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Systems thinking on the resource nexus: Modeling and visualisation tools to identify critical interlinkages for resilient and sustainable societies and institutions

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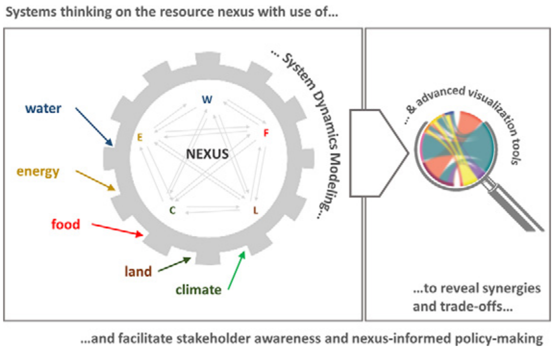
HIGHLIGHTS

- A system-dynamics model of the water-energy-food-climate nexus in Greece is developed.
- Decoupling of strong interlinkages among nexus sectors leads to increased system resilience.
- The Nexus chord plot is developed to reveal strong resource interlinkages and Nexus hotspots.

GRAPHICAL ABSTRACT



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ABSTRACT

Achieving the UN Sustainable Development Goals depends on using resources efficiently, avoiding fragmentation in decision-making, recognising the trade-offs and synergies across sectors and adopting an integrated Nexus thinking among policymakers. Nexus Informatics develops the science of recognising and quantifying nexus interlinkages. Nexus-coherent solutions enhance the effect of policymaking in achieving adequate governance, leading to successful strategic vision and efficient resource management. In this article, we present the structure of a System Dynamics Model—the Nexus_SDM—that maps sector-specific data from major databases (e.g., EUROSTAT) and scenario models (e.g., E3ME-FTT OSeMOSYS and SWIM) for the national case study of Greece. Disaggregation algorithms are employed on annual national-scale data, turning them into detailed spatial and temporal datasets, by converting them to monthly values spread among all 14 River Basin Districts (RBDs). The Nexus_SDM calculates Nexus Interlinkage Factors and quantifies interlinkages among Water, Energy, Food, Built Environment, Natural Land and greenhouse gas (GHG) emissions. It simulates the nexus in the national case study of Greece as a holistic multi-sectoral system and provides insights into the vulnerability of resources to future socio-economic scenarios. It calculates the link between crop type/area, irrigation water and agricultural value, revealing which crops have the highest agricultural value with the least water and crop area. It demonstrates that fossil fuel power generation and use of oil for transportation are responsible for the most GHG emissions in most RBDs and presents projections for years 2030 and 2050. The analysis showcases that to move from a general nexus thinking to an operational nexus concept, it is important to focus on data availability and scale.

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Advanced Sankey and Chord diagrams are introduced to show distribution of resource use among RBDs and an innovative visualisation tool is developed, the Nexus Directional Chord plot, which reveals Nexus hotspots and strong interlinkages among sectors, facilitating stakeholder awareness.

1. Introduction

A large part of the population globally does not have access to vital resources, such as energy, water and food. According to the World Bank (2017), more than 1.06 billion people lack access to electricity, 2.1 billion lack access to safe drinking water (World Health Organisation and United Nations Children's Fund, 2017) and 815 million lack adequate food and are undernourished as of 2016 (Food and Agriculture Organisation, 2017). This trend is expected to worsen in the near future, as a result of growing resource demands driven by climate change, population growth, economic development, urbanization, changing lifestyles, governance & policies and technology & innovation, making the availability and management of resources a priority in political agendas. Research and policy circles now recognize more and more the need for an integrated approach in planning and management of resources, in order to address the interconnected risks to water, energy, and food security, since each resource 'security' implies tradeoffs for the others. As natural resources are increasingly under pressure, interlinkages, synergies and tradeoffs among resources as well as their interactions with economy and livelihoods under climate change becomes increasingly evident (Markantonis et al., 2019). This interplay is essential for addressing effectively current sustainability challenges. Moreover, food, water and energy systems managed in an integrated fashion is key to achieving the UN Sustainable Development Goals (SDGs) (United Nations, 2018) (specifically No. 2 for food security, No. 6 for water, No. 7 for energy and No. 13 for climate change) and requires a better understanding of the interactions between the Goals, both at and across different scales, to promote social equity, human wellbeing and ecological integrity. Decision-makers need such multifaceted knowledge in order to recognise synergies and tradeoffs and try to enhance the former and minimise the latter. In response to this, the Water-Energy-Food (WEF) nexus concept highlights the interactions between these systems and provides insights into the implications across sectors of strategies in a single sector. The significance of the interdependent relationship of the WEF nexus has been lately recognized by the research community which moves towards the development and adoption of integrated modelling approaches that could contribute to efficient resource management, including qualitative and quantitative, natural and social-science-mixed methods (Endo et al., 2020).

The United Nations, the European Commission and the FAO (Flammini et al., 2014) have all acknowledged the importance of dealing with the nexus between resources in an integrated manner. Hoff (2011) described the process illustrating that the "nexus" concept provides a new way of thinking that is not limited to just the Water, Energy and Food sectors while the World Economic Forum launched a report entitled "Water Security: The Water - Energy - Food - Climate Nexus", marking the emergence of the nexus as we know it today. Other approaches have been described in recent years as well, such as the Water-Soil-Waste nexus (Avelan et al., 2017), the Water-Food-Energy-Ecosystems nexus (SETIS, 2018), the Water-Energy-Food-Land-Climate nexus (Laspidou et al., 2018, 2019) and others. The nexus approach is also used as a defined area of work under the UNECE Water Convention with a strong focus on transboundary aspects, since transboundary water bodies often form the connecting resource for food and energy, while international food trade and regional markets for electricity and energy carriers cross state borders (UNECE, 2018). The strong presence of the nexus at the World Water Forum and the Rio + 20 conference in 2012 is proof of the impact that this is an emerging idea worldwide. In few years, the number of books, academic articles and policy reports that refer to the analysis and management of the nexus have grown exponentially. A large body of academic research on the nexus concept is available (Asumadu Sarkodie and Asantewaa Owusu, 2020): some are more conceptual, while others focus on quantitative analysis (Laspidou et al., 2019; Sušnik et al., 2018; Lawford, 2019; Yung et al., 2019; Kurian et al., 2019; McNally et al., 2019; Payet-Burin et al., 2019). Life-cycle assessment may also aid in the quantification of environmental loads within the Nexus by contributing in the optimization of resource consumption and total environmental burden in the system under study (Mannan et al., 2018; Kaab et al., 2019; Nabavi-Pelesaraei et al., 2018). Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) (Giampietro et al., 2009) and Climate Land use Energy and Water (CLEW) (Howells et al., 2013) are among the most robust and integrated frameworks for the assessment of various Nexus interlinkages under different levels of assessment (McGrane et al., 2019; Schull et al., 2020).

Geographical diversity of publications is also impressive: Nexus analysis has been conducted for MENA countries (Hoff et al., 2019), for Japan (Taniguchi et al., 2019), for China (Liu et al., 2019), for Ethiopia (Haskett et al., 2019) and for South Africa (Simpson et al., 2019), to name a few. The application of the nexus concept in policy and decision-making processes are very limited due mainly to the complex dynamic nature of the system and the lack of integrated tools capable to model these nexus interlinkages in a system. As the complexity of the nexus tools increases their ability to better represent specific nexus interlinkages, at the same time they are unable to capture all possible interlinkages among the various nexus components of a system (Dargin et al., 2019). Liu et al. (2017) and Brouwer et al. (2018) provide recent reviews and references on nexus research from the technical perspectives of water and energy, respectively, while Weitz et al. (2017) discuss governance across sectors. This proliferation has resulted in the concept being defined by usage, while the variety of perspectives under which the nexus is assessed results from its inherent complexity and context specificity.

A recent literature review by Galaitsi et al. (2018) revealed that the WEF nexus is closely interlinked with governance, economic forces and socio-physical factors. Thus, economic considerations might be those that create and enhance some of the interlinkages within the nexus and include economic incentives for managing resources and promoting innovations, variable pricing schemes to curb demand, fossil fuel taxation, mechanisms for ecosystem service payments, etc. Sustainable development and efficient resource use necessitate the decoupling of economic growth and resource depletion, thus bringing the economy at the heart of resource nexus management schemes. The global community can promote a multisector integrated approach to complex trade-offs and challenges in order to strengthen resource security by developing governance processes that engage stakeholders from the nexus arena and empower them in analyses and management decisions, using appropriate tools. Such tools need to tackle the complexity of the system, introducing enough detail to capture the important trends, but also providing the data needed to enable informed decisions and quantified nexus analysis. The nexus perspective in policymaking gets more dysfunctional when stakeholders with conflicting interests and objectives are forced to operate within a complex institutional and highly dependent political environment (van Gevelt, 2020; Papadopoulou et al., 2020). Morphological approaches have been lately used as a potential solution to develop and analyze transdisciplinary policy scenarios for a complex physical system under the nexus concept (Hoolohan et al., 2019).

In the work of Mercure et al. (2019), a systematic attempt to analyze the interdependencies among water-energy-food sectors in Brazil highlighted the influence of global environmental and economic challenges on the country's resources. Recent work of Ravar et al. (2020) presents a spatiotemporal disaggregate water-energy-food nexus model to assess water and food supply security at a river basin scale in Iran. At the Urmia lake Basin in Iran, Bakhshianlamouki et al. (2020) develop a System Dynamics Model (SDM) to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia lake Basin.

