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Climate and southern Africa's water–energy–food nexus

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In southern Africa, the connections between climate and the water–energy–food nexus are strong. Physical and socioeconomic exposure to climate is high in many areas and in crucial economic sectors. Spatial interdependence is also high, driven, for example, by the regional extent of many climate anomalies and river basins and aquifers that span national boundaries. There is now strong evidence of the effects of individual climate anomalies, but associations between national rainfall and gross domestic product and crop production remain relatively weak. The majority of climate models project decreases in annual precipitation for southern Africa, typically by as much as 20% by the 2080s. Impact models suggest these changes would propagate into reduced water availability and crop yields. Recognition of spatial and sectoral interdependencies should inform policies, institutions and investments for enhancing water, energy and food security. Three key political and economic instruments could be strengthened for this purpose: the Southern African Development Community, the Southern African Power Pool and trade of agricultural products amounting to significant transfers of embedded water.

Numerous challenges coalesce to make southern Africa emblematic of the connections between climate and the water–energy–food nexus, which has important economic influence throughout the region. Physical and socioeconomic exposure to climate is high in socioeconomically vulnerable areas and crucial sectors, such as agriculture, but also in energy generation and mining. For example, almost 100% of electricity production in the Democratic Republic of Congo (DRC), Lesotho, Malawi and Zambia is from hydropower. Hydropower further comprises a major component of regional energy security through extensive sharing as part of the Southern African Power Pool (SAPP). The region's population is concentrated in areas exposed to high levels of hydrometeorological variability[1] and is projected to roughly double by 2050[2]. Of the 13 mainland countries and Madagascar (Table 1) that comprise the Southern African Development Community (SADC), six are defined as low income, three as lower-middle income and four as upper-middle income, according to the World Bank classification (using 2012 gross national income per capita). There are few quantified examples of the links between climate and economic activity in the region, although South Africa experienced a decrease in gross domestic product (GDP) in the 1983 El Niño year[3], and economic modelling studies in Malawi and Zambia indicate that the severe 1992 drought caused a drop in GDP of approximately 7–9% and adversely affected household poverty[4]. Climate variability has important consequences for resource management in the region, including for non-equilibrium production systems such as rangeland ecology[5], irrigation[6] and lakes[7]. Southern Africa is also a region where seasonal climate forecasts can potentially benefit areas where sustained forecast skill is demonstrated. Seasonal climate forecasting has been the subject of many studies in sub-Saharan Africa (SSA)[8,9] and the Southern Africa Regional Climate Outlook Forum provides advance information about the likely character of seasonal climate. Yet, despite more than a decade of research on hydrological applications of seasonal forecasts, there is limited evidence of their operational use in the water sector[9]. With ongoing climate change, annual precipitation, soil moisture and runoff are likely to decrease, while rising temperatures could increase evaporative demand in large parts of the region[10] (Fig. 1).

The past decade saw rapid growth in research and policy interest in natural resource scarcity, with water–energy–food interdependencies increasingly framed as a nexus, or resource trilemma. The Bonn nexus conference in 2011[11] is notable in this process of recognizing the complex interactions between sectors and resource systems, and the need to minimize the trade-offs and risks of adverse cross-sectoral impacts[11,12]. The nexus is increasingly prominent on policymakers' agendas, partly in relation to the post-2015 agenda for the sustainable development goals[13]. The private sector was another early promoter of the nexus concept[14] owing to growing associated risks affecting production security along supply chains, such as (but not exclusively) for water[15]. In southern Africa, for example, South African brewers SABMiller are seeking better approaches to handling trade-offs between water, energy and food by attempting to make business decisions through a resource nexus lens[16]. Strong interdependencies on a range of scales give rise to a large number of trade-offs and co-benefits, according to the heterogeneous configurations of societal uses of water across river basins and aquifers. The region's many transboundary basins require actions among upstream and downstream water uses to be reconciled between countries.

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Table 1 | Economic indicators and climate-sensitive economic activities across water, energy and food.

Country	GDP (current US$ billion)	GDP per capita (current US$)	Energy imports (% consumption)	Freshwater withdrawal (% TARWR)	Cereal import dependency ratio (%)	Area equipped for irrigation (% cultivated land)
Angola	115	5,540	32	0.48	55	2
Botswana	14.5	7,250	63	1.6	90	1
DRC	18	420	5	0.05	37	0.1
Lesotho	2.3	1,130	–	1.4	85	1
Madagascar	10	440	–	4.9	10	31
Malawi	4.2	270	–	7.9	6	2
Mozambique	14.4	570	21	0.4	31	3
Namibia	13.4	5,930	84	1.6	65	1
South Africa	382	7,310	46	24	19	13
Swaziland	4.1	3,290	–	23	79	26
Tanzania	28	610	13	5.4	13	2
Zambia	20.6	1,460	14	1.5	5	6
Zimbabwe	12.5	910	10	21	52	5

Sources: GDP (2012)[90]; energy (2012)[91]; water use (2000–2005)[72,92]; food trade (2007–2009)[93]; and irrigation (1960–2005)[72,92].

Previous nexus studies have concentrated on global interdependencies[17], problem framing[18] or case studies of specific systems such as islands[19] and irrigation and hydropower production[20]. Here, we examine southern Africa's nexus from the perspective of climate and modify Hoff's nexus framework[11], which integrates global trends (drivers) with fields of action, to highlight the role of climate as a driver (Fig. 2). Climate encompasses average (that is, 30-yr) conditions, variability over years to decades (that is, as observed) and anthropogenic climate change. In terms of the nexus, we consider the main elements of intraregional links in water–energy–food at a national level, while highlighting connections on the river basin scale and drawing attention to case studies of the many examples of specific trade-offs and synergies[21]. We base our review on published studies, complemented by empirical analysis of available national-level data on climate, water resources, crop production, trade and GDP. We first consider national-level exposure of water, energy and food production to climate variability in aggregate economic terms and analyse the relationship between interannual and multiyear climate variability and economic activity, focusing on GDP and agricultural production. We then outline the potential for seasonal climate forecasting in areas with high forecasting skill and socially and economically important nexus-related activities, and summarize studies that model the impact of anthropogenic climate change on elements of the nexus. Finally, we describe three key intraregional mechanisms for balancing nexus components, and conclude by identifying knowledge gaps in southern Africa's climate and water–energy–food nexus.

