [online] URL: https://CRAN.R-project.org/package=rgdal

Bivand, R., and C. Rundel. 2019. *rgeos: Interface to Geometry Engine - Open Source ('GEOS')*. R package version 0.5-2. https://CRAN.R-project.org/package=rgeos

Blanchet, F. G., P. Legendre, and D. Borcard. 2008. Forward selection of explanatory variables. *Ecology* 89(9):2623–2632.

Bohannan, P. 1953. Concepts of time among the Tiv of Nigeria. *Southwestern Journal of Anthropology* 9(3):251-262.

Bohannan, P. 1957. *Tiv Farm and Settlement.* Her Majesty's Stationery Office, London.

Bohannan, P. 1966. *Three source notebooks in Tiv ethnography*. Human Relations Area Files, New Haven.

Bohannan, P., and L. Bohannan. 1953. *The Tiv of Central Nigeria*. International African Institute, London.

Bohannan, P., and L. Bohannan. 1968. *Tiv economy.* Northwestern University Press, Evanston.

Boilat, A. P. 1853. *Senegalese Sketches.* P. Bertrand Libraire-Editeur, Paris.

Bollig, M. 2001. Turkana Herders of the Dry Savanna. Ecology and Biobehavioral Response of Nomads to an Uncertain Environment. *American Journal of Human Biology* 13:81-91.

Bonat, Z. A. 1989. Aspects of the economic and social history of the Atyab (Katab) c. 1800-1960 AD. *Savanna: A Journal of the Environmental and Social Sciences* 10(1):39-57.

Borcard, D., F. Gillet, and P. Legendre. 2018. *Numerical Ecology with R*. Springer International Publishing.

Borcard, D., and P. Legendre. 2002. All-scale spatial analysis of ecological data by means of principal coordinates of neighbour matrices. *Ecological Modelling* 153(1–2):51–68.

Borcard, D., P. Legendre, C. Avois-Jacquet, and H. Tuomisto. 2004. Dissecting the spatial structure of ecological data at multiple scales. *Ecology* 85(7):1826–1832.

Borcard, D., P. Legendre, and P. Drapeau. 1992. Partialling out the Spatial Component of Ecological Variation. *Ecology* 73(3):1045–1055.

Bridge, J. 1996. Nematode Management in Sustainable and Subsistence Agriculture. *Annual Review of Phytopathology* 34(1):201–225.

Burling, R. 1963. *Rengsanggri: family and kinship in a Garo village*. University of Pennsylvania Press, Pennsylvania.

Butchee, K., D. B. Arnall, A. Sutradhar, C. Godsey, H. Zhang, and C. Penn. 2012. Determining Critical Soil pH for Grain Sorghum Production. *International Journal of Agronomy* 2012:1–6.

Butt, A. 1952. *The Nilotes of the Anglo-Egyptian Sudan and Uganda*. International African Institute, London.

Cantor, S. B., C. C. Sun, G. Tortolero-Luna, R. Richards-Kortum, and M. Follen. 1999. A Comparison of C/B Ratios from Studies Using Receiver Operating Characteristic Curve Analysis. *Journal of Clinical Epidemiology* 52(9):885–892.

Chang, Y. T. 1933. *The Economic Development and Prospects of Inner Mongolia (Chahar, Suiyuan, and Ningsia)*. Commercial Press Limited, Shanghai.

Chapelle, J. 1982. *Black nomads of the Sahara*. Human Relations Area Files, New Haven.

Chipanshi, A. C., R. Chanda, and O. Totolo. 2003. Vulnerability assessment of the maize and sorghum crops to climate change in Botswana. *Climatic Change* 61(3):339–360.

Chŏn, K. S. 1984. *Reciprocity and Korean society: An ethnography of Hasami*. Seoul National University Press, Seoul.

Clarke, J., N. Brooks, E. B. Banning, M. Bar-Matthews, S. Campbell, L. Clare, M. Cremaschi, S. di Lernia, N. Drake, M. Gallinaro, S. Manning, K. Nicoll, G. Philip, S. Rosen, U.-D. Schoop, M. A. Tafuri, B. Weninger, and A. Zerboni. 2016. Climatic changes and social transformations in the Near East and North Africa during the ‘long’ 4th millennium BC: A comparative study of environmental and archaeological evidence. *Quaternary Science Reviews* 136:96–121.

Cliggett, L. 2005. *Grains from Grass: Aging, Gender, and Famine in Rural Africa.* Cornell University Press, Ithaca.

Cohen, R. 1967. *The Kanuri of Bornu*. Holt, Rinehart & Winston, New York.

Colson, E. 1986. Land law and land holdings among Valley Tonga of Zambia. *Journal of Anthropological Research* 42(3):261-268.

Culwick, A. T., M. G. Culwick, and T. Kiwanga. 1935. *Ubena of the Rivers*. G. Allen & Unwin Limited, London.

