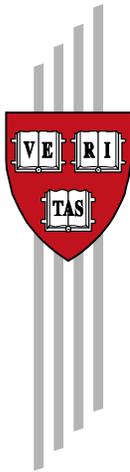


Limitations to Crop Diversification for Enhancing the Resilience of Rain-fed Subsistence Agriculture to Drought

Matthew E. Gilbert and N. Michele Holbrook

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Abstract

Diversification of agricultural systems is a standard suggestion for increasing the resilience of rain-fed subsistence farming to drought. However, grain crops share many physiological characteristics, potentially forming a plant functional type (PFT), a term ecologists apply to groups of species that respond in functionally similar ways to environmental variation. Here we test whether grain crops are a PFT, and whether diversification between grain crops, to other crops or livestock that feed on natural plants results in sufficient variation in water-use physiology to form a diversified agricultural portfolio. To this end, we simulated the response of crops and natural PFT's to rainfall variation using a simple plant growth model. We then predicted subsistence farmer allocation with a safety-first economic analysis and compared these to observed allocations at 78 sites across a rainfall gradient in South Africa. We demonstrate that there are shifts from crop to livestock farming with aridity, and that this is correlated with the extant natural PFT's. That is, as the simulated probability of crop failure diverges from that of the natural vegetation, there is a shift to livestock farming. Diversifying within grain crops would lead to little increase in resilience due to limited physiological variation – an indication that grain crops are one PFT – while other crops had some potential for greater diversification advantages, and livestock feeding on natural plants the greatest. Thus, a plant functional type approach is vital in understanding the developmental economics of subsistence farmer diversification with the goal of increasing resilience to drought.

Keywords: diversification, plant functional types, safety-first portfolio, South Africa

JEL subject codes: Q15, Q51, Q56, Q57, R14

Citation, Context, and Program Acknowledgements

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It is available at <http://www.hks.harvard.edu/centers/cid/publications/research-fellow-graduate-student-working-papers/cid-research-fellow-and-graduate-student-working-paper-no.-228>. Professor N. M. Holbrook has approved this paper for inclusion in the working paper series. Comments are welcome and may be directed to the author, mgilbert@oeb.harvard.edu.

Matthew E. Gilbert is jointly a Giorgio Ruffolo Post-doctoral Fellow with the Land-Water Initiative in the Sustainability Science Program at Harvard's Center for International Development and the Organismic and Evolutionary Biology Department. The Land-Water Initiative, led by Professor N.M. Holbrook, seeks to understand the opportunities and constraints facing the sustainable use of resources needed to create food and livelihood security.

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I. Introduction

Providing realistic links between plant physiology and development programs for subsistence farmers is a priority. Climate change, population growth, increasing agricultural and economic demand for water will result in increasing demand for food from decreasingly available water resources (Falkenmark et al., 2009). While the gene revolution and modern agronomic techniques have some potential for addressing these issues, these must be coupled with studies of what environmental envelopes crop types are functional in, and ultimately ground truthing prior to introducing new technologies to marginal subsistence farming areas. An interesting approach is the diverse-portfolio analogy that has been used to link ecology with economics, where plant diversity leads to ecosystem service stability (Koellner and Schmitz, 2006; Lehman and Tilman, 2000; Schlapfer et al., 2002). Here we attempt to provide a bridge between crop physiology and developmental economics, with the goal of illustrating the utility of a plant functional type approach to agricultural diversification. In particular we ask how plant physiology would affect agricultural choices for subsistence farmers living along a rainfall gradient in the Eastern Cape province of South Africa.

The majority of calories consumed by people derive from grain crops (FAO, 2006; Scholes and Biggs, 2004) that share many of the same characteristics, or physiological traits. In ecology, a group of plants that have similar responses to environmental variation are termed a plant functional type (PFT) (Lavorel et al., 1997). In many regards grain crops may be considered to be a PFT. That is, grain cereals such as millet, maize and sorghum, and grain legumes such as soybean, cowpea and beans share a high leaf area per unit ground area, shallow rooting depth (0.5-2m) relative to natural vegetation, high transpiration rates and nutrient requirements, and a summer annual growth pattern. Most importantly, the yield of grain crops relies on the completion of a growing season with limited drought to enable reproductive success. Thus such plants are likely to be similarly susceptible to drought, and therefore may represent limited diversification potential for subsistence farmers. However, other crops, vegetables or natural plants have greater physiological diversity, and therefore, may offer greater diversification advantages than diversification within grain crops – consider the range of physiological diversity between lettuce to citrus. Practically, the use of natural plants as an agricultural choice is embodied in livestock browsing and grazing, and thus the diversification strategy with the most potential may be the choice between crops and/or livestock.

Crops have been usefully grouped into PFT's in the past. Examples include distinguishing between plants with C_3 and C_4 physiologies, nitrogen-fixing, growth habit and annuals versus perennials (Monfreda et al., 2008). Agroecological work also links crops with suitable environments – a form of PFT analysis – functional examples include Ecocrop2 for global crops (<http://ecocrop.fao.org/ecocrop/>), Ehlers crop suitability zones for South Africa (Ehlers, 1988) and agroecological zones (Sivakumar and Valentin, 1997). While this information allows excellent crop selection with respect to many environmental variables it necessarily cannot attempt to link the drought tolerance of crops and livestock with local environments to the necessary degree of complexity to predict optimal agricultural system allocations for subsistence farmers, particularly in specific situations. Alternatively it is not possible to undertake long term yield trials of many crops that are representative of farming over a widespread region, although this may be done on a local scale. A number of modeling approaches do allow some degree of representation of general crop (and natural plant) water use physiology (Allen et al., 1998; Potter et al., 1993; Purcell et al., 2003).

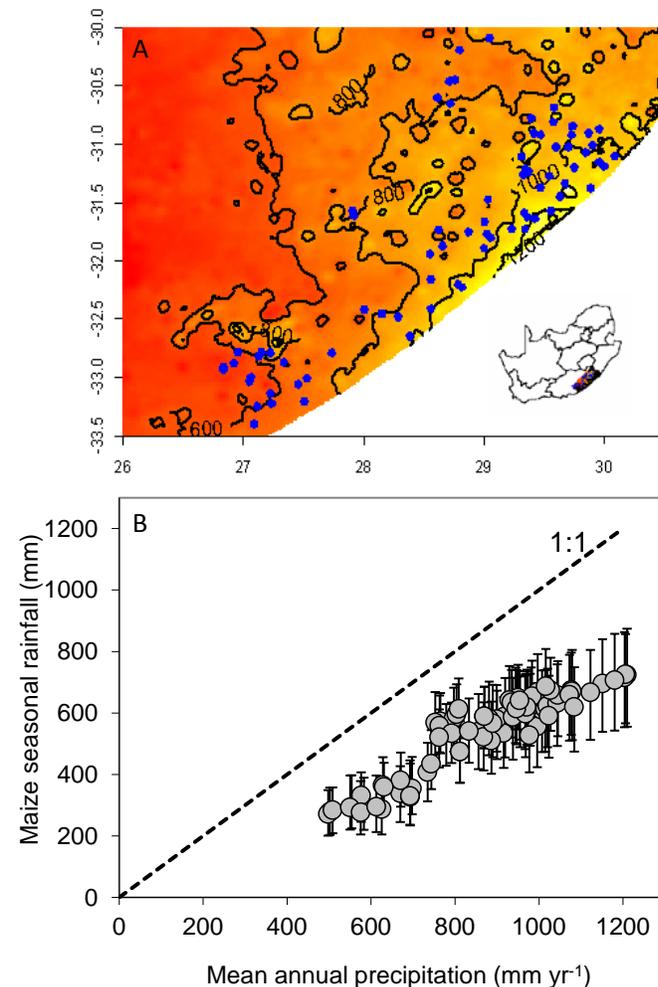
Thus the starting point for understanding what types of diversification are likely to be useful for subsistence farmers could productively be done using a local, plant productivity simulation approach, that

includes explicit variation in plant physiology between diversification options. Here we attempt such an analysis, and develop a custom crop and natural plant simulation model largely based upon published approaches to assess the effects of rainfall variation on the resilience of agricultural systems. We test: 1) whether grain crop yields are highly correlated, and represent a plant functional type – of limited diversification value, 2) whether other non-grain crops have a wider range of physiological diversity, and thus represent some diversification advantages, and 3) livestock, and the natural plants they feed upon, offer the most resilience to drought due to high diversity of physiology. Land use data is used as a comparison to assess the validity of the simulation model results. Thus the study is unique in providing a local analysis of agronomic options for subsistence farmers, while using relatively abstract plant physiological theory to determine this.