In a previous work, Laspidou et al. (2018) defined the elements of a five-component nexus system (water, energy, food, land, climate) and described their complex interactions, while in Laspidou et al. (2019), the authors proposed a heuristic algorithm for assessing sector vulnerability and strength of influence of each nexus sector on others. This assessment was done based on expert-opinion and after recording stakeholder concerns. Moving a step further, in this article, a comprehensive SDM is presented that establishes and quantifies interlinkages among resources and Nexus components by mapping data and incorporating outputs from well-established models, thus producing a modeling platform that can incorporate various data sets and modeling outputs in order to run scenarios and produce forecasted trends for future decades. The modeling platform can be used as a testing bed for newly introduced policies, subsidies and incentives and can capture cross-sectoral implications of policies that are not obvious at first. The multitude of modeling results and complex interlinkages make the need for an innovative visualisation tool quite urgent. Nexus Directional Chord plots are presented in this article to address this need and their use in depicting complex interlinkages in a compact form is showcased. This results in raising awareness on the nexus among stakeholders and actors in governance systems. Modeling results and visualization tools are presented for the case of Greece, which is developed both at a national scale, but also at a River Basin District (RBD) scale. Finally, the resource nexus is presented for 2030 and 2050 for Greece, using the baseline EU Reference Scenario.

2. Materials and methods

At the core of this study, there is an SDM (the Nexus_SDM) that includes five modules/sub-models, one for each nexus component—Water, Energy, Food, Land Use and Climate. Definitions of the five nexus components in the context of the Nexus_SDM are included in Laspidou et al. (2018). All Nexus_SDM modules are integrated by using the STELLA software (https://www.iseesystems.com/), a high-level visual-oriented programming and simulation language. Forward Euler step was used as the integration method with a monthly time step. The modules use spatial and statistical datasets to quantify the interlinkages among components and estimate the water, energy, agricultural production and GHG emissions of different land uses and of the built environment, comprising population and tourists. The model is developed in a generic format and is applied for the national case study of Greece. A description of the five modules of the SDM is provided herein. All data presented in this study are published in Mellios and Laspidou (2020).

2.1. Water

To ensure that the uneven distribution of water resources in the country is captured—the western part of the country has abundant water resources, while the eastern part faces serious water scarcity issues (more details can be found in Mellios et al., 2018)—the model is subdivided and modeled in 14 River Basin Districts (RBDs). This was proven to be a valid approach, especially when taking hydrologic balances, since RBDs offer boundary conditions, i.e. they are more or less hydrologically independent; furthermore, the EU Water Framework Directive is employed at the RBD level, so such a classification is valid. For each RBD, all water demands are mapped—public water supply covering household and commercial water uses, irrigation, livestock, industrial and cooling water for thermoelectric power plants. A further distinction on all water demand categories is done between surface water and groundwater sources, making this tool an important source of information, since it distinguishes between groundwater and surface water withdrawals and enables tracking of groundwater levels and pumping. Negative deficits in water-scarce RBDs with aquifers that are heavily exploited by agriculture, e.g., Thessaly (GR08), can now be seen in the model and the effect of different policies and water use or Nexus scenarios can be evaluated. Fig. 1 shows a schematic representation of the water module where all water demands are mapped; out of all demands, urban, industrial and cooling water are associated with the built environment. Nexus interlinkages of the water sector with other sectors are also shown: Energy is needed for pumping, Cooling Water is needed for Power Generation, Irrigation and Livestock Water lead to Food Production and Wastewater treatment leads to GHG emissions. It should be noted that only the direct interlinkages are shown here (Water to Energy, Energy to Water, Water to Food and Water to Climate) and not the indirect ones. For example, energy is needed for water pumping and this energy use results in GHG emissions; however, these GHG emissions are not listed here, but are included in the Energy module (the latter would be the Energy to Climate interlinkage) (Laspidou et al., 2019).

Data originate from a series of databases and are worked through algorithms to produce spatio-temporally disaggregated results, i.e., monthly values for each RBD. In the Nexus_SDM, input data come from published databases along with model outputs, information form the literature and computational results from calibration, or from data mapping and aggregating/processing via Geographic Information System (GIS) software. Combining all this information culminates to the calculation of Nexus Interlinkage factors, which reduce all quantities on a “per unit” basis, such as an “urban water-use per capita & tourist”. Nexus Interlinkage Factors are listed in detail in Section 2.6 and are shown in Figs. 2, 5, 8, 10 and 12. As shown in Fig. 2, Eurostat provided all water demands per RBD for groundwater and surface water, while current population and projections were provided by thematic model E3ME-FTT (https://www.e3me.com/). To quantify pressures from human consumption, population data was combined with data on tourism in Greece, obtained from the Association of Greek Tourism Enterprises (https://sete.gr/). Monthly data for year 2010 for tourist overnight stays was mapped to all RBDs using Geographical Information System (GIS) software; when added to permanent population (assumed to remain constant throughout the year), a total human population was produced that varied in space and time, per RBD and per month, respectively. To calculate the Nexus Interlinkage factor “urban water use per capita & tourist”, the Nexus_SDM takes (i) permanent population from E3ME, (ii) tourists from SETE, (iii) water consumption per tourist from the literature (Goesslink et al., 2012) and (iv) performs calibration to calculate the Interlinkage factor in order to match the total RBD-level urban water use reported by ELSTAT (Fig. 2).

An important dataset was provided by the Hellenic Electricity Distribution Network Operator (DEDDIE) (https://deddie.gr/), which included a monthly electricity consumption set for 2010 for all municipalities in Greece for different sectors (urban, industrial and agricultural). Using GIS software, municipality data was aggregated to RBD level and then the produced data set (DEDDIE dataset) was used to produce four different monthly “activity profiles”— industrial activity, agricultural activity, urban activity and total electricity use profile. These profiles distribute the yearly activity across all months and allow for the temporal disaggregation of yearly values for not only energy but also for water, since energy consumption patterns can be used as proxy for water consumption patterns. Industrial water is expressed as water per industrial plant capacity. All industrial plants are obtained

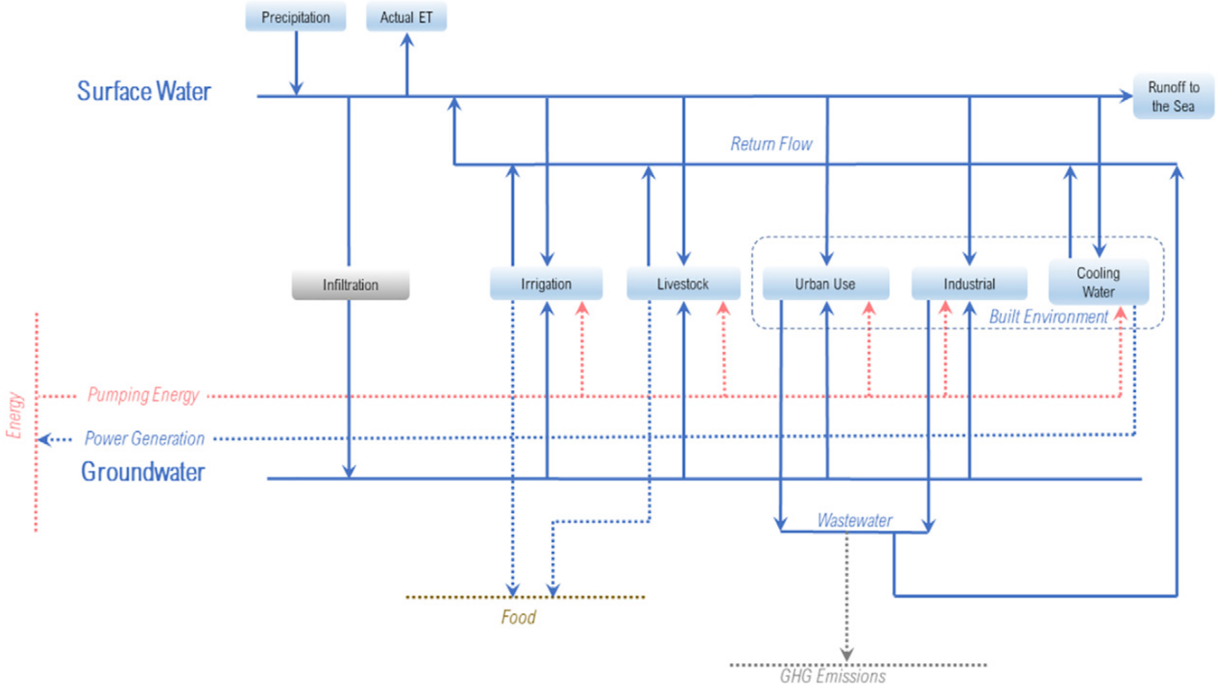


Fig. 1. The Water module in the Nexus_SDM, where all modeled water uses are shown, as well as all associated Nexus components that interlink with Water. Dashed lines show interlinkages of Water with other Nexus components.

