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Assessing water-energy-food-ecosystem nexus policy trajectories under uncertainty in the Inkomati-Usuthu water management area, South Africa

Janez Sušnik [a,*], Blaine Haupt [b], Daniella Kristensen [b], Alice Harvey [b], Gareth Simpson [b,c], Roberto Roson [e], Muhammad Faizan Aslam [d,f], Chaymaa Dkouk El Ferroun [g], Antonio Trabucco [d]

[a] *Land and Water Management Department, IHE Delft Institute for Water Education, PO Box 3015, 2601DA Delft, The Netherlands*
[b] *Jones & Wagener, PO Box 1434 Rivonia, 2128, South Africa*
[c] *WSP Australia PTY Ltd., Newcastle, NSW 2300, Australia*
[d] *CMCC Foundation – Euro-Mediterranean Centre on Climate Change, Italy*
[e] *CF Applied Economics, Fondazione Università Ca'Foscari, Venice, Italy*
[f] *Department of Agriculture, University of Sassari, Viale Italia, 39, 07100 Sassari, Italy*
[g] *Eurecat, Centre Tecnològic de Catalunya, Unit of Applied Artificial Intelligence, Lleida, 25003, Spain*

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ABSTRACT

The water-energy-food-ecosystems (WEFE) nexus promotes holistic management of natural resources. WEFE sectors are linked through socio-economic connections, for example the food sector depends on water availability, and through policies largely developed in silos. South Africa has c. 80% of households reporting inadequate access to food and water resources, but has mineral wealth supported by high-value agriculture and tourism. The primary energy source is coal, with aging infrastructure leading to intermittent energy supply. This paper presents the development of a system dynamics WEFE nexus model in the Inkomati-Usuthu Water Management Area, capturing interactions between sectors to 2050 under climate and socio-economic pathways. The model integrates policies to assess their impact across sectors. Implemented one-at-a-time, policy impacts tend to be confined to the sector to which they are developed. The land sector is a key nexus impact driver, and land-based policies have wide impacts across sectors. Food production is shown to drop up to 52% compared to the reference, with nitrogen leaching dropping by up to 37%. With all policies implemented simultaneously, impacts across sectors are greater and most sectors benefit for example crop production is enhanced by up to three times, nitrogen leaching drops by up to 48%, and greenhouse gas emissions are reduced by up to 19%, reflecting policy design. By integrating multiple uncertainties, in terms of modelling biases and strong radiative forcing, variables such as crop yield and biomass growth under some RCP8.5 simulations can expand with predicted values well above feasible levels. Results trends were validated by local stakeholders and against observation. Results suggest that interactions between policies are very complex, an important message for policy makers dealing with natural resources management. Results show unintended consequences (trade-offs) of siloed policy development and implementation, with some policies countering the effects of others. For example, land and ecosystems preservation policies tend to reduce local food production, an issue for food security concerns. There are hundreds of millions of combinations, opening opportunities for machine learning to search vast spaces and suggest 'optimal' policy strategies. This work contributes to: i) improved understanding of multi-sectoral response to policy implementation; ii) providing updates to policy makers regarding resource response to policy actions; and iii) promoting holistic, integrated thinking about natural resources management and policy development in the region.

1. Introduction

The water-energy-food (WEF) nexus emerged in the 2011 Bonn Nexus Conference (cf., [1,2]) as a concept promoting the holistic management of natural resources. The WEF nexus has been expanded to include ecosystems (thereby forming the WEFE nexus) as foundational

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* Corresponding author.
E-mail address: j.susnik@un-ihe.org (J. Sušnik).

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to providing the services on which the WEF sectors depend [3–5]. Central to the WEFE nexus is the idea that the resources of the nexus sectors, such as water, soil, fossil fuels, etc., are inextricably linked to each other [6]. WEFE nexus sectors provide outputs which are demanded, exploited, and used by society (e.g. drinking water supply, food provision, electricity generation, natural areas). The WEFE nexus sectors are tied to each other through socio-economic connections, for example the food sector depends on energy and water generation, acquisition, and supply for the generation of food products. Globally, about 70 % of freshwater withdrawals are used in irrigated agriculture, 15 % of water withdrawals are used in energy generation, 10 % of energy generated is used in water provisioning, and a further 30 % of energy is used in the agricultural sector [7]. The WEFE sectors are governed through governance systems and policies. Such policies and governance are still largely developed and organised in distinct silos that ignore or overlook the connections between sectors, potentially leading to unanticipated and/or detrimental impacts (e.g. [8]). Better understanding of trade-offs and highlighting opportunities for improved policy and governance design could lead to more effective and efficient management of resources, something that recent work in Africa has shown [8,9]. Further, research on the nexus has been carried out worldwide, with numerous examples in the literature (e.g. [10–14]). Despite the strengths in the nexus approach, it is not without criticism, and a number of authors have pointed out flaws and gaps in the WEFE nexus approach [6,15,16]. As such, it is increasingly important to start offering real-life case studies with actionable recommendations grounded in reality to prevent ‘the nexus’ from becoming another academic buzzword (cf., [17–19]). This paper aims to contribute to such grounded, actionable insight.

Due to the interconnectedness between WEFE sectors and policies [6], a holistic and comprehensive systems approach is critical [20] to attempt to better understand and analyse system-wide effect and implications. The nexus concept is an attempt to improve on sectoral resources management paradigms [21] such as Integrated Water Resources Management (IWRM; [22]) as it intends to be holistically integrative [23]. However, the WEFE nexus has come under criticism for not delivering consistently-applied tools, falling short of capturing all nexus interactions, favouring quantitative assessment and being confined to disciplinary silos [15]. A further shortfall is the urgent need to move from ‘nexus thinking’ to ‘nexus doing’ [7], making research more actionable. Despite this, the nexus concept is gaining traction as a way of thinking more broadly and coherently about efficient and sustainable integrated resources management.

South Africa is a third world country with an estimated population of over 63 million people (STATSSA, 2024) with up to 80 % of South African households reporting inadequate access to food in 2021 in some rural locations (with a national average of about 13 % (STATSSA, 2024). Further, South Africa is considered a water scarce country [24] but with an abundance of mineral resources ranging from diamonds, gold and platinum to coal, manganese and iron ore. South Africa’s primary energy source is coal, with aging energy infrastructure leading to intermittent energy supply challenges. The economy is supported by high-value agriculture and tourism. Given the significant challenges faced by the WEF sectors there is pressure on holistic policy design and implementation. As is similar worldwide, policy design and implementation in South Africa is typically sectoral with little consideration of the subsequent trade-offs and synergies to other sectors. In order for South Africa to move towards relief in the WEFE sectors it is critical that there is a shift towards nexus thinking. An important aspect not to be overlooked is that South Africa supports nine terrestrial biomes [25], demonstrating rich biodiversity. Water, energy, and food inherently impact on these biomes and are also critically dependent on functioning ecosystems, and thus the environment must be considered when applying nexus thinking. Despite the urgency in the southern African context, few studies have quantitatively assessed the impact of policies on the WEFE nexus, and the few that do focus on major cities such as Cape Town or on the whole country [26–29]. There are a distinct lack of studies examining policy impact at the river basin scale in South Africa under uncertain futures, although recent work has started to make progress in this direction in other African nations (e.g. [8,9,14,30]), though none of these studies consider either/or policy impacts, uncertainty analysis, or use the latest climate and socio-economic projection data.

In this regard, this paper presents the development of a quantitative system dynamics WEFE nexus model in the Inkomati-Usuthu Water Management Area (IUWMA), South Africa, a river-basin level study. The model captures, quantitatively and dynamically, key interactions between the water, energy, food, and ecosystems sectors. It assesses system trajectories to 2050 under diverse future climatic and socio-economic pathways using the latest climate and socio-economic projections, accounting for the uncertainty in the projections associated with these pathways. The model integrates important policies linked to each of the WEFE sectors in order to assess their impact across sectors and under different future pathways. The study uses system dynamics modelling as the quantitative approach, augmented by stakeholder co-produced qualitative conceptual systems mapping. It is hoped that this work will: i) contribute to the better understanding of multi-sectoral response to policy implementation in the IUWMA region; ii) provide updates and comprehensive information to policy and decision makers regarding the WEFE nexus and its long-term response to policy actions; iii) will promote a more holistic, integrated way of thinking about natural resource management and policy development in the region. The study showcases a number of novel aspects including integrating ecosystems explicitly into WEF nexus models at river basin scale, quantification of uncertainty in WEFE nexus systems models (novel in the WEFE nexus context), and the potential implication of implementing policies on the whole WEFE system in the IUWMA, where such an analysis has yet to be carried out, thus contributing to local considerations on natural resources planning and integrated development aiming to avoid trade-offs. The holistic, integrated assessment of resources-wide impacts in this context is also novel, and is a step towards moving from nexus thinking to nexus doing [7], ensuring that the WEFE nexus concept does not become a mere buzzword with no practical relevance. This work therefore has the potential to contribute to discussions around integrated policy, policy efficiency, and natural resources management and planning, issues that are all increasingly called for.

2. The inkomati-usuthu water management area

The Inkomati-Usuthu Water Management Area (Fig. 1) is a transboundary river basin shared between Eswatini, South Africa, and Mozambique. It covers approximately 46 800 km^2, of which 2600 km^2 (6 %) are in Eswatini, 28,700 km^2 (61 %) in South Africa, and 15,500 km^2 (33 %) in Mozambique (Slinger et al., 2010). In this study, only the South African portion of the IUWMA, in the Mpumalanga Province, was modelled, although transboundary water obligations were accounted for. The IUWMA includes four river catchments: Sabie-Sand, Crocodile, Komati and Usuthu. The dominant economic activities are agriculture, ecotourism, forestry and mining, which are critical for ensuring energy security, food security, and livelihoods. Several of these pose a threat to water quality and water availability, as well as to land quality. The IUWMA contains critical conservation areas, such as part of the Kruger National Park (about 37 % of the Park). Irrigated agriculture and forestry provide about 60 % of jobs and use most of the water, with 31 % and 21 % being utilised for irrigation and forestry, respectively (www.iucma.co.za). While irrigated sugarcane is a significant water and land user, the sugarcane and sugar industry are also major employers in the region, while macadamia farming is gaining importance for export. Surface water makes up the most important water supply source, while a general trend of depletion of groundwater resources is also observed [31]. Negative impacts on water quality stem from poorly managed wastewater infrastructure, informal settlements and illegal connections, mining effluent, land conversion and diffuse pollution from agriculture.

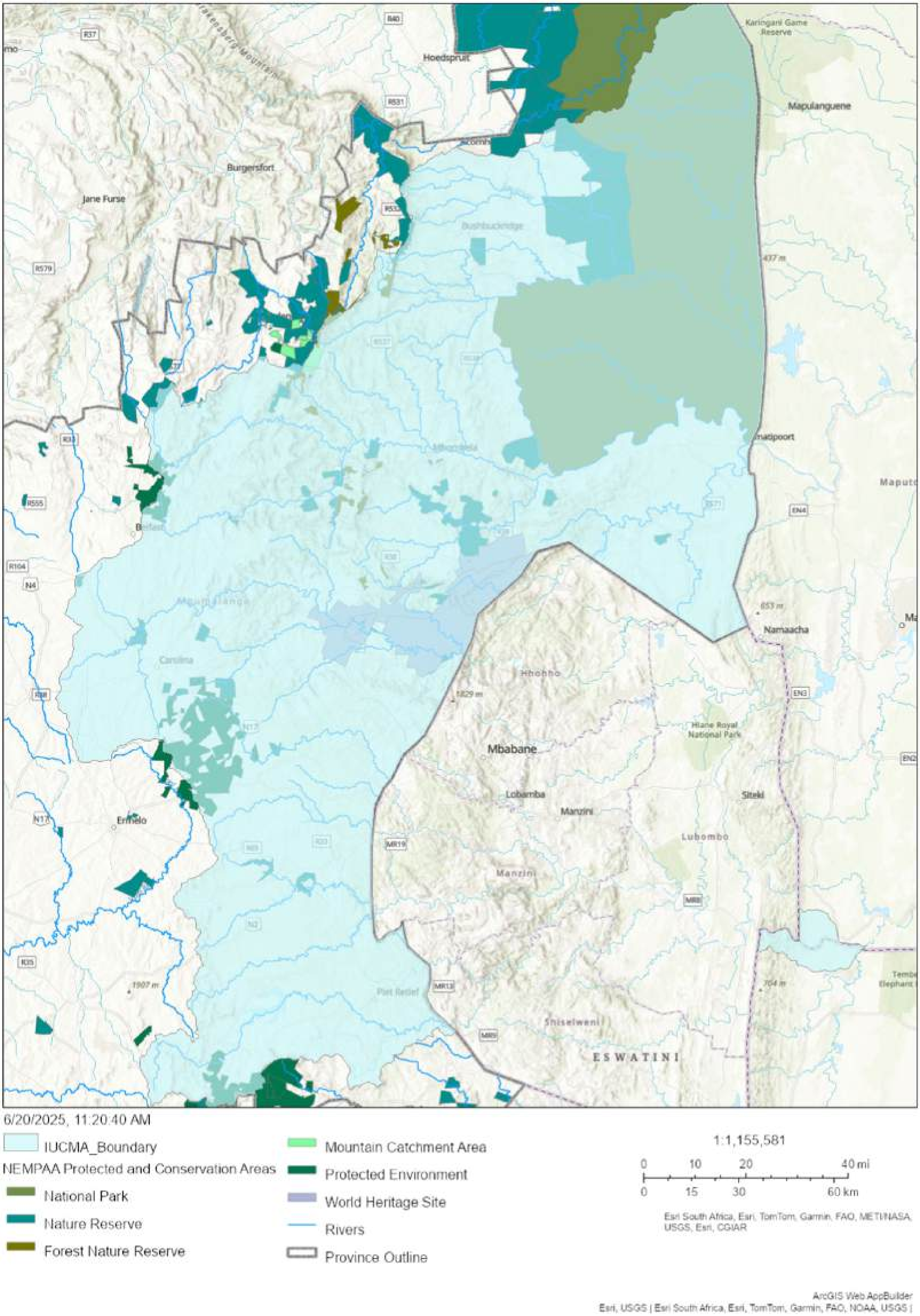

Fig. 1. the Inkomati-Usuthu Water Management Area. From: Department of Agriculture, Land Reform and Rural Development. 2021.