National-level exposure of nexus sectors to climate

We characterize exposure as the interaction between characteristics of the climate system (particularly interannual rainfall variability) and a country's dependence on climate-sensitive economic activities such as the share of agriculture in GDP, the proportion of rainfed agricultural land and the energy contribution from hydroelectric sources (Table 1; Fig. 3). South Africa's GDP is larger than that of the other 12 southern African economies combined. The direct contribution of agriculture to the economy is lowest (<10%) in South Africa, Botswana, Swaziland, Namibia, Angola and Lesotho, 13% in Zimbabwe and more than 20% in the other countries. If agricultural processing were included in agricultural GDP, the shares would be substantially larger in most, if not all, SADC countries. The share of cropland equipped for irrigation is low in most of the region, with the exception of Madagascar, South Africa and Swaziland (Table 1). The contribution of hydropower to energy production is very high overall (Fig. 3), but varies considerably across the region, from 1.5% in South Africa to more than 30% in Madagascar, Swaziland and Zimbabwe, and to almost 100% in DRC, Lesotho, Malawi and Zambia. Reliable electricity production is at risk during prolonged droughts and also during extreme flood events, when dam safety is an additional risk. More than 90% of South Africa's energy generation is coal-based[22], well above the rest of the region. Coal-fired power plants with wet cooling systems consume far more water than most other energy technologies[22]. Thus, South Africa's main energy utility, Eskom, uses about 2% of the country's freshwater resources, mainly for coal-fired power stations[23]. Coal mining and energy generation from coal both substantially impact water quality and availability[24]. To reduce these impacts, Eskom has implemented a dry-cooling system in two existing and all new power stations[25], enabling a 15-fold reduction in water use.

Overall, there are strong contrasts (Table 1) in energy (8–84% of energy consumption imported) and food (5–90% of cereal food imported) self-sufficiency, and in the intensity of freshwater use, expressed as freshwater withdrawals relative to total actual renewable water resources (TARWR; 0.1–24%). Countries facing most water shortage, expressed as share of TARWR withdrawn (Table 1), are South Africa (24%), Swaziland (23%) and Zimbabwe (21%), well within categories defined as physically water scarce (ratio larger than 20%[26]). We interpret this indicator with caution, noting its failure to capture the complex spatial and temporal distribution of water, political economic access, differences in water needs and socioeconomic capacity to support effective water utilization[27,28]. Subnational areas of high demand relative to availability include southern Malawi, Namibia and Botswana. Low ratios of water withdrawal to TARWR (such as 0.05% in DRC[28]) could also indicate economic water scarcity owing to inadequate investments to harness and deliver water.

The cereal import dependency ratio (Table 1) reflects the importance of imports for the volume of grains available for consumption in the country (that is, production + imports − exports). It is particularly high for the small countries of Swaziland and Lesotho, and more strikingly so for larger nations such as Botswana (90%), Namibia (65%) and Angola (55%). Dependency ratios are lowest in Zambia and Malawi. Total food aid received by the region (260,000 tons in 2012; Supplementary Fig. 1) was equivalent to