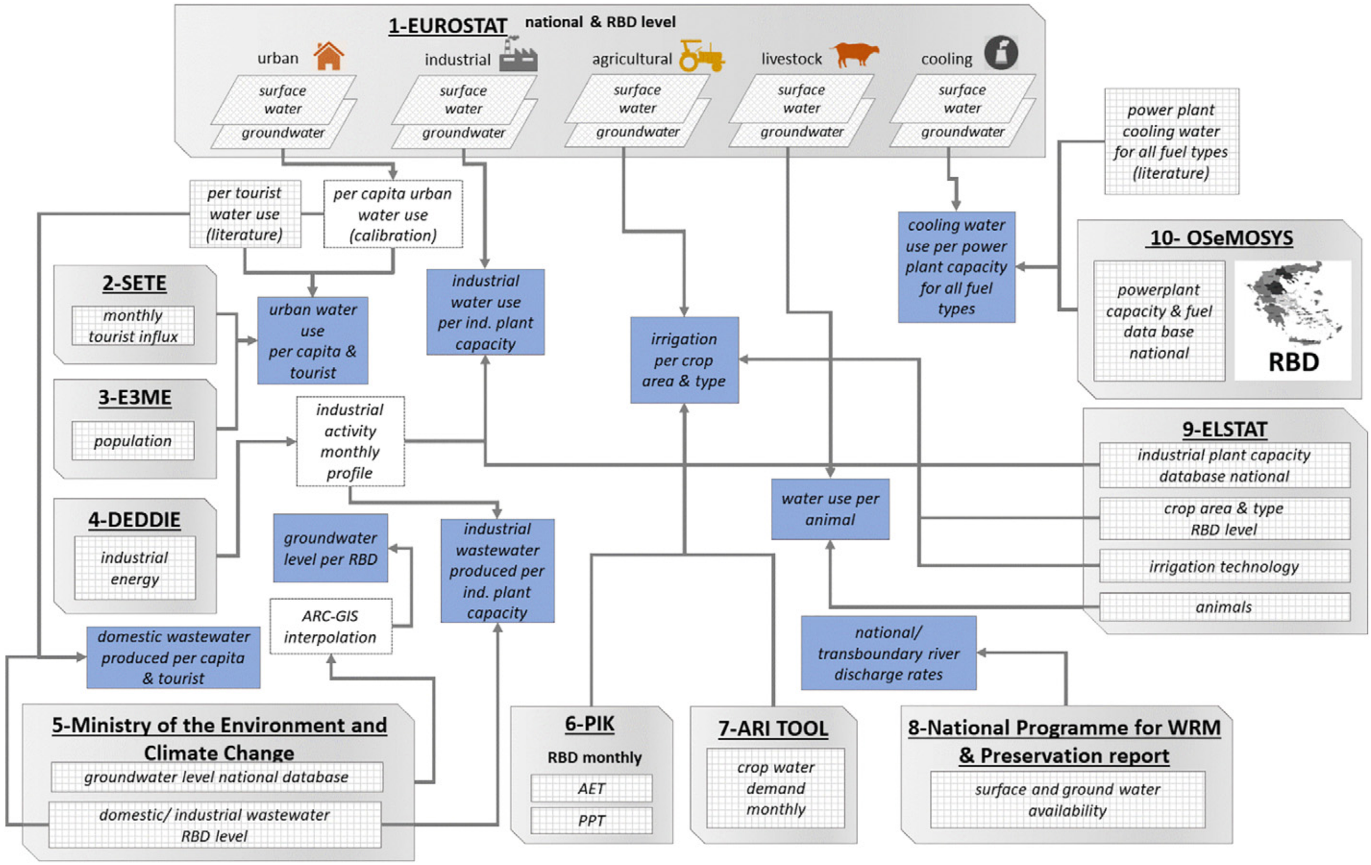


Fig. 2. Data sources and data processing in the Nexus_SDM for the Water Module: Computational steps are shown in white boxes; Input data from published databases, model outputs, or the literature are shown in hatched boxes; Nexus Interlinkage factors for the Water sector are shown in blue boxes.

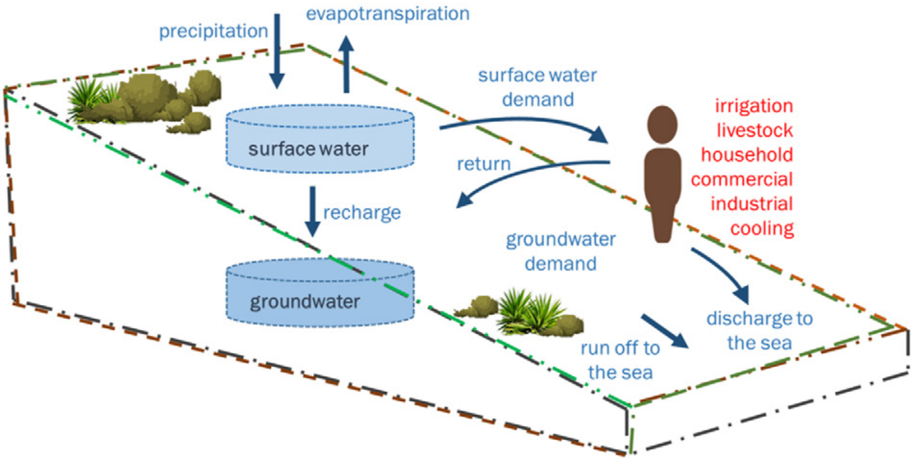


Fig. 3. The water cycle as modeled in the Nexus_SDM.

by ELSTAT and mapped in the RBDs. The corresponding Nexus Interlinkage factor "industrial water use per industrial plant capacity" is derived by using RBD-level plant capacity, industrial water use (EUROSTAT) and industrial activity profile (DEDDIE), as shown in Fig. 2.

Water availability on surface water and groundwater is mapped on each RBD with data from the National Programme for Water Resources Management and Preservation (Koutsogiannis et al., 2008), while parameters such as river flows, transboundary water bodies, groundwater infiltration rates and outflow to the sea also come from Koutsogiannis et al. (2008). A series of groundwater level values for 2010 were obtained from the Ministry of the Environment and Climate Change and provided several values per RBD, which were aggregated to a single "groundwater level value per RBD" with Thiessen polygon analysis. Depending on aquifer level, all groundwater demands exert a corresponding pumping energy demand (a Water-Energy Nexus interlinkage).

Modeling the hydrological cycle as a whole includes a climate dataset provided by Potsdam Institut Klimatologie (PIK) (shown in Fig. 2), which provides regional climate change projections for Greece within the timeline of the Fifth Assessment Report (AR5) and beyond at a spatial resolution of EUR-11: 0.11° (12 km). The relevant climate model used is the GFDL-ESM2M. For the calculation of actual evapotranspiration (ET_a), the thematic model SWIM is used. SWIM is spatially discretized by hydrotopes, areas characterized by unique combinations of soil profiles, distance between soil surface and groundwater level, land use, crop rotation (if agriculture), elevation, and sub basin

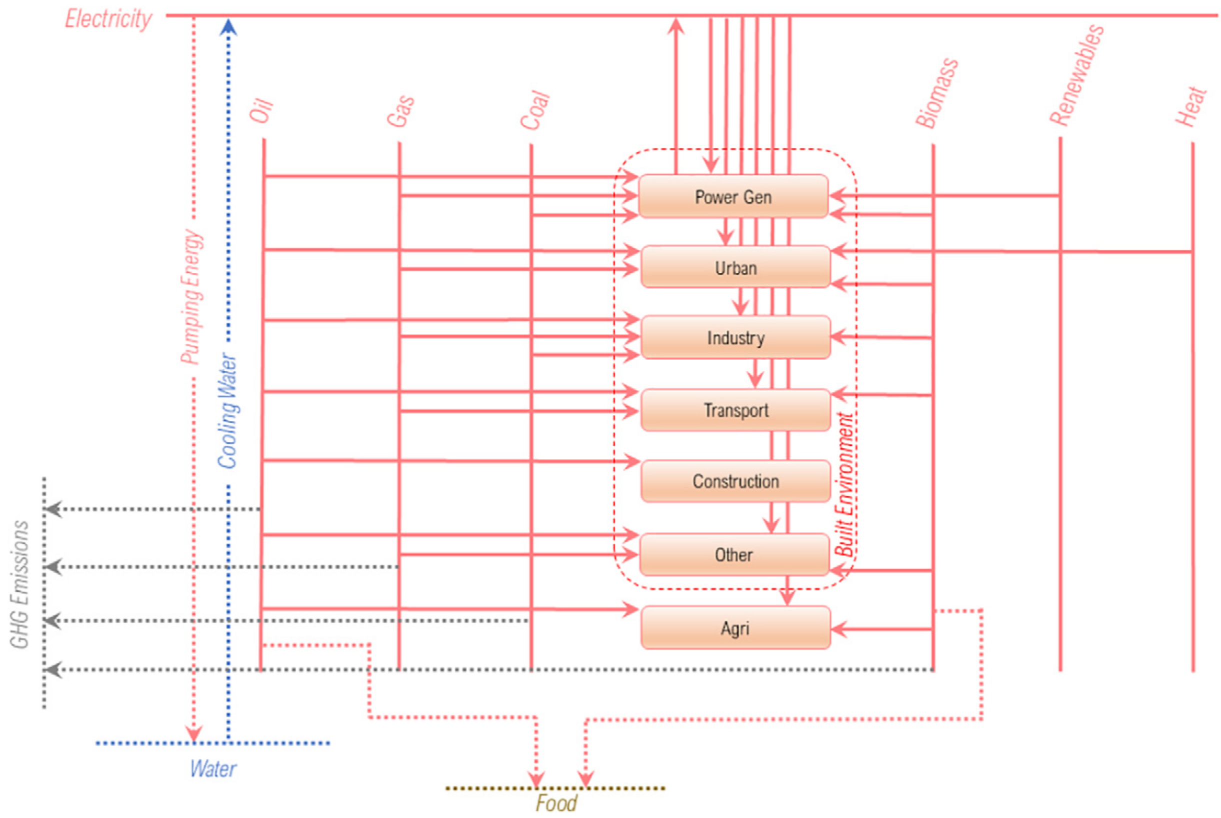


Fig. 4. The Energy module in the Nexus_SDM, where all modeled energy uses are shown, as well as all associated Nexus components that interlink with Energy. Dashed lines show interlinkages of Energy with other Nexus components.

allocation. According to the daily meteorological variables, potential ET (ET_p) is calculated at the individual locations of the hydrotopes. This is the first step and is based on a Turc-Ivanov approach with monthly tuning factors. In a second step, ET_a is derived from ET_p for the two components soil evaporation and plant transpiration in an approach similar to Ritchie (1972).

The hydrological cycle is modeled as follows (Fig. 3): precipitation and actual evapotranspiration are mapped on RBDs as input (a single value per RBD calculated from given spatial resolution using Thiessen polygons); for each time step, surface and ground water balances are calculated using precipitation, evapotranspiration, aquifer recharge, return water, wastewater recharge and runoff to the sea, while exerting demands on surface and groundwater by all sectors.