Based on data associated with the 2011 Census (www.statssa.gov.za) together with 2021 mid-year population estimates (www.statssa.gov.za), the population in the IUWMA was estimated to be 2.3 million in 2021 (3.8 % of South Africa's population). In 2012 it was estimated that the Gross Geographic Product (GGP) of the IUWMA was approximately 9 billion Rand, contributing about 0.3 % of South Africa's Gross Domestic Product (GDP) [32]. The manufacturing and mining sectors were the most significant contributors. Coal mining and agriculture are critical for ensuring energy, food and job security, but impact on water quality and water availability for all users. Inter-basin transfers for power generation form an important component in the region. While little energy is generated within the IUWMA, mining in the region contributes significantly to national coal supply, the energy from which is fed back into the basin for consumption. Climate change is expected to exacerbate resource sector challenges and threatens economic development, making it more difficult to meet sustainable development objectives. Between 2009–2018, average cumulative rainfall trends have been declining [31]. If these trends continue, and predicted increases in frequency, duration and intensity of extreme weather events such as droughts and floods are realised water-related issues will be exacerbated.

Therefore, in the study area, water (declining supply), energy (from mining activities), food (being a breadbasket regionally for maize, soy, sugarcane, and macadamia), ecosystems (housing part of the Kruger National Park), climate, and socio-economic considerations (e.g. energy and food access) all converge, posing development challenges in the near to midterm future. In addition, the basin was chosen as it includes several other interesting features. The basin was selected as it has a formal Catchment Management Authority, which is not common in South African basins. Secondly, it was selected for its diversity and competing land uses. In addition to coal mining and agriculture, the basin contains significantly important areas of biodiversity, such as the Kruger National Park. Lastly, the transboundary considerations add to the complexity and analysis required for the basin. These issues make the IUWMA an ideal 'nexus hotspot' to study in the context of integrated resources management and attempting to assess and confront likely trade-offs in development and resource security objectives.

3. Methods and data

Two complementary approaches, both commonly adopted in nexus studies, were used to design and build the WEFE system dynamics model for the IUWMA: i) conceptual mapping of the case study (e.g. [33]) for qualitative understanding of the links between nexus sectors and; ii) system dynamics modelling (SDM; [34]) for quantitative assessment of future climate, socio-economic, and policy trajectories under uncertainty. Such an approach has been adopted in similar nexus studies (e.g. [30,35–41]). Outputs from the conceptual stage (i) guided development of the SDM (ii). Both approaches underwent multiple iterations until final versions were validated by local partners in stakeholder workshops (Table 1). A detailed report on the stakeholder engagement process, including attendees and outcomes, can be found in NEXOGENESIS Deliverable 5.6 [42], available on https://nexogenesis.eu/downloads/, or by contacting the corresponding author.

3.1. Conceptual systems mapping and system dynamics modelling

A conceptual map is an abstract representation to aid understanding of a system [33,43,44]. Conceptual maps typically include boundaries, structure and connections between components. They often take the form of a 'map' of the system and can be the basis of simulation models. Here, each WEFE sector is developed with its own conceptual map describing the interconnections within and between sectors. Conceptual map development, as well as policy identification and selection, was carried out with local project partners familiar with the study area.

SDM [45,46] is used to quantitatively analyse complex systems. SDM can be used as a tool to understand the potential impact of policy implementation on a WEFE resources system [30,41,47], or to assess system trajectories under scenarios (e.g. climate or socio-economic futures), and has a long history of similar applications [48]. SDMs comprise stocks (which store material), flows (which move material in and out of stocks), and convertors (which alter the flow rates). These objects are linked by connectors, which transfer information in the model, forming feedback loops [34]. Model parameters can be populated with constants, variables, arrays, or equations derived from data-based, statistical, physical, or empirical sources. Module structures are used to partition sectors (e.g. 'water' or 'energy' sectors), making model development manageable, transparent, and helping trace links within and between modules. Exponential growth (positive feedback), goal seeking (negative feedback), and oscillation (dynamic equilibrium) are common behaviour modes [49]. Definition of the system boundary is critical to ensure modelling tractability. In this study, the boundary is the catchment of the IUWMA (Fig. 1). The SDM was implemented in STELLA Professional (www.iseesystems.com), a dedicated SD modelling software. All modelling languages, notations, and formulas are based on the STELLA system. The model covers the period 2015–2050, and runs at a monthly timestep (420 months). Although there are too many equations to list them all (the equation file is available on request, see Data Statement), here some representative equations are shown. All material balances follow the same general structure, where:

Table 1
summary of the stakeholder workshops related to the model development and results validation presented in this paper. Note that not all stakeholder workshops are summarised here, only those directly related to the modelling work presented in this paper.

Workshop dates	Number of participants	Main outcomes
2 (20 October 2022)	14	Changes to WEFE nexus variables and indicators to model
3 (5 June 2023)	38	Final selection and validation of policy instruments to model
4 (19 March 2024)	14	Feedback and validation of SDM simulations, with and without policy implementation
5 (online) (17 October 2024)	19	Final results validation and identification of core policy goals to consider
5 (in person) (28/29 June 2025)	9	Validation of policies and SDM impacts

$$\begin{aligned} \mathit{Material\ balance}(t) &= \mathit{Material\ balance}(t-dt) \\ &\quad + (\mathit{Material\ supply} - \mathit{Material\ consumption}) * dt \end{aligned} \tag{1}$$

where t is the model time and dt is the delta time (timestep), which here = 1 month. For example, for the water balance, material supply would be water supply into the study area, while material consumption would represent water abstractions from all users.

An example of a crop production calculation is given:

$$\begin{aligned} &\mathit{Irrigated\,macadamia\,production} \\ &\quad = \mathit{Land\_Use.Irrigated\_macadamia} * \mathit{Irrigated\_macadamia\_yield} \end{aligned} \tag{2}$$

where 'Land_Use.' Indicates a dynamic link to the area under irrigated macadamia cultivation.

A final example shows how a policy can act to alter the reference values. This is related to Policy 7 on achieving emissions targets, with this specific application to reducing emissions from livestock:

$$\begin{aligned} Emission\,per\,head\,of\,cattle = {} & IF\,Policy\,7 \\ & = 1\,THEN\,PREVIOUS(SELF,0) \\ & - (PREVIOUS(SELF,0) \\ & * Policy\,7\_cattle\_emission\_reduction)\,ELSE\,IF\,P07 \\ & = 2\,THEN\,PREVIOUS(SELF,0)\,ELSE\,0.06875 \end{aligned}$$

where PREVIOUS is a built-in function returning the value of itself (SELF) at the previous time step or 0 if there is no previous time step, and 0.06875 is the reference scenario cattle emissions factor expressed in tons CO_2e head^{-1}.

3.2. Model input data

To develop the SDM and enable simulations to be run, many data were sourced, described here. There are three primary domains for which data were sourced in this work: (i) biophysical domain (e.g. climate, hydrology, land); (ii) socio-economic domain (e.g. GDP, population); and (iii) local domain (e.g. local statistics, policy documents). This section outlines the data sources in each of these three domains. Table 2 summarises the input data used in this work, while Supplementary Information SI1 shows the complete information with all relevant data details. Section 3.3 outlines how uncertainty was captured, while Section 3.4 described how policies were translated into the SDM.

3.2.1. Biophysical domain data

This domain includes climatic, hydrological and environmental variables characterizing relevant biophysical processes across the WEFE nexus. These are included for two Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCPs; van Vuuren et al., 2011) scenarios spanning from low (RCP2.6) to high (RCP8.5) emission scenarios. The data are generated under a coherent framework consolidated under uniform climate driving projections and protocols generated across intercomparison projects and climate data services. The latest runs from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP v3b) were used. Data have been selected from ISIMIP 3b, driven by the latest Coupled Model Intercomparison Project (CMIP) climate projections, namely CMIP6 climate projections, in line with the recent 2021 IPCC sixth assessment report (AR6). CMIP6 model runs represent state of the art and have a higher climate sensitivity than models in CMIP5 [75]. The following bias-adjusted CMIP6 climate driving projections from ISIMIP3b dataset are available [76] and have been used: Max Planck Institute Earth System Model (mpi-esm1–2-hr); NOAA Geophysical Fluid Dynamics Laboratory Earth System Model v 4.1 (gfdl-esm4); Institut Pierre-Simon Laplace Climate Model 6A (ipsl-cm6a-lr). Driven by these climate projections, ISIMIP3b inter-sectorial assessment are derived from different impact models for several sectors, including water, ecosystem biomes, agriculture and food production, forests and terrestrial biodiversity.

Monthly time series projections covering the period 2015–2050 were used to coincide with the modelling period. Original data at 0.5 degrees, was disaggregated at 0.25 degrees to better represent basin extent, then aggregated to represent spatial average values representative of the Inkomati-Usuthu basin. Projections are derived for an ensemble of climate and impact model projections (Table 2). For detailed agricultural water use and crop production data, the atmosphere-soil-water-crop SIMETAW_GIS (Simulation of Evapotranspiration of Applied Water; [60,61]) model is used to simulate daily crop water requirements, crop yield losses due to water stress, and irrigation scheduling for specific crops of relevance for the Inkomati-Usuthu region (e.g., Maize, Soy, Sugarcane, Citrus, Peach, Macadamia).

For consistency, data simulation from SIMETAW has been driven by the same ISIMP3b climate projections/emission scenarios, while soil hydraulic properties [77] and site-specific information was gathered to characterize cropping calendars and agricultural management practices [78–81]. Results were aggregated at monthly scale. Using crop yields as an example of the impact of RCPs, under RCP2.6 in 2015, irrigated

Table 2

summary of data sources used as model input.

Variable	Temporal coverage and resolution	Spatial resolution	Raw unit	Source / references
Surface water runoff	2015–2050 / monthly	0.5 degrees	kg m^{-2} s^{-1}	[50–52]
Reservoir storage	2015–2050 / monthly	0.5 degrees	kg m^{-2}	[50,51];
Industrial water use	2015–2050 / monthly	0.5 degrees	mm s^{-1}	[51]
Wetland storage	2015–2050 / monthly	0.5 degrees	mm	[51]
Crop yield.	2015–2050 / growing season (Nov-Mar)	0.5 degrees	ton ha^{-1} growing season^{-1}	[53–58]
Biomass yield.	2015–2050 / growing season (Nov-Mar)	0.5 degrees	ton ha^{-1} growing season^{-1}	[53–59]
Crop Irrigation requirements, yield losses due to water stress.	2015–2050 / growing season (Nov-Mar)	0.5 degrees		[60,61]
Nitrogen leaching.	2015–2050 / monthly	0.5 degrees	ton ha^{-1}	[54,58,62]
Carbon mass in vegetation	2015–2050 / monthly	0.5 degrees	kg m^{-2}	[63]
Carbon Mass Flux out of atmosphere	2015–2050 / monthly	0.5 degrees	kg m^{-2} s^{-1}	[52]
Mean Species Richness.	Values in 2010, 2020, 2026, 2032, 2048.	300 × 300 m	-	[64]
Population	2015–2054.	South Africa.	% change form 2015	OECD ENV-Growth model
Total water services	2015–2050.	South Africa.	% change from 2015	G-RDEM model
Food demand.	2015–2050.	South Africa.	% change from 2015	G-RDEM model
Energy supply.	2015–2050.	South Africa.	% change from 2015	G-RDEM model
Energy demand – electricity	2015–2050.	South Africa.	% change from 2015	G-RDEM model
Land use. Total in IUWMA, and total in protected areas inside IUWMA.	2015 baseline.	IUWMA.	ha	[65]
Protected Areas	2022 baseline	IUWMA	ha	South African Protected Areas Database Q4, 2022
Transboundary water obligations.	2015 baseline.	IUWMA	m^{3} yr^{-1}	[66], Tables 4.7–4.8, p. 14
Water exported for Eskom	2023 baseline	IUWMA	m^{3} yr^{-1}	Detailed Eskom water use provided by the Inkomati-Usuthu Catchment

(continued on next page)

Table 2 (*continued*)

Variable	Temporal coverage and resolution	Spatial resolution	Raw unit	Source / references
				Management Agency (IUCMA) on 31/10/2023
Domestic water demand	2018 baseline	Mpumalanga	l capita^{-1} day^{-1}	Department of Water and Sanitation, 2015
Population	2015 baseline	IUWMA	capita	Statistics South Africa [[67] SA], 2012 & [68]
Chicken yield, meat	2014 baseline	N/A	kg head^{-1}	[69]
Water consumption, chickens for meat	N/A	National	m^3 head^{-1} yr^{-1}	[70]
Chickens yield, eggs	N/A	National	kg head^{-1}	[70]
Water consumption, chickens for eggs	N/A	National	m^3 head^{-1} yr^{-1}	[70]
Yield, cattle for meat (beef)	N/A	National	kg head^{-1}	Department of Agriculture, Forestry and Fisheries [71], 2014
Water consumption, cattle for meat (beef)	N/A	National	m^3 head^{-1} yr^{-1}	[70]
Yield, cattle for dairy	N/A	National	kg head^{-1}	[72]
Water consumption, cattle for dairy	N/A	National	m^3 head^{-1} yr^{-1}	Milk SA Logiχ data, 2015 and [73]
Electricity splits	2022	National	%	[74]
Domestic food demand	2022	Global	Kcal capita^{-1} day^{-1}	UN DESA, 2022 & FAO, 2023

maize yield is on average 6.4 tons ha^{-1}, while it is 7.6 tons ha^{-1} in 2050. For irrigated soy, the average values are 4 tons ha^{-1} and 5 tons ha^{-1} respectively. Under RCP8.5 for irrigated maize, yields are 11.7 tons ha^{-1} in 2015 and 12.2 tons ha^{-1} in 2050, while for irrigated soy, the values are 7.9 tons ha^{-1} in 2015 and 8 tons ha^{-1} in 2050. These are significant increases that may impact on results interpretation.