Culwick, G. M. 1950. *A dietary survey among the Zande of the South-Western Sudan*. Ministry of Agriculture, Sudan Government, Khartoum.

Czekanowski, J. 1959. *Investigations in the area between the Nile and the Congo*. Human Relations Area Files, New Haven.

D’Odorico, P., and A. Bhattachan. 2012. Hydrologic variability in dryland regions: Impacts on ecosystem dynamics and food security. *Philosophical Transactions of the Royal Society B: Biological Sciences* 367(1606):3145–3157.

Danielson, J. J., and D. B. Gesch. 2011. Global multi-resolution terrain elevation data 2010

(GMTED2010). US Geological Survey Open-File Report 2011-1073, Washington D.C.

Davison, J. 1996. *Voices from Mutira: Change in the lives of rural Gikuyo women, 1910-1995.* Lynne Rienner Publishers of Agriculture, Sudan.

de Luis, M., J. C. González-Hidalgo, M. Brunetti, and L. A. Longares. 2011. Precipitation concentration changes in Spain 1946–2005. *Natural Hazards and Earth System Science* 11(5):1259–1265.

Dempsey, J. 1956. *Mission on the Nile*. Burns & Oates, London.

Diamond, N. 1993. Ethnicity and the state: the Hua Miao of Southwest China. In Ethnicity and the State (pp. 55-78). Pages 55-86 *in* J.B. Toland, editor. *Ethnicity and the State*. Transaction Publishers, New Brunswick.

Diamond, N. 2009. *Culture Summary: Miao*. Human Relations Area Files, New Haven.

Divale, W. 2004. Codebook of variables for the standard cross-cultural sample. *World Cultures: The Journal of Cross-Cultural and Comparative Research* 14(2):1-347.

Dray, S., D. Bauman, G. Blanchet, D. Borcard, S. Clappe, G. Guenard, T. Jombart, G. Larocque, P. Legendre, N. Madi, and H.H. Wagner. 2020. *adespatial: Multivariate Multiscale Spatial Analysis*. R package version 0.3-8. [online] URL: https://CRAN.R-project.org/package=adespatial

Dumont, L. 1983. *A Sub-caste of South India: Social Organization and Religion of the Pramalai Kallar*. Human Relations Area Files, New Haven.

East, R. M. 1939. *Akiga's Story: the Tiv tribe as seen by one of its members*. Oxford University Press, London.

eHRAF World Cultures. 2020. *eHRAF World Cultures*. eHRAF World Cultures, viewed 1 April 2020. [online] URL: https://ehrafworldcultures.yale.edu/ehrafe/

Ellis J.E., and D. M. Swift. 1988. Stability of African ecosystems: alternate paradigms and implications for development. *Journal of Range Management* 41(6):450-459.

Ember, C., and M. D. Fischer. 2017. Using eHRAF World Cultures with other cross-cultural samples. Pages 1-26 *in* D. White, editor. *Cross-cultural Research Companion*. Wiley-Blackwell, New York.

Estima, J., N. Fichaux, L. Menard, and H. Ghedira. 2013. The global solar and wind atlas. Pages 36–39 *Proceedings of the 1st ACM SIGSPATIAL International Workshop on MapInteraction - MapInteract '13*. ACM Press, New York.

Evans, J. S. 2020. _*spatialEco*_. R package version 1.3-0. [online] URL: https://github.com/jeffreyevans/spatialEco

Evans-Pritchard, E. E. 1938. Economic life of the Nuer: cattle. *Sudan Notes and Records* 21:31-37.

Evans-Pritchard, E. E. 1940. *The Nuer: A description of the modes of livelihood and political institutions of a Nilotic people*. Oxford University Press, Oxford.

Ezekiel, M. 1930. *Methods of correlational analysis*. Wiley, New York.

FAO 2020, FAOSTAT crop data retrieved and downloaded on March 30th, 2020 from http://www.fao.org/faostat/en/?#data/QC

Faris, J. C. 1989. *Southeast Nuba social relations*. Alano Edition Herodot, Aachen.

Fick, S. E., and R. J. Hijmans. 2017. WorldClim 2: new 1‑km spatial resolution climate surfaces for global land areas. *International Journal of Climatology* 37(12):4302–4315.

Fielder, R. J. 1979. Economic spheres in pre-colonial Ila society. *African Social Research* 28:617-641.

Folberth, C., N. Khabarov, J. Balkovič, R. Skalský, P. Visconti, P. Ciais, I. A. Janssens, J. Peñuelas, and M. Obersteiner. 2020. The global cropland-sparing potential of high-yield farming. *Nature Sustainability* 3(4):281–289.

Foley, J. A., N. Ramankutty, K. A. Brauman, E. S. Cassidy, J. S. Gerber, M. Johnston, N. D. Mueller, C. O'Connell, D. K. Ray, P. C. West, C. Balzer, E. M. Bennett, S. R. Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman, and D. P. M. Zaks. 2011. Solutions for a cultivated planet. *Nature* 478(7369):337–342.