A detailed power plant dataset was based on the OSeMOSYS dataset (www.osemosys.org), allowing the mapping of all power plants in Greece into the 14 RBDs along with their capacities and fuel type. The following fuel types were listed: coal, oil, gas, biomass and combustible waste, as well as the renewables wind, hydropower and solar for the production of electricity. Cooling water use per RBD is combined with the mapped power plant capacity and with power plant cooling water factors from the literature for different fuel types (Spang et al., 2014) to generate the Nexus interlinkage factors "cooling water use per power plant capacity for all fuel types". Wastewater treatment plants were also mapped in the RBDs (http://astikalimata.ypeka.gr/, data from the Hellenic Ministry of the Environment and Climate Change), along with their discharge rates (m^3/month) and discharge location (sea, or adjacent freshwater body). Wastewater data are differentiated for urban and industrial uses, producing corresponding Nexus interlinkage factors for the two waste streams. Agricultural water demand was computed from a variety of sources, including historical irrigation data for typical irrigated crops in the region and statistical data (ELSTAT; Agricultural Research Institute, 2019) (Mellios et al., 2018). Datasets were calibrated to match reported crop areas and types and agricultural water demand for base year 2010 and the Nexus Interlinkage factor "irrigation per crop area and type" was obtained (Fig. 2). In a similar way, livestock water is modeled via the "water use per animal" interlinkage factor.

2.2. Energy

An important source of data for the case study of Greece has been the E3ME-FTT model (https://www.e3me.com/) from Cambridge Econometrics. E3ME is a macroeconomic simulation model that is demand-driven and characterised by non-optimisation (post-Keynesian economic principles); it includes behavioural aspects by employing macro-econometric behavioural equations, further fitted into the standard national accounting framework of Greece, in this case. E3ME is combined with FTT (Future Technology Transformations), a model of technology diffusion that enables the user to simulate the impact of detailed climate policies. E3ME-FTT models the power and transport sectors and has delivered relevant data for Greece by sector on GDP, employment, population, output, CO_2 emissions, energy demand for coal, oil, gas, electricity, heat, biomass & combustible waste, as well as electricity generated by all sources including renewables. Sectors include (i) power generation, (ii) industries, (iii) construction, (iv) transport, (v) households, (vi) other final use and (vii) agriculture, with uses (i) through (vi) being associated to "built environment". This "master" E3ME-FTT run was delivered in the framework of the Horizon 2020 SIM4NEXUS project (https://sim4nexus.eu/) and has provided all of the Energy module data and has allowed establishing direct interlinkages with the Climate module by associating energy demand by fuel and sector with their corresponding Green House Gas (GHG)

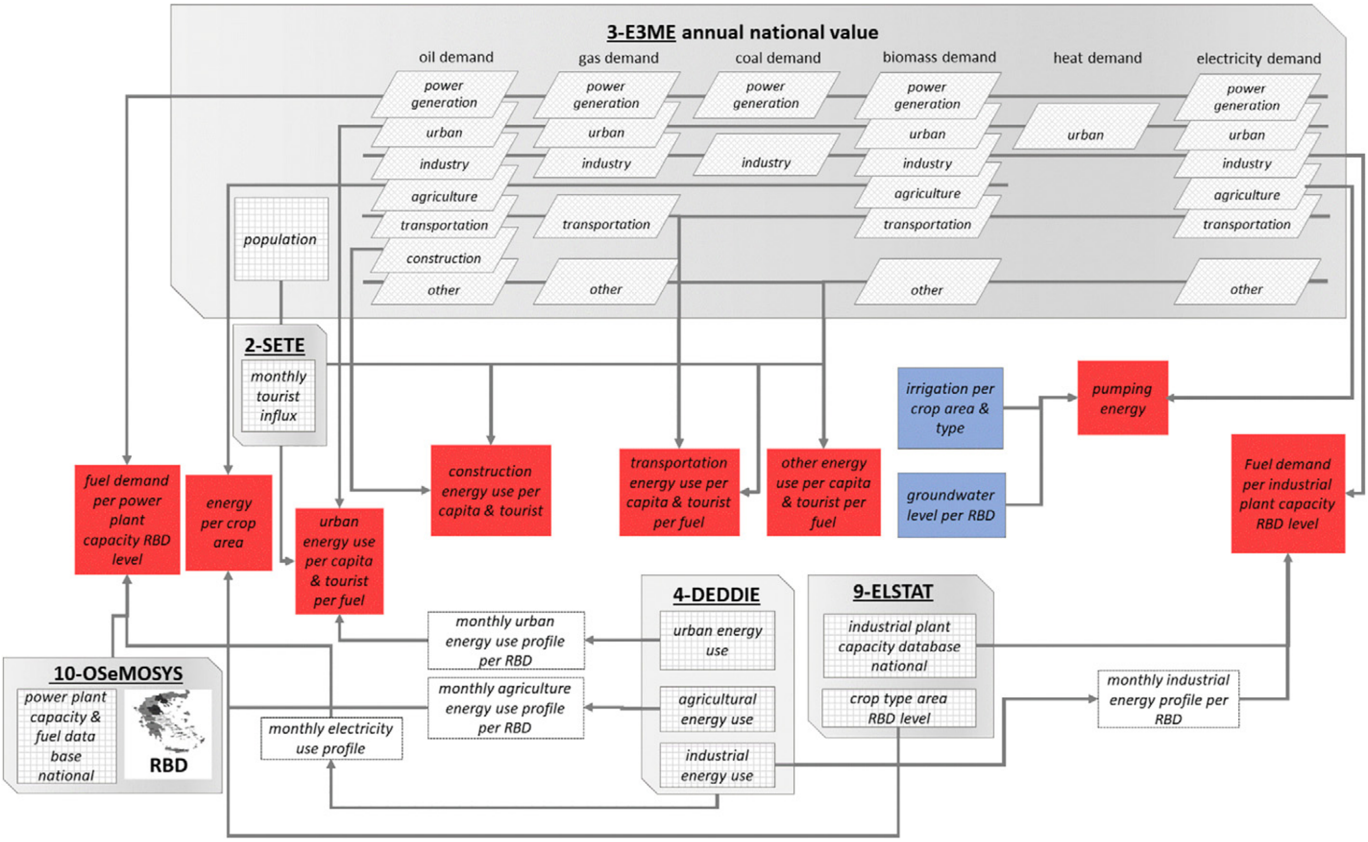


Fig. 5. Data sources and data processing in the Nexus_SDM for the Energy Module: Computational steps are shown in white boxes; Input data from published databases, model outputs, or the literature are shown in hatched boxes; Nexus Interlinkage factors for the Energy sector are shown in red boxes, while blue boxes are factors coming from the Water module.

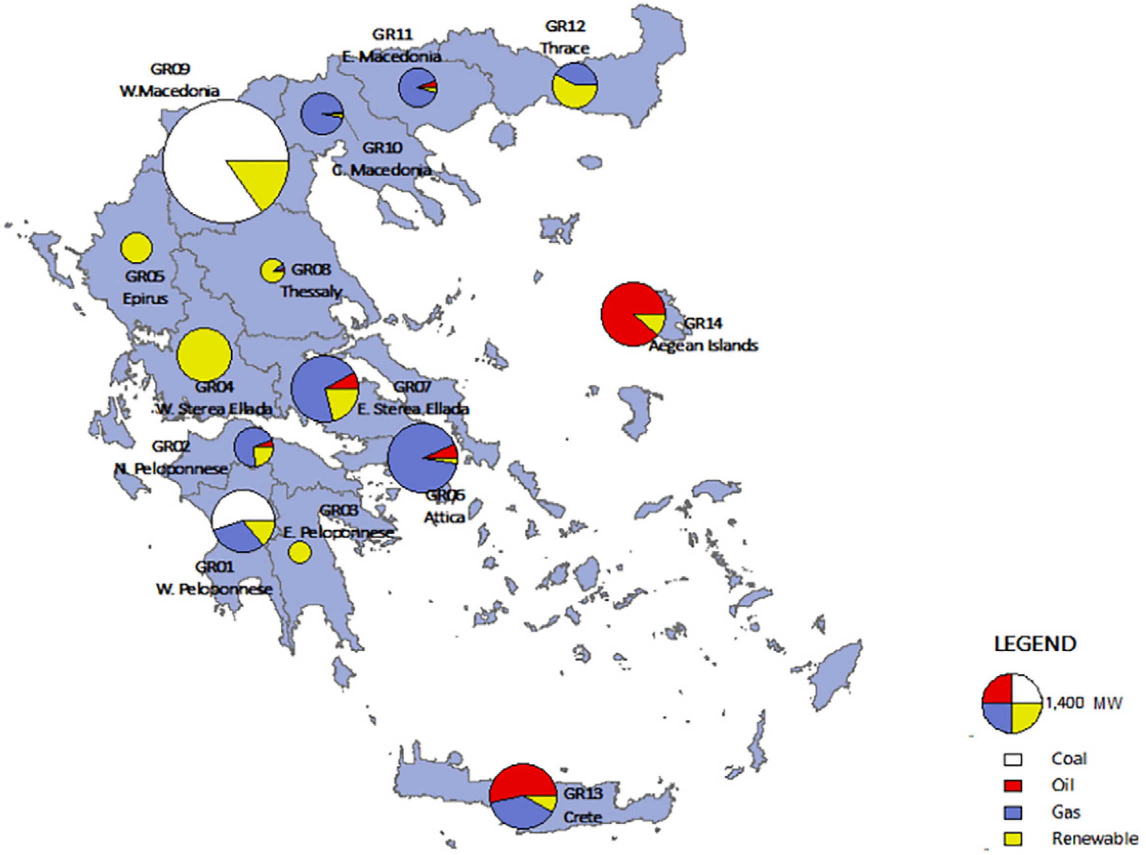


Fig. 6. Map of power plants per RBD in Greece. The size of the circle corresponds to the total capacity of power generated, while pie charts show distribution of fuel types used.

emissions, in CO_2 equivalents. Fig. 4 presents a schematic diagram of the energy module in the Nexus_SDM, where all energy uses, fuels and cross-sectoral interlinkages with Water and Climate (GHG emissions) are shown.