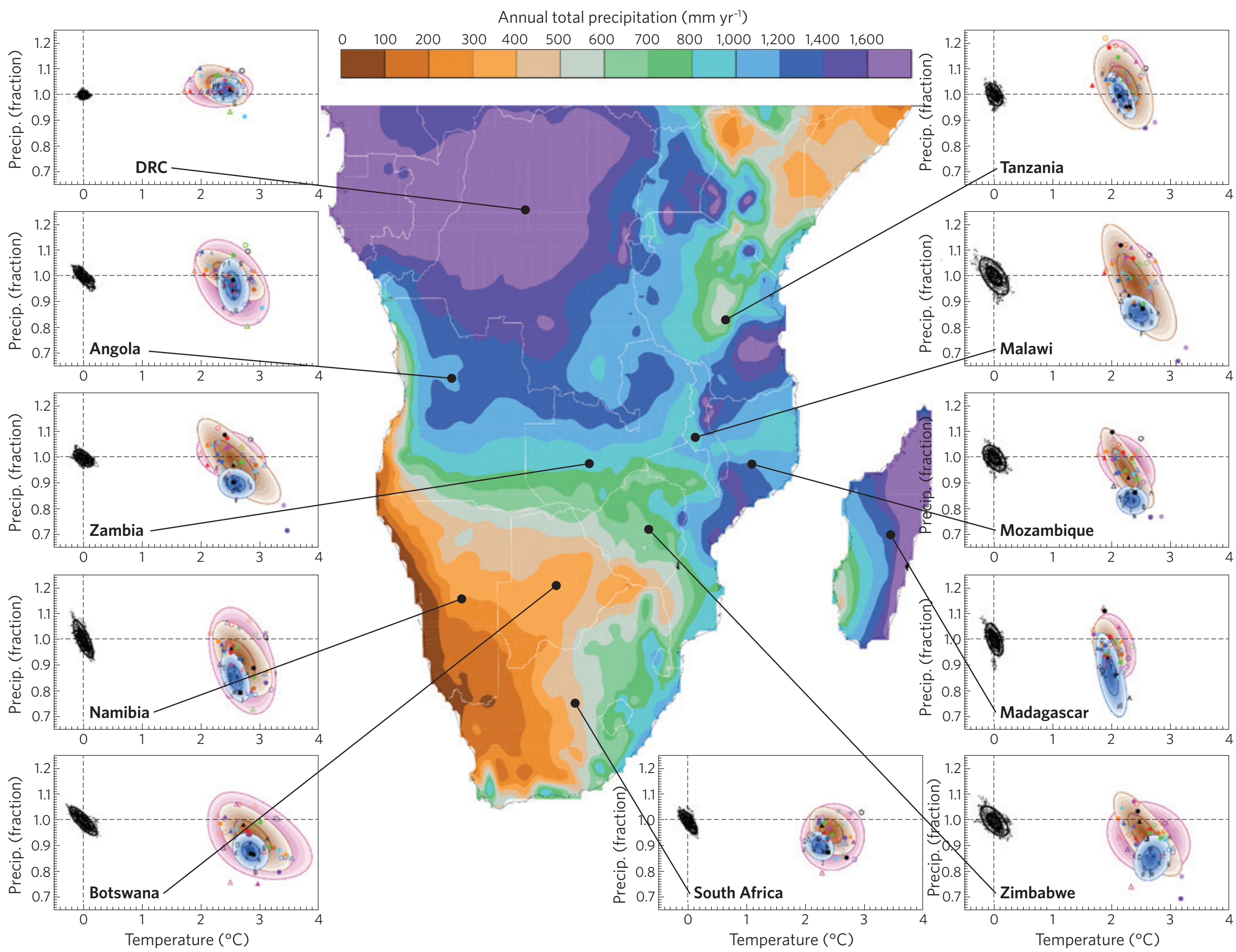

Figure 1 | Average annual total precipitation (1961–1990) and multimodel ensembles of projected changes in national average annual precipitation (as a fraction of 1961–1990 mean) and national average annual mean temperature (°C change from 1961–1990 mean). Estimates are for global warming of 2 °C using a pattern-scaling approach (T. J. Osborn, C. J. Wallace, I. C. Harris and T. M. Melvin, manuscript in preparation). The three ensembles are CMIP3 (21 models: open coloured symbols and pink shaded distribution), CMIP5 (20 models: filled coloured symbols and brown shaded distribution) and Quantifying Uncertainty in Model Predictions (QUMP) (17 versions of the Hadley Centre Coupled Model Version 3 (HadCM3) with perturbed physical parameter values: black symbols and blue shaded distribution). The shaded distributions are fit to the data to represent the bivariate ±2 standard deviation ranges and have been included to facilitate comparison of the model ensembles rather than to represent probabilistic projections of climate. Black dots and black fitted distributions illustrate the ranges of internal variability of 30-yr mean climate simulated in a 1,000-yr control simulation of HadCM3, for comparison with the projected changes in climate.

about 2–3% of food imported by the region from the rest of the world (9 million tons in 2008). Thus, chronic and episodic food insecurity remain important problems in the region. The causes are numerous and, at the household and individual level, are dominated by poverty, environmental stressors and conflict, often underpinned by structural elements in the lives of communities, intensified by sudden shocks that can be climate related such as decrease in cereal availability and food price spikes[29,30].

Climate signals in nexus sectors

Multiyear rainfall variability in southern Africa is higher than in many other parts of the world[31,32]. Interannual variability, expressed as the coefficient of variation (COV), is not particularly high on national scales: <20% for most countries, except for Botswana and Namibia, the driest two countries (Fig. 3). However, rainfall shows much greater local variability (local COV exceeds 20% across much of the SADC region), strong seasonality and a range of multi-annual to decadal variations[33]. At the national level, long-term trends in rainfall between 1901 and 2012 are modest (the linear trend is insignificant relative to the long-term average), without evidence of any clear spatial pattern (Supplementary Table 1). Linear trends during the past two decades show varied behaviour; three countries with wetting trends above 20% of the long-term mean annual rainfall (Botswana, Namibia and Zambia) and Tanzania with a drying trend of 21% (Supplementary Table 1). National-level analysis is likely to obscure local trends and the results are highly sensitive to the period chosen for analysis, particularly in regions with strong multi-annual variability.

National variations in rainfall and temperature have been found to exert major influence on agricultural production in all of SSA, but with considerable regional heterogeneity in the response to rainfall[34]. Another study for SSA used panel regressions to explore the effects of temperature and precipitation variability on country-level economic growth indicators, and found drought was the most significant climate influence on GDP per capita growth[35]. We use

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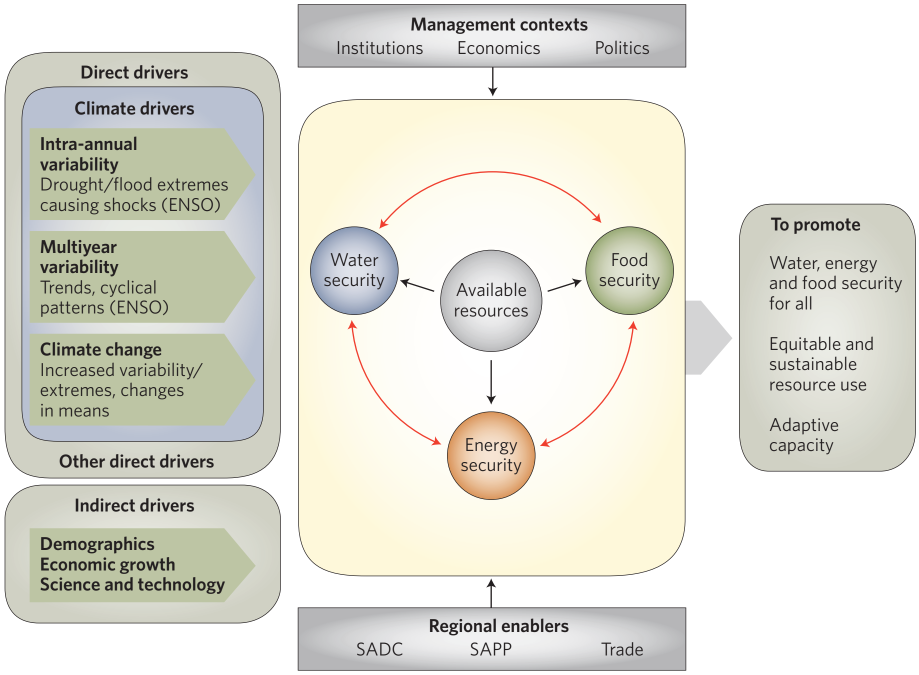

Figure 2 | Modified version of the nexus framework of Hoff[11] integrating global drivers with fields of action, to illustrate the main timescales of climate as a driver in southern Africa. SADC, Southern African Development Community; SAPP, Southern African Power Pool.

correlation analysis to explore, for each country, the associations between annual rainfall and national economic activity (GDP annual growth rate) and agricultural production (all cereals and maize — the most significant crop in the region). Fifteen-year sliding correlations are used to examine the temporal stability of associations between variables (see Supplementary Information). There are no statistically significant relationships between annual rainfall and GDP growth rate (Supplementary Table 2). Correlation of rainfall with total production of cereals and maize shows three countries with significant relationships at the 1% level and three at the 5% level (although for DRC it is negative and possibly spurious). The average sliding correlations are somewhat higher (Supplementary Table 3).