II. Methods

Area description

The former Ciskei and Transkei homelands within the Eastern Cape Province of South Africa include the poorest regions within the country (Statistics_SouthAfrica, 2000). Subsistence farming is practiced by the



majority of households within this region in conjunction with limited economic activities and income from remittances and social grants (Adams et al., 1999; Perret, 2002; van Averbeke and Khosa, 2007). Household economic surveys suggest that crop farming provides a significant proportion of household nutrition, and rarely a small percentage of a crop is sold (van Averbeke and Khosa, 2007). With the removal of *apartheid*, agricultural subsidies, land degradation and other factors, resulted in farmers from some areas shifting from extensive fields towards more intensive home gardens (Andrew and Fox, 2004). The

Figure 1. Mean annual precipitation (MAP) isohyts (mm yr^{-1}) for the former Ciskei and Transkei region of the Eastern Cape Province of South Africa (panel A), and the shift in maize seasonal rainfall with MAP (panel B). In panel A points represent the 78 sites included in this study. Inset – South Africa and highlighted region. MAP and maize seasonal rainfall patterns were estimated from the South African Rain Atlas (Zucchini and Nenadic, 2006). Points in B represent the median seasonal rainfall and error bars the 10 and 90th percentiles for a 200 year simulation of rainfall for each site.

region does not currently have considerable land under irrigation, although historically many irrigation and meso-scale agriculture projects were initiated, while now only localized irrigation schemes exist with a large degree of variation in output (Fanadzo et al., 2010; Ntsonto, 2005). While irrigation is not common, there may be some degree of enhanced water conservation and water addition to intensive gardens (van Averbek and Khosa, 2007). Livestock (including cattle, sheep, goats, pigs and chicken) account for 44% of household agricultural income and nutrition (Adams et al., 1999), and particularly cattle have considerable cultural value as a form of wealth (Duvel and Afful, 1996). The larger livestock are dependent on grazing and browsing on natural plants, which also offer a number of alternative resources such as fire wood, traditional uses including medicine and are of some nutritive value (McGarry and Shackleton, 2009; Shackleton, 2003).

Coordinates of seventy-eight sites were randomly selected from within the former Ciskei and Transkei, South Africa (Fig. 1A). Spatial gradients in the density of sites were caused by inland areas having insufficient satellite image resolution to perform the analysis, however inland and higher altitude sites were present in the analysis at a range of latitudes. The study sites encompassed a gradient from 500 mm to 1200mm mean annual precipitation (MAP) across a distance of 400 km SW to NE (Fig. 1A). Summer rains predominate, although the relative contribution of winter frontal rainfall increases along the coast and in the semi-arid south west, such that at approximately 800mm MAP the sites transition from reliable maize growing season rainfall of greater than 400mm to considerably less than 400mm (Fig. 1B). The sites had: an average altitude of 643 m (range: 83 to 1835 m), a mean annual temperature of 16.3°C (12.2 to 19.2°C), for July an average minimum temperature of 4.7°C (-0.7 to 10.4°C) and MAP of 871 mm yr⁻¹ (498 to 1210 mm yr⁻¹) (Fig. 1A).

Analysis of land use from satellite images

High resolution (0.25m pixel⁻¹) satellite images of each site were obtained from Google Earth (<http://earth.google.com/>). The closest houses to the coordinates selected were found and partitioned into the three nearest households. Households were determined as a group of buildings in close proximity, dissociated from other houses and associated with single units of agricultural land: crop fields or livestock enclosures. In the case of higher density settlements hedges and fencing allowed definition of households. For each of the households, demographic characteristics were recorded, such as the proportion of houses using thatch versus galvanized iron roofs and the density of houses in the settlement or area. The total land area per household under crop cultivation was determined using ImageJ 1.38x digital analysis software (<http://rsb.info.nih.gov/ij/>) and assessed as land that showed presence of crops, or had been recently ploughed, but excluded fallow land. Similarly, the total area of livestock enclosures per household was determined, excluding enclosures associated solely with cultural activities (Cocks et al., 2006) by distinguishing characteristics, such as shape (round versus rectangular in the SW of the region) and the distinctive presence of vegetation versus dark earth in the enclosures. Livestock enclosure area was assumed to be proportional to the numbers of livestock kept – a common assumption for studies in the area (Andrew and Fox, 2004).

A proportional allocation to crop farming versus livestock was calculated based upon the assumption that for the entire region the average nutritional value of livestock equals that for crop farming. This assumption was based upon the meta-analysis of the value of traditional agriculture to households in South African former homelands by Adams et al. (1999). They found that crops contributed 56% of the value for crop and livestock farming combined, over areas that had comparable rainfall variation to those described in this study.

PFT productivity model: introduction

A custom PFT productivity model was developed from first principles, in which the production of 15 plant functional types could be simulated for a specific site, over a period of 100 years. The model is more fully described in the Supplementary material. In summary, the model was a radiation use efficiency model similar in form to the widely-used CASA model of Potter et al. (1993) with the major differences that the current model is applied separately to 15 PFT's and crops, operates daily rather than monthly, uses a global constant leaf area index (LAI), includes no specification of carbon allocation apart from the mass fraction of shoots (SMF_i), has no soil nutrient modules and incorporates a PFT specific effect of drought on yield. The productivity of livestock feeding upon the natural PFT's was simulated by assigning the harvest index for each PFT as the palatable portion of the aboveground part of the plant, and dividing the resulting productivity value by eight – an approximate value for the conversion of biomass to livestock mass (Sheridan et al., 2003).

The predominant driver of variation in production was variation in daily precipitation between years and extant PFT characteristics at a site. Productivity (and water use) was the weighted sum of the relative contributions of each PFT to the flora present at a site. That is, the simulation calculated annual productivity (and water use) for each PFT assuming that each PFT was dominant at a site. Then the contribution of these values to total production or water use were then scaled proportional to the observed percentage of the flora made up by that PFT. This was considered to be a first order approximation of PFT contribution to site natural plant productivity, but it is acknowledged that this may not be representative of the biomass composition of PFT's. The initial simulation predicted the yields of two C_4 grain crops using the same model, these were parameterized to represent a long- and short-season crop (approximately maize and millet, respectively).

These results should be viewed as a means to compare the relative variation in productivities of different PFT's at a site in response to a rainfall simulation for each site. Secondly, the simple definition of PFT characteristics (Table S1 and S2) allows a relative comparison of the influence of a few physiological and phenological characters on productivity and thus the effects of physiological diversity on productivities of different agricultural systems. The model is thus a generic plant model, and does not represent a specific crop. DSSAT, APSIM, FAO-Aquacrop and other crop-specific models are preferred when the goal of a study is to simulate the productivity of a named crop for a specific site. These models were not used as they do not represent natural plant PFT variation of the study area, a necessary part of the exploration here.

Environmental inputs

Daily values (t , day of Julian year) of environmental inputs for the productivity model were calculated for each site from raw data as follows: 1) Maximum and minimum daily air temperatures ($T_{max,t}$ and $T_{min,t}$; °C) were estimated by linear interpolation from 55 year average monthly values for the quarter degree cell that the site fell into; temperature data was derived from SAFARI 2000 (New et al., 2000) for the period 1935 to 1990. 2) Photosynthetically active radiation (PAR_i ; $MJ\ m^{-2}\ day^{-1}$) was estimated from site latitude, elevation, $T_{max,t}$ and $T_{min,t}$ using the Donatelli and Bellochi approach (Donatelli et al., 2003), where elevation was taken from the CIAT GIS database (Jarvis et al., 2008), and the parameter values for the PAR model were obtained (http://www.sipeaa.it/ASP/ASP2/RadEst_DB/parameters_search.html) for Durban, the nearest sub-tropical site. 3) Daily reference evapotranspiration (ET_{0i}) was calculated according to Allen et al. (1998) for a standard grassy reference surface with an approximate LAI of 2.88, and for consistency with the approach of Allen et al. (1998) net radiation was defined for this submodule as described in Allen et al. (1998). 4) Daily vegetation evapotranspiration (ET_i) was calculated from ET_{0i} using a modification of the approach of Allen et al. (1998): the crop maximum evapotranspiration coefficient (K_c) and water stress coefficient function (K_s) of each PFT/crop, were taken from the values in