Nexus Interlinkage factors for energy are computed for all energy uses in the Energy Module of the Nexus_SDM. Different energy demands along with population (E3ME) and tourist influx (SETE) are used to reduce urban, construction, transportation and other energy

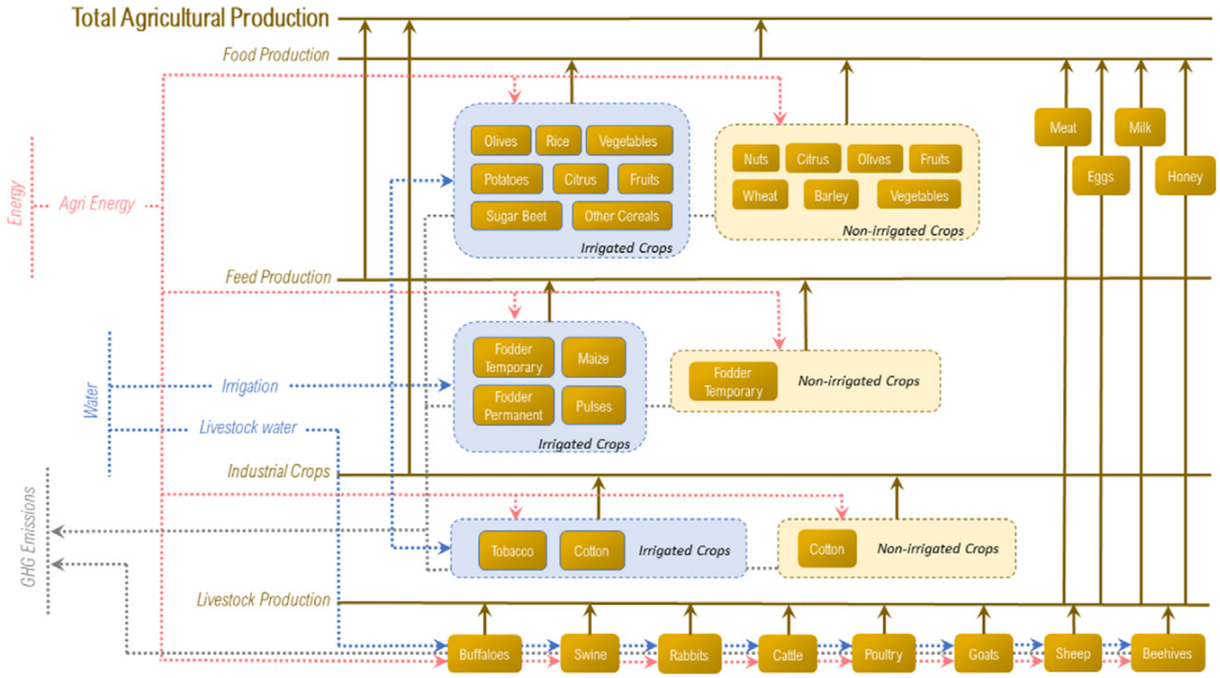


Fig. 7. The "Food" module in the Nexus_SDM, where all modeled agricultural products are shown, as well as all associated Nexus components that interlink with Energy, Water and Climate. Dashed lines show interlinkages of Agricultural Production with the other Nexus components.

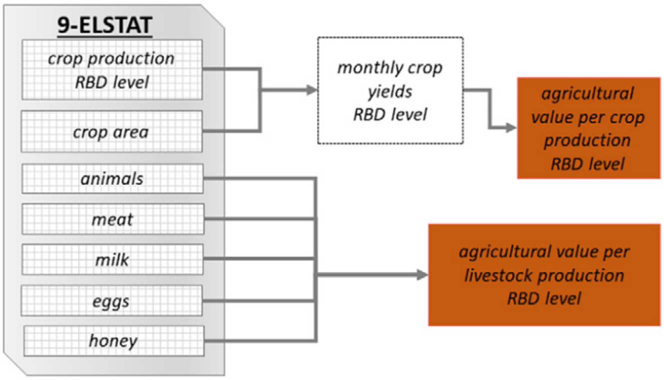


Fig. 8. Data sources and data processing in the Nexus_SDM for the Food Module: Computational steps are shown in white boxes; Input data from published databases are shown in hatched boxes; Nexus Interlinkage factors for the Energy sector are shown in brown boxes.

use on a per capita & tourist basis (shown in Fig. 5). Power generation is modeled using the dataset by E3ME and is disaggregated per RBD using the national power plant capacity database provided by OseMOSYS that maps all power plants for all fuels in Greece. A map of all power plants and corresponding fuel used distributed per RBD in Greece is provided in Fig. 6. Monthly time step for power generation is produced by using the total DEDDIE electricity use profile that includes all electricity uses. Industrial energy is modeled using demand by E3ME that is spatio-temporally disaggregated using the industrial activity profile by the DEDDIE dataset. Agricultural energy is modelled on a "per crop area" basis, using the E3ME agricultural energy dataset, the ELSTAT crop area dataset and the DEDDIE agricultural energy use for the spatio-temporal disaggregation. Pumping energy is calculated using groundwater level and irrigation water demand via standard water pumping calculations, quantifying a Water-Energy interlinkage.

2.3. Food/agricultural production

Agricultural production in the Nexus_SDM includes the production of crops and livestock, with the latter comprising a series of irrigated and non-irrigated crops (14 in total) and the latter eight animal types and their products, as shown in Fig. 7. Crops are classified as Food, Feed and Industrial Crops. In terms of interlinkages with other Nexus components, Water is required for irrigation of irrigated crops and livestock breeding, while energy is required for both crops and livestock. Agricultural production also results in GHG emissions from both crops and livestock, which are shown in Fig. 7.

All input data in this module (Fig. 8) come from ELSTAT and include all crop areas and crop types and all animal types at RBD level. In combination with the total crop production data, this module produces crop yields at RBD level and then translates this livestock and crop production in total Agricultural Values for each RBD.

2.4. Land

Land use is divided in Agricultural (includes Cropland and Livestock Area), Forest, Wetland, Grassland and Artificial Area (Built Environment), as shown in Fig. 9. Interlinkages with the Climate Sector are also shown in the Figure—specifically emissions related to Land Use, Land Use Change and Forestry (LULUCF). Data on land uses for the national case were obtained from the CORINE database (https://land.copernicus.eu/). To spatially disaggregate this information, national land uses are uniformly distributed throughout the RBDs, taking into account the RBD surface areas (Fig. 10). Crop areas are obtained directly from ELSTAT at RBD level.

2.5. Climate

The climate module sums up all GHG emissions coming from all other modules. This information is summarised in Fig. 11:

- Water: through wastewater treatment emissions—domestic and industrial
- Energy: through fuel emissions. A distinction between emissions covered by the European Union Emissions Trading Scheme (ETS) and those not covered (non-ETS) is made.
- Food: through agricultural activities, such as rice crops, field burning, urea application and emissions associated with managed agricultural soils and livestock emissions, i.e., enteric fermentation and manure management
- Land: with mostly negative emissions from forest, cropland, grassland, and wetlands.

Fig. 12 shows the databases used to calculate all emissions in this module. E3ME provided a detailed (by fuel and by sector) annual national emissions dataset that was used together with the energy use data for all fuels (presented in the Energy module). The spatio-temporal discretisation that was done in the Energy module is used here to discretise the same way the fuel emissions, producing a comprehensive list of GHG emission factors for all sectors and all fuels. Eurostat provided all other emission data that correspond to the Water, Energy, Food and Land modules and they were reduced on a "per unit" basis through Nexus Interlinkage Factors.

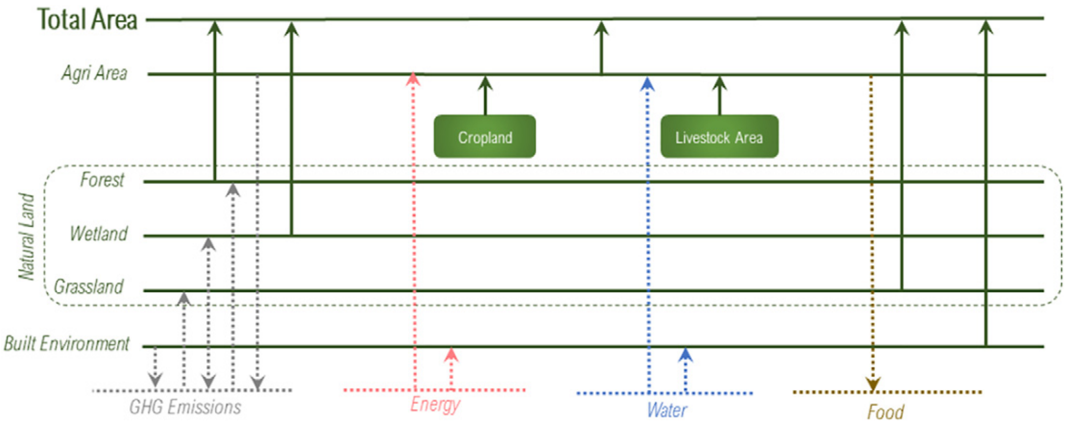


Fig. 9. The "Land" module in the Nexus_SDM, where all modeled land uses are shown, as well as all associated Nexus components that interlink with Climate. Dashed lines show interlinkages with Climate through LULUCF emissions.

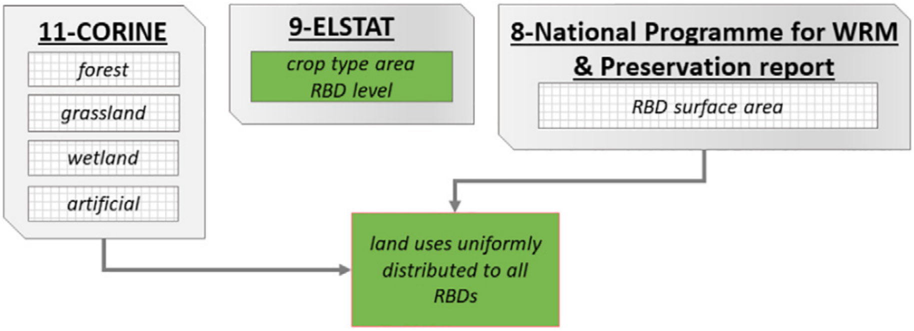


Fig. 10. Data sources and data processing in the Nexus_SDM for the Land Module: Input data from published databases are shown in hatched boxes; Resulting datasets for the Land module are shown in green boxes.