Foning, A. R. 1987. *Lepcha, my vanishing tribe*. Sterling Publishers, New Delhi.

Forde, C. D., and R. Scott. 1946. *Native Economies of Nigeria: Being the First Volume of a Study of the Economics of a Tropical Dependency*. Faber and Faber Limited, London.

Fortes, M. 1937. Communal fishing and fishing magic in the Northern Territories of the Gold Coast. *The Journal of the Royal Anthropological Institute of Great Britain and Ireland* 67:131-142.

Fortes, M. 1945. *The dynamics of clanship among the Tallensi: Being the first part of an analysis of the social structure of a Trans-Volta tribe*. Routledge, London.

Fortes, M., and S. L. Fortes. 1936. Food in the domestic economy of the Tallensi. *Africa* 9(2):237-276.

Foster, S., and D. Loucks. 2006. *Non—renewable groundwater resources. A guidebook on socially—sustainable management for water policy—makers*. UNESCO, Paris.

Fraser, J. A., V. Frausin, and A. Jarvis. 2015. An intergenerational transmission of sustainability? Ancestral habitus and food production in a traditional agro-ecosystem of the Upper Guinea Forest, West Africa. *Global Environmental Change* 31(March):226–238.

Freeman, E. A., and G. Moisen. 2008. PresenceAbsence: An R Package for Presence-Absence Model Analysis. *Journal of Statistical Software* 23(11):1-31. [online] URL: http://www.jstatsoft.org/v23/i11

Fuchs, S. 1960. *The Gond and Bhumia of Eastern Mandla.* Asia Publishing House, London.

Galaal, M. H. 1968*. The Terminology and Practice of Somali Weather Lore, Astronomy, and Astrology*. Mogadishu, Somalia.

Gamble, D. P. 1967. *The Wolof of Senegambia: together with notes on the Lebu and the Serer.* International African Institute, London.

Garcia, A. 2013. GIS-based methodology for Palaeolithic site location preferences analysis. A case study from Late Palaeolithic Cantabria (Northern Iberian Peninsula). *Journal of Archaeological Science* 40(1):217–226.

George, H., J. M. Faurès, J. Hoogeveen, G. Franceschini, J. Delacruz, J. Gault, R. Biancalani, and G. Munoz. 2010. *SOLAW Background Thematic Report - TR15. Sustainable option for addressing land and water problems - a problem tree and case studies*. Food and Agriculture Organization, Rome.

Gilbert, B., and J. R. Bennett. 2010. Partitioning variation in ecological communities: Do the numbers add up? *Journal of Applied Ecology* 47(5):1071–1082.

Gluckman, M. 1941. *Economy of the central Barotse plain*. Rhodes-Livingstone Institute, Livingstone.

Gluckman, M. 1943. *Essays on Lozi land and royal property.* Rhodes-Livingstone Institute, Livingstone.

Gluckman, M. 1951. *The Lozi of Barotseland in north-western Rhodesia.* Pages 3-93 *in* E. Colson, and M. Gluckman, editors. *Seven tribes of British Central Africa.* Manchester University Press, Manchester.

Gorer, G., and J. H. Hutton. 1938. *Himalayan village: an account of the Lepchas of Sikkim*. Michael Joseph Ltd, London.

Griaule, M. 1994. *Masques dogons*. Institut d'Ethnologie, Paris

Griaule, M. and G. Dieterlen. 1986. *The pale fox*. Afrikan World Books, Baltimore.

Gulliver, P. H. 1951. *A preliminary survey of the Turkana: A report compiled for the Government of Kenya*. University of Cape Town, Cape Town.

Gupta, S. M., S. Arora, N. Mirza, A. Pande, C. Lata, S. Puranik, J. Kumar, and A. Kumar. 2017. Finger millet: A “certain” crop for an “uncertain” future and a solution to food insecurity and hidden hunger under stressful environments. *Frontiers in Plant Science* 8:1–11.

Gurdon, P. R. T. 1907. *Khasis. Macmillan and Co., London.*

Hadebe, S. T., A. T. Modi, and T. Mabhaudhi. 2017. Drought Tolerance and Water Use of Cereal Crops: A Focus on Sorghum as a Food Security Crop in Sub-Saharan Africa. *Journal of Agronomy and Crop Science* 203(3):177–191.

Hakansson, T. 1990. *Bridewealth, women and land: Social change among the Gusii of Kenya*. Uppsala University Press, Uppsala.

Hakansson, N. T. 1994. Grain, cattle, and power: social processes of intensive cultivation and exchange in precolonial western Kenya. *Journal of Anthropological Research* 50(3):249-276.

Halina, M. 2017. Mechanistic explanation and its limit. Pages 213–224 *in* S. Glennan and P. Illari, editors. *The Routledge handbook of mechanisms and mechanical philosophy*. Routledge, London.