3.2.2. Socio-economic domain data

The primary data source is the GTAP Global Social Accounting Matrix [82]. The GTAP database is a consistent representation of the world economy, in the form of a global Social Accounting Matrix, for a pre-determined reference year (2017 in the latest version). Underlying the database are several data sources, including: national input-output tables, trade, macroeconomic, energy and protection data. The database combines detailed bilateral trade, transport and protection data characterizing economic linkages among regions, together with individual country input-output (I-O) databases accounting for inter-sectoral linkages within regions. These data may be complemented by sources such as regional statistics, for instance those provided by Eurostat, allowing a disaggregation of some macroeconomic data at NUTS2 regional level.

The GTAP database is employed to calibrate structural parameters in a dynamic, general equilibrium model of the world economy, G-RDEM [83]. Contrary to most of available Computable General Equilibrium (CGE) models, G-RDEM considers drivers of long run structural change, which are especially relevant in the assessment of WEFE systems, namely: (1) items in household consumption with different degrees of income sensitivity; (2) productivity growth differentiated by sector; (3) debt accumulation from foreign savings and trade imbalances; (4) aggregate saving rates linked to population and income dynamics; and (5) time-varying and income dependent industrial cost shares. G-RDEM is itself steered by a limited set of aggregate macroeconomic indicators, obtained from the OECD Env-Growth model [84], which provides a quantification of the IPCC Shared Socio-economic Pathways (SSP; [85]). SSPs are reference future scenarios, widely adopted in the context of climate change impacts and policy assessment, defining projected global changes up to the year 2100, based on narratives describing alternative socio-economic developments. Quantifications of SSP narratives include GDP projections, and various demographic characteristics (population structure by age, educational attainment, sex, urbanization rates).

Two SSPs are considered: SSP2, and SSP4. SSP2 (middle of the road) represents a world that follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly. Global and national institutions work toward but make slow progress in achieving Sustainable Development Goals. Environmental systems experience degradation, although there are some improvements and overall, the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves slowly. SSP4 (inequality) describes highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, leading to increasing inequalities and stratification. The gap between an internationally connected society, and a fragmented collection of lower-income, poorly educated societies that work in a labour intensive, low-tech economy, widens. Social cohesion degrades and conflict and unrest become increasingly common. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels, and low-carbon energy sources. Environmental policies focus on local issues around middle- and high-income areas.

The cumulative percentage change in parameters from 2015 to 2050 was made available, along with an estimate of the standard deviation around this cumulative percentage change. Table 3 gives the socio-economic parameters used in this study together with their cumulative percentage changes to 2050 under SSPs 2 and 4, and the associated standard errors.

3.2.3. Local domain data

The local data used as model input included land use data, protected area status, population domestic water demand, domestic dietary requirements, transboundary water obligations, livestock yield and

Table 3
socio-economic parameters and their respective cumulative percentage changes to 2050 under both SSPs used. Estimated standard errors for each parameter are also given.

Socio-economic parameter	Cumulative percentage change in 2050 relative to 2015 [SSP2, SSP4]	Standard error about the cumulative percentage change (in %) [SSP2, SSP4]
Population	[20.53 %, 20.04 %]	Both negligible (<0.01 %)
Total water demand	[307 %, 271 %]	Both negligible (<0.1 %)
Food demand:		
cereal grains;	[93 %, 98 %]	[<0.1 %, <0.1 %]
vegetables;	[164 %, 93 %]	[<0.1 %, <0.1 %]
oil seeds;	[118 %, 97 %]	[<0.1 %, <0.1 %]
sugar cane;	[322 %, 338 %]	[<0.1 %, <0.1 %]
cattle, sheep,	[119 %, 149 %]	[<0.1 %, <0.1 %]
goats;	[178 %, 271 %]	[<0.1 %, <0.1 %]
animal products;	[138 %, 203 %]	[<0.1 %, <0.1 %]
raw milk.		
Energy supply.	[171 %, 191 %]	[negligible, 0.23 %]
Energy demand – electricity	[171 %, 191 %]	None defined

livestock water demand. A summary of the local data used, and the associated sources is detailed further in Table 2. Land use was summarised into 17 classes with the grouping of land use into the following classes: forestry (natural and planted), natural grassland, dams, wetlands, irrigated macadamia, irrigated orchards, irrigated sugarcane, irrigated maize and soy, rainfed maize and soy, rainfed subsistence farming, fallow land, residential, urban green space, commercial, industrial, mining, and other. The base year of the land use data was 2018. The protected area status was determined based on the South African Protected Area Database (SAPAD Q4, 2022).

3.3. Uncertainty assessment

Uncertainty was assessed by accounting for the variability in input data. As shown in Table 2, biophysical data derive from multiple climate drivers and multiple impact models per-driver. Each combination of drivers and models per-variable gives uncertainty in the parameter values. These values differed between the two RCPs. Socio-economic data consisted of a (cumulative) average percent change over time relative to the base year (2015) as well as a standard deviation around this average cumulative change (Table 3). To account for the uncertainty in biophysical and socio-economic parameter values, the following approach was taken: i) for every timestep (i.e. for each of 420 months), for each parameter, the minimum and maximum values given by the input model data distribution were found; ii) define a uniform distribution bounded by the minimum and maximum values obtained. The probability of any value occurring between the minimum and maximum is by definition, equal. The probability of obtaining a value lower than the minimum or greater than the maximum is zero. A uniform distribution was selected as there was insufficient data information to estimate the distribution of values from the input data. Therefore, empirical distributions could not be reliably assessed at every timestep. In addition, the computational load to calculate empirical distributions at every timestep for every variable would have been prohibitive; iii) in the SDM, the uniform distributions between minimum and maximum were sampled 100 times (i.e. the simulation was run 100 times, each time pseudo-randomly sampling from the parameters with uniform distributions defined). This procedure resulted in 100 outputs being generated from the SDMs for each RCP-SSP combination, with the output dependent on the stochastic parameter input values samples. The results of 100 Monte-Carlo simulations are shown in the results, sampling from the uncertainty in model input data, along with the mean of all simulations.

3.4. Policy scenarios

Apart from the biophysical (i.e. RCP) scenarios, RCP2.6 and RCP8.5, and socio-economic (i.e. SSPs) scenarios, SSP2 and SSP4, a number of local policy scenarios were simulated in the SDM. These policy scenarios were simulated under each RCP-SSP combination (the ‘reference scenarios’) to assess their relative impact to WEFE nexus resource trajectories under different climatic and socio-economic futures. The policy scenarios are based on policy ambitions in South Africa/the IUWMA and cover all WEFE nexus sectors. Policies were selected in stakeholder workshops with stakeholder (Table 1). Table 4 summarises the policy scenarios tested in this work. In the model, policies (Table 4) are allocated a ‘switch’. If the switch is turned off (value 0), then the corresponding policy is inactive (i.e. running the reference scenario). Once the switch is turned on (value 1), the policy becomes active, impacting resource trajectories. This is done through another variable that codes the policy objectives in Table 4 in the SDM (see equation 3). For example, activating a policy switch may cause the area of agricultural land to be decreased, while the area of protected land increases by the same amount. Changing land types may subsequently lead to changes in crop production, irrigated water demand, energy demand, GHG emissions, carbon sequestration, and biodiversity indices, showing how connected the WEFE sectors are. Policies can be implemented either one-at-a-time, or in any and all combinations. In the case that multiple land policies are enacted simultaneously on the same tract of land, their relative impact is scaled by the number of policies implemented. For example, if three policies are enacted at the same time on irrigated maize, each policy’s impact is scaled by 1/3 under the assumption that if implemented in parallel, their impact would be equally distributed. This may not be realistic per-se, but does avoid the situation where many policies are implemented in their entirety on the same tract of land, which would be unreasonable.

4. Results

4.1. Conceptual map

The high-level conceptual map (Fig. 2a) shows the main connections between the WEFE nexus sectors and gives an impression of the complexity of the system. For example, water is needed in the energy sector, for food production, and to support ecosystems. Food production impacts on water quality and demands freshwater resources, and land conversion and nutrient leakage degrade ecosystems. Energy is used in water supply, food production processes, and food/crop residues are used in energy generation. The local population demands and requires access to water, energy, and food resources in sufficient quantity and quality, and at appropriate times.

Similarly, detailed conceptual maps for the individual WEFE sectors are shown in the Supplementary Information (SI) 2. These sectoral maps give more detail as to the connections within each WEFE sector, as well as interactions with other sectors. In the water sector, both quantity and quality are emphasised. Water is sourced primarily from groundwater and surface water resources and is modulated by climate change. Some of this water is required for transboundary flow requirements. Water is consumed by a wide range of sectors, with irrigated agriculture and mining activities featuring prominently (Fig. 2b).

Food production and mining alter land use and ecosystems, with impacts on water quality in particular. Food is produced via rainfed and irrigated agriculture, and there is livestock rearing in the basin. Water quantity and quality affect food production. The amount of local food demand is driven by the population. Changes in food production affect the energy consumed in the agricultural sector, and emissions from livestock. Many larger farmers are energy-independent through the development of small-scale solar power. Nutrient and pesticide applications, energy demand, and changes in land use characteristics impact on ecosystems.

In the energy sector, most energy is sourced from coal thermal power stations outside the study area, contributing to enhance GHG emissions and exacerbate climate change impacts. Population changes drive energy demand. Energy is produced from both renewable sources and non-renewable sources (coal-fired power stations). Challenges relate to boosting renewable sources, and creating energy storage solutions for more reliable supply. This is coupled with land use constraints resulting in competition between renewable energy generation facilities and high-value agricultural land.

In terms of ecosystems, these are impacted by, and impact upon, several nexus sectors. Agricultural production, energy consumption, and population all impact ecosystems, either directly, or indirectly by altering land use patterns and patterns of nutrient and pollutant loads. Ecosystems are impacted by climate change but can also mediate climate impacts by sequestering greenhouse gasses (GHGs). Changes in water quality characteristics affect ecosystems and their services. The coal mining sector, important economically and for power generation, plays a significant local role in affecting fragile ecosystems, thus representing a substantial trade-off, though this is not modelled in the SDM.

Table 4
summary of the policy scenarios tested in the IUWMA SDM.