Time series data of hydropower production are neither publically available nor easily comparable between sites/countries, making it difficult to assess the importance of climate variability as a driver of energy production fluctuations. A study of the effects of modified reservoir operation on downstream environmental flows of the Zambezi shows considerable variability in observed hydropower production at three sites, but does not consider the role of climate[36]. Electricity insecurity is known to negatively affect total factor productivity and labour productivity of small and medium-sized enterprises, but the relationship is not simple, with differences between countries and measurement effects[37]. Studies of specific events highlight the major consequences of drought-induced reductions in electricity production[38]. Ref. 18 cites examples of drought impact on the Kariba Dam (Zambezi Basin) during 1991–1992, resulting in estimated reductions of US$102 million in GDP and US$36 million in export earnings; and Kenya, where, during 2000, a 25% reduction in hydropower capacity resulted in an estimated 1.5% reduction in GDP. A review of the economics of climate change in Tanzania profiled the consequences of the 2003 drought, which brought the Mtera Dam reservoir levels close to the minimum required for electricity generation[39]. This prompted the Tanzania Electric Supply Company to approach a private provider to use gas turbine units at huge cost. A more recent World Bank estimate put costs of power shortages in Tanzania at US$1.7 million per day, with an average 63 days per year with power outages[39].

Early warnings from the climate system

Given the links between climate and the water–energy–food nexus in the region, seasonal forecast information can play an important role in guiding nexus-related decision making, depending on forecast skill and utility. Seasonal to interannual variability in southern Africa is high, but so is its predictability relative to other regions, depending on location, time of year[40] and phase of the El Niño–Southern Oscillation[41] (ENSO). This can be seen by considering the association (Fig. 4a) between NINO3.4 sea surface temperatures — as a representation of ENSO — and gridded rainfall over southern Africa south of 15° S (ref. 41). A state-of-the-art coupled ocean–atmosphere model has some skill in predicting seasonal (December to February, DJF) rainfall over the region at a one-month lead time (DJF forecasts produced in November; Fig. 4b shows areas with statistically significant correlation[41]; see Supplementary Information). Stronger ENSO associations and the best model performance are found for maximum temperatures (Supplementary Fig. 2). The areas where ENSO impacts significantly and where forecast skill levels are relatively high include the river basins of the Limpopo, Orange, Umgeni and lower Zambezi.

The Limpopo Basin is particularly notable as having both high economic productivity and strong ENSO associations and forecast skill. Comprising 408,800 km^2, and including the countries of South Africa, Botswana, Mozambique and Zimbabwe, the Limpopo Basin is one of the most water stressed in SSA, and features some of the largest urban conglomerations (including Pretoria, Johannesburg, Gaborone, Francistown and Bulawayo). Irrigation comprises more than 50% of basin water use and other infrastructure (including industry and mining) is also highly dependent on basin water. There are significant mining activities in the basin — particularly in South Africa and Zimbabwe[42] — that generate major water pollution downstream[43]. The Limpopo is heavily regulated, with extensive plans for further development.

Despite forecast skill and potential utility in economic productivity hotspots such as the Limpopo Basin, a comprehensive review of seasonal forecasting status in SSA identified persistent barriers in realizing the benefits of forecast products, which were generally