Table S2; their derivation is provided in the Supplementary material. K_s was a bilinear response to the fraction of transpirable soil water (FTSW_t):

$$K_s = \min(1 + a_1 * (FTSW_t - FTSW_{thres}), a_2 * FTSW_t + b_2),$$

using the relevant values from Table S2. For natural PFT's daily site K_c and K_s were averages weighted proportional to the flora composition for a site. Thus, the reference ET_{0t} was adjusted to ET_t for the crop or natural PFT's characteristics based upon K_c and the response of K_s to FTSW_t. 5) Precipitation (P_t) was derived from a 100 year daily simulation of rainfall for each site using the rainfall atlas for South Africa of Zucchini and Nenadic (2006) – a rainfall simulator consisting of a first order seasonal Markov chain and continuous distribution of seasonal variation, and fit to rainfall data from 5070 sites and then spatially interpolated to produce representative MAP totals, yearly, monthly and dry-spell frequency variation across South Africa (Zucchini and Nenadic 2006). 6) The fraction of total transpirable soil water (FTSW_t) was calculated as a soil water budget where water efflux (ET_t) and influx (P_t) occurred from the rooting volume of a standard vegetation with 2300mm of rooting depth and soil water holding capacity of 13% of the rooting depth ~ 299mm - values representative of mature stands of a generic crop and average soils taken from Purcell et al. (2003). In this module the constraint $\Delta FTSW \geq 0$ was applied with no runoff or infiltration beyond the root zone.

Thus, the some of the model's environmental inputs were adjusted for site differences (daily PAR_t, $T_{min,t}$ and $T_{max,t}$, and ET_{0t}) and varied daily, but not between years, while the main driver of plant productivity of interest was water (P_t and FTSW_t) and varied by year, day and site.

Definitions of plant functional types used in the productivity model

Two generic C_4 grain crops were included in the productivity model; a 155 day crop was used as an indication of maize production - using approximate growing season dates for the area from 28 October to 1 April (Bryndum et al., 2007; Fanadzo et al., 2010). A short season 90 day crop was used as an indication of millet production, growing from the 1 Jan to 1 Apr. Millet is not reportedly grown in the area, but was included as it represents an extreme grain crop where the short growing season would reduce the probability of drought.

The flora was divided into eight functional groups, some of which were further divided into annuals and perennials, for a total of 15 natural PFT's. Across all sites C_3 grasses made up 1 to 2.7% of the flora, C_4 NADP-me and PCK grasses 2.9 to 6%, C_4 NAD-me grasses 0.9 to 2.3%, trees 9.7 to 22.3%, Fabaceae 5 to 9.4 %, Asteraceae 5.3 to 14%, and succulents 6.6 to 16.1%. The composition of the flora at each site was determined from herbarium records collected within the quarter-degree square the site was in and obtained from the SIBIS database (SANBI, 2011). Sites were not used if less than 300 species had been collected near the locality (range 339 to 2149, average 980 spp. per site). Each PFT was determined based upon taxonomic family, genus (lists of C_4 photosynthetic subtype by genus), or species name (species lists of annuals, succulents and trees) (POSA, 2011). As a simplifying generalization Fabaceae were assigned as N_2 fixers, succulents as Crassulacean Acid Metabolism (CAM) plants, and tree Fabaceae as trees, not N_2 fixers.

These PFT's were selected as they represent the dominant vegetation on the rainfall gradient i.e. the Albany (succulent) thicket, savanna, grassland biomes from arid to mesic (Mucina and Rutherford, 2006). Grasses were divided into three groups based upon functional variation between each photosynthetic subtype's response to aridity; C_3 grasses are associated with mesic cool areas, C_4 non-Chloridoid grasses (generally NADP-me and PCK subtypes) with mesic hot areas and the C_4 Chloridoid grasses (generally NAD-me subtype) with arid areas (Ellis et al., 1980). The derivation and values of productivity model parameters for each PFT are described in the Supplementary material, and Tables S1 and S2.

Economic safety-first analysis

The variation in production output of the PFT productivity model for the two grain crops and livestock was used to model subsistence farmer allocation of resources between these three agricultural choices. As the data was non-normally distributed (crops failed in numerous years), and subsistence farmers with little alternative income may be expected to be failure-averse a safety-first analysis was adopted. A custom procedure was used, based upon Tesler's rule (Tesler, 1955), in which a farmer requires the individual agricultural system to fail less often than a threshold ($P_{\text{fail,threshold}}$). The farmer then chooses the portfolio that includes all agricultural systems that satisfy the safety-first rule, with allocation proportional to the expected yield of each system (thus safe, high yielding systems have highest allocation). In the absence of *a priori* values for $P_{\text{fail,threshold}}$, this parameter was assigned as 0.2; equivalent to subsistence farmers accepting drought causing crop failure twice in ten years. The sensitivity of this assumption on the results is considered in the Results.

Validation and sensitivity analyses

Due to a lack of local data, the PFT productivity model was tested using a number of published datasets and models of vegetation aboveground net primary productivity (ANPP). A literature search found ANPP and annual precipitation data for 12 Southern African sites (Buis et al., 2009; Caylor et al., 2004; Dunham, 1989; Fynn and O'Connor, 2000; Mills and Cowling, 2006; Mills et al., 2005; O'Connor et al., 2001; Scholes and Walker, 1993; Swemmer et al., 2007) and 49 global grassland or savanna sites (Huxman et al., 2004; Scurlock et al., 2003).

The sensitivity of the MAP at which a simulated crop failed more often than two in ten years (the point at the simulated crop was excluded from the subsistence farmer's agricultural portfolio) was determined for a range of K_c and K_s values (K_c from 0.5 to 1.2; K_s from 0.1 to 1) representing all plausible crop/plant water use characteristic combinations. Other characteristics of the simulated crop were kept constant at those listed for the long season C_4 grain crop (~maize) (Table S1 and S2). This simulation was performed for a subset of 26 sites representing the full range in MAP. A sigmoidal function was fit to the average P_{fail} of the simulated physiology at each site against average site MAP, and the MAP at which a P_{fail} of 0.2 occurred was interpolated from these fits.

III. Results

Patterns in crop cultivation and livestock allocation

Mean annual precipitation (MAP) was positively associated with area under crop cultivation, and negatively associated with the area of livestock enclosures per household (Fig. 2 and Table 1). The house density in the area had a significant negative correlation with the area under crops or devoted to livestock enclosures (Table 1). When expressed as a proportion of total allocation to crops (Fig. 3A) the effect of house density was removed, and allocation to crops was positively associated with MAP. The proportion of houses thatched, an indication of ruralness or poverty, was positively correlated with MAP, and resulted in a negative relationship with allocation to livestock enclosure area (i.e. for livestock the effect of poverty or MAP was not possible to distinguish).

The observed proportional allocation to crops (Fig. 3A), and area under crop cultivation (Fig. 2A), displayed a marked shift at approximately a threshold MAP of 800mm, corresponding to a decrease to half the livestock area and 5.6 times crop area at high rainfall. The ratio of the cash value of home-

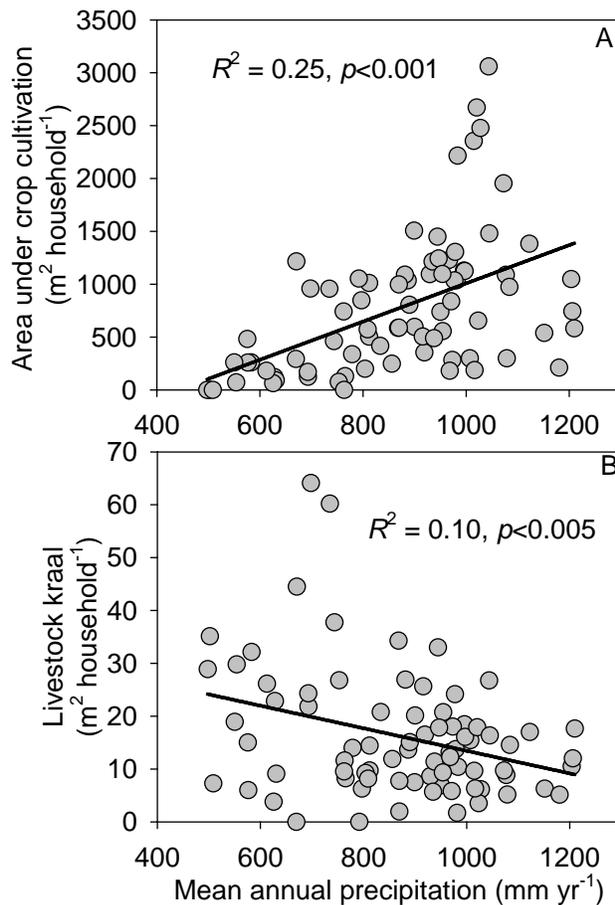
produced crop and livestock derived from four household surveys in rural areas in South Africa demonstrated a similar pattern to the observed data (Fig. 3A): Monde (2003) for two Eastern Cape sites, Kirsten et al. (1998) for Nkandla KwaZulu-Natal and Dovie et al. (2006) for Limpopo province.