Policy scenario ID	Brief description of policy	WEFE sectors directly impacted*	Policy start date/ duration of policy	Policy impacts ambition/goal	Source / references
1	Investments to set up inclusive local food value-chains.	Land, food, water	2015 / 8 years	Increase irrigated maize and soy area (10.6 %) Increase rainfed maize and soy area (2.7 %) Increase irrigated orchards area (32.6 %) Reduce macadamia orchards area (20 %) Reduce fallow land area (15 %) Increase subsistence agriculture area (27.6 %)	Through a thorough stakeholder engagement process (a detailed report on the stakeholder engagement process, including attendees and outcomes, can be found in NEXOGENESIS Deliverable 5.6 (Implementation Report for Inkomati-Usuthu CS), available on https://nexogenesis.eu/downloads/, or by contacting the corresponding author), it was indicated that a large portion of fallow land in South Africa was previously agricultural land. Therefore, by investing in the local food value chain, it was assumed that this would result in the conversion of a portion of fallow land to subsistence, subsistence to rainfed maize & soy (locally valued crops), and rainfed maize and soy to irrigated. Similarly, it was assumed that the policy would favour the conversion of Macadamia farming (which is exported) to more locally valued fruit orchards
2	Budget allocations and grants (public sector funding mechanisms) for protected area institutions to expand on protected areas.	Land, ecosystems	2023 / 5 years	Increase protected areas Reduce agricultural land, fallow land, residential, urban green, commercial, industrial, mining, and other land	National Protected Area Expansion Strategy, [25]
3	Develop and strengthen economic incentives to encourage appropriate investment by the private sector in biodiversity management and conservation, such as tax incentives, conservation agriculture incentives to farmers and others.	Water, food, climate, land	2020 / 10 years	Reduce irrigation water demand (11 %)	It was assumed that similar technologies would be considered as policy 9 and the same reduction in water demand was assumed.
				Reduce nitrogen runoff (60 %)	It was assumed that conservation-agriculture systems would include legume or high-residue phases, resulting in an increasing soil organic N, and we assumed a reduction in fertiliser N demand.
				Increase crop yield (5 %)	Although research on CA's impact on yield is conflicting, a maize trial indicated that CA practices resulted in an approximate increase in yield of +4 % [86]. Furthermore, sugarcane trials in KwaZulu-Natal reported 5–20 % higher plant-cane yields after a bare fallow and 10–40 % after a legume green-manure fallow compared with continuous cane ([87] a; [88]). A 5 % yield increase was assumed when conservation agriculture is implemented.
				Increase wetland area (2.128 %) Reduce area of agricultural land uses	National Biodiversity Assessment (NBA) 2018 outlines biodiversity areas, including freshwater areas. Within these areas, it was found that there is farming land use on wetlands in the basin. The assumption is that with the change in status of freshwater and terrestrial critical biodiversity areas, farming land uses within wetlands will drop, helping protect and expand the wetlands land cover up to 2.128 % [89]
4	Identification and registering & change of status of priority areas for ecological infrastructure and national biodiversity priority areas (including freshwater ecosystem priority areas)	Ecosystems, land	2025 / 10 years	Increase mean species richness (0.338 %) Increase natural grassland and wetlands Reduce agricultural land and mining, industrial, and commercial areas	Mpumalanga Biodiversity Sector plan Critical Biodiversity Areas: Fresh Water Aquatic (MTPA & DARLES, 2022) and Terrestrial [90]
5	Investment in reparation of water distribution and treatment infrastructure and in maintenance and monitoring of these systems to prevent leakage.	Water	2015 / 15 years	Reduce per-capita and industrial water demand (20 %) Reduce nitrogen load per capita (50 %)	The Status of Water Loss, Water-Use Efficiency and Non-Revenue Water in South African Municipalities, indicates that 46.3 % of treated water is lost through leaks in the supply network in Mpumalanga [[90]tment of Water and Sanitation [DWS], 2023]. It was assumed that the leaks will reduce by 20 % and 50 % of and Waste Water Treatment Works [WWTW] will be repaired.
6	Monitoring of water usage to ensure effective water-supply planning,	Water, food	2025 / 5 years	Reduce per-capita water demand (10 %)	The Smart-meter effect found that the installation of smart meters results in an

(continued on next page)

Table 4 (*continued*)

Policy scenario ID	Brief description of policy	WEFE sectors directly impacted*	Policy start date/ duration of policy	Policy impacts ambition/goal	Source / references
	development and operation (Impose higher tariffs for excessive water usage and fines for excessive Nitrogen Runoff rates)			Reduce industrial water demand (12.5 %)	average reduction of 2 % in consumption [91]. Furthermore by increasing tariffs on water by 50 % over the 5 year period will result in a reduction of 8 % by applying a price elasticity of 0.17 which is in line with figures for South Africa presented by Hoffman & du Plessis (2013). It was further assumed that price elasticity of industry would be higher than that of domestic.
				Reduce domestic nitrogen runoff (20 %) Reduce agricultural nitrogen runoff (5 %)	It was assumed that monitoring water quality and imposing fines on non-compliant WWTW and on high nitrogen runoff agriculture would result in a reduction in Nitrogen runoff.
7	Sectoral Emission Targets or SETs, which are quantitative greenhouse gas emission targets allocated to an emitting sector or sub-sector, over a defined time period (Carbon Tax, Fines for exceeding air emissions standards)	Climate, food, energy	2023 / 10 years	Reduce cattle greenhouse gas emissions (15 %)	"Pathways towards lower emissions" (FAO, 2023) provides a pathway from 6 190 Mt CO_2 equivalents to 1922 Mt CO_2 equivalents, a reduction of 69 % in livestock emissions. If it is assumed that just over 25 % of this reduction is achieved, it will result in a 15 % reduction in livestock emissions.
				Reduce number or heads of cattle (10 %)	It was assumed that awareness and carbon taxes on red meat would result in a reduction in consumption of meat products and ultimately head of livestock.
				Reduce agricultural greenhouse gas emissions (10 %) Reduce agricultural energy consumption (10 %)	Labandeira et al. (2017) estimate the long-term average price elasticity of 0.65 for energy. A 15 % increase in tariffs will result in a 10 % reduction in energy consumption.
				Reduce industrial energy consumption (6 %)	"How Do Carbon Taxes Affect Emissions?" [92] indicate that carbon tax lowered emissions by 4 % and increased production by 1.8 % and lowered emissions intensity by 6 %. It was therefore assumed that keeping production constant will result in a 6 % reduction in consumption and ultimately emissions.
				Reduce domestic energy consumption (10 %)	Labandeira et al. (2017) estimate the long-term average price elasticity of 0.65 for energy. A 15 % increase in tariffs will result in a 10 % reduction in energy consumption.
8	Subsidise or lower tariffs of the most expensive input material for production systems that contribute most to food security (Fertilizer/seed, lower electricity costs, bridging the knowledge gap)	Land	2015 / 8 years	Increase subsistence agricultural land (55.1 %) Reduce fallow land (20 %)	Through a thorough stakeholder engagement process (a detailed report on the stakeholder engagement process, including attendees and outcomes, can be found in NEXOGENESIS Deliverable 5.6 (Implementation Report for Inkomati-Usuthu CS), available on https://nexogenesis.eu/downloads/, or by contacting the corresponding author), it was indicated that a large portion of fallow land in South Africa was previously agricultural land; therefore, by bridging the knowledge gap and providing subsidies it was assumed that this would result in the conversion of Fallow land to subsistence agriculture.
9	Subsidies/incentives for adoption of more efficient irrigation techniques	Water, food	2020 / 10 years	Reduce irrigation water demand (11 %)	Irrigated agriculture accounts for 62 % of South Africa's total water, with conveyance and on-farm wastage in older schemes reported as high as 45 % [93]. Implementing lining and modern flow-monitoring in an irrigation scheme resulted in a 19 % reduction in losses [93]. Switching from centre-pivot to subsurface drip combined with thick mulch in sugarcane reduced the blue-water footprint, resulting in a 15–20 % reduction in irrigation demand [94]. FAO irrigation benchmarks corroborate these reductions, with field-application efficiencies of 90 % for drip and 60 % for surface methods (FAO, n.d.). As a result, a reduction of 11 % was applied taking into account that some farmers have already implemented drip irrigation, not all farmers will adopt the more efficient techniques and

(*continued on next page*)

Table 4 (*continued*)

Policy scenario ID	Brief description of policy	WEFE sectors directly impacted*	Policy start date/ duration of policy	Policy impacts ambition/goal	Source / references
					there may still be some inefficiencies in the irrigation schemes once applied.
				Reduce maize and soy nitrogen leaching (31 %)	Patel & Rajput [95], show that switching from surface or conventional drip to subsurface or alternate partial-root-zone drip fertigation reduces nitrate leaching by between 12 – 50 %. It was thus assumed that implementing more efficient irrigation techniques would result in a 31 % reduction in Nitrogen leaching.
				Increase maize, soy, macadamia, sugarcane, and orange yields (12 %)	Based on Yang et al., [96] on average drip irrigation has the potential to improve crop yields by 11.8 % over other irrigation methods., [97] indicate a yield increase of 9.2 % in maize an 17.32 % in wheat., [98] indicate an improvement of 7–25 % in sugarcane yield. An increase in yield of 12 % was assumed for implementing more efficient irrigation techniques.
10	Renewable Energy Independent Power Producer Procurement - REIPPP (power purchase programme) that encourages renewable energy development	Energy, land	2023 / 7 years	Reduce agricultural land uses marginally (<<1 %), Reduce coal energy fraction (72.48 %) Reduce diesel energy fraction (1.48 %) Increase renewables energy fraction (25.34 %) Increase hydropower energy fraction (0.7 %)	Draft Integrated resource plan, [99]

*Directly impacted means that a variable is directly altered in the model. Due to connections within the model, many other variables may subsequently be indirectly affected.

4.2. Systems dynamics model (SDM)

The SDM consists of eight interacting modules (Fig. 3): population, water, energy, food, land, ecosystems, and climate. In this paper, WEFE Index results (see Fig. 3) are not reported as this module is not fully developed. Qualitatively, Fig. 3 reflects Fig. 2a, showing the connections between the WEFE sectors. The pink arrows indicate a computational connection between modules, showing that if changes are made in one sector, this has impacts in many other sectors. Fig. 4 shows the detail of the water sector module. The other SDM modules are shown in Supplementary Information 3. Tables 2 and 3 outline data sources.

The water module (Fig. 4) consists of water resource supply and demand, with the water balance computed as the difference between the two. Water resource supply consists of surface water runoff and contribution from dams. Groundwater is not accounted for due to lack of data. Water demand consists of: transboundary obligations to neighbouring countries; water exported to other regions in South Africa; industrial water demand; domestic water demand (modulated by population); livestock water demand (modulated by the number of animals and the per-head water demands); and agricultural water demand. The demand from agriculture considers only irrigated crops, with the crops considered being oranges, peaches, soy, macadamia, sugarcane, and maize. The land covered by each crop is specified in the land use module, which itself can be impacted by policy decisions (Table 4).

The energy module (Supplementary Information 3) consists of energy supply from diesel, coal and renewable sources, imported to the study area via the grid. There is a proportion of locally-generated renewable energy consisting of hydropower and small-scale, off-grid solar. In terms of local energy consumption, the following aspects are modelled: domestic energy demand; the energy required for water supply (linking to the water sector); mining energy consumption; industrial energy consumption; and energy consumed for irrigated agriculture, based on values for the amount of energy used to produce a unit mass of food.

The food module (Supplementary Information 3) consists of local food production and local food consumption. Imports and exports across the catchment boundary are not modelled. Food production is split into rainfed and irrigated crops. The rainfed crops are maize and soy, while irrigated crops consist of maize, soy, orchards, sugarcane, macadamia, and citrus fruits. To estimate production, the area covered by each type of crop is combined with estimates of yield per area for each crop type (Table 2). Livestock production consists of the numbers of beef cattle, dairy cattle, and chickens multiplied by the beef meat yield, milk yield, and chicken meat yield respectively. Food demand is the product of food consumption per capita multiplied by the population. Food consumption per-capita values are taken from the FAOSTAT database (https://www.fao.org/faostat/en/), using values for South Africa for the year 2015. Of all the products available in the FAO database, the following categories were used: maize and products; sugar - raw equivalent; nuts and products; soyabeans; soyabean oil; oranges, mandarins, lemons, limes, and products; grapefruit and products; other citrus; apples and products; other fruits; bovine meat; poultry meat; and milk. These categories match closely the food production categories considered. As a result of this per-capita demand selection, the demand will be overall underestimated. The FAOSTAT total food demand for South Africa is 0.04 tons capita^{-1} month^{-1} while the sum of the stated categories is 0.021 tons capita^{-1} month^{-1}. The food module estimates nitrogen (N) leaching from agricultural production. Nitrogen leakage rates per crop type are given from data specified in Table 2. These rates are multiplied by the land areas of each crop type. Differences are distinguished between irrigated and rainfed crops.

The land use module (Supplementary Information 3) tracks the area of land covered by different uses. The land uses tracked are: fallow land; grassland; dams; residential areas; urban green areas; commercial areas; industrial areas; wetlands; forests; mines; irrigated citrus; macadamia; sugarcane; irrigated maize and soy; orchards; rainfed subsistence agriculture; and rainfed maize and soy. The proportion of protected land is also assessed. Land use data are from local sources (Table 2).