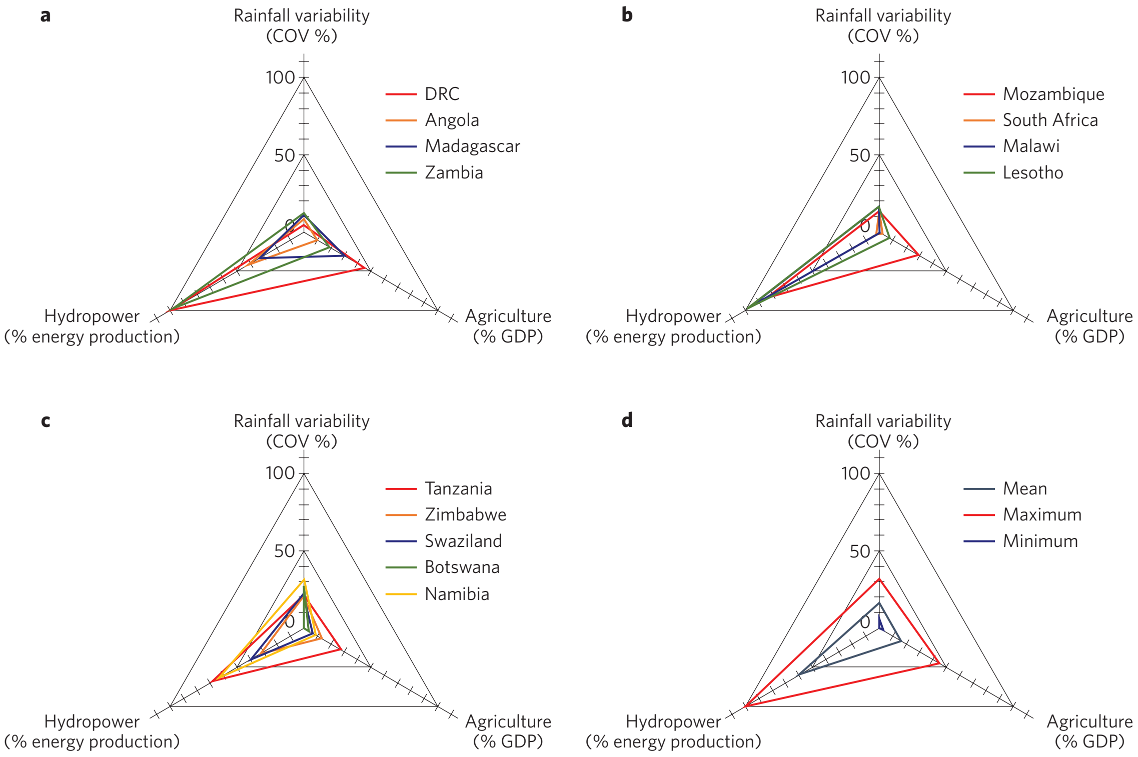

Figure 3 | National rainfall variability and socioeconomic exposure to hydroclimate. a–c, Individual countries. **d**, Average, minimum and maximum of 13 countries. Data for rainfall interannual variability (COV, %) from ref. 84; hydropower share in energy production (%) from ref. 90; and agriculture (crop and livestock production, forestry, hunting and fishing) value added share of GDP (%) from ref. 90. Note: data for agricultural GDP in Malawi are not available.

insufficient to inform response actions, such as production decisions and institutional actions[44]. If these barriers can be overcome, seasonal forecasting has the potential to contribute to anticipating fluctuations in nexus sectors and could inform guidance on reservoir multi-use, water allocation, early targeting of or access to agricultural inputs and credit, design of interventions during food crises, and improvements to trade and agricultural insurance[45].

Modelling nexus sectors in a changing climate

The challenges for the water–energy–food nexus posed by interannual variability occur in the context of a gradually changing climate. Even if an international agreement to limit global warming to 2 °C above pre-industrial conditions is successfully developed, climate models project significant changes that exceed the range of natural climate variability (Fig. 1). According to the majority of climate models, most southern African countries will warm more than the global mean, with annual mean temperatures rising by 2 to 3 °C in most cases. Precipitation changes are more uncertain, with both increases and decreases possible. Nevertheless, for most countries the majority of models project decreases in annual precipitation, by 20% or more for some models and countries. Except for the southernmost countries, there is a tendency for models that project most warming to simulate stronger reductions in precipitation. Analysis of extreme precipitation in the climate models used for the Intergovernmental Panel on Climate Change Fourth Assessment Report shows a marked delay in rainy season onset over most of the region and an early end to the season in parts of the region[46].

Most nexus studies for southern Africa have been motivated by climate change and assess biophysical impacts for specific sectors, for example, rainfall and irrigation water availability on crop production, or river flow changes on hydropower generation. Some crop models simulate sizable yield losses for southern Africa[47], suggesting that the region's food system could be particularly vulnerable to climate change[48]. However, differences in climate scenarios, impact models, spatial and temporal scales, and processes represented restrict our ability to reliably define impacts for specific sectors and, importantly, secondary effects across the water–energy–food nexus. Nevertheless, an estimate of the range of potential impacts on maize yield (and the wide uncertainty range) can be determined from the 30-member ensemble of global gridded crop models run by the Inter-Sectoral Impact Model Intercomparison Project[49] (see Supplementary Information). The simulated maize yield averaged across southern Africa decreases by 15.7 ± 16.3% (rain fed) and 8.3 ± 20.4% (irrigated) by the 2080s relative to the 2000s, that is, a median yield reduction with a substantial range of different outcomes. The wide range is owing to uncertainties in climate and in our understanding of crop response to climate change, particularly the role of increased atmospheric CO_2 concentration on photosynthesis. In the top five southern African producers, median impacts are relatively small in the 2020s and 2050s, becoming more substantially negative by the 2080s, with a stronger level of agreement in the sign of change among simulations (Fig. 5). Among these countries, rainfed cultivation is most negatively impacted, highlighting that water stress is an important limiting factor of crop yield in the region. Average crop water use decreases, resulting in a 5.9 ± 20.7% increase in estimated crop water productivity (Supplementary Information; Supplementary Fig. S3) by the 2080s.

An ensemble of global hydrological models driven by five climate scenarios from the Coupled Model Intercomparison Project Phase 5 (CMIP5) shows reductions in annual discharge from 0 to 50% for the multimodel mean across much of southern Africa, excluding southwest Botswana[50]. River basin and water management models indicate higher risks for Zambezi hydropower generation[51], while regional and global water and food models suggest