Hallpike, C. R. 1970. Konso agriculture. *Journal of Ethiopian Studies* 8(1):31-43

Hallpike, C. R. 2008. *Konso Of Ethiopia: A Study of the Values of an East Cushitic People.* Oxford University Press, Oxford.

Hallpike, C. R. 2016. *Culture summary: Konso.* Human Relations Area Files, New Haven.

Hammond, P. B. 1959. Economic change and Mossi acculturation. Pages 238-256 *in* W.R. Bascom, and M.J. Herskovitz, editors. *Continuity and change in African cultures*. University of Chicago Press, Chicago.

Han, C. C. 1949. *Social organization of an upper Han hamlet in Korea*. Doctoral dissertation, University of Michigan, Michigan.

Handschuch, C., and M. Wollni. 2016. Improved production systems for traditional food crops: the case of finger millet in western Kenya. *Food Security* 8(4):783–797.

Haswell, M. R. 1967. *Economics of development in village India*. Taylor & Francis, London.

Heald, S. 1989. *Controlling anger: the sociology of Gisu violence*. Manchester University Press, Manchester.

Helander, B, and J. Beierle. 1997. *Culture summary: Somali*. Human Relations Area Files, New

Haven.

Herskovits, M. 1938. *Dahomey: an ancient west African kingdom*. J. J. Augustin, New York.

Hiederer, R., and M. Köchy. 2011. Global soil organic carbon estimates and the harmonized world soil database. *EUR* 79:25225.

Hijmans, R. J. 2020. *raster: Geographic Data Analysis and Modeling*. R package version 3.0-12. [online] URL: https://CRAN.R-project.org/package=raster

Hill, P. 1972. *Rural Hausa: a village and a setting*. Cambridge University Press, Cambridge.

Hill, R., G. Nates-Parra, J. J. G. Quezada-Euán, D. Buchori, G. LeBuhn, M. M. Maués, P. L. Pert, P. K. Kwapong, S. Saeed, S. J. Breslow, M. Carneiro da Cunha, L. V. Dicks, L. Galetto, M. Gikungu, B. G. Howlett, V. L. Imperatriz-Fonseca, P. O'B. Lyver, B. Martín-López, E. Oteros-Roza, S. G. Potts, and M. Roué. 2019. Biocultural approaches to pollinator conservation. *Nature Sustainability* 2(3):214–222.

Hoben, A. 1973. *Land tenure among the Amhara of Ethiopia; the dynamics of cognatic descent*. University of Chicago Press, Chicago.

Holleman, J. F. 1969. *Shona customary law: with reference to kinship, marriage, the family and the state*. Manchester University Press, Manchester.

Hooper, D., J. B. McNair, and H. Field. 1937. *Useful plants and drugs of Iran and Iraq*. Field Museum of Natural History, Chicago.

Howell, P. P. 1954. *A manual of Nuer law: Being an account of customary law, its evolution and development in the courts established by the Sudan Government*. Routledge, London.

ICRISAT and FAO. 1996. *The World Sorghum and Millet Economies. Facts, Trends and Outlook*. ISBN 92-5-103861-9.

IEG Review Team. 2018. *ET: Agricultural Growth Program*. World Bank Group, Washington DC.

Isett, C. M. 2007. *State, peasant, and merchant in Qing Manchuria, 1644-1862*. Stanford University Press, Stanford.

Jaspan, M. A. 1953. *The Ila-Tonga Peoples of North-Western Rhodesia: West Central Africa*. Routledge, London.

Jiao, F., X. R. Shi, F. P. Han, and Z. Y. Yuan. 2016. Increasing aridity, temperature and soil pH induce soil C-N-P imbalance in grasslands. *Scientific Reports* 6(May 2015):1–9.

Jones, J. W., J. M. Antle, B. Basso, K. J. Boote, R. T. Conant, I. Foster, H. C. J. Godfray, M. Herrero, R. E. Howitt, S. Janssen, B. A. Keating, R. Munoz-Carpena, C. H. Porter, C. Rosenzweig, and T. R. Wheeler. 2016. Brief history of agricultural systems modeling. *Agricultural Systems* 155:240–254.

Jones, J. W., J. M. Antle, B. Basso, K. J. Boote, R. T. Conant, I. Foster, H. C. J. Godfray, M. Herrero, R. E. Howitt, S. Janssen, B. A. Keating, R. Munoz-Carpena, C. H. Porter, C. Rosenzweig, and T. R. Wheeler. 2017. Toward a new generation of agricultural system data, models, and knowledge products: State of agricultural systems science. *Agricultural Systems* 155:269–288.

Judd, P. 1973. Irrigated agriculture in the Central Plain of Thailand. Pages 137-172 *in* R. Ho, and E.C. Chapman, editors. *Studies of Contemporary Thailand*. Australian National University, Canberra.

Junod, H.A. 1927. *The life of a South African tribe*. Neuchâtel Impr. Attinger, Hauterive.