2.6. Quantifying the Nexus: interlinkage factors

Nexus interlinkages are modelled in the Nexus_SDM by reducing all major variables to a “per unit” basis, producing relevant factors that could be used for different scenarios, when the “unit” changes. On the Energy module, for example, an aggregate national yearly oil demand figure for agriculture was provided by E3ME-FTT. This value was disaggregated in 14 RBD values and each one of the RBD values was further disaggregated in a time series of 12 monthly values per year, using the DEDDIE dataset. For each RBD, the Land Use module includes the cropland area in m^2, so dividing the disaggregated oil demand time series by the agricultural area produces a time series of factors that express agricultural oil demand units per m^2 of cropland, used mainly for tractors and other oil-burning agricultural machines. This factor establishes the interlinkage between cropland area and agricultural oil demand and enables the user to quantify this interlinkage and try out scenarios either extending or limiting cropland and seeing the effect on oil demand. A comprehensive list of such factors that establish interlinkages throughout the Nexus is presented in Table 1. Interlinkage factors may be used either within each module or linking two different modules. Changes in quantities listed in the first column of Table 1 triggers, in a domino-like fashion, changes in all variables listed in the second column, which in turn may bring about changes to other variables, thus quantifying the interlinkages among Nexus components. As a result, we can see for example that a change in population or tourism will trigger a series of changes in various different variables and different Nexus sectors. This way, cross-sectoral implications are identified and quantified and critical interlinkages and hotspots can be singled out.

3. Results and discussion

3.1. Sector data mapping

Fig. 13 shows the distribution of both surface- and groundwater among the 14 Greek RBDs; it also shows how this fresh water is used in the RBDs. At a national level, we see that about half of the water used comes from surface water, while the rest comes from groundwater; at the same time, we see that a large percentage (about 82%) of water in the country is used for irrigation and/or livestock use, so it is associated with Food production, thus establishing a strong interlinkage between Water and Food. Urban water supply comes second, while industrial water use and cooling water follow. Urban and industrial water use are grouped under demands associated with the “Built Environment (BE)”, so the interlinkage established between Water and BE is considerably weaker than the one with Food. The same is true for “Cooling Water”, which expresses the interlinkage from Water to Energy (it is

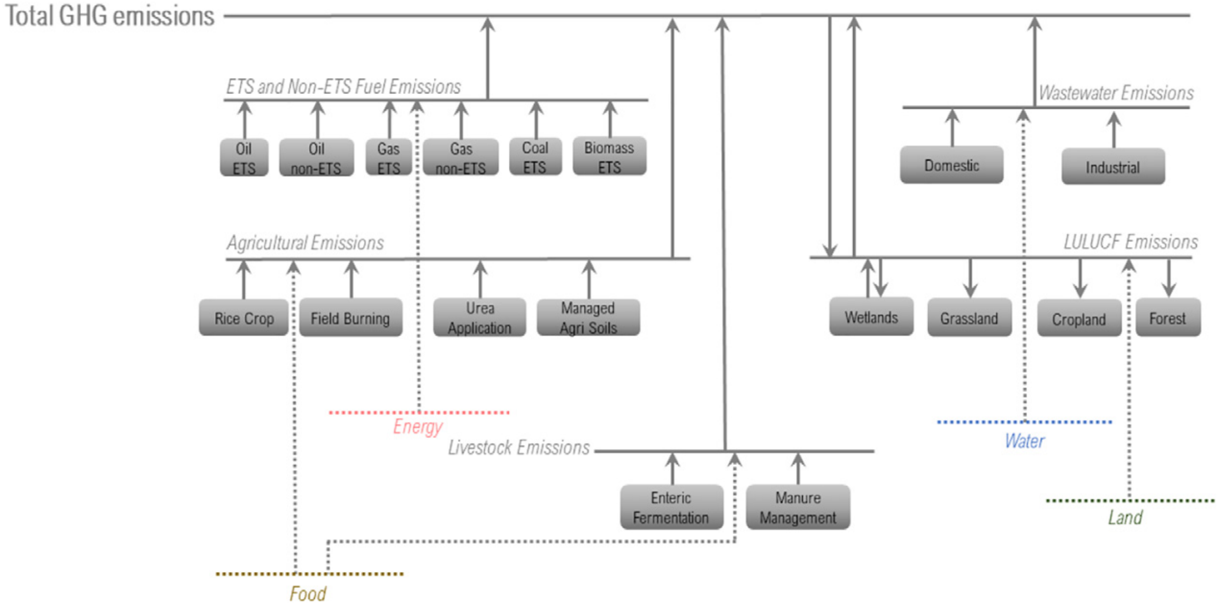


Fig. 11. The “Climate” module in the Nexus_SDM, where all modeled GHG emissions are shown, as well as all associated Nexus components that interlink with Climate. Dashed lines show interlinkages with Water, Energy, Food and Land. Negative emissions are shown with opposite arrows.

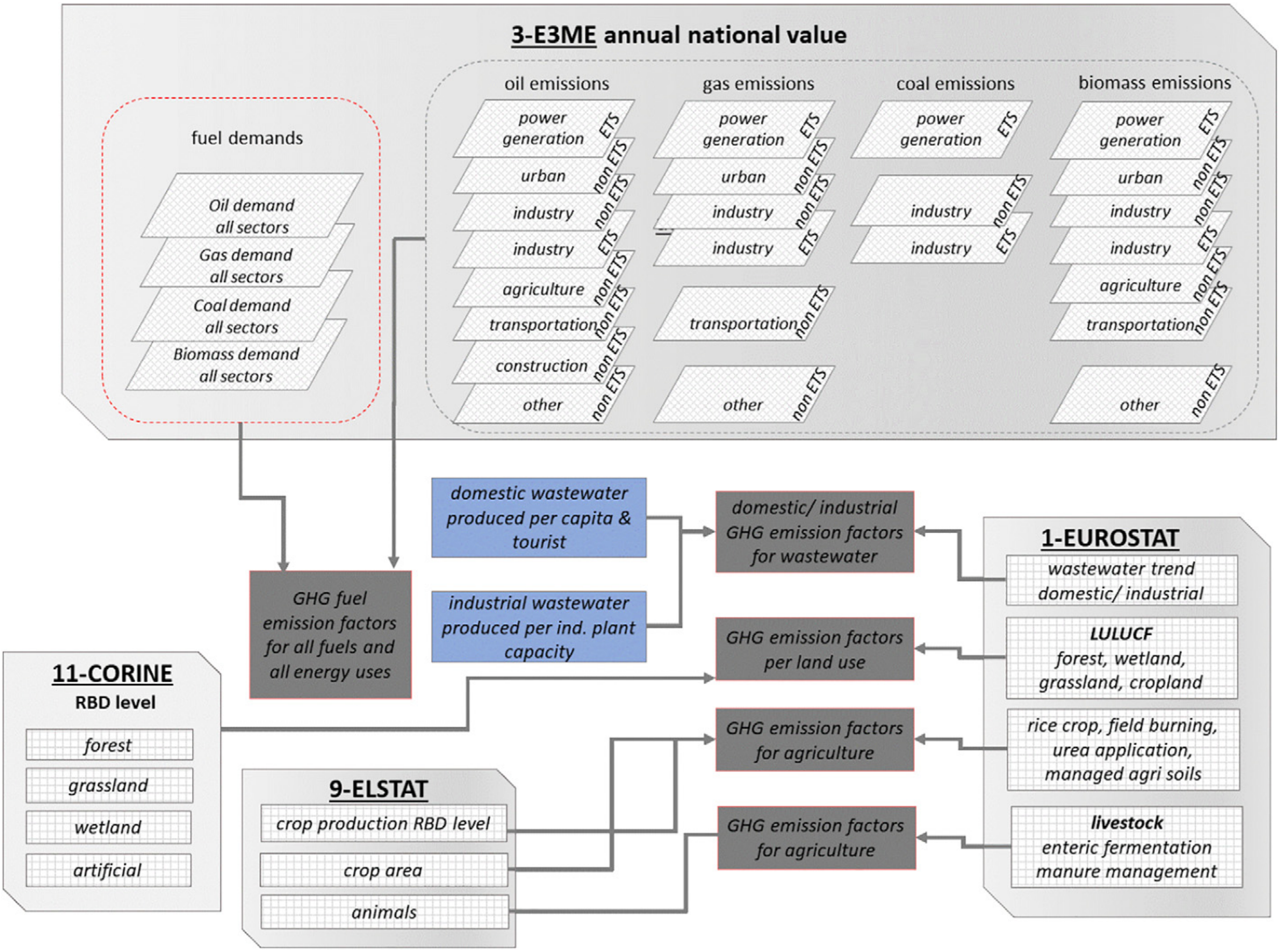


Fig. 12. Data sources and data processing in the Nexus_SDM for the Climate Module: Input data from published databases and model outputs are shown in hatched boxes; Nexus Interlinkage factors for the Climate sector are shown in grey boxes, while blue boxes are factors coming from the Water module.

the amount of water required for power generation). From Fig. 13, one can see which RBDs are the ones exerting the biggest pressures on the country's water resources, namely GR08 (Thessaly), GR09 (W. Macedonia), GR10 (C. Macedonia) and GR04 (W. Central Greece). The former three are predominantly agricultural regions producing a large percentage of the country's agricultural products, thus they spend most of the water for Irrigation, while the latter has the largest contribution in the country in the urban water supply category. This is true because the country's capital, Athens, located in GR06 (Attica) has insufficient water resources to meet demand and has water transferred from GR04 and GR07. This is why the Attica RBD (GR06) shows a small urban water supply consumption overall.