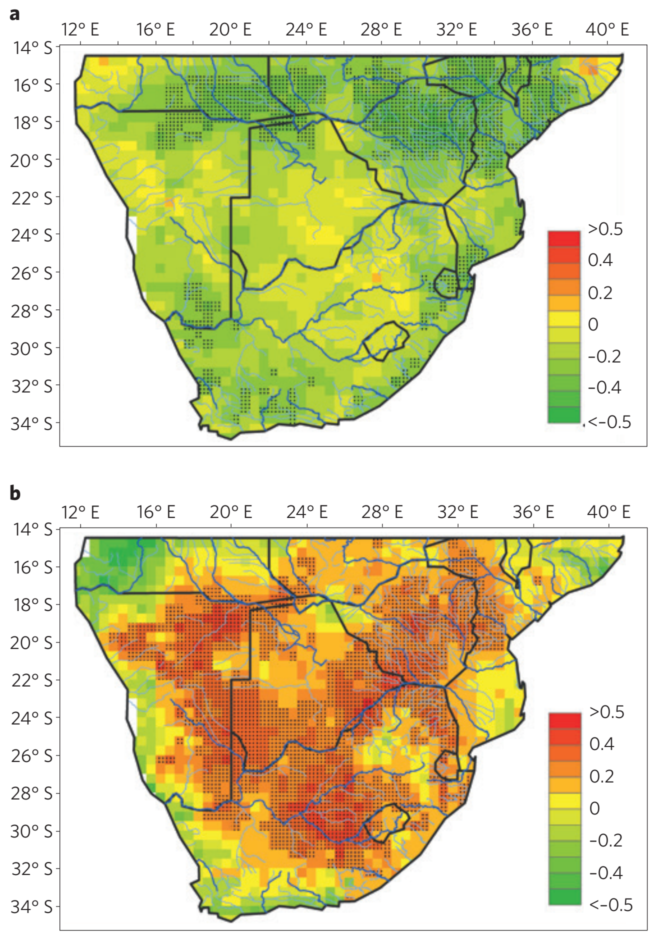

Figure 4 | Rainfall and sea surface temperature; Kendall's tau correlations. a, Between concurrent DJF NINO3.4 sea surface temperatures and DJF rainfall for the 30 years from 1982/1983 to 2011/2012. **b**, Between ECHAM4.5-MOM3-DC2 downscaled seasonal rainfall forecasts for DJF produced in November and observed DJF rainfall. Data for panel **b** from ref. 41. Correlations significant at the 95% level are shaded. See Supplementary Information.

lower runoff raises risks for water and food security in southern Africa in general[52].

The economic dimensions of the nexus in southern Africa can be studied using general equilibrium models that translate biophysical impacts into economic outcomes. This approach simulates economies as adapting to shocks, albeit imperfectly, through market and resource adjustments. Incorporating economic adaptation generally leads to smaller impacts than those from biophysical studies. As global models rarely separate southern Africa from SSA, country-level studies are the region's main evidence base. Historical climate variability imposes high costs on low-income agrarian economies[53] and climate change is likely to have adverse effects on food security[54]. Long-term changes in annual precipitation and temperature may have less impact than historical variability until 2050[4,55]. Historical data show substantial variability in smallholder farm yields and incomes. Increased future variability of smallholder farm yields from climate change is therefore likely to increase the livelihood and food insecurity risks for farmers who are already at high risk[54]. Although most studies focus on agriculture, this is not always the main climate impact channel. For example, nexus studies find that road damages from flooding and weather stress are equally or more important drivers of the economic losses associated with climate change in Mozambique and South Africa[56]. More integrated multisector/country-level studies are needed to guide adaptation responses.

A second strand of economic research focuses on climate and energy policy. A high proportion of SADC greenhouse gas emissions are from South Africa due especially to its reliance on coal-fired power. Curbing these emissions may reduce national income and employment, because financing domestic renewable options requires higher electricity tariffs[57,58]. Lifting South Africa's restrictions on hydropower imports would reduce investment costs and economic losses[59]. Climate change will have considerable indirect impacts on electricity generation with positive feedbacks. Higher water and air temperatures make cooling processes in coal-fired power plants less effective and potentially reduce water availability during longer dry periods[24]; this could result in an overall reduction of power plant efficiency and higher carbon emissions. In its climate change strategy, Eskom aspires to diversify its energy generation mix to lower-carbon-emitting technologies[60]. Solar photovoltaic and wind energy are considered to be the most viable renewable options in terms of water withdrawal and consumption compared with biofuel and hydropower[25]. Biofuels may reduce the region's imported fossil fuels and rural poverty, but have potential food security trade-offs[61]. The research indicates that continued climate change, economic development and urbanization will strengthen interdependencies in the water, energy and food nexus in southern Africa and that climate and associated energy policy will further reinforce the costs of trade-offs and complementarities across the nexus, especially if expansionist regional hydropower and biofuel strategies are adopted.

Intraregional instruments for the nexus

Southern Africa can be characterized as a single economic block of strongly interlinked economies where water, energy and food flow between producers and consumers, which also displays considerable heterogeneity in its natural resource endowments and infrastructure distribution, sociopolitical cohesion and economic development. For both the region and individual nations, this implies significant challenges in attempting to balance supply and demand while maintaining coherent policies towards integrated management of water–energy–food resources. The region is well placed to transfer resources intraregionally to meet energy and food shortfalls. However, rising demand for electricity, food and water throughout southern Africa may sharpen the region's sensitivity to climate-induced shocks. Fifteen transboundary river basins transect the region, including the large Congo and Zambezi basins, shared by nine and eight countries, respectively, as well as many smaller shared catchments. Surface catchments are underlain by an estimated 16 transboundary aquifers[62]. The origin of the southern African economic block can be tied to the dominant position of South Africa and its history alongside other ex-South African and British colonies such as Swaziland, Zimbabwe, Botswana, Namibia and Zambia. South Africa in particular has great cultural, economic and political influence over its neighbours, making its role as a source (and sometimes a sink) of energy, water and food hegemonic[63]. This alliance and influence is also shown through the SAPP (South Africa has 77% of SAPP's installed power supply capacity[64]), the SADC and other agreements.

In responding to the distribution of and demand for water–energy–food resources, three key instruments have emerged. First, the SADC, based in Botswana, addresses how member countries sharing rivers might resolve water allocation priorities through a protocol on shared watercourses[65,66]. The presence of significant water demands arising from irrigated agriculture and the Gauteng urban industrial complex in South Africa has led to relatively sophisticated water-sharing agreements such as the Joint Development and Utilization of the Water Resources of Komati River Basin[67] and the Lesotho Highlands Development Project. Large-scale dams and interbasin transfers, often transboundary, (ref. 68 reports 27 existing ones) form part of national

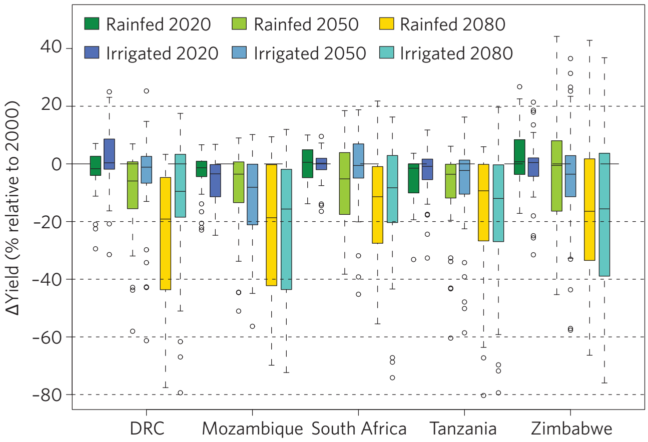

Figure 5 | Simulated climate change impacts on rainfed and irrigated maize yield in the top five producing countries of southern Africa for the near, medium and long time horizon under Representative Concentration Pathway 8.5. The bottom and top of the box are lower and upper quartiles, respectively; the band near the middle of the box is the median value across each set of simulations, which comprises an ensemble of 30 impact simulations[49].