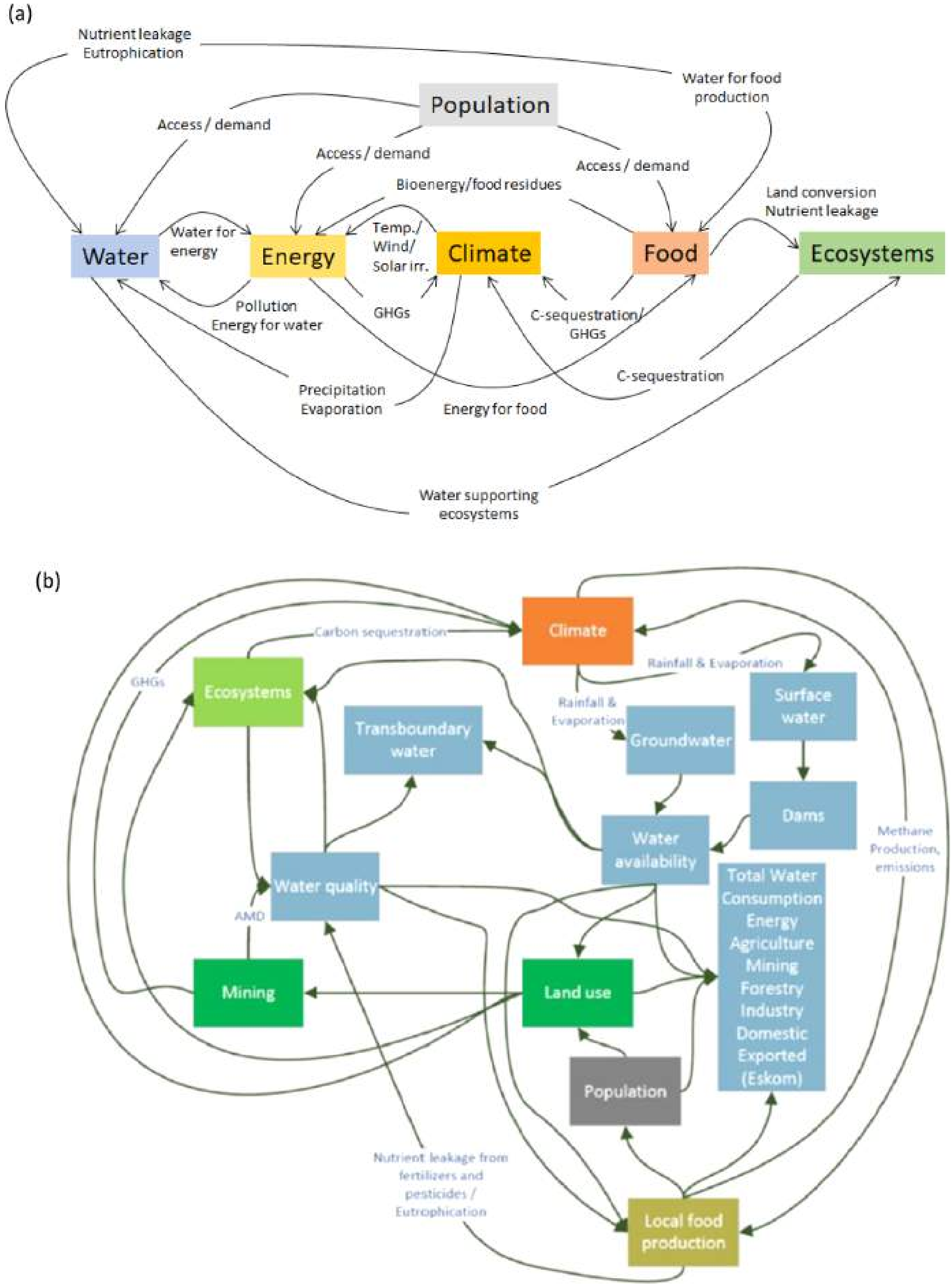

Fig. 2. (a) high-level conceptual map of the Inkomati-Usuthu WEFE nexus system showing the major connections between nexus sectors. Sectoral conceptual maps are shown in Supplementary Information 1. (b) the water sector conceptual map showing qualitative, stakeholder validated, connections between the water sector in the IUWMA and other WEFE nexus sectors. Key issues include details on water consumers and the links to land use and food production.

The ecosystems module (Supplementary Information 2) tracks a number of variables including: water stored in wetlands; the carbon mass stored in vegetation, with vegetation classes including fallow land, rainfed and irrigated agriculture, forests, and grasslands; N leaching from agriculture and domestic runoff; above ground biomass (AGB) estimated from maize, soy, and sugarcane (other above ground biomass estimates were not available in the datasets); and carbon sequestration (carbon emissions and sinking from the atmosphere) using the same land use classes as for the carbon mass. In addition, the Mean Species Richness (MSR) for birds, mammals, and amphibians is tracked.

In the climate module (Supplementary Information 3), carbon sequestration is that as estimated in the ecosystem module. GHG, expressed in tons CO_2e, comprise of those from agricultural land uses, livestock emissions, and the emissions related to local consumption of energy, both fossil-based and renewable. It is acknowledged that many GHG emitting sectors are not accounted for (e.g. transport), due to the unavailability of data and not being the focus of the study, or due the external nature of thermal power generation (external meaning outside the study area).

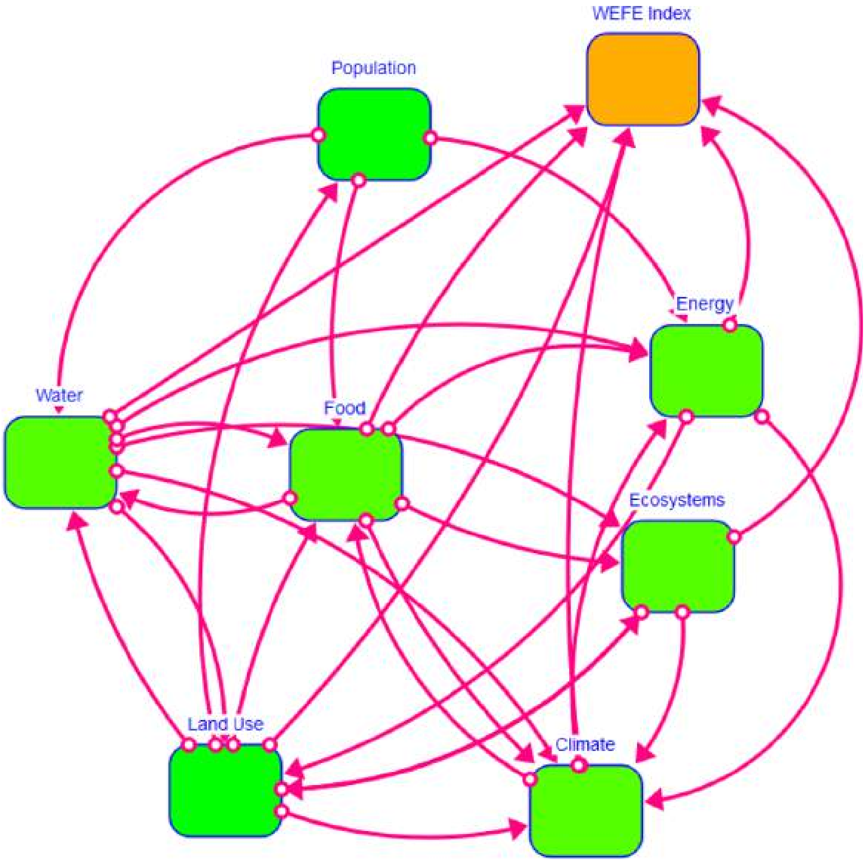

Fig. 3. the modular structure of the SDM for the IUWMA. In this work, results for the WEFE Index module are not reported. Pink arrows denote dynamics interaction between modules. The module interconnections imply that changes in one module (nexus sector) will lead to changes in others. For example, a change in land use characteristics will lead to changes in the water, food, energy, ecosystems, and climate sectors.

4.3. Simulation results: reference scenarios

In this set of results, four RCP-SSP combinations (i.e. RCP-SSP 2.6–2; 2,6–4; 8.5–2; and 8.5–4), are shown with no modification to 2050 forming a set of 'reference scenarios' against which other simulation results are compared (Fig. 5; Table 5). The variables shown are: water balance, crop production, N leaching from agriculture, above ground biomass, GHG emissions, and carbon sequestration. The water balance (cumulative over time; Fig. 5a) shows a positive trend, implying that less water is demanded/abstracted than available, a trend observed under all reference scenarios. This bodes well for water resources sustainability from a quantity perspective, though care is needed to ensure resources are not overexploited in the future. It is noted that some stakeholders suggested that the water sector is over-allocated, impacted food production. Results mask potential seasonal water stress periods when supply may limit demand that can be supplied. Crop production (Fig. 5b) shows significant differences between RCPs 2.6 and 8.5, with RCP2.6 results showing lower overall totals, as well as a reduction in production over the first c. 50 months of the simulation. There is a difference between RCP2.6-SSP2 and RCP2.6-SSP4 results from c. month 300 when the latter demonstrate a decrease in production. Nitrogen leaching (Fig. 5c) trends are similar between scenarios, although RCP8.5 simulations show greater uncertainty than those for RCP2.6. The differences between RCP2.6 and 8.5 in Figs. 5b and c result from differences in the underlying input model data (Table 2). Above ground biomass trends are similar (Fig. 5d), though RCP2.6 values tend to be greater than RCP8.5. GHG emissions trends (Fig. 5e) are comparable in all simulations, as are carbon sequestration trends (Fig. 5f), which show an apparent lack of discernible trend and show seasonality. In terms of validation, a traditional validation was not performed due to data constraints, but rather a 'soft' validation of SDM outputs was done. For example, runoff values were compared to the mean annual runoff for the Inkomati catchment and found to be within 50 % of observed values. Runoff trends were simulated well. To validate this, mean annual runoff is reported in the Inkomati River at 700–1000 Mm^3 (https://www.nairobiconvention.org/CHM%20Documents/WIO-Lab%20Outputs/Regional%20reports/Incomati%20Environmental%20Profile%20final%20.pdf, accessed October 2025). Under RCP2.6 in 2015, the mean runoff was modelled as 780 Mm^3, while under RCP8.5 it is 900 Mm^3. Crop yield statistics are given in Section 3.3.1. When compared with data from the South African Grain Laboratory (https://sagl.co.za/, accessed October 2025) which reports maize yields in the Mpumalanga Province (part of the IUWMA) at c. 10 tons ha^{-1} and soy at 3.5 tons ha^{-1}, model input data are similar for RCP2.6 (6–8 tons ha^{-1} for maize and 4–5 tons ha^{-1} for soy) but much higher for RCP8.5 (10–12 tons ha^{-1} for maize and 8–9 tons ha^{-1} for soy; also see Section 3.3.1). Likewise, energy usage was compared to domestic use of local team members as a 'sanity check', with simulated values being reasonable. In addition, data from the National Energy Regulator of South Africa implies that domestic monthly electricity consumption is in the order 100 MkWh $month^{-1}$ (https://www.nersa.org.za/wp-content/uploads/bsk-pdf-manager/2022/10/Approved-Municipal-Electricity-Tariffs-2022-23.pdf, accessed October 2025). Modelled results in 2015 without policies are c. 93 MkWh $month^{-1}$, supporting reported figures. Stakeholders, in workshops, did not point out any glaring deviations from expectation or experience. Model results were presented to stakeholders during dedicated stakeholder workshops within the NEXOGENESIS project (Table 1). Further details of these workshops are found in NEXOGENESIS Deliverable 5.6 [42], available from https://nexogenesis.eu/downloads/ or by request from the lead author. It is pointed out that it was WEFE variable *trends* that were more

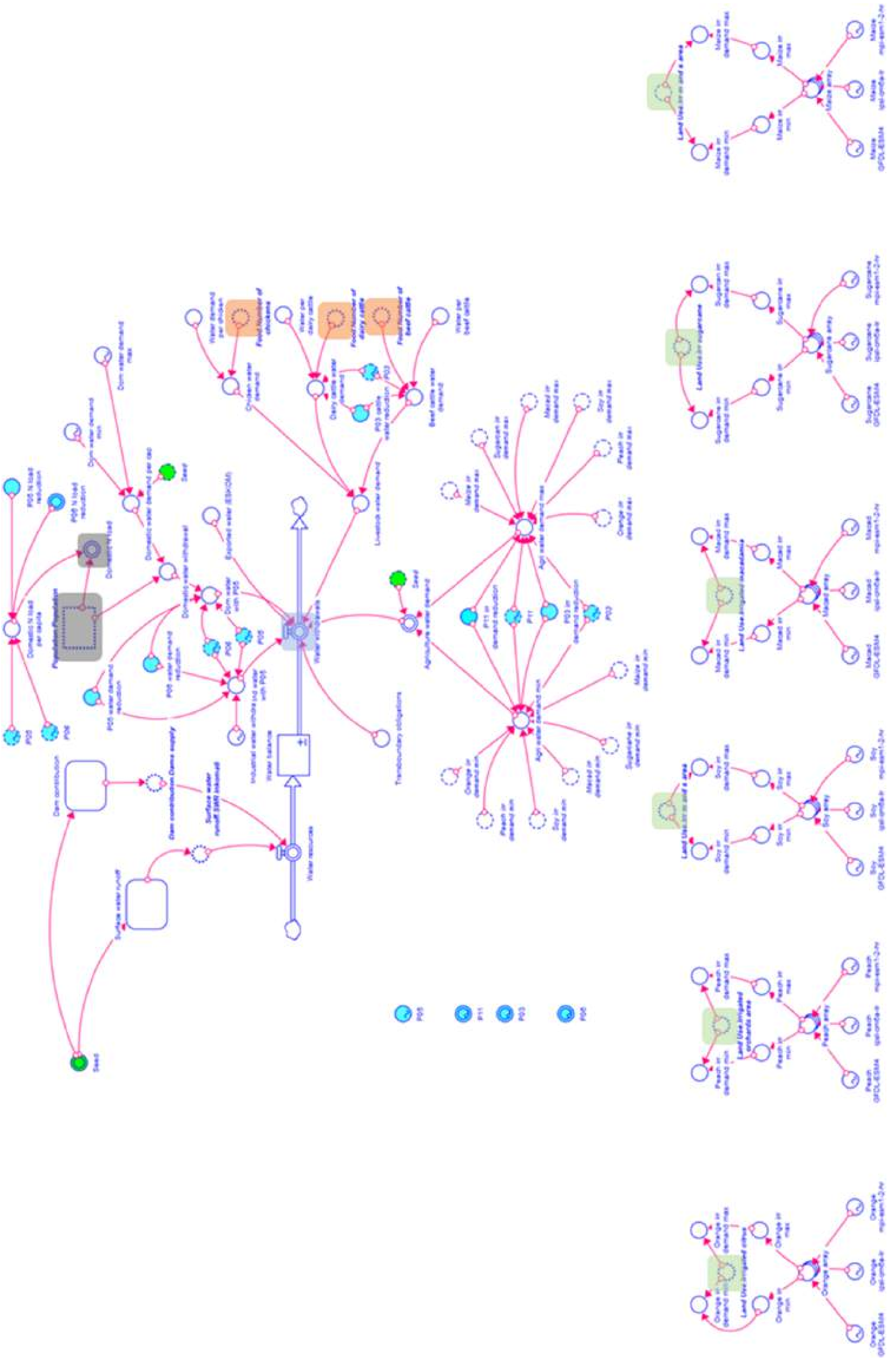

Fig. 4. detail of the water module of the IUWMA SDM. Translucent coloured variables indicate those that either affect the water sector from other nexus sectors, or those water variables that subsequently impact on other nexus sector modules: to/from the land sector (green), the population sector (black), the food sector (orange), and the energy sector (blue). The other modules are shown in Supplementary Information 3.