Table 1. Summary of relationships between agricultural options and major variables observed from satellite data. Regression coefficients are given with standard errors in brackets. The significance of R^2 's or of a coefficient's difference to zero are represented by ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$; ·, $p < 0.1$.

Variables	R^2 with MAP	Response variables:		
		Area under crop cultivation (m^2 household $^{-1}$)	Area for livestock enclosure (m^2 household $^{-1}$)	Allocation to crop (prop.)
MAP	-	1.76(0.507)***	-0.0029(0.0099)	0.0006(0.0002)**
Houses in settlement (#)	0.001	-7.29(3.09)*	-0.18(0.06)**	0.00046(0.0012)
Prop. houses thatched	0.50***	65.3(325)	-15.9(6.4)*	0.221(0.128)·
Intercept	-	-584(362)	29.6(7.08)***	-0.143(0.142)
R^2	-	0.282***	0.192***	0.333***

Simulation of crop versus livestock allocation

The simulation of two C_4 long and short-season grain crops, intended to approximate maize and millet, and livestock as a function of the productivity of natural plants, demonstrated a similar abrupt shift from



high allocation to crops above the 800mm MAP threshold to only livestock allocation at lower rainfalls (Fig. 3B). The short-season grain crop had a similar pattern to the longer-season crop, but at three sites was a suitable safe allocation when the longer-season crop regularly failed, and the allocation to this crop increased as MAP approached the 800mm threshold (Fig. 3C). Thus although there was some diversification advantage in using a grain crop of alternate physiology/phenology to maize this did not result in substantial expansion of the range of MAP under which grain crops could be cultivated. The sharp transition between crop and livestock dominated agricultural allocations was determined by the grain crops being “safe” at rainfall's above 800mm, and becoming failure prone at lower rainfall's (Fig. 3C). This pattern was robust irrespective of the safety-first risk

Figure 2. Patterns of area under crop cultivation (A) and area of livestock enclosures per household (B) over a precipitation gradient for 78 sites in the Eastern Cape province, South Africa. Regression lines, R^2 's and p values represent the OLS fits for the two variables, excluding the variables included in Table 1.

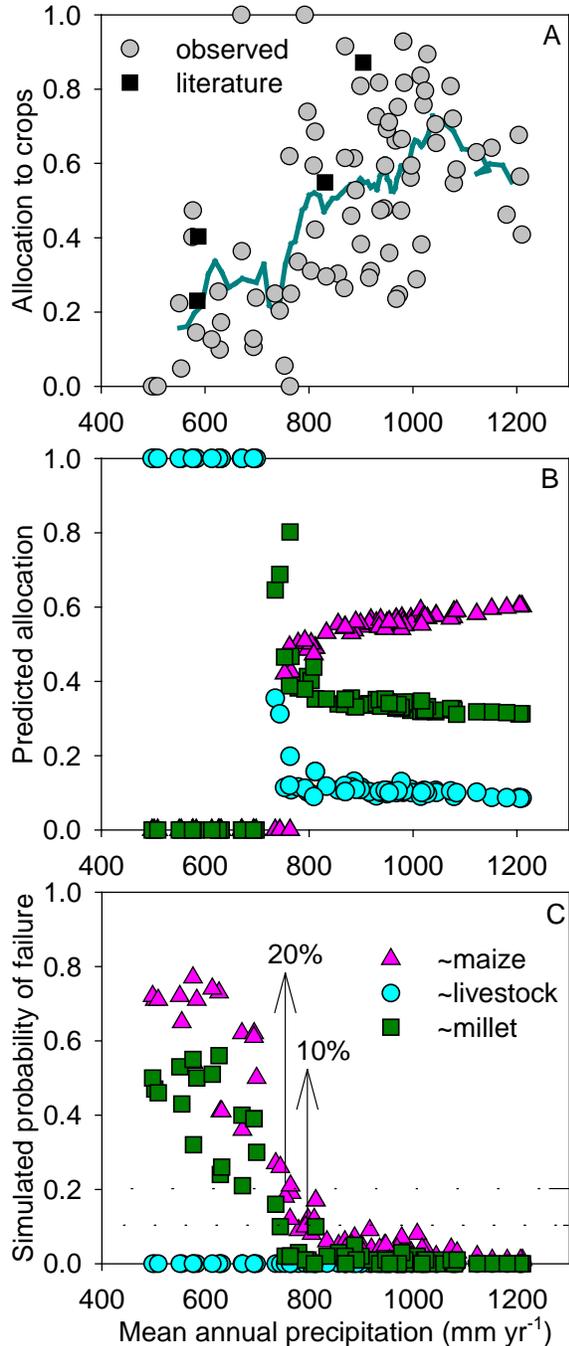


Figure 3. The observed allocation to crops or livestock for the 78 sites (A) and the predicted allocation based upon a safety-first portfolio (portfolio with maximum yield for a $P_{fail} \leq 0.2$) of simulated yields for two grain crops and livestock where livestock rely on the natural PFT's present at a site (B). The associated probability of crop failure (P_{fail}) for the yields of two crops and livestock measured as a function of a simulation of natural PFT productivity (C). Lines in C show threshold P_{fail} of 0.2 and 0.1 above which safety-first models would result in portfolio's with allocation to livestock.

aversion characteristics assumed on behalf of the subsistence farmers. That is, a shift from the assumed risk aversion threshold ($P_{fail,threshold}$) of 0.2 to 0.1 or 0.3 would have resulted in a less than 60mm MAP shift in the transition between crop and livestock dominated allocations (Fig. 3C).

The simulation of natural and crop plant growth resulted in comparable aboveground net primary productivity (ANPP) values to those found for global grassland sites, and 12 Southern African sites (Fig. 4). A component of the maintenance of high yield for natural plants at lower rainfalls was due to the contribution of the succulent PFT included in the model (Fig. 4). Long-season grain crop (~maize) biomass yield response to MAP was approximately proportional to natural plant yield, until the 800mm threshold upon which consistent crop failure reduced the expected yields. Thus the shift to livestock dominated agriculture occurs at the point where crop and natural plant productivity diverge.

Natural flora distributions

The PFT's within the natural flora display a shift towards drought adapted PFT's at lower rainfall (Fig.

5). Drought adapted PFT's made up about 15% of the flora at high rainfall, and increased to almost 30% of the flora at 500mm MAP, transitioning at a breakpoint of 903mm (confidence interval: 845 to 1006mm). Drought adapted PFT's such as, C_4 Chloridoid grasses increased linearly with aridity, succulent (CAM) species made increasing contributions to the flora below a breakpoint of 803mm (c.i.: 753 to 1034mm), and drought-avoiding annuals showed a similar pattern with a breakpoint of 920mm (c.i.: 844 to 1065mm) (Fig. 5). C_4 non-Chloridoid grasses, a more drought susceptible PFT than the C_4 Chloridoid grasses (Ellis et al., 1980) displayed a slight decrease at lower rainfall (data not shown). A principal components analysis of the flora PFT composition confirmed this pattern (data not shown). The