Kalinga, O. J. 1984. Towards a Better Understanding of Socio-Economic Change in 18th-and 19th-Century Ungonde. *Cahiers d'Études africaines* 93(24-1):87-100.

Kassambara, A. and F. Mundt. 2019. *factoextra: Extract and Visualize the Results of Multivariate Data Analyses*. R package version 1.0.6. [online] URL: https://CRAN.R-project.org/package=factoextra

Kenyatta, J. 1953. *Facing Mount Kenya: The Tribal Life of the Gikuyu (1938)*. Secker and Warburg, London.

Krätli, S., C. Huelsebusch, S. Brooks, and B. Kaufmann. 2013. Pastoralism: A critical asset for food security under global climate change. *Animal frontiers* 3(1):42-50.

Knox, J., T. Hess, A. Daccache, and T. Wheeler. 2012. Climate change impacts on crop productivity in Africa and South Asia. *Environmental Research Letters* 7(3).

Kronenberg, A. 1958. *Die Teda von Tibesti*. Verlag Ferdinand Berger, Vienna.

Kuivanen, K. S., M. Michalscheck, K. Descheemaeker, S. Adjei-Nsiah, S. Mellon-Bedi, J. C. J. Groot, and S. Alvarez. 2016. A comparison of statistical and participatory clustering of smallholder farming systems - A case study in Northern Ghana. *Journal of Rural Studies* 45:184–198.

Kunwar, R. 1989. *Fire of Himal. An Anthropological Study of the Sherpas of Nepal Himalayan Region*. Nirala, Delhi.

Kuper, H., A. J. B. Hughes, and J. Van Velsen. 1954. *The Shona and Ndebele of Southern Rhodesia: Southern Africa.*

Lagacé, R.O. and I.A. Skoggard. 1997. *Culture Summary: Bemba*. Human Relations Area Files, New Haven.

Lam, D. P. M., E. Hinz, D. J. Lang, M. Tengö, H. von Wehrden, and B. Martín-López. 2020. Indigenous and local knowledge in sustainability transformations research: a literature review. *Ecology and Society* 25(1).

Lancelotti, C., S. Biagetti, A. Zerboni, D. Usai, and M. Madella. 2019. The archaeology and ethnoarchaeology of rain-fed cultivation in arid and hyper-arid North Africa. *Antiquity* 93(370):1026–1039.

Larken, P. M. 1926. An account of the Zande. *Sudan notes and records* 9(1):1-56.

Lasco, R. D., M. L. O. Espaldon, and C. M. D. Habito. 2016. Smallholder farmers' perceptions of climate change and the roles of trees and agroforestry in climate risk adaptation: evidence from Bohol, Philippines. *Agroforestry Systems* 90(3):521–540.

Laux, P., G. Jäckel, R. M. Tingem, and H. Kunstmann. 2010. Impact of climate change on agricultural productivity under rainfed conditions in Cameroon-A method to improve attainable crop yields by planting date adaptations. *Agricultural and Forest Meteorology* 150(9):1258–1271.

Le, S., J. Josse, and F. Husson. 2008. FactoMineR: An R Package for Multivariate Analysis. *Journal of Statistical Software* 25(1):1-18. [online]
URL: https://CRAN.R-project.org/package=FactoMineR

Legendre, P., D. Borcard, and D. W. Roberts. 2012. Variation partitioning involving orthogonal spatial eigenfunction submodels. *Ecology* 93(5):1234–1240.

Legendre, P., and M. De Cáceres. 2013. Beta diversity as the variance of community data:

dissimilarity coefficients and partitioning. *Ecology Letters* 16(8):951–963.

Legendre, P., and E. D. Gallagher. 2001. Ecologically meaningful transformations for ordination of species data. *Oecologia* 129(2):271–280.

Legendre, P., and L. Legendre. 2012. *Numerical Ecology*. Elsevier, Amsterdam.

Legendre, P., J. Oksanen, and C. J. F. ter Braak. 2011. Testing the significance of canonical axes in redundancy analysis. *Methods in Ecology and Evolution* 2(3):269–277.

Lewis, I. M. 1962. *Marriage and the family in Northern Somaliland.* East African Institute of Social Research, Kampala.

Lewis, I. M., and S.S. Samatar. 1999. *A Pastoral Democracy: a study of pastoralism and politics among the northern Somali of the Horn of Africa.* International African Institute, London.

Lhote, H. 1944. *The Hoggar Tuareg*. Human Relations Area Files, New Haven.

Liu, C., P. M. Berry, T. P. Dawson, and R. G. Pearson. 2005. Selecting thresholds of occurrence in the prediction of species distributions. *Ecography* 28(3):385–393.

Lobell, D. B., M. B. Burke, C. Tebaldi, M. D. Mastrandrea, W. P. Falcon, and R. L. Naylor. 2008. Prioritizing Climate Change Adaptation Needs for Food Security in 2030. *Science* 319(5863):607–610.