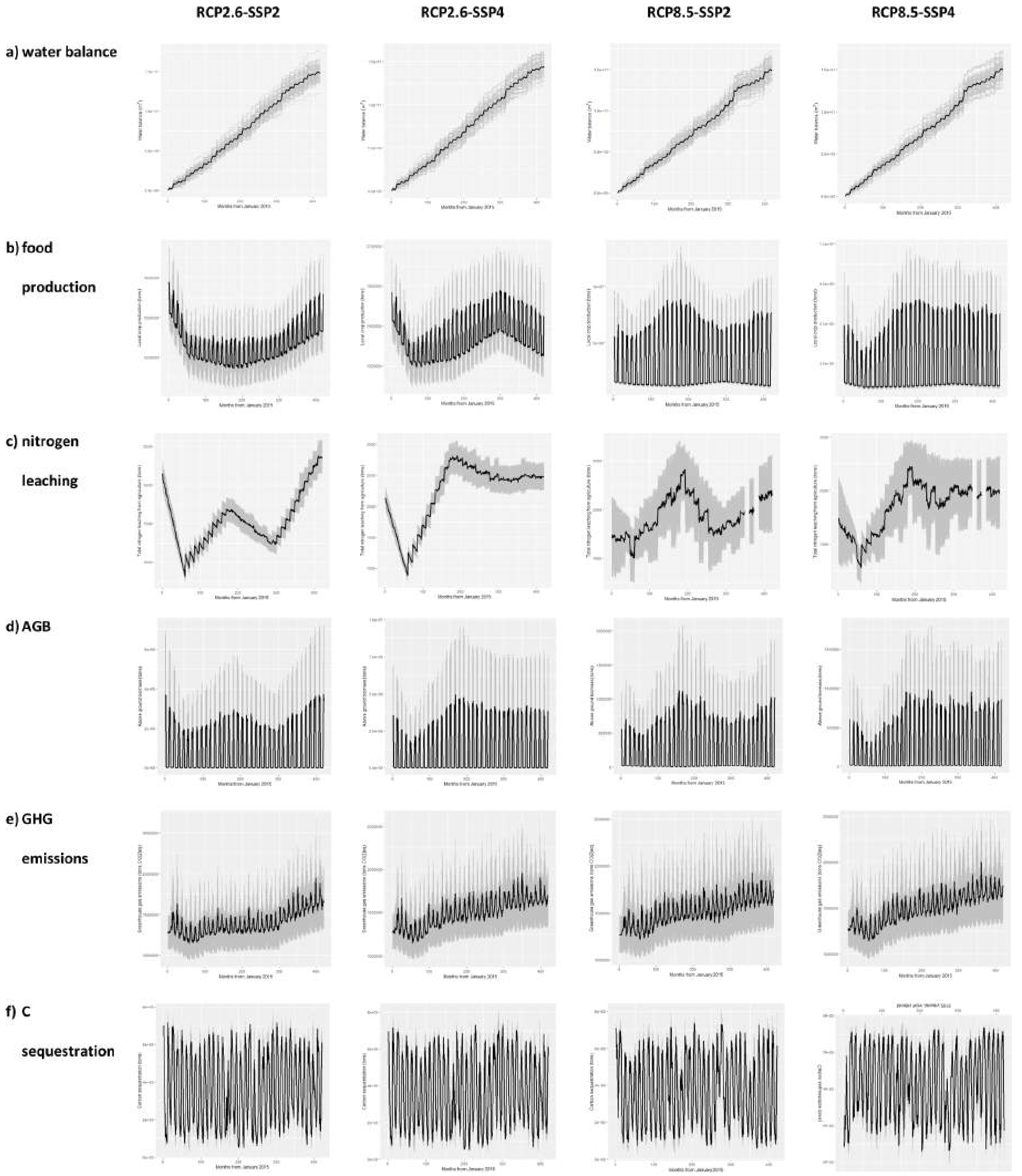

Fig. 5. reference scenario results showing trends in: (a) the water balance (cumulative over time); (b) food production; (c) nitrogen leaching; (d) above ground biomass (AGB); (e) GHG emissions; and (f) carbon sequestration, under the reference scenarios, indicated in the top row. Light grey lines indicate the results of each of the 100 Monte-Carlo simulations. Black line is the mean of all 100 simulations and shows dominant trends in variables between the reference scenarios. These trends are especially apparent in e.g. the water balance, nitrogen leaching, and GHG emissions.

important than absolute values, especially in response to policy implementation. In this case, the SDM, via stakeholder workshops, was deemed to perform well and according to expectations from experts.

4.4. Simulation results: single policies implemented

In this set of simulations, policies 1, 3, 5, 7, and 10 (Table 4) were implemented one-by-one in the SDM, and the impacts assessed relative

Table 5
summary of the main results presented by RCP and timeslice without policy implementation. For each variable, the value presented is the end-year monthly value averaged over 100 simulations. In the square brackets are rounded [5th; 95th] percentile values.

Variable		2030	2040	2050
Water balance (Mm^3)	RCP2.6	6.5×10^4 [5.6×10^4; 7.4×10^4]	1.1×10^5 [1.02×10^5;1.29×10^5]	1.5×10^5 [1.36×10^5; 1.63×10^5]
	RCP8.5	6.7×10^4 [5.8×10^4; 7.6×10^4]	1.14×10^5 [1×10^5; 1.26×10^5]	1.5×10^5 [1.35×10^5; 1.64×10^5]
Food production (tons month^{-1})	RCP2.6	1.3×10^6 [1.1×10^6; 1.4×10^6]	1.4×10^6 [1.2×10^6; 1.55×10^6]	1.7×10^6 [1.45×10^6; 1.8×10^6]
	RCP8.5	7.5×10^6 [4.6×10^6; 1.2×10^7]	7.2×10^6 [3.9×10^6; 9×10^6]	6.8×10^6 [4.3×10^6; 1×10^7]
N leaching (tons month^{-1})	RCP2.6	1638 [1497; 1780]	1316 [1206; 1439]	2348 [2174; 2550]
	RCP8.5	2444 [2325; 3291]	2083 [1356; 2131]	1990 [1627; 2986]
Above ground biomass (tons)	RCP2.6	2800,000 [195,000; 5300,000]	2000,000 [300,000; 4000,000]	3300,000 [250,000; 6800,000]
	RCP8.5	880,000 [150,000; 1800,000]	735,000 [110,000; 1100,000]	860,000 [150,000; 1800,000]
GHG emissions (tons CO_2e)	RCP2.6	1300,000 [1100,000; 1500,000]	1450,000 [1200,000; 1750,000]	1650,000 [1400,000; 2000,000]
	RCP8.5	1500,000 [1200,000; 1800,000]	1600,000 [1300,000; 2100,000]	1750,000 [1400,000; 2000,000]
C sequestration (tons)	RCP2.6	4700,000 [3700,000; 5600,000]	4900,000 [4300,000; 5500,000]	6000,000 [5400,000; 680,000]
	RCP8.5	5800,000 [5700,000; 6100,000]	5700,000 [5100,000; 6200,000]	6250,000 [4700,000; 7600,000]

to the RCP2.6-SSP4 and RCP8.5-SSP4 reference scenarios. These were chosen to represent different policy objectives applied across nexus sectors. Implementing policies one-at-a-time has significant impacts on the water balance, food production, N leaching, and above ground biomass (Figs. 6a-d), with lesser impacts on GHG emissions and carbon sequestration (Figs. 6e and f) under RCP2.6-SSP4. The water balance always improves (from 1.4415×10^5 Mm^3 month^{-1} in 2050 in the reference to a maximum of 1.60313×10^5 Mm^3 month^{-1} in 2050 under policy 5). Total local food production is notably reduced, potentially causing concern for food security ambitions (from 1557,681 tons month^{-1} in 2050 in the reference to a low of 734,548 tons month^{-1} under policy 5, a 52 % decline), while N leaching drops (2478 tons month^{-1} in 2050 under the reference to a low of 1711 tons month^{-1} in 2050 under policy 3, a 37 % decline), a positive response for ecosystems and water quality goals. Under RCP8.5-SSP4, the impacts of individual policy implementation are lower than under RCP2.6-SSP4 (Fig. 6a-f). Food production drops less than under the RCP2.6 simulations, but also is not as high under the reference, with similar results for nitrogen leaching and GHG emissions.

4.5. *Simulation results: all policies implemented*

When every policy in Table 4 is implemented, the impacts are significantly different to when implemented individually (compare Figs. 6 and 7). Under all RCP-SSP combinations, the water balance is barely affected (Fig. 7a), good news for water security concerns. Food production increases significantly (more than 3 times) over the reference under RCP8.5 futures but declines up to 42 % under RCP2.6 futures (Fig. 7b), but N leaching reduces under all scenarios by up to 48 % (Fig. 7c). Above ground biomass is increased significantly compared to the reference, particularly under RCP2.6 (Fig. 7d), positive for ecosystem services. GHG emissions, as with N leaching, drop with respect to the reference by up to 19 % (Fig. 7e). This marks a significant change compared with single policy implementation when the impact to GHG emissions is negligible. Carbon sequestration appears relatively unaffected (Fig. 7f). In terms of uncertainty in the simulations, changing RCP-SSP combinations alone has relatively little impact to the results (i.e. low sensitivity). Differences in the impact models have relatively more impact (Fig. 5), though this depends on the variable. Water variables are lesser affected by impact model variation than food production or above ground biomass. Policy implementation has varying degree of impact on results, and is highly dependent on the variable, with lesser impacts to the water variables than to e.g. food production.

5. Discussion

As Figs. 5–7 demonstrate, implementing policies impacts on reference scenario trends, with the impact varying significantly whether policies are implemented in isolation or together, and depending on the future pathway. All policy impact results represent exploratory assessment of policy impact on WEFE nexus resource trajectories rather than claiming to be numerically precise representations of specific variables over time. This relates to the assumptions and limitations of the modelling work, discussed later in this section. *Individual policies* show occasionally significant impacts depending on the sector, scenario, and policy. N leaching and GHG emissions are most affected, and food production is hampered under RCP2.6. Policy 3 shows significant impact on N leaching trends, while the water balance improves under all policies under RCP2.6 (Fig. 6a). The decrease in food production under individual policy implementation (Fig. 6b) is troubling, particularly considering South African food security ambitions. This is partly explained by complex variable interactions within the SDM, and reflects the trade-offs linked to policies intended to benefit ecosystems, reduce water demand and implement renewable energy initiatives with compete land uses, resulting from the potential land use changes modelled in the SDM. This highlights a core issue in resource nexus research – not everything can be optimised, and trade-offs and compromise are the norm. The high seasonality in food production (Fig. 6b) is related to the underlying input data used and the variability therein. All individually-applied policies reduce GHG emissions whether this is due to changes in land-use makeup (policies 1 and 3), energy use reductions and/or clean energy initiatives (policy 10), or changes to energy demand (policy 7).

When policies (Table 4) are *implemented together*, the resultant impacts compared to individually applied policies, change markedly (Fig. 7). The overall dynamics are of compounding benefits or losses, or of cancelling effects (trade-ffs) between policies, and generally, improvement over single-policy implementation is shown. This can be because cross-sectoral impacts are augmented when policies are combined. While the model complexity makes it extremely challenging to identify exact reasons for these differences, knowledge of the policies and of the model development process can offer some speculative insight. For example, the dramatic improvement in N leaching is likely due to ‘stacking gains’ from different, seemingly unrelated policies, being implemented together, such as policies 3 and 5 which target different issues yet both contribute to N reduction targets. This represents a concrete example of real policies that could be enacted in ways to harness this synergy, boosting efforts to control N leaching.