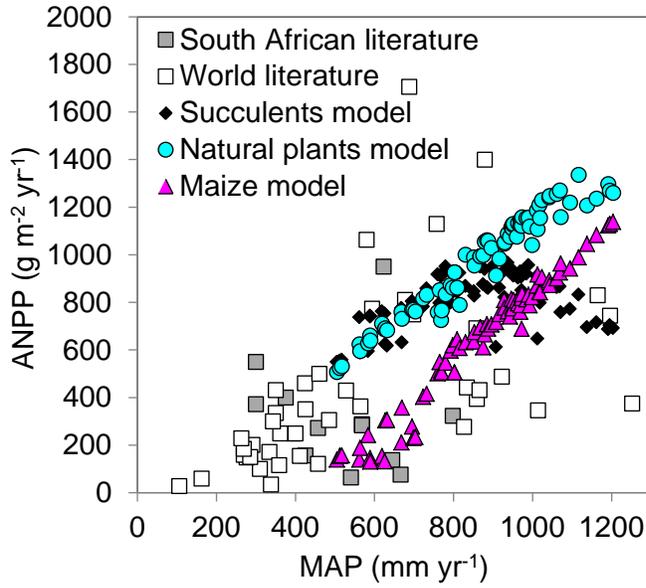


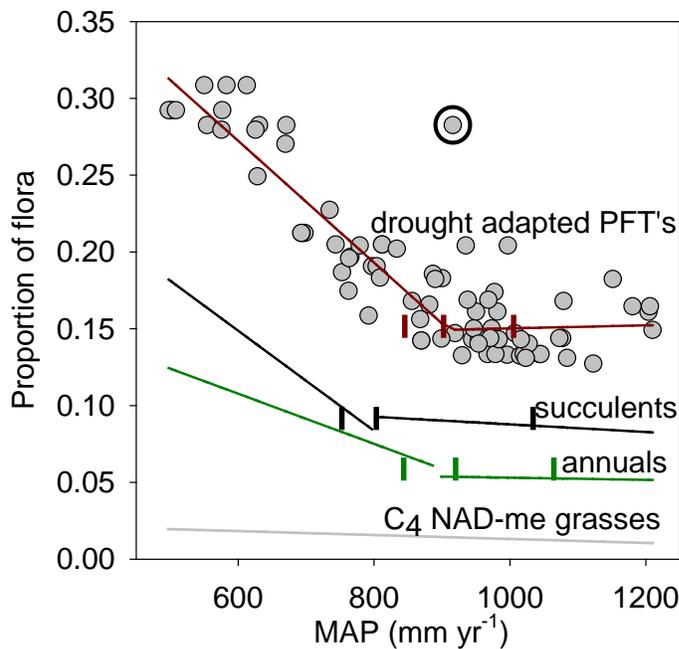
Figure 4. Comparison of above ground net primary productivity (ANPP) for succulents, natural plants weighted by flora composition, and maize from the output of the PFT model for 78 sites and literature data for natural vegetation in South Africa, and globally (literature listed in Methods).

second principal component was most related to the observed crop allocation and summer rainfall, with higher proportions of the flora made up of CAM (succulents) and annual Asteraceae PFT's corresponding to decreased crop allocation, and higher proportions of perennial N-fixer's corresponding to increased crop allocation. The first principal component was most strongly related to winter rainfall, with high tree and low perennial Asteraceae

diversity at high winter rainfall and was unrelated to crop or livestock allocation.

Potential for diversification within the grain crop PFT

The relationship between evapotranspiration (ET) as a proportion of the potential evapotranspiration (ET_o) and soil water content is key to determining whether crops cause drought by using all the soil available water derived from rainfall. The maximum ET is determined by the crop specific parameter K_c , and this transitions to soil water limiting evapotranspiration at soil water contents lower than the threshold K_s . Data, largely from the table of Allen et al. (1998), suggests that grain crops have limited variation in K_c , and high values, while the remaining crops have more variation with some species having low K_c , and natural plants are likely to have a broader range than either of the crop groups (Fig. 6A). The position of the K_s threshold is more variable, and no consistent differences are apparent between crops and natural



plants. The effect of physiological variation in K_c and K_s on the rainfall at which subsistence farmers are modeled to transition from crop to livestock dominated agriculture was estimated through a sensitivity analysis. Here 80 plausible,

Figure 5. A shift in the flora at each of the 78 sites towards increased proportions of drought adapted PFT's (succulents, C₄ Chloridoid (NAD-me) grasses and annual species of the remaining PFT's). Segmented linear functions were fit to three of the PFT's and the drought adapted group, where the 95% confidence interval and median for the breakpoint (bars; determined from segmented regression of 1000 resamples of the data) was within the MAP range, while the C₄ NAD-me grasses were fit with a linear function. The circled site was excluded from all the analyses.

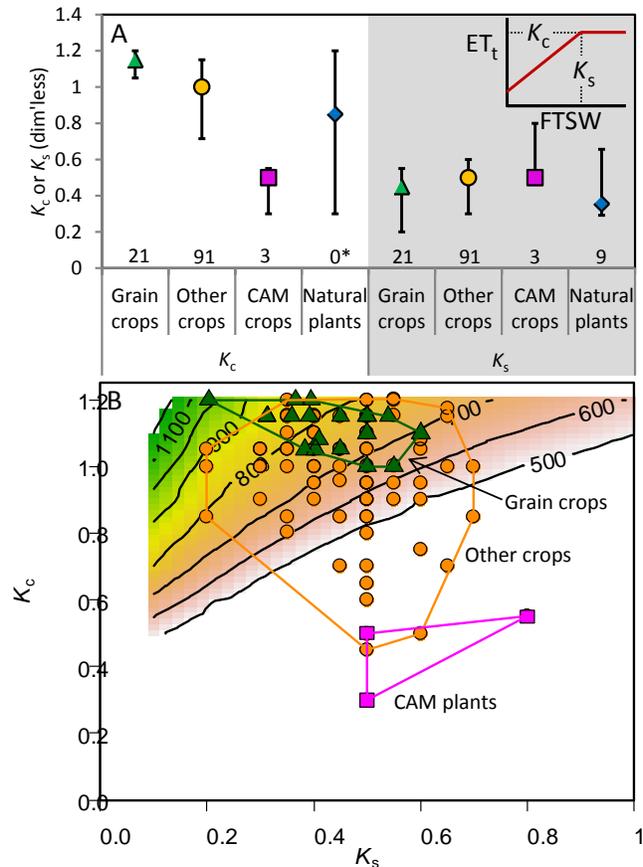


Figure 6. Variation between the water use physiology of grain crops, other crops, CAM physiology crops and natural plants (panel A). Physiology is represented by K_c , the crop evapotranspiration rate as a proportion of ET_0 , and K_s , the threshold fraction of transpirable soil water content (FTSW) at which soil water limits K_c (see inset schematic in A). A scatter plot of these physiologies are shown in panel B, with contours overlaid to represent the mean annual precipitation ($mm\ yr^{-1}$) at which a crop with specific physiology (K_c and K_s values) has a $P_{fail} > 0.2$, the site rainfall threshold at which livestock is simulated to replace the crop in a subsistence farmer's portfolio.

Symbols are the same in panel B as A. Unshaded areas in B represent physiologies that were not simulated, or physiologies that predicted rainfall thresholds for $P_{fail} > 0.2$ that were outside the range of MAP for study area (i.e. $500 < MAP < 1200\ mm\ yr^{-1}$). *The values in A are the numbers of crops per group, with natural plants K_c values represented by the range of other groups. The points and bars represent the median and 95th percentiles for the groups, respectively, with $n < 4$ representing the full range.

hypothetical combinations of K_c and K_s (~physiologies) were simulated for a subsample of 26 sites presented as contours of physiologies that resulted in similar MAP thresholds for crop failure (Fig. 6B), superimposed are the ranges of physiology of extant crops.

Simulation of these physiologies indicated that crop physiological variation in K_c affects the MAP at which crops become unreliable ($P_{fail} > 0.2$) (Fig. 6B), when holding K_s constant i.e. crops with the same threshold soil water content at which transpiration is reduced by low soil water content. K_s affects the steepness of this trend, such that the ET reference crop (a K_c of 1) becomes failure prone at 1100 or 500 mm MAP if K_s is 0.1 or 1, respectively. Specifically, crop physiologies with either a low K_s or high K_c are more likely to result in crop failure for a given rainfall regime. These two factors also had a significant interaction ($F_{1,36} = 8.33$, $p < 0.007$) such that low K_s resulted in disproportionate effects of K_c on the threshold MAP. The sensitivity analysis suggests that the variation in K_c and K_s reported for grain crops limits their use to areas above 650mm and the realistic maximum diversification potential (~change in the threshold MAP at which the crops start failing) for these crops is approximately ~200mm. The remaining crops have a broader range of physiologies, and lower values of K_c , resulting in their potential use in lower rainfall environments (<500mm) and a greater diversification advantage, from 900 to <500mm. Natural plants, including CAM species, having at least as wide a range of K_c values as those of crops, and thus the greatest diversification potential to well below 500mm and greater than 400mm diversification potential (Fig. 6B).

IV. Discussion

Rainfall variability is a major factor affecting subsistence farming, maintaining poverty, reducing incomes and limiting nutrition in southern Africa (Scholes and Biggs, 2004). Diversification of agricultural systems is an important mechanism of increasing the resilience of subsistence farming to rainfall variability. Since most crops share many characteristics, diversification that reduces the correlations of yields between agricultural systems should be a priority. In ecological terms, groups of plants that respond to rainfall variability in different manners are called plant functional types (PFT's). Thus the aim of this study is to demonstrate that the concept of PFT's is useful in defining how the resilience of subsistence farming may be enhanced through diversification with respect to variation in rainfall.