Ludwig, D., and L. Poliseli. 2018. Relating traditional and academic ecological knowledge: mechanistic and holistic epistemologies across cultures. *Biology and Philosophy* 33(5–6):1–19.

Mair, L. P. 1965. *An African People in the Twentieth Century*. Routledge, London.

Majumdar, D. N. 1978. *Culture change in two Garo villages.* Anthropological Survey of India, Calcutta.

Makadho, J. 1996. Irrigation timeliness indicators and application in smallholder irrigation systems in Zimbabwe. *Irrigation and Drainage Systems* 10(4):367–376.

Manel, S., H. C. Williams, and S. J. Ormerod. 2002. Evaluating presence-absence models in ecology: the need to account for prevalence. *Journal of Applied Ecology* 38(5):921–931.

Mangin, E. 1959. *The Mossi: Essay on the Manners and Customs of the Mossi People in the Western Sudan.* Human Relations Area File, New Haven.

Marteau, R., B. Sultan, V. Moron, A. Alhassane, C. Baron, and S. B. Traoré. 2011. The onset of the rainy season and farmers' sowing strategy for pearl millet cultivation in Southwest Niger. *Agricultural and Forest Meteorology* 151(10):1356–1369.

Martí, M. P. 1957. *Les Dogon*. Presses universitaires de France, Paris.

Mas, B., E. Allué, M. Sánchez de la Torre, Ó. Parque, J. M. Tejero, X. Mangado, and J. M. Fullola. 2018. Settlement patterns during the Magdalenian in the south-eastern Pyrenees, Iberian Peninsula. A territorial study based on GIS. *Journal of Archaeological Science: Reports* 22(June):237–247.

McCabe, J. T. 2004. *Cattle bring us to our enemies: Turkana ecology, politics, and raiding in a disequilibrium system*. University of Michigan Press, Michigan.

McCabe, J. T., and R. Dyson-Hudson. 1985. South Turkana Nomadism: Coping with an Unpredictably Varying Environment. HRAFlex Books, New Haven.

Meyer, H. 1959. *Die Barundi, Eine völkerkunlich Studie aus Deutsch-Ostafrika*. Ott Spamer, Leipzig.

Meyer-Rochow, V. B. 2009. Food taboos: their origins and purposes. *Journal of Ethnobiology and*

Ethnomedicine 5(1):18.

Misra, R. C., S. Das, and M. C. Patnaik. 2009. AMMI Model Analysis of Stability and Adaptability of Late Duration Finger Millet (Eleusine coracana) Genotypes. *World Applied Sciences Journal* 6(12):1650–1654.

Morris, J. 1938. *Living with Lepchas: a book about the Sikkim Himalayas*. Heinemann Limited, Portsmouth.

Murdock, G. P. 1981. *Atlas of world cultures*. University of Pittsburgh Press, Pittsburgh.

Nadel, S. F. 1942. A Black Byzantium: The Kingdom of Nupe in Nigeria. International Institute of African Languages and Cultures, Oxford.

Nakane, C. 1967*. Garo And Khasi: A Comparative Study in Matrilineal Systems*. Mouton De Gruyter, Berlin.

Nambiar, P. K. 1965. *Census of India 1961*. Manager of Publication, Delhi.

Nenzén, H. K., and M. B. Araújo. 2011. Choice of threshold alters projections of species range shifts under climate change. *Ecological Modelling* 222(18):3346–3354.

Neter, J., M. H. Kutner, C. J. Nachtsheim, and W. Wasserman. 1996. *Applied linear statistical models*. Irwin, Chicago.

Nicolaisen, J. 1959. *Political systems of pastoral Tuareg in Air and Ahagga.* Harper and Row, New York.

Nicolaisen, J. 1963. *Ecology and culture of the pastoral Tuareg: with particular reference to the Tuareg of Ahaggar and Ayr.* The National Museum of Copenhagen, Copenhagen.

National Land Use Plan Project, NLUPP. 2010. Land Use Atlas of Pakistan. Ministry of Environment, Government of Pakistan, Islamabad.

Nolan, J. M., and A. Pieroni. 2014. Introduction to Special Issue on Food Security in a Changing World. *Journal of Ethnobiology* 34(1):4–6.

Oksanen, J., F. G. Blanchet, M. Friendly, R. Kindt, P. Legendre, D. McGlinn, P. R. Minchin, R. B. O'Hara, G. L. Simpson, P. Solymos, M. H. H. Stevens, E. Szoecs, and H. H. Wagner. 2019. *vegan: Community Ecology Package*. R package version 2.5-6. [online] URL: https://CRAN.R-project.org/package=vegan

Pagès, F. G. 1960. *A Hamitic Kingdom in the Center of Africa in Rwanda on the Shores of Lake Kivu (Belgian Congo)*. Human Relations Area Files, New Haven.

Paques, V. 1954. *Les Bambara*. Presses Universitaires de France, Paris.