water–energy–food security strategies. South Africa and Zimbabwe, which have the largest numbers of dams, use these predominantly for irrigation and water supply, whereas Mozambique, which has one of the largest total dam capacities, concentrates on hydropower production (Supplementary Table 4). Notwithstanding these institutional and physical structures, in some instances water sharing still suffers from a lack of integration (particularly between agricultural and water institutions) and incomplete efforts to increase stakeholder participation and decentralize water management (ref. 69, reviewing South Africa, Zimbabwe and Mozambique). Coordination during flood events can also be challenging. For example, the persistent 2010–2011 summer rainfall in the Zambezi Basin resulted in high water levels in Lake Kariba. Opening of spillway gates raised downstream water levels, which increased flooding and compromised effective reservoir management at Cahora Bassa farther downstream in Mozambique[70].

Second, the SAPP is a remarkable alliance of 12 energy-generating bodies from 12 countries interconnected through a grid to help smooth spatial and temporal shortfalls in electrical capacity. It was established in 1995 by the member governments of the SADC (excluding Mauritius) to develop an interconnected electrical system, coordinate and enforce common regional standards, harmonize relationships, develop expertise across member utilities and promote sustainable development[71]. The SAPP electricity-generating mix in 2012–2013 was 54,923 MW, comprising a significant proportion from hydropower (17.4%), but dominated by coal (72.9%). The network is intended to function as a competitive market in which surpluses and deficits are resolved via trades and negotiations, and therefore has the potential to serve as a buffering mechanism for climate-induced river-basin-scale electricity insecurity.

Third, food trade in southern Africa naturally results from regional variability in production, especially of maize. Large and efficient producers in South Africa induce a trade surplus with other SADC members. Importantly, trade of agricultural products corresponds to significant transfers of embedded water resources, or 'virtual water trade' (VWT; see Supplementary Information). Water resources embedded in the regional food exports of South Africa and Zambia (0.9 and 1.2 km^3 in 2011, respectively; Fig. 6a)[72] account for two-thirds of the total intraregional flow (3.2 km^3). The dominant link is from Zambia to Zimbabwe, with a volume of 0.8 $km^3\ yr^{-1}$ of virtual water, followed by Mozambique to Malawi and South Africa to Zimbabwe (both 0.5 $km^3\ yr^{-1}$). Zimbabwe was the region's major virtual water importer in 2011, importing 2.0 $km^3\ yr^{-1}$ from other southern African nations. Considering all international food trade, southern Africa is largely a net importer of virtual water. Indeed, international imports from outside the region (10 million tons of food, or 20.5 km^3 of virtual water) dominate the VWT flows of southern Africa (27.9 $km^3\ yr^{-1}$; Fig. 6b). In return, smaller volumes are exported to outside the region mainly from South Africa (3.2 $km^3\ yr^{-1}$). Most of South African virtual water exports via food are embedded in maize, of which less than 10% is irrigation (blue) water (0.066 km^3). This represents almost all of the intraregional blue VWT (0.067 km^3)[73]. This small percentage reflects the dominance of rainfed (green water) agriculture in the region. Although strong open trade is an important tool to alleviate climate-induced food deficits[74,75], and VWT openness tends to reduce undernourishment[76], southern African countries have varying levels of trade connectivity and link strengths, both for intra- and extra-regional food trade links. Informal border trade plays a crucial role in alleviating food shortages. Estimates suggest that 150,000–250,000 tonnes of maize flow from Mozambique to Malawi during years of good production in Mozambique and high demand in Malawi[77]. Informal traders are less encumbered by trade regulations than larger formal grain traders, and hence can respond to arbitrage opportunities more quickly[78]. Thus, the potential benefits of food trade to alleviate production shocks are likely to be uneven across the region, and require further investigation.

One of SADC's main goals for regional integration is to promote trade across member countries. Efforts are ongoing to reduce major existing barriers, such as trade regulations and lack of reliable transportation infrastructure[79] — notably via the protocol on trade[80] — including facilitation of customs processes and a regional infrastructure plan for the transport sector[81]. SADC is currently exploring opportunities for greater cross-sectoral coordination in the SADC climate change and green economy strategy (under revision at time of writing[82]), in which key recommendations focus on implementations that will ensure actions do not take place in a single directorate. Such recommendations have arguably comprised the most demanding area of work for the strategy development, reflecting the importance of ensuring cross-sectoral coordination, as well as finding agreement on how to achieve it on the regional scale.

Conclusion and outlook

Climate plays an important role in determining medium-term water availability, potential agricultural production and some components of energy production and demand. Climate variability drives fluctuations in water–energy–food elements with secondary effects across the whole nexus (Fig. 2). Exposure to climate variability and climate change are high across nexus sectors that include substantial areas of economic activity in southern Africa and there is strong evidence of the effects of individual climate events. For example, South Africa experienced a 7% drop in GDP in the 1983 El Niño year, and climatic fluctuations resulted in GDP variations of up to US$5 billion[3]. The 2000 floods in Mozambique led to devastating impacts on livelihoods, electricity supplies and basic infrastructure[83]. Yet our analysis of associations between rainfall, GDP and crop production using available data shows mostly weak and statistically insignificant correlations in contrast to other studies for SSA based on panel regressions[34,35]. This is likely to be partly a function of scale, where national and annual scales obscure stronger relationships that may exist at finer levels of analysis. Data availability (for example, absence of publically available hydropower production time series) and quality also play a role. The country climate estimates are often based on sparse station coverage, particularly since the 1980s[84], and recent scrutiny of GDP data for SSA has highlighted a lack of transparency in data sources and collection methods, lack of metadata and lack of detail on methods of aggregation[85]. This leads to differences between GDP estimates, non-random