A simulation of crop and natural plant response to variation in rainfall predicted that along a rainfall gradient, subsistence farmers should transition between allocation to grain crop cultivation at high rainfall and reliance on livestock at low rainfall. The implications of this prediction are assessed here.

A lack of diversification potential for the annual grain crop PFT

The threshold mean annual precipitation (MAP) at which crops became failure prone was least sensitive to changes in plant physiology in the range of values reported for grain crops. Thus changing grain crop physiological characteristics (K_c or K_s) by a practical amount through breeding, agricultural practices or by choosing a different grain crop would result in little diversification advantage for rain-fed farming. For instance, a change in K_c or K_s by 0.2 (~20%) within the range of values for grain crops would result in an approximately 100mm shift in MAP at which the crop begins to consistently fail (Fig. 6B). Given that grain crops displayed little variation and high whole plant water use (K_c ; Fig. 6A) it is clear that they represent a plant functional type. The significance of this is that drought is likely to similarly affect these plants and reduce their usefulness as a diversification tool.

Non-grain crops, including vegetables, had much greater variation in physiology such as whole plant water use (Fig. 6A). This variation led to a wide range of MAP's at which these crops failed, and large potential for diversification. Non-grain crops are of limited use for subsistence farming, as grain crops comprise the majority of calories eaten, but the former may contribute to nutrition or provide cash. The physiological diversity of non-grain crops means that they should be classified as many PFT's as was done for natural plants; however this activity may best be done based upon observed drought resilience. Natural plants had the greatest variation in physiology and correspond to many plant functional types. This diversity of plant response to rainfall variability resulted in livestock being a more consistent option to crops. An extreme example of drought tolerance are non-grain crops with Crassulacean Acid Metabolism (CAM), a physiological adaptation to limited rainfall, and exemplified by pineapple, sisal and agave – crops with cash value in environments where other crops will not survive. Indeed pineapples are grown in this region by large-scale commercial farmers (pers. obs.).

Livestock as a buffer stock

Fafchamps, Udry and Czukas (1998) find little evidence of livestock acting as a buffer stock to income during drought induced shocks for semi-arid west African areas. There are a number of reasons that this may not apply globally, with southern African research often considering livestock as insurance for drought periods (Coetzee et al., 2004; Hoddinott, 2006). The climate patterns of west and southern Africa are different, with an especially long winter drought in the sahel in west Africa (Ellis and Galvin, 1994). In contrast the eastern Eastern Cape region has considerable winter rainfall, although limited opportunity for winter crop growth. This may enable livestock in the Eastern Cape Province to be a more reliable buffer than in west Africa.

A caveat to implementation

A number of factors should influence the interpretation of the results reported here. Firstly, the abrupt transition between crop and livestock allocation appears to be primarily determined by a shift to winter rainfall making up a greater proportion of MAP at the expense of crop growing season rainfall. Thus this transition should be less sharp for rainfall gradients where decreasing MAP is entirely comprised of summer rainfall. This implies that grain crops may have greater diversification advantages in other environments (~reliable at lower MAP's), although diversification potential must ultimately be limited due to high water use relative to other plants. Livestock, particularly cattle, have great social value for *Xhosa* culture (Duvel and Afful, 1996), and thus are not a purely substitutable food resource, an explanation for the consistent allocation to livestock under all rainfall regimes (Fig. 2). Crop cultivation also varies in type between extensive farms and intensive gardens (Andrew and Fox, 2004), with variation in crop species grown, agricultural inputs and limited home garden irrigation. The use of intensive home gardens explains the consistent low area of crops grown below the 800mm threshold. Resource extraction from the natural vegetation also represents a major contribution to household economy for people in this region (McGarry and Shackleton, 2009; Shackleton, 2003), and thus livestock are not the only portfolio option that relies on natural plants. Finally, diversification within grain crops is beneficial for other reasons than increasing resilience to drought, for example varying nutrition and differential pest or disease tolerance would promote the use of some grain crop diversity. Thus social and natural systems that determine rain-fed subsistence farming characteristics must necessarily be more complex than the simplistic model used here, and any idea deriving from these type of studies must be tested locally prior to large-scale implementation. However, this study serves as a first pass at establishing the importance of plant ecological principles in determining choices between agricultural systems for subsistence agriculture.

Concluding remarks

Diversification, as a principle by which risk can be reduced, is a common suggestion for subsistence farmers. However diversification is only useful if it reduces the correlation of yield between entities within the agricultural portfolio. Thus the implication of the plant functional type simulations undertaken here is that grain crops are physiologically similar and represent little diversification advantage for subsistence farmers in the face of drought in the Eastern Cape Province of South Africa. The diversification shift with the most utility is a shift from crop to livestock farming, a result borne out by the simulation model as well as observed allocation patterns. This embodies a plant functional principle: agriculture that relies on plants with diverse physiologies (non-grain crops or livestock feeding upon natural plants) will be more resilient to drought than diversification within crops of similar physiologies.

V. References

- Adams, M., Cousins, B., Manona, S., 1999. Land tenure and economic development in rural South Africa: Constraints and opportunities, Overseas Development Institute, London.
- Allen, R., Pereira, L., Raes, D., Smith, M., 1998. *Crop evapotranspiration. Guidelines for computing crop water requirements (Irrigation and drainage paper 56)*. Food and Agriculture Organization, Rome.
- Andrew, M., Fox, R., 2004. 'Undercultivation' and intensification in the Transkei: a case study of historical changes in the use of arable land in Nomp, Shixini. *Development Southern Africa* 21, 687-706.
- Bryndum, S., Boye, C., Chongtham, I.R., Montagne, J., 2007. Present and Future Potentials of Agriculture in Pepela Village, Eastern Cape Province, South Africa. University of Copenhagen.
- Buis, G.M., Blair, J.M., Burkepile, D.E., Burns, C.E., Chamberlain, A.J., Chapman, P.L., Collins, S.L., Fynn, R.W.S., Govender, N., Kirkman, K.P., Smith, M.D., Knapp, A.K., 2009. Controls of Aboveground Net Primary Production in Mesic Savanna Grasslands: An Inter-Hemispheric Comparison. *Ecosystems* 12, 982-995.
- Caylor, K.K., Dowty, P.R., Shugart, H.H., Ringrose, S., 2004. Relationship between small-scale structural variability and simulated vegetation productivity across a regional moisture gradient in southern Africa. *Global Change Biology* 10, 374-382.
- Cocks, M.L., Bangay, L., Wiersum, K.F., Dold, A.P., 2006. Seeing the wood for the trees: the role of woody resources for the construction of gender specific household cultural artefacts in non-traditional communities in the Eastern Cape, South Africa. *Environment, Development and Sustainability* 8, 519-533.
- Coetzee, L., Montshwe, B.D., Jooste, A., 2004. The marketing of livestock on communal lands in the Eastern Cape Province: Constraints, challenges and implications for the Extension Services. *South African Journal of Agricultural Extension* 34, 81-103.
- Donatelli, M., Bellocchi, G., Fontana, F., 2003. RadEst3.00: software to estimate daily radiation data from commonly available meteorological variables. *European Journal of Agronomy* 18, 363-367.
- Dovie, D., Shackleton, C., Witkowski, E., 2006. Valuation of communal area livestock benefits, rural livelihoods and related policy issues. *Land Use Policy* 23, 260-271.
- Dunham, K., 1989. Litterfall, nutrient-fall and production in an *Acacia albida* woodland in Zimbabwe. *Journal of Tropical Ecology* 5, 227-238.
- Duvel, G.H., Afful, D.B., 1996. Sociocultural constraints on sustainable cattle production in some communal areas of South Africa. *Development Southern Africa* 13, 429-440.
- Ehlers, J.H., 1988. *Ekologiese beplanning van gewasse [Ecological planning for crops]*. Department van Landbou Tegnieëse Dienste, Transvaal streek, South Africa.
- Ellis, J., Galvin, K.A., 1994. Climate Patterns and Land-Use Practices in the Dry Zones of Africa. *Bioscience* 44, 340-349.
- Ellis, R.P., Vogel, J.C., Fuls, A., 1980. Photosynthetic Pathways and the Geographical-Distribution of Grasses in South-West-Africa-Namibia. *South African Journal of Science* 76, 307-314.
- Fafchamps, M., Udry, C., Czukas, K., 1998. Drought and saving in West Africa: are livestock a buffer stock? *Journal of Development Economics* 55, 273-305.
- Falkenmark, M., Rockstrom, J., Karlberg, L., 2009. Present and future water requirements for feeding humanity. *Food Security* 1, 59-69.
- Fanadzo, M., Chiduzza, C., Mnkeni, P., van der Stoep, I., Stevens, J., 2010. Crop production management practices as a cause for low water productivity at Zanyokwe Irrigation Scheme. *Water SA* 36, 27-36.
- FAO, 2006. *World Agriculture: Towards 2030/2050. Prospects for Food, Nutrition, Agriculture and Major Commodity Groups. Interim report*. Global Perspective Studies Unit, Rome.