Pasternak, B., and J. W. Salaff. 1993. *Cowboys and Cultivators: The Chinese Of Inner Mongolia*. Routledge, London.

Paulme, D., and F. Schützw. 1940. *Social organization of the Dogon (French Sudan)*. Edition Domat Montchrestien, Paris.

Pearce, T., J. Ford, A. C. Willox, and B. Smit. 2015. Inuit Traditional Ecological Knowledge (TEK) Subsistence Hunting and Adaptation to Climate Change in the Canadian Arctic. *ARCTIC* 68(2):233.

Peraza-Villarreal, H., A. Casas, R. Lindig-Cisneros, and A. Orozco-Segovia. 2019. The marceño agroecosystem: Traditional maize production and wetland management in Tabasco, Mexico.

Sustainability 11(7):1978-1996.

Peres-Neto, P. R., and P. Legendre. 2010. Estimating and controlling for spatial structure in the study of ecological communities. *Global Ecology and Biogeography* 19(2):174–184.

Peres-Neto, P. R., P. Legendre, S. Dray, and D.P. Borcard. 2006. Variation partitioning of species data matrices: estimation and comparison of fractions. *Ecology* 87(10):2614–2625.

Peters, D. U. 1960. *Land usage in Barotseland.* Rhodes-Livingstone Institute, Livingstone.

Playfair, A. 1909. *The Garos*. David Nutt, London.

Reynolds, B. 1968. *The material culture of the peoples of the Gwembe Valley*. Praeger, New York.

Richards, A. I. 1939. *Land, labour and diet in Northern Rhodesia: an economic study of the Bemba tribe*. LIT Verlag Münster, Münster.

Richards, A. I. 1956. *Chisungu: a girls' initiation ceremony among the Bemba of Northern Rhodesia*. Faber & Faber, London.

Robinson, L. W., P. J. Ericksen, S. Chesterman, and J. S. Worden. 2015. Sustainable intensification in drylands: What resilience and vulnerability can tell us. *Agricultural Systems* 135:133–140.

Rockström, J., and A. De Rouw. 1997. Water, nutrients and slope position in on-farm pearl millet cultivation in the Sahel. *Plant and Soil* 195(2):311–327.

Rockström, J., J. Barron, J. Brouwer, S. Galle, and A. de Rouw. 1999. On-Farm Spatial and Temporal Variability of Soil and Water in Pearl Millet Cultivation. *Soil Science Society of America Journal* 63(5):1308–1319.

Rockström, J., and M. Falkenmark. 2015. Agriculture: Increase water harvesting in Africa. *Nature* 519(7543):283–285.

Rosman, A. 1978. *Social structure and acculturation among the Kanuri of northern Nigeria*. University Microfilms International, Ann Arbor.

Routledge, W. S., and K. Routledge. 1968. *With a prehistoric people: the Akikuyu of British East Africa*. Psychology Press Ltd, London.

Rurinda, J., P. Mapfumo, M. T. van Wijk, F. Mtambanengwe, M. C. Rufino, R. Chikowo, and K. E. Giller. 2014. Comparative assessment of maize, finger millet and sorghum for household food security in the face of increasing climatic risk. *European Journal of Agronomy* 55:29–41.

Satir, O., and S. Berberoglu. 2016. Crop yield prediction under soil salinity using satellite derived vegetation indices. *Field Crops Research* 192:134–143.

Schlippe, P. D. 1956. *Shifting cultivation in Africa: the Zande system of agriculture*. Routledge, London.

Scudder, T. 1962. *The ecology of the Gwembe Tonga.* Manchester University Press, Manchester.

Scudder, T. 1971. *Gathering among African woodland savannah cultivators. University of Zambia Institute, Lusaka.*

Scudder, T. 1972. *Ecological bottlenecks and the development of the Kariba Lake basin.* Pages 206-235 *in* T. Favar, and J. Milton, editors. *The Careless Technology.* Tom Stacey, London.

Sebastian, K. 2014. *Atlas of African agriculture research & development*. International Food Research Policy Institute, Washington.

Shangguan, W., Y. Dai, Q. Duan, B. Liu, and H. Yuan. 2014. A global soil data set for earth system modeling. *Journal of Advances in Modeling Earth Systems* 6(1):249–263.

Siiger, H., and J. Rischel. 1967. *The Lepchas: Culture and religion of a Himalayan people*. National Museum of Denmark, Copenhagen.

Silungwe, F. R., F. Graef, S. D. Bellingrath-Kimura, E. A. Chilagane, S. D. Tumbo, F. C. Kahimba, and M. A. Lana. 2019. Modelling rainfed pearl millet yield sensitivity to abiotic stresses in semi-arid central Tanzania, Eastern Africa. *Sustainability* 11(16).

Singh, R., and G. S. Singh. 2017. Traditional agriculture: a climate-smart approach for sustainable food production. *Energy, Ecology and Environment* 2(5):296–316.