Fig. 14 shows an analysis of agricultural production in relation to three factors: surface area of cultivated land with a specific crop, the corresponding agricultural monetary value of the crop and the irrigation water needed. It is interesting to observe how these three quantities relate to each other for the national case, as well as for the 14 RBDs. The bars for water-intensive crops are longer under the "water" category, when compared to other crops. For the same crop, the latter reflects *blue water* used according to Water Footprint Terminology (https:/waterfootprint.org/), so when *green water* meets crop demand, or when part of the crop area is non-irrigated, then the bar will appear smaller, compared to the length of the "area" bar. On the other hand, "value" is related to the market value of the crop and is important to relate to "water" and "area", making the crops with high "value" and low "water" or "area" really desirable for sustainability, since they

enhance the economic benefits and do so with relatively little water and occupying relatively little land. Olives, fruits and vegetables exhibit high "value" and low "water" and "area" for the national case, while cotton appears very water-intensive offering relatively relatively little "value" overall. Examining the data for all RBDs, along with the national case, shows the importance of scale: when "zooming in", crop data can be very different, since precipitation quantities and patterns differ throughout the country, as well as crop yields and extent of food production from non-irrigated crops. Nevertheless, vegetables consistently score higher in "value" when compared to "water" and "area" and cotton is a very water-intensive crop; olives and fruits show a high "value" while cereal/pulses a relatively low value.

Fig. 15 shows results in a chord diagram, where an analysis of the energy sector at national scale is presented. In this chord diagram, half of the circle is fragmented in energy-consuming entities/sectors (Power Generation, Construction, Transport, etc.), while the other half is fragmented in fuel type/technology (Coal, Oil, Gas, Electricity, etc.). The arcs drawn between the entities show the interconnection between the two categories. The arcs have the same colour with the originating entity and they end up in another entity from the other category, linking the two categories of the circle; the size of the arc is proportional to the size of the flow. Thus, a thick teal arc (Oil) leaves the "Oil" entity and ends up in "Transport" signifying that a large part of oil is used by the

Table 1
List and description of Nexus interlinkage factors.

Unit	Nexus interlinkage factors: Ratios of quantities in this column per *Unit* listed in column to the left
Per capita (including population and tourists)	• Public water supply (distinguishing origin of water—surface or groundwater, according to current practice) • Household/commercial electricity demand • Urban wastewater produced • Industrial wastewater produced • GHG emissions from urban wastewater treatment plant • Fuel demand for transportation • GHG emissions from transportation • Fuel demand for construction • GHG emissions from construction • Fuel demand for other final uses • GHG emissions from other final uses
Per power plant capacity (either new installations, or retirements, or increase/decrease of power in plants)	• Fuel demand for power generation per MW of power plant (different factor for each fuel type: coal, oil, gas, biomass) • Cooling water for power plants (different factor for each fuel type; numbers based on Macknick et al., 2012 and Spang et al., 2014) • Electricity generated (different per power plant, depending on fuel type used) • GHG emissions (different factor for each fuel type)
Per agricultural land area	• Fuel demand for agricultural land use • GHG emissions from agriculture energy use
Per specific crop type area	• Agricultural water demand for different crop types (irrigated only) • Yield for each crop type (Food/Feed/-Industrial crop produced); different yields for irrigated and non-irrigated crops.
Per irrigation technology (sprinkler, drip, or furrow)	• Losses in irrigation network • Agricultural water demand • Fuel demand for agricultural land use • GHG emissions from agriculture energy use
Per livestock land use	GHG emissions associated with manure management
Per animal head and/or beehive	• Livestock water demand • Yield for animal products (Food produced)
Per m^3 groundwater pumped	Electricity demand for every meter of pumping head
Per m^3 surface water pumped	Electricity demand
Per industrial production capacity (either new installations or retirements of industrial plants, or increase/decrease of production capacity in plants)	• Industrial water demand • Industrial demand for fuel • GHG emissions from industrial fuel use (different for ETS and non-ETS industries) • Industrial wastewater produced • GHG emissions from industrial wastewater treatment.
Per managed agricultural soil area	Agricultural GHG emissions
Per irrigated rice area	Agricultural GHG emissions (Rice emissions)
Per agricultural field burning area	Agricultural GHG emissions (Field Burning emissions)
Per forest area	LULUCF GHG emissions
Per wetland area	LULUCF GHG emissions
Per grassland area	LULUCF GHG emissions

transportation sector. A very fine yellow arc (electricity) ends up in "Transport" as well, indicating that only a tiny part of energy demand by this sector is met by electricity. This diagram identifies which sectors consume Oil in Greece, which consume Coal, etc. It also shows for each sector which fuel/technology is used to meet its demand. The units are the same throughout the chord diagram for both entity categories.

Having mapped the energy data this way, one can see which fuel types dominate energy consumption and which sectors are the major consumers of these fuel types: The biggest part of the national energy needs are met by Oil and the largest part of that is consumed by the transportation sector. Coal is used mostly for power generation, while Gas use by households is quite small. Other than transportation, large Oil consumers are Power Generation, while household heating and industrial use are quite significant as well. Power generation also uses up large parts of Gas in Greece, while Electricity is split among households, industry and other uses. The largest part of Biomass is used by households for heating, while Heat is only a very small part of all energy sources and is used exclusively by households.

Directly related to the energy sector is the analysis of climate impact, which is conducted by quantifying GHG emissions. Fig. 16 uses a Sankey diagram to show how total GHG emissions on a national scale are distributed among the 14 RBDs in Greece and which sectors are responsible for these emissions. The biggest GHG emission generation by far is associated with fuel (Oil, Coal and Gas) consumption, with oil maintaining its first place. This is expected, also according to the data presented in Fig. 15. The RBD with the largest GHG emissions is Western Macedonia (GR09); this is the region where the largest power plants in Greece are located serving the needs of the whole country. The communities in W. Macedonia are the ones that endure the effects of large GHG emissions, showcasing that emissions associated with fossil fuel power plants have an intense "localised character", even though the power generated is fed through the grid to serve the needs of the rest of the country. Livestock and agricultural emissions are the categories that follow in size and appear to be relatively significant. There is a lot of potential for improvement in the national GHG emissions that could be realised by switching to renewable energy sources both in power generation, but also in the transportation sector, with the replacement of conventional vehicles by electric ones. Negative emissions by LULUCF could be enhanced by actions like reforestation in order to alleviate massive emissions associated with fuel consumption.

3.2. Directional Nexus chord plots

Understanding and assessing the significance of interlinkages can become quite complex, especially when all sectors are quantified, since there is a lot of information that needs to be processed. This is especially true when this information needs to be communicated to policy- and decision-makers and not to scientists who are accustomed to dealing with complex graphs and charts. In this article, we introduce an innovative way to visualise the complex resource nexus data; such visualisation can be useful to engage stakeholders and help authorities to prioritize investment and develop strategies to accomplish their goals. Fig. 17 introduces an innovative resource nexus visualisation tool (the *Nexus Directional Chord plot*) for the national case study of Greece. In this case, the circle is fragmented in six parts, one for each Nexus element: Water, Energy, Food, BE, Natural Land and Climate (GHG emissions); the length of each part varies according to the quantities depicted, while the flows/arcs that link two parts in the chord diagram quantify the interlinkages within the Nexus, with their thickness being proportional to the quantities. Arcs originate at one entity and form an arrow at the end, showing the direction of flow, while their total thickness corresponds to the total national quantity for Greece. Each variable has different units as shown on the plot; units should be read at the point where the arc originates, not at the point where it ends up. So, for example, a large part of national Water goes towards Food; the thickness of the purple arrow is read with Water units (in million cubic meters), while regarding Food, the quantity of Food produced using this Water is read on the teal arrow units (million tons) leaving the Food sector. The thickness of the purple arrow ending up in Food does not correspond to any Food units, but only to Water units. Food

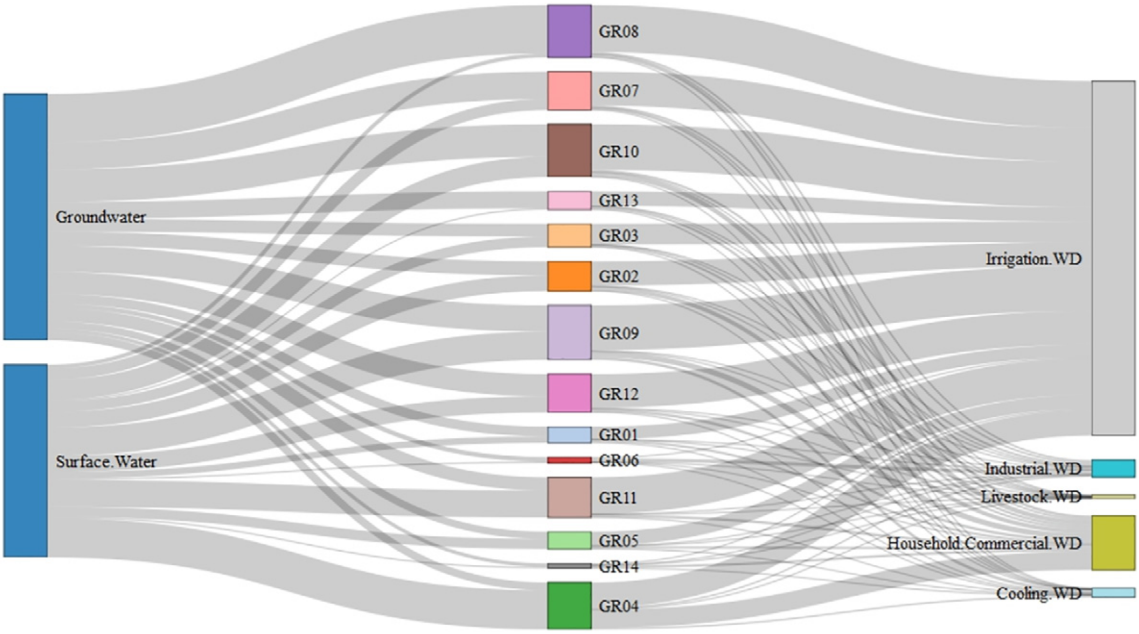


Fig. 13. Allocation of national surface and ground water consumption in Greece per RBD and per water use type for year 2010.

units are only interpreted with the thickness of the teal arrow. The same is true for Energy, Natural Land, Climate (GHG Emissions), etc. We mention indicatively that the purple Water arc that originates in Water and ends up in Food should be read as "the quantity of Water that is consumed for Food production" in Greece; the yellow arrow that originates in Energy and ends up in the BE is "the Energy consumed by the BE", etc. Since BE only consumes resources, it has no outgoing arrow, but only incoming ones. On the other hand, climate arrows that end up in different sectors of the Nexus quantify the GHG emissions that are associated with that sector. So the Climate arrow that ends up in Energy should be read in Climate units to indicate "amount of GHG emissions that are associated with energy production." Climate only has outgoing arcs/arrows, except for an arrow from Natural Land which is incoming; the latter has the opposite direction only because it is negative.