- Fynn, R.W.S., O'Connor, T.G., 2000. Effect of stocking rate and rainfall on rangeland dynamics and cattle performance in a semi-arid savanna, South Africa. *Journal of Applied Ecology* 37, 491-507.
- Hoddinott, J., 2006. Shocks and their consequences across and within households in rural Zimbabwe. *Journal of Development Studies* 42, 301-321.
- Huxman, T.E., Smith, M.D., Fay, P.A., Knapp, A.K., Shaw, M.R., Loik, M.E., Smith, S.D., Tissue, D.T., Zak, J.C., Weltzin, J.F., Pockman, W.T., Sala, O.E., Haddad, B.M., Harte, J., Koch, G.W., Schwinning, S., Small, E.E., Williams, D.G., 2004. Convergence across biomes to a common rain-use efficiency. *Nature* 429, 651-654.
- Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2008. Hole-filled seamless SRTM data V4. International Centre for Tropical Agriculture (CIAT).
- Kirsten, J., Townsend, R., Gibson, C., 1998. Determination of agricultural production to household nutritional status in KwaZulu-Natal, South Africa. *Development Southern Africa* 15, 573-587.
- Koellner, T., Schmitz, O.J., 2006. Biodiversity, ecosystem function, and investment risk. *Bioscience* 56, 977-985.
- Lavorel, S., McIntyre, S., Landsberg, J., Forbes, T.D.A., 1997. Plant functional classifications: from general groups to specific groups based on response to disturbance. *Trends in Ecology & Evolution* 12, 474-478.
- Lehman, C.L., Tilman, D., 2000. Biodiversity, stability, and productivity in competitive communities. *American Naturalist* 156, 534-552.
- McGarry, D., Shackleton, C., 2009. Children navigating rural poverty: Rural children's use of wild resources to counteract food insecurity in the Eastern Cape, South Africa. *Journal of Children and Poverty* 15, 19-37.
- Mills, A., Cowling, R., 2006. Rate of carbon sequestration at two thicket restoration sites in the Eastern Cape, South Africa. *Restoration Ecology* 14, 38-49.
- Mills, A., Cowling, R., Fey, M., Kerley, G., Donaldson, J., Lechmere-Oertel, R., Sigwela, A., Skowno, A., Rundel, P., 2005. Effects of goat pastoralism on ecosystem carbon storage in semiarid thicket, Eastern Cape, South Africa. *Austral Ecology* 30, 797-804.
- Monde, N., 2003. Household food security in rural areas of central Eastern Cape: The case of Guquka in Victoria East and Koloni in Middledrift districts. University of Fort Hare.
- Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles* 22, -.
- Mucina, L., Rutherford, M.C., 2006. *The vegetation of South Africa, Lesotho and Swaziland*. South African National Biodiversity Institute, Pretoria, South Africa.
- New, M., Hulme, M., Jones, P., 2000. Representing twentieth-century space-time climate variability. Part II: Development of 1901-96 monthly grids of terrestrial surface climate. *Journal of Climate* 13, 2217-2238.
- Ntsonto, N., 2005. Economic performance of smallholder irrigation schemes: A case study in Zanyokwe, Eastern Cape, South Africa., Department of Agricultural Economics, Extension and Rural Development. University of Pretoria, Pretoria.
- O'Connor, T.G., Haines, L.M., Snyman, H.A., 2001. Influence of precipitation and species composition on phytomass of a semi-arid African grassland. *Journal of Ecology* 89, 850-860.
- Perret, S., 2002. Livelihood strategies in rural Transkei (Eastern Cape Province): how does wool production fit in?, Department of Agricultural Economics, University of Pretoria, South Africa.
- POSA, 2011. Plants of Southern Africa: an online checklist. South African National Biodiversity Institute.
- Potter, C.S., Randerson, J.T., Field, C.B., Matson, P.A., Vitousek, P.M., Mooney, H.A., Klooster, S.A., 1993. Terrestrial Ecosystem Production - a Process Model-Based on Global Satellite and Surface Data. *Global Biogeochemical Cycles* 7, 811-841.

- Purcell, L.C., Sinclair, T.R., McNew, R.W., 2003. Drought avoidance assessment for summer annual crops using long-term weather data. *Agronomy Journal* 95, 1566-1576.
- SANBI, 2011. South African Biodiversity Information Facility. South African National Biodiversity Institute
- Schlapfer, F., Tucker, M., Seidl, I., 2002. Returns from hay cultivation in fertilized low diversity and non-fertilized high diversity grassland - An "insurance" value of grassland plant diversity? *Environmental & Resource Economics* 21, 89-100.
- Scholes, R., Biggs, R., 2004. Ecosystem services in Southern Africa: a regional assessment. Millenium Ecosystem Assessment, Available from: http://www.maweb.org/documents_sga/SAfMA_Regional_Report_-_final.pdf.
- Scholes, R., Walker, B., 1993. *An African savanna: synthesis of the Nylsvley study*. Cambridge University Press, New York.
- Scurlock, J.M.O., Johnson, K., Olson, R.J., 2003. NPP grassland: NPP Estimates from Biomass Dynamics for 31 Sites, 1948-1994. Data set. Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge.
- Shackleton, C., 2003. The prevalence of use and value of wild edible herbs in South Africa. *South African Journal of Science* 99, 23-25.
- Sheridan, R., Ferreira, A.V., Hoffman, L.C., 2003. Production efficiency of South African Mutton Merino lambs and Boer goat kids receiving either a low or a high energy feedlot diet. *Small Ruminant Research* 50, 75-82.
- Sivakumar, M.V.K., Valentin, C., 1997. Agroecological zones and the assessment of crop production potential. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences* 352, 907-916.
- Statistics_SouthAfrica, 2000. *Measuring poverty in South Africa*. Statistics SouthAfrica, Pretoria.
- Swemmer, A.M., Knapp, A.K., Snyman, H.A., 2007. Intra-seasonal precipitation patterns and above-ground productivity in three perennial grasslands. *Journal of Ecology* 95, 780-788.
- Tesler, L., 1955. Safety first and hedging. *Review of Economic Studies* 23, 1-16.
- van Averbeke, W., Khosa, T., 2007. The contribution of smallholder agriculture to the nutrition of rural households in a semi-arid environment in South Africa. *Water SA* 33, 413-418.
- Zucchini, W., Nenadic, O., 2006. A Web-based rainfall atlas for southern Africa. *Environmetrics* 17, 269-283.

VI. Supplementary material

Full plant functional type model description

The environmental variables (detailed in Methods) were used as inputs into the productivity model for each of the PFT's defined in Table S1. The annual production of each PFT ($Prod_i$) was the sum of the daily products of a number of variables as follows:

$$Prod_i = Drought_i() * \sum_{t=1}^{365} GrowingSeason_{t,i} * \varepsilon_i * F_{apar} * PAR_t * \min[Temp(), Water()] * K_{HI,SMF_i} \text{ with}$$

functions and variables described below. $Drought(DroughtThres_i, DroughtDays_i)$ is a continuous negative exponential function that causes a total loss of production if a threshold ($DroughtThres_i$) or greater number of consecutive days of drought ($DroughtDays_i$; $FTSW_t=0$) occurred in a growing season. Thus,

$$Drought(...) = \frac{2/(1 + \exp(-4.08285 * (DroughtThres_i - DroughtDays_i)/DroughtThres_i))}{1/(1 + \exp(-4.08285 * 1))} - 1$$