Sivertsen, D. 1963. *When caste barriers fall. A study of social and economic change in a south Indian village*. Scandinavian University Humanities Press, New York.

Smith, E. W., and A. M. Dale. 1920. *The Ila-speaking peoples of northern Rhodesia.* MacMillan, London.

Smith, T. W., and J. T. Lundholm. 2010. Variation partitioning as a tool to distinguish between niche and neutral processes. *Ecography* 33(4):648–655.

Solh, M., and M. Van Ginkel. 2014. Drought preparedness and drought mitigation in the developing world's drylands. *Weather and Climate Extremes* 3:62–66.

Stevens, S. F. 1990. *Sherpa settlement and subsistence: cultural ecology and history in highland Nepal*. Doctoral Dissertation, University Microfilms International, Ann Arbor.

Stifel, L. D. 1989. Transforming traditional agriculture. Pages 6–11 *in* L. Brader, editor. *International Institute of Tropical Agriculture Annual Reports*. International Institute of Tropical Agriculture, Ibadan, Nigeria.

Stoller, P. 1989. *Fusion of the worlds: An ethnography of possession among the Songhay of Niger.* University of Chicago Press, Chicago.

Stoller, P. 2016*. Culture Summary: Songhai*. Human Relations Area Files, New Haven.

Tapper, B. E. 1988. *Rivalry and tribute: Society and ritual in a Telugu village in south India*. South Asia Books, London.

Tauxier, L., and A. Brunel. 1912. *The black population of the Sudan, Mossi and Gourounsi country, documents and analyses*. Emile Larose, Librairie-Editeur, Paris.

Tharwat, A. 2018. Classification assessment methods. *Applied Computing and Informatics* 2018.

The Montpellier Panel. 2013. *Sustainable intensification: A new paradigm for African agriculture*. Agriculture for impact, London.

Tittonell, P. 2014. Ecological intensification of agriculture-sustainable by nature. *Current Opinion in Environmental Sustainability* 8:53–61.

Toulmin, C. 1992. *Cattle, women and wells: managing household survival in the Sahel*. Oxford University Press, Oxford.

Van Beek, W. E. 1991. *Harmony vs. autonomy: models of agricultural fertility among the Dogon and the Kapsiki. Uppsala University Press, Uppsala.*

Van Beek, W. E. 2002. Processes and limitations of Dogon agricultural knowledge. Pages 55-82 *in* M. Hobart, editor. *An anthropological critique of development*. Routledge, London.

Van den Putte, A., G. Govers, J. Diels, K. Gillijns, and M. Demuzere. 2010. Assessing the effect of soil tillage on crop growth: A meta-regression analysis on European crop yields under conservation agriculture. *European Journal of Agronomy* 33(3):231–241.

Venema, L. B. 1978. *The Wolof of Saloum: social structure and rural development in Senegal*. Centre for Agricultural Publishing and Documentation, Wageningen.

Weidmann, N. B., J. K. Rød, and L. E. Cederman. 2010. Representing ethnic groups in space: A new dataset. *Journal of Peace Research* 47(4):491–499.

White, R. P., and J. Nackoney. 2003. Drylands, People, and Ecosystem Goods and Services: A Web-based Geospatial Analysis. *World Resource Institute* (2003):1–58.

Wilson, G. 1938. *Land Rights of Individuals Among the Nyakyusa*. Rhodes-Livingstone Institute, Livingstone.

Wilson, M. H. 1977. *For Men and Elders: Change in the Relations of Generations of Men and Women among the Nyakyusa-Ngonde People, 1875-1971.* International African Institute, London.

Winkel, T., J.-F. Renno, and W. A. Payne. 1997. Effect of the timing of water deficit on growth, phenology and yield of pearl millet (Pennisetum glaucum (L.) R. Br.) grown in Sahelian conditions . *Journal of Experimental Botany* 48(5):1001–1009.

Woodward, J. 2013. Mechanistic Explanation: Its Scope and Limits. *Aristotelian Society Supplementary Volume* 87(1):39–65.

World Agroforestry Centre (ICRAF). 2014. *Local Knowledge (including indigenous and traditional knowledge)*. ICRAF Policy Guidelines Series Local, Nairobi.

Yogeesh, L. N., A. B. Naryanareddy, Y. A. Nanjareddy, and M. V. Channabyre Gowda. 2016. High temperature tolerant genotypes of Finger Millet (Eleusine coracana L.). *Nature Environment and Pollution Technology* 15(4):1293–1296.

Zerboni, A., S. Biagetti, C. Lancelotti, and M. Madella. 2017. The end of the Holocene Humid Period in the central Sahara and Thar deserts: societal collapses or new opportunities?. *Past Global Changes Magazine* 24(2):60-61.

Zomer, R. J., A. Trabucco, D. A. Bossio, and L. V. Verchot. 2008. Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. *Agriculture, Ecosystems & Environment* 126(1–2):67–80.