Food production under RCP2.6 oscillates below the reference values, while RCP8.5 simulations show dramatic variability, reaching unfeasibly high values. These differences reflect differences in the underlying input data between the RCPs, reflected in the reference scenarios (Fig. 5). For example, some of the projected crop yields under RCP8.5 are much higher than those under RCP2.6. Thus, the food production results in Fig. 7 appear largely to be an ‘echo’ of the input data (see

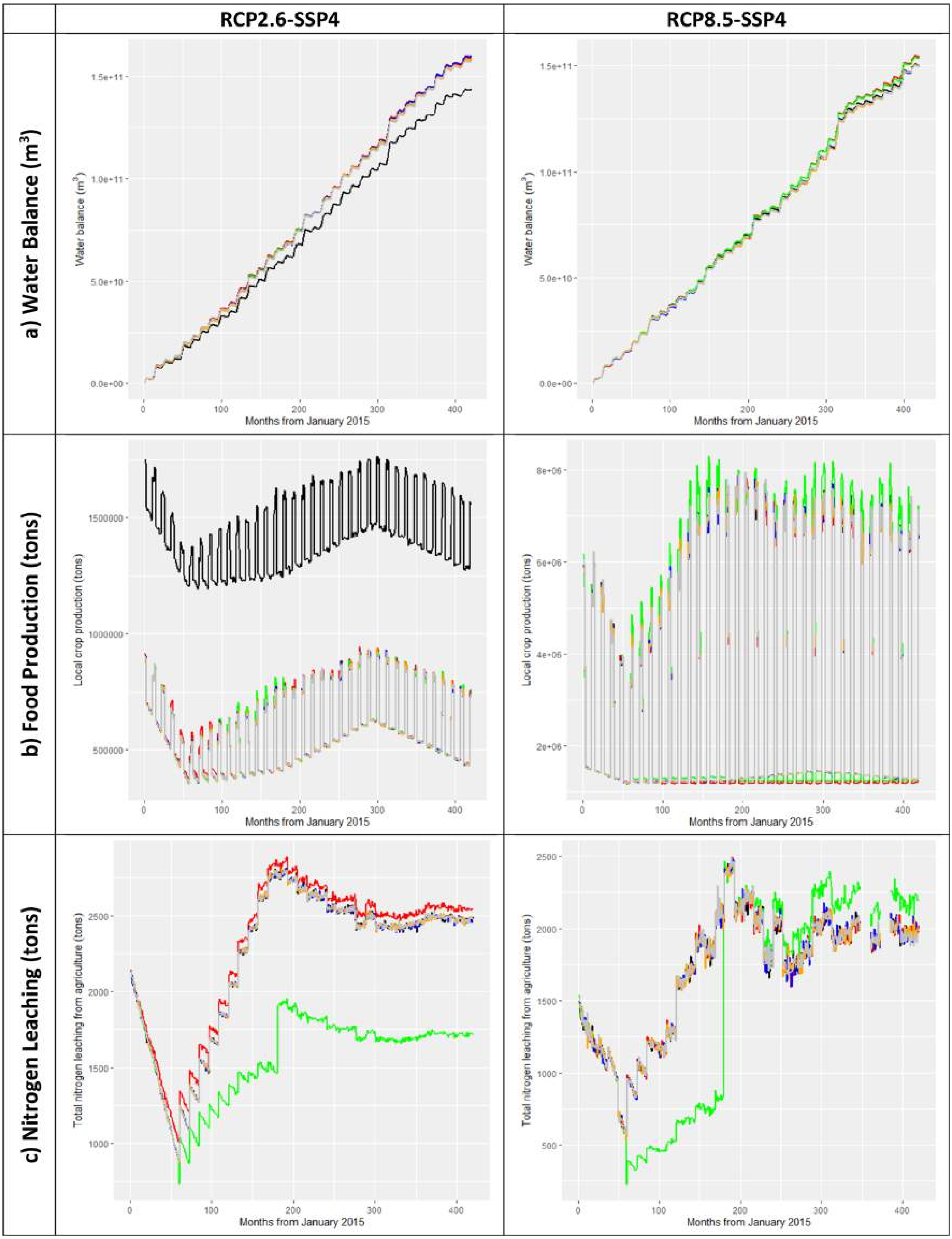

Fig. 6. results when policies in Table 4 are implemented on-at-a-time relative to the RCP2.6-SSP4 and RCP8.5-SSP4 reference scenarios. Black line is the reference scenario mean. Coloured lines indicate the mean of 100 Monte Carlo simulations implementing individual policies (red = policy 1; green = policy 3; blue = policy 5; orange = policy 7; grey = policy 10).

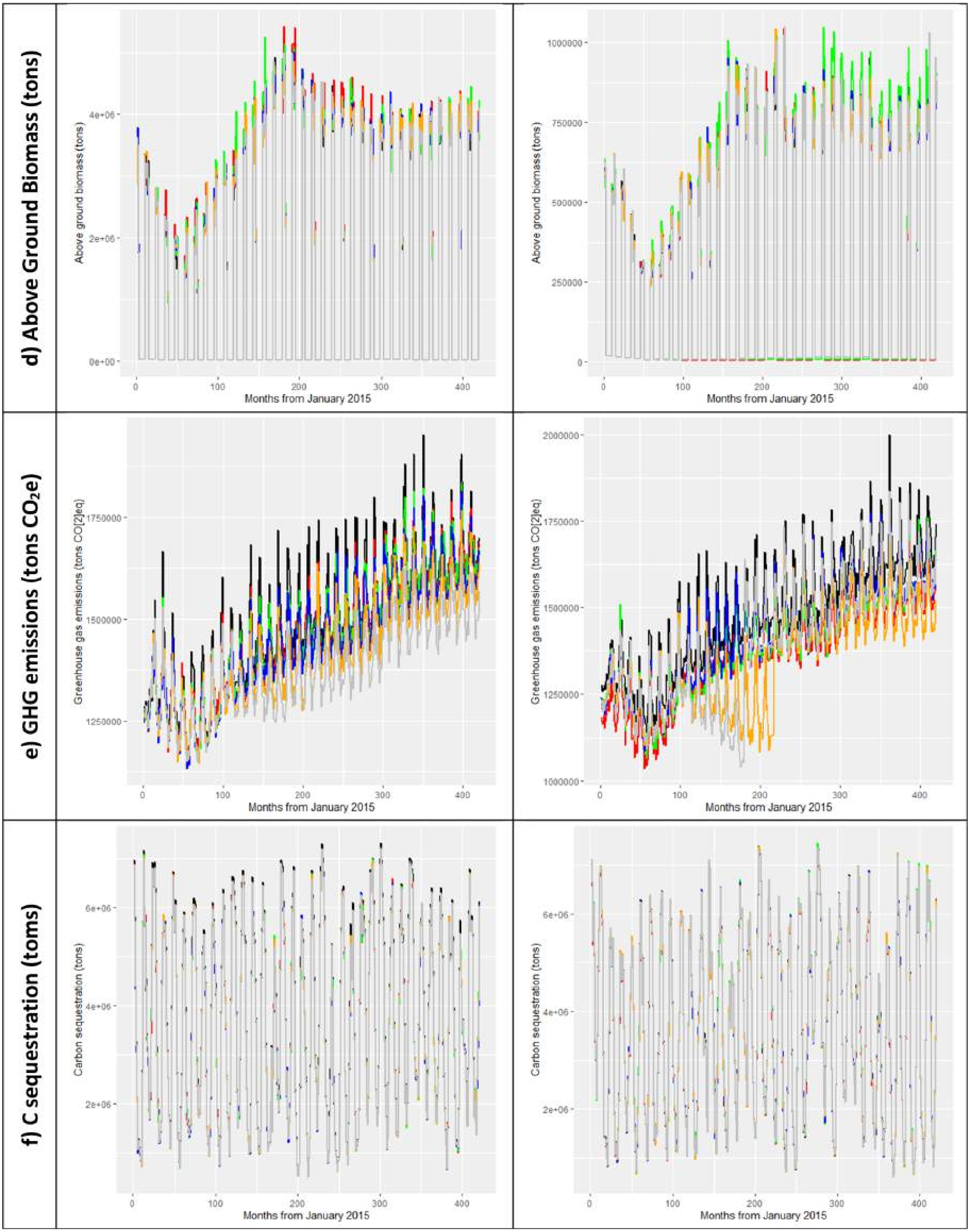

Fig. 6. (*continued*).

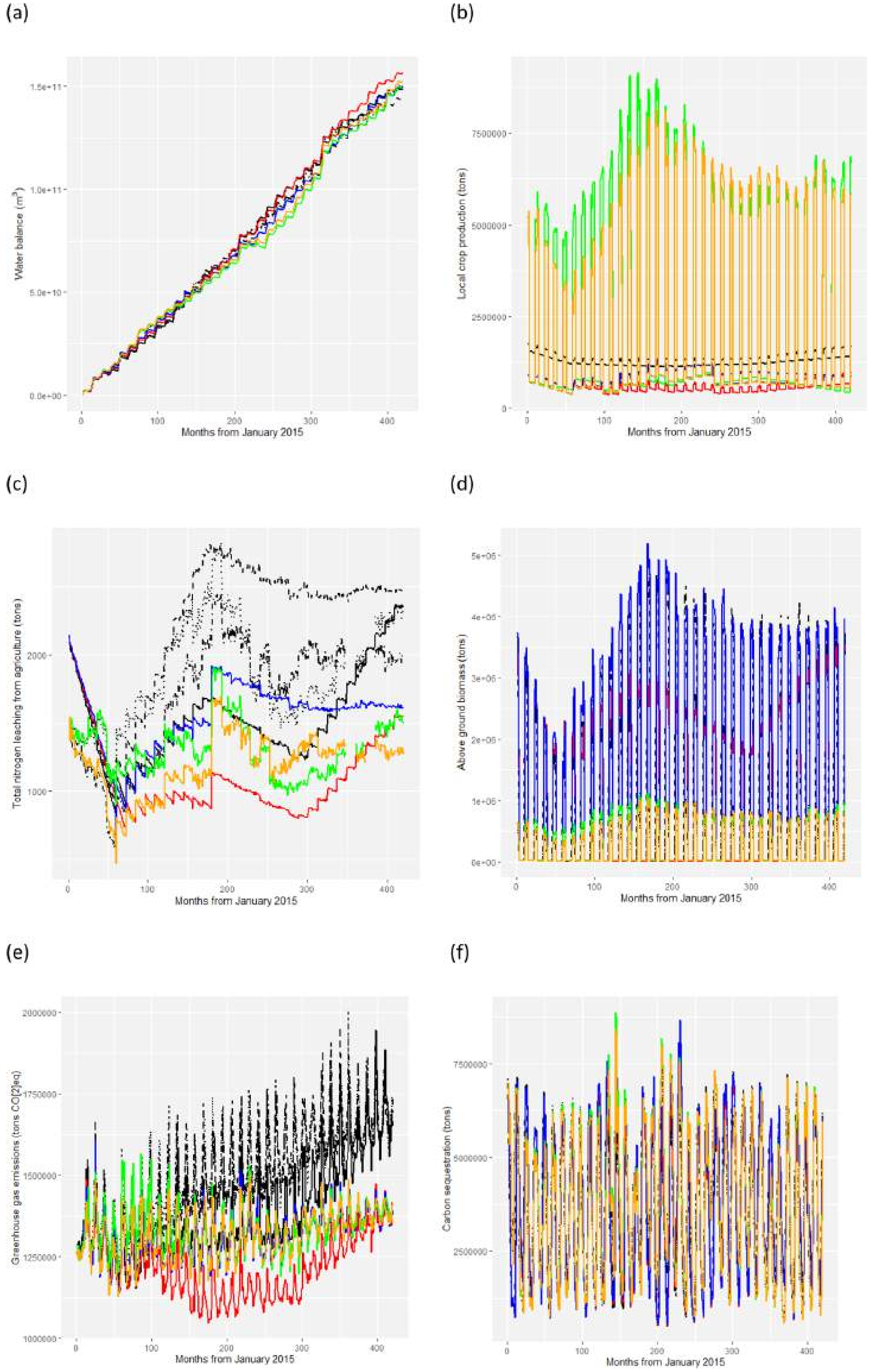

Fig. 7. impacts relative to the reference scenarios (black lines) when all policies in Table 4 are implemented in the SDM. Red = RCP2.6-SSP2 with all policies; blue = RCP2.6-SSP4; green = RCP8.5-SSP2; orange = RCP8.5-SSP4. Lines are the mean of 100 Monte Carlo simulations.

Section 3.3.1, 4.3, and Table 5). For example, data statistics in Mpumalanga Province give yields of around 10 tons ha^{-1} for irrigated maize, and 3.5 tons ha^{-1} for irrigated soy, while under RCP8.5, input data give values of c. 12 tons ha^{-1} for maize and 8 tons ha^{-1} for soy. Under RCP8.5, the impact of policies has limited impact relative to the magnitude of values for food production. Actual food production would be unlikely to reach the levels simulated particularly as it is suggested that much of South Africa's cropping systems are degraded [100], and because it is projected that climate change will decrease crop yields for a number of staple crops [101].