where $Drought(...) \geq 0$ (4.08285 was used as it results in 20% yield reduction for a drought of half $DroughtThres_i$). $GrowingSeason_{t,i}$ was defined (0 or 1) according to planting and harvest dates (crops) or according to definition of the PFT as annual (growing season on days of year of $T_{min,t} > 4^\circ C$) or perennial (growing season on days of year of $T_{min,t} > 0^\circ C$). The radiation use efficiency (ε_i) of absorbed photosynthetically active radiation (PAR) was defined from values in Table S1: the maximum ε_i multiplied by PAR and the fraction of absorbed PAR (F_{apar}) as defined by a LAI of 2.88 (the reference ETo surface) and the Beer-Lambert equation. The ε_i was reduced by the minimum of two potentially limiting processes: $Temp(...)$ and $Water(...)$. The beta distribution equation of Yan and Hunt (1999) for proportional thermal responses was used: $Temp(T_{max,t}, T_{opt}, T_{maxkill})$, the temperature response constants were not varied between PFT's and were set to the average for maize growth characteristics by Yan and Hunt (1999): $T_{maxkill}$, 41 and T_{opt} , 31.4°C. The reduction in ε_i with the fraction of transpirable soil water was modeled as a bilinear response: $Water(FTSW_t, FTSW_{thres}, m_1, m_2, c_2)$, consistent with Sadras and Milroy (1996), and variation in the equation constants as defined in Table 1. Thus,

$$Temp(...) = \left(\frac{T_{maxkill} - T_{max,t}}{T_{maxkill} - T_{opt}} \right) \left(\frac{T_{max,t}}{T_{opt}} \right)^{\frac{T_{opt}}{T_{maxkill} - T_{opt}}}$$

and

$$Water(...) = \min(1 + m_1 * (FTSW_t - FTSW_{thres}), m_2 * FTSW_t + c_2).$$

Finally, the K_{HI*SMF} represents the multiple of the fraction of shoot mass either harvested or eaten by livestock (harvest index; HI_i) and the fraction of total biomass made up by the shoot (SMF_i) of the PFT defined in Table S1.

Derivation of PFT characteristics

The parameters used in the PFT productivity model were largely obtained from literature sources incorporating data for as many species as possible, however where data was absent, PFT's were assigned values from related crops, or from first principles. Thus, the majority of values for aboveground harvest index and shoot mass fraction (K_{HI*SMF}), and radiation use efficiency for each PFT were taken from average data for the species groups listed in Gower et al. (1999). Where unavailable for a PFT, values similar to other appropriate PFT's were used. The response of radiation use efficiency (ε) to $FTSW_t$ (K_ε) was taken as the average response for ε or leaf extension rate metadata reported by Sadras and Milroy

(1996) for species representative of each PFT, in some cases crops within the same family. Additional responses were taken from Pimienta-Barrios et al. (2000) using CAM plant gas-exchange. Similarly, the responses of K_s to $FTSW_t$ were from the normalized transpiration ratio metadata of Sadras and Milroy (1996), with additional data for trees from Sinclair et al. (2005). The crop/PFT specific proportion of reference ETo transpired (K_c) was obtained for similar species to the PFT in question from Table 12 of Allen et al. (1998). Maize was an exception as a value of 1.05 was used, consistent with the FAO Aquacrop value, and with lower LAI's present for subsistence farming. The days of drought necessary to induce complete yield loss was assigned in a relative fashion, starting with 14 days for the crops and assigning values to other PFT's in 7 day increments increasing with perceived drought tolerance and access to alternative water supplies (CAM plants = 35days).

VII. References for supplementary material

- Allen, R., Pereira, L., Raes, D., Smith, M., 1998. *Crop evapotranspiration. Guidelines for computing crop water requirements (Irrigation and drainage paper 56)*. Food and Agriculture Organization, Rome.
- Gower, S.T., Kucharik, C.J., Norman, J.M., 1999. Direct and indirect estimation of leaf area index, f(APAR), and net primary production of terrestrial ecosystems. *Remote Sensing of Environment* 70, 29-51.
- Pimienta-Barrios, E., Zanudo, J., Yopez, E., Pimienta-Barrios, E., Nobel, P.S., 2000. Seasonal variation of net CO₂ uptake for cactus pear (*Opuntia ficus-indica*) and pitayo (*Stenocereus queretaroensis*) in a semi-arid environment. *Journal of Arid Environments* 44, 73-83.
- Sadras, V.O., Milroy, S.P., 1996. Soil-water thresholds for the responses of leaf expansion and gas exchange: A review. *Field Crops Research* 47, 253-266.
- Sinclair, T.R., Holbrook, N.M., Zwieniecki, M.A., 2005. Daily transpiration rates of woody species on drying soil. *Tree Physiology* 25, 1469-1472.
- Yan, W.K., Hunt, L.A., 1999. An equation for modelling the temperature response of plants using only the cardinal temperatures. *Annals of Botany* 84, 607-614.

Table S1: Values for growing season, total harvest index (K_{HI*SMF}), radiation use efficiency (ε) and proportional effect of low FTSW_t on ε (K_ε) parameters used for simulation of yield variability of crop and natural plant functional types

PFT	Annual	Growth $T_{min}>$	K_{HI} *SMF	ε g MJ ⁻¹ d ⁻¹	$K_\varepsilon(m_1, FTSW_{thre}, m_2, c_2)$			
					m_1	FTSW _{thre}	m_2	c_2
<i>Crop functional types</i>								
C ₄ crop (155day)	1	4	0.3300	4.37	1.67	0.60	0	1
C ₄ crop (90day)	1	4	0.3300	3.45	2.29	0.55	0	1
<i>Natural plant functional types</i>								
C ₃ grass	1	4	0.0413	3.00	1.89	0.53	0	1
C ₃ grass	0	0	0.0413	3.00	3.03	0.33	0	1
C ₄ grass non-Chlorid	1	4	0.0413	3.45	1.32	0.76	0	1
C ₄ grass non-Chlorid	0	0	0.0413	4.09	2.05	0.56	0	1
C ₄ grass Chlorid	1	4	0.0413	3.45	2.08	0.48	0	1
C ₄ grass Chlorid	0	0	0.0413	4.09	3.57	0.28	0	1
Trees	0	0	0.0338	1.17	2.50	0.40	0	1
N ₂ fixers	1	4	0.0375	2.10	2.22	0.45	0	1
N ₂ fixers	0	0	0.0375	2.10	4.00	0.25	0	1
Asteraceae	1	4	0.0375	2.67	1.15	0.87	0	1
Asteraceae	0	0	0.0375	2.67	1.58	0.67	0	1
CAM plants	1	4	0.0625	1.00	10.0	0.10	-	1.081
CAM plants	0	0	0.0625	1.00	10.0	0.10	-	1.081
Other	1	4	0.0425	2.67	1.55	0.64	0	1
Other	0	0	0.0425	2.67	4.39	0.44	0	1

Table S2: Values for the effect of drought, the crop coefficient for ET_{o_t} (K_c), and proportional effect of low $FTSW_t$ on ET_{o_t} (K_s) parameters used for simulation of yield variability of crop and natural plant functional types

PFT	Annual	Drought effect		K_c	$K_s(a_1, FTSW_{thres}, a_2, b_2)$			
		Days of 0 FTSW	Loss of yield		a_1	$FTSW_{thres}$	a_2	b_2
<i>Crop functional types</i>								
C ₄ crop (165day)	1	14	1.00	1.050	2.3	0.34	0	1
C ₄ crop (90day)	1	14	1.00	1.00	2.1	0.37	0	1
<i>Natural plant functional types</i>								
C ₃ grass	1	14	0.10	0.75	2.5	0.32	0	1
C ₃ grass	0	14	0.10	0.75	2.5	0.32	0	1
C ₄ grass non-Chlorid	1	14	0.20	0.75	2.0	0.39	0	1
C ₄ grass non-Chlorid	0	14	0.20	0.75	2.0	0.39	0	1
C ₄ grass Chlorid	1	14	0.10	0.75	2.0	0.39	0	1
C ₄ grass Chlorid	0	14	0.10	0.75	2.0	0.39	0	1
Trees	0	21	0.30	0.95	2.0	0.39	0	1
N ₂ fixers	1	14	0.40	1.00	2.1	0.38	0	1
N ₂ fixers	0	14	0.40	1.00	2.1	0.38	0	1
Asteraceae	1	27	0.10	1.00	1.9	0.41	0	1
Asteraceae	0	27	0.10	1.00	1.9	0.41	0	1
CAM plants	1	35	0.00	0.30	1.3	0.58	0.130	0.870
CAM plants	0	35	0.00	0.30	1.3	0.58	0.130	0.870
Other	1	21	0.16	1.00	2.2	0.36	0	1
Other	0	21	0.16	1.00	2.2	0.36	0	1