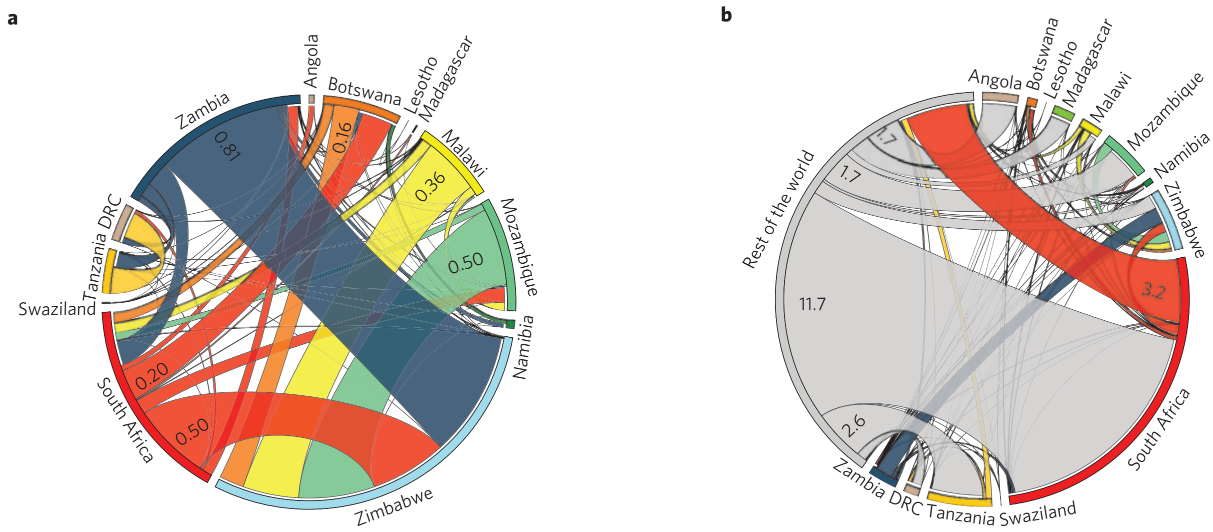

Figure 6 | Water resources transfers (km³) through food trade in 2007. a, Among southern African nations; and **b**, with the rest of the world. Ribbon colours indicate the country of export. Data from refs 93–95.

errors, adjustments to historical data and inhomogeneity in time series. National statistical offices are woefully under-resourced in SSA, while the need for good-quality data is paramount and urgent, to underpin reliable physical and economic modelling and detailed narrative of the causal links between climate and nexus sectors[86].

River flows in the region are strongly linked to seasonal rainfall and temperature variations, and the information reviewed here provides evidence that seasonal forecasting of river flows in some basins has application potential. However, the benefits from seasonal forecasting for reducing net food and energy imports through enhanced agricultural and hydropower production/energy mix have yet to be studied and, even more importantly, implemented in practice. For the future, climate models show fairly strong agreement that the southern countries in the region may become drier and the secondary impacts, although very uncertain, are likely to be substantial across the water–energy–food nexus.

Water, energy and food are linked across different scales in southern Africa. Spatial interdependence is high and climate anomalies can produce regional scale effects, for example, ENSO-related droughts and river-basin-scale floods. At the national level, water and energy are closely coupled through significant hydropower production in several countries. Water use for biofuels and cooling for electricity generation remains relatively modest, except for cooling in South Africa. In South Africa, policies rarely cross sectoral boundaries of water and energy at all governance levels, yet integration of renewable technologies for pumping and heating has the potential to benefit mitigation and achieve expenditure savings[21]. Water and food links are strong, primarily through green water requirements in rainfed agriculture and some hotspots of blue (irrigation) water demand, which account for most freshwater consumption in the region. Food and energy links are growing due to increasing irrigation, mechanization and fertilization of agriculture, while biofuel development remains low. The rapidly increasing demand for energy by industry and mining, rapidly growing urban areas and agricultural intensification is likely to impose increasing strain on the water–energy–food nexus. At the regional level, nexus interdependencies are strong, due to multiple shared major river basins and aquifers, the SAPP power-sharing infrastructure, and intraregional food and embedded water trade. These links are enhanced by governance mechanisms such as the SADC, which has established protocols on shared water, energy and food security, the Southern Africa Regional Climate Outlook Forum, and initiatives on trade and the green economy.

Debate is ongoing about whether there is anything new about the nexus that distinguishes it from earlier integrative framings[87,88]. Some argue that a nexus framing is better at uncovering more effective approaches and methods for cross-sectoral integration by examining trade-offs and co-benefits, and through linking disparate knowledge sets and improving governance[89]. However, entrenched vertically structured government departments and sector-based structures of agencies, policies and regulatory mechanisms complicate coordination, and remain challenges to cross-sectoral integration[87–89]. The political economy of governance and operation is further challenged by regional and intraregional institutional capacity and power imbalances. Our review suggests that climate change, combined with increasing demand associated with wider socioeconomic development pathways, will intensify interdependencies in the water–energy–food nexus, particularly shorter-term pressures associated with extreme events. We have outlined some of the main interdependencies and key regional institutional and policy structures in southern Africa. There is a need to map these structures on finer scales, to understand and share insights into where trends and shocks have been managed effectively in the past, and to identify measures that enhance successful cross-sectoral approaches. There are some efforts in regional strategy and policy formulation to better achieve cross-sectoral coordination, but the modalities for attaining such coordination are still under debate. In a highly climate-sensitive environment such as southern Africa, emerging strategies — such as those under the SADC — will bear fruit only if recognition of co-dependencies and inter-relationships in the nexus provides the basis for credible and well-monitored actions.

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Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to D.C.

Competing financial interests
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