Conversely, AGB simulations show very high variability in RCP2.6 simulations, with values fluctuating around the reference in RCP8.5 simulations. This is due to variability in the underlying input data (in AGB estimations in RCP2.6 data, and for maize and soy yields, both rainfed and irrigated, for RCP8.5 data) and subsequent interactions within the SDM. This raises the issue of potential problems in underlying data feeding these simulations (Table 2), with the models producing the raw input data potentially needing to be revisited. Nitrogen leaching is reduced in all simulations when compared to the reference by 2050, demonstrating the potential impact that policies have on reducing N leaching to water bodies (Table 4). These trends reflect evidence that the intensity of nitrogen applications in South Africa is decreasing [102].

GHG emissions reduce relative to the reference, indicating the potential climate mitigation impact of policy implementation (e.g. policies 1, 5, 6, 7, 10; Table 4). Increases in biomass, reductions in water demand (leading to reduced energy for water pumping), reducing cattle numbers, and changing the energy mix to more renewable sources, all contribute to the emissions reduction over time, a positive impact. Such a decrease aligns with recent studies that suggest that emissions from certain sectors, especially transport, in South Africa may decline in the near future [103] and because per-capita emissions have stabilised (Energy Research Centre, n.d.), meaning efficiency gains and emissions reductions schemes could outweigh population increase. Conversely, other analyses suggest emissions growth in South Africa of up to four-fold by mid-century [104,105], reinforcing the need to monitor and mitigate emissions across sectors. The maintenance of energy infrastructure is critical to ensure that load-shedding and the associated use of fossil fuels to support the energy grid during unexpected shutdowns is critical to ensure emissions decline. This is especially important as transport-related emissions are not captured in the model, and neither are the emissions of energy generation, only of local (i.e. within-IUWMA) consumption. Despite this positive message, the decline in food production, leading to potential food security concerns, demonstrate clearly that trade-offs are inevitable, and policy must be enacted so as to minimise these reductions. As in the single-policy simulations, the land sector is shown to be key in leading to impacts across sectors.

In reality, the reference scenarios (i.e. with no additional policies imposed) and the single-scenario simulations are unlikely to be realised. Multiple policies are enacted concurrently according to national (e.g. National Adaptation Plans), regional (e.g. EU Water Framework Directive), or international (e.g. Paris Agreement) goals, yet consideration of their joint impact is rarely considered. Individually-applied policies showed significant impacts that tended to be constrained to the sector in which they were applied with minor co-impacts in other resource sectors. The impacts most affected by single-policy implementation were food production, N leaching, above-ground biomass, and GHG emissions, with the land sector being the key impacting sector. When all policies (Table 4) were implemented, reference scenario results were significantly altered (Fig. 7). The major conclusion is that implementing all policies together leads to a general improvement in the WEFE resource sectors, aligning with policy ambitions. This can be partly explained by separate policies cumulating impacts. On the other hand, some policy objectives counter each other: measures to expand (irrigated) agricultural land offset concurrent policies aiming to reduce water demand or energy use, resulting in no major changes in the water balance (e.g. decreases in water consumption in some sectors may be offset by expanding irrigated agriculture which demands more water, counteracting gains made by other policy ambitions). The land sector is a key impact driver, with subsequent impacts on the water, food, energy, climate, and ecosystems sectors (Fig. 2a). Policies 1 and 3 appear to show significant impacts across sectors. Recognising sectoral interconnectedness is critical to holistic, integrated policy development, not just in the IUWMA, but in South Africa, and more generally in the southern African region. In this regard, recognising the importance that the land sector and related policies play is a key message. Much work is ongoing in the wider Southern African Development Community (SADC) region towards WEFE nexus approach implementation in policy and governance, especially when attempting to achieve multiple Sustainable Development Goals important in the region [106,107]. The results and messages from this analysis could contribute to these initiatives, especially in highlighting sectoral interconnections, critical policy actions that impact across sectors with a focus on land, and showing that multiple policies enacted in parallel often show surprising, unanticipated, effects (e.g. enhancing ecosystems outcomes but at the expense of food security ambitions). In so doing, a move towards actionable nexus research would start to be realised, something that has been increasingly called for [7]. This research suggests that policy ambitions should be aligned where possible to ensure the achievement of WEFE resources goals across sectors, and that policies focussing on land protection and recovery would be natural entry point to realising wider nexus gains due to the 'centrality' of the land sector in leading to nexus-wide impacts. Recent research has shown that policy coherence analyses could play an important role here, helping identify exactly where in policy synergies and trade-offs lie (both horizontally across resource sectors, and vertically between governance levels), posing actionable suggestions to improve coherence across policies (e.g. [9,108,109]).

Ways to potentially achieve wider policy goals and ambitions across resource sectors while avoiding trade-offs where possible could be attained with more intelligent policy combinations. However, in this study there are potentially 12! (c. 480 million) policy combinations available, something that cannot be explored manually even against one policy goal, let alone multiple, potentially competing goals, across multiple futures. With so many combinations, exploring the entire space is not possible and it may be the case that goals cannot be attained to their full expectations due to trade-offs in the policy and biophysical systems. This is where recent advances in machine learning (ML), and reinforcement learning (RL) techniques come in [110]. ML/RL could be implemented to search vast policy-combinatorial spaces in short time. Combinations can be evaluated against multiple policy goals using optimisation algorithms, constantly searching for combinations that best achieve targeted goals over time (i.e. that generate the greatest reward for the lowest trade-off). These evaluations may change under different scenarios. Such innovative Artificial Intelligence approaches have recently been explored within nexus research, incorporating multi-objective mechanisms into the decision-making process [111]. The ML processes can run SDMs many times using Monte-Carlo routines [112], accounting for uncertainty in data and learning how the system responds to different policy actions under different scenarios when trying to meet multiple policy goals. As such, undesirable policies (i.e. those leading away from goal attainment) and trade-offs can be identified and avoided in future searches, improving the efficiency of the optimisation. Using such a scheme, ML/RL techniques could be used to propose promising policies or policy combinations that address a policy goal or set of goals. These combinations could be considered in more depth by policy and decision makers to further study their feasibility (technical, financial, social, political, etc.). If the original list of policies modelled was discussed in a stakeholder/workshop setting, then suggestions of promising policy combinations may be more likely to be taken up and considered. Such advances would help contribute towards the need to resource nexus research to move out of dominantly academic exercises and be practically applicable [7]. Exploring the use of ML techniques in a resource nexus / decision-making context is an area of active ongoing research, for example in the EC Horizon2020 project NEXOGENESIS where ML techniques have been demonstrated in the online Nexus Policy Assessment Tool (NEPAT), which is fully functional and available to explore (www.nexogenesis.eu and https://nepat-dev.nexogenesis.eu/). It is in this respect that the model's primary strength is to be found. In allowing the possibility to compare and contrast policy impact and trade-offs across sectors, under different development futures, and with uncertainty assessment, practitioners can get a handle on the broad system trends of key WEFE resources variables over time. With this information, policies can be compared at least in a relative sense: does implementing 'policy A' lead to a better or worse outcome from a trend perspective than 'policy B?'. Once favourable trends are identified, further research can be carried out to determine more reliably absolute numbers as well as practical, technical, financial, and social feasibility.

The model presented is innovative in its complexity and the coherent way in which policies are integrated along with the ability to project their WEFE resource trajectory impacts under various climate and development futures, and assessing uncertainty in model input data. These advances mark a major advance in WEFE nexus systems modelling. At the same time, a number of assumptions and shortcomings in the model should be mentioned. Foremost, it is recognised that not every part of the WEFE nexus system is included. For example, emissions did not account for all sectors, especially the transport sector which is a major emitting sector in South Africa [103] because in the context of this study, this was not considered a priority area for investigation. Likewise, not all foodstuffs were accounted for in food production, and food import and exports were not considered, and were left out of food demand. This is because of data limitations, and because of the choice to focus on the most economically and socially important crops grown in the IUWMA. Similarly, groundwater was not included as a water source due to data constraints. As the entire WEFE nexus could not be modelled, decisions were made to focus on those issues most pertinent to the study area, including issues that had policy relevance, something done during stakeholder workshops (Table 1). Furthermore, due to the lack of interest shown by stakeholders involved in the mining sector, the mining sector was not modelled in the SDM in any depth. The inclusion of mines could result in significant impacts on the WEFE nexus. Another assumption is that input data are accurate. As described in the Methods, data derive largely from the latest CMIP6 simulations and GTAP/GRDEM results. They represent the state-of-the-art in relation to biophysical and socio-economic future projections. Even so, they are relatively coarse in resolution compared with the size of the study area, and it is assumed that the data are applicable here. Locally-derived and downscaled data may be more representative of the conditions and their spatial patterns, but may be older/outdated, and subject to their own uncertainties and assumptions. In addition, further local data could be sourced as they become available to better ground-truth and validate data coming from the secondary sources used in this study. A further assumption is that the model structure (i.e. the relationships between variables in the SDM) is correct, accurately describing on-the-ground dynamics. While this may not strictly be true for every link, the overall dynamics are captured well, as became apparent through discussions in stakeholder workshops and benchmarking results against observations. System trends were deemed reasonable according to stakeholder inputs (i.e. during the workshops), though the magnitude of some variables (e.g. GHG emissions) was not captured correctly, largely due to the entire system not being considered as mentioned above. More important in this study was to assess policy impacts on system trends, rather than focussing too closely on absolute numbers. The final main shortcoming is on how policies are implemented. For example, if many policies in the land sectors are implemented in parallel for example, they may behave as if each one acts on its 'own' tract of land, whereas in reality, complementary policies will be enacted on the same tract of land. One way this was overcome in the SDM is that if multiple policies were enacted on the same land type, then the impact of each was scaled according to the number of policies (e.g. if there were three policies, the impact of each was scaled by one-third). This shortcoming led to situations where crop production or above-ground biomass rose to unreasonably high levels, although this is also related to the raw input data. In addition, there is inherent uncertainty in how to 'translate' from a textual policy to a model variable. Such shortcomings could be revised in future iterations. Despite the shortcomings, the model implemented remains one of the most advanced of its kind at this scale of application, capturing multi-sector dynamics including the incorporation of ecosystem metrics, using the latest biophysical and socio-economic projection data, accounting for input data uncertainty through Monte-Carlo simulations, and applying multiple locally-relevant policies across sectors to assess their impacts across the WEFE nexus to 2050, advancing previous similar efforts (e.g. [61]).

6. Conclusions

This study has presented the first quantitative System Dynamics Model of the water-energy-food-ecosystems (WEFE) nexus for the Inkomati-Usuthu Water Management Area (IUWMA), South Africa. The model, developed with local stakeholders, captures interactions between the WEFE sectors, the supply and demand of which are determined by the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs). A suite of policies is integrated to assess their system-wide impacts. When the model is run without policy implementation (the reference scenarios), results show that some parameters do not differ significantly between scenarios (e.g. water balance), while others such as nitrogen leaching show substantial differences. When policies are implemented one-at-a-time, impacts tend to be confined to the sector to which they are intended, although some such as the land-based policies, have wider implications, occasionally significant. When all policies are implemented, the impacts are greater when compared with one-at-a-time. Most sectors benefit (e.g. food production, GHG emissions, nitrogen leaching), reflecting the combined impact of policy ambitions. The land sector is a key nexus impacting node: land-related policies can have outsized, nexus-wide impacts, some of which may be detrimental (e.g. reductions in food production). A key result is that interactions between policies are not intuitive and maybe counterproductive (e.g. land policies reducing food production). This is an important message for policy makers dealing with natural resources management, and this study can contribute to greater awareness and consideration of the linkages not just between the resource themselves, but also between policies, ensuring policy makers are designing them to avoid trade-offs. Policies in the land and food sectors should be checked against ambitions in other sectors such that synergies are augmented and that trade-offs (e.g. irrigated agricultural expansion counteracting water savings gains in water policy) are avoided. This is another important policy message. Although a number of shortcomings are acknowledged, overall the main trends are representative of the study area and can give useful insight and suggestions for policy advice. Specific policy combinations were not tested. There are hundreds of millions of combinations, so trying to determine which combinations are the most promising across sectors is not manually possible. This opens the opportunity to use machine learning techniques in future research to search vast combinatorial spaces and to assess these combinations' performance against multiple policy goals. This study yields new information and insight for integrated resources management in the IUWMA and offers policy directions (e.g. focus on harmonising ambitions in the food and land sectors), with the general approach being adaptable for the wider South Africa and Southern Africa Development Community region.

Data statement

All data used are reported either in the main text or in the Supplementary Information except the SDM equation file. Readers can request the SDM equation file from the corresponding author, which is not included here due to its length (>700 pages). The NEXOGENESIS Deliverable 5.6 [42] can be requested from the lead author, and will be available for free download from early 2026 from https://nexogenesis.eu/downloads/.

CRediT authorship contribution statement

Janez Sušnik: Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Blaine Haupt:** Writing – original draft, Visualization, Data curation. **Daniella Kristensen:** Writing – original draft, Visualization, Data curation. **Alice Harvey:** Writing – original draft, Validation, Data curation. **Gareth Simpson:** Writing – original draft, Data curation. **Roberto Roson:** Writing – original draft, Data curation. **Muhammad Faizan Aslam:** Writing – original draft, Data curation. **Chaymaa Dkouk El Ferroun:** Software, Formal analysis, Data curation, Writing – review & editing. **Antonio Trabucco:** Writing – original draft, Data curation.

Declaration of competing interest

The authors declare no conflicts of interest in the submission of this manuscript.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2026.100690.

Data availability

Data are included in the paper or as SI.

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