An analysis of the directional Nexus chord plot for the national case of Greece shows that a large part of Water goes towards Food Production, which includes irrigation and livestock water, while a small part goes towards (or is consumed by) the BE (household, commercial use, tourism, industry, etc.). An even smaller part goes towards the Energy sector—this is the cooling water used to operate thermal power plants. A more detailed view of the water sector information is shown in Fig. 13; in fact, the Sankey and chord diagrams (Fig. 13, Fig. 15 and Fig. 16) should be used in conjunction with the Nexus Chord plot to provide further detail (or zooming-in) when needed. Incoming arrows in the Water sector are small: Energy (this is pumping and desalination energy) and Climate (GHG emissions associated with wastewater treatment). Almost all Energy is consumed by the BE, while agriculture (Food) consumes only a small part of the overall national energy; again, if one wants to zoom in to see which sectors consume which fuel within the BE and agriculture, then the diagram of Fig. 15 contains all the relevant detail. A thick arrow from Climate to Energy signifies the massive GHG emissions associated with energy production (power generation); this is expected for Greece that relies heavily on coal and other fossil fuels for power generation (as shown in Fig. 6). A part of Natural Land (forest and biomass) is used for energy production and a small part of Food (waste) is used as well, shown by the green arrow from Food to Energy. The arrow leaving the Food sector goes almost exclusively to BE, since it is assumed to be consumed or exported and has a few incoming arrows signifying the fact that food production requires Water, Energy, Natural Land and has relatively significant GHG emissions associated with livestock and managed agricultural soils. A tiny arrow from Food goes back to Food—this is reuse by the Food industry.

The Nexus Directional Chord plots are used to show what the national case will look like in years 2030 and 2050. Results are shown in Fig. 18. These results show the baseline scenario for the EU, which is calibrated to the PRIMES Reference Scenario 2016 (European Commission, 2016) and is based mainly on the E3ME-FTT run provided in the framework of the SIM4NEXUS project. This scenario focuses on the EU energy system, transport and GHG emission developments, including specific sections on emission trends not related to energy, and on the various interactions among policies in these sectors. In the construction of the baseline, E3ME-FTT model is matching energy balances and emission values from the Reference scenario; thus, while some policies may not be explicitly presented in the model, they are implicit in the baseline numbers used.

According to Fig. 18, the baseline scenario forecast for 2030 and 2050 for Greece show an increasing reduction in GHG emissions associated to Built Environment, with the reduction being more dramatic from 2010 to 2030. This is for the most part due to the transport sector, where highly efficient hybrid and electric vehicles are expected to penetrate more the Greek market. Large decreases in GHG emissions are also observed in association with power generation (arrow going from Climate to Energy sectors). A decreasing trend in the Energy allocated to Built Environment is also observed, which is a result of deploying more energy-efficient technologies in many different sectors (transport, industry, households, etc.). Overall, the Nexus Directional Chord Plot for Greece shows a less GHG-emitting and a more energy-efficient economy, while no major water changes are observed in the agricultural sector, even though we see that Carbon emissions associated with Food production are expected to shrink slightly.

In order to showcase the utility of the Nexus Directional Chord plot tool, the Nexus is "visualised" for all RBDs in Greece. This is essentially the disaggregation of the National case (Fig. 17) in its 14 parts and it is shown in Fig. 19. Some interesting results can be observed in a glance, when seeing the RBD Nexus Chord plots. The W. Macedonia RBD (GR09) has really high amounts of GHG emissions, which are mostly associated with Energy production, since many of the nation's fossil fuel power plants are located there (see also Fig. 6). Attica (GR06), where Athens, the nation's capital, is located (population of 3,090,508

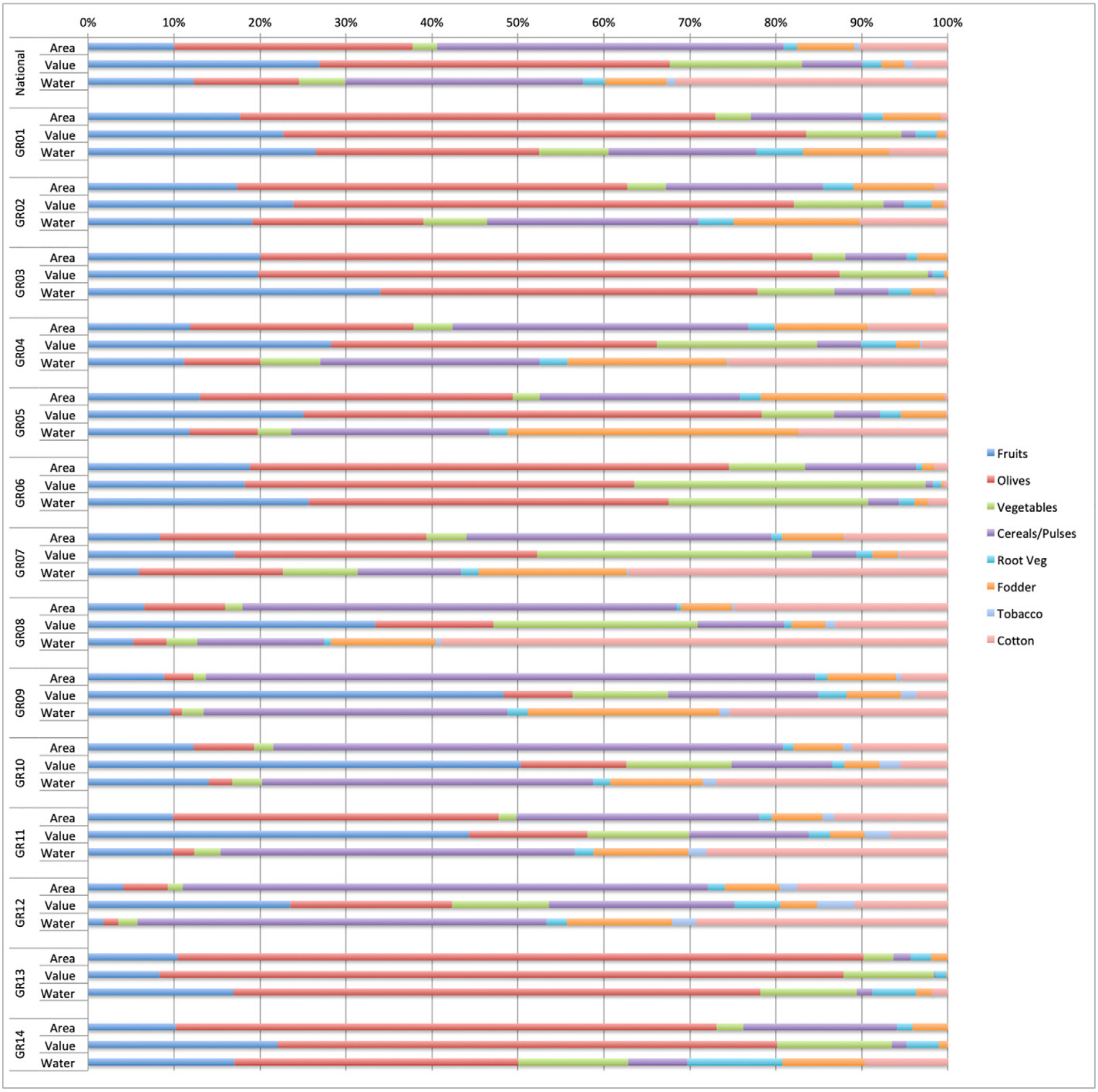


Fig. 14. Percent proportional split in cropping in terms of surface area, agricultural value and irrigation water in Greece (results shown per RBD and at a national level).

according to 2011 census) shows large GHG emissions, but this time associated with BE. This is mostly due to transportation and industrial emissions. The nation's second largest city, Thessaloniki, is located in C. Macedonia (GR10) and this is reflected in the large GHG emissions associated with the BE (transportation and industry). W. Peloponese (GR01) is also the RBD with many power plants, thus the energy-associated GHG emissions are found there (Fig. 6). Food production is significant in Thessaly (GR08), in W. and C. Macedonia (GR09 and GR10, respectively); these regions are the three major agricultural producers in Greece.

There is a lot of information that can be extracted from the Nexus Directional Chord plots and they are proposed as a tool to inform policy-makers of sector couplings, dependencies and interlinkages, thus promoting informed, sustainable and resilient institutions and ecosystems. An important question that comes up however is *what does a "sustainable" Nexus Chord plot look like*? This nexus analysis showcases the strength of interlinkages among different Nexus sectors, by quantifying them and showing the cross-sectoral implications of each sector. Further to that, a successful resource nexus analysis emphasises where strong couplings exist, thus identifying areas of vulnerability. If a strong Water-Energy interlinkage exists and energy production requires large amounts of water, then energy availability becomes vulnerable in case of water scarcity, thus making the energy sector less resilient overall and placing energy security at risk. The same is true for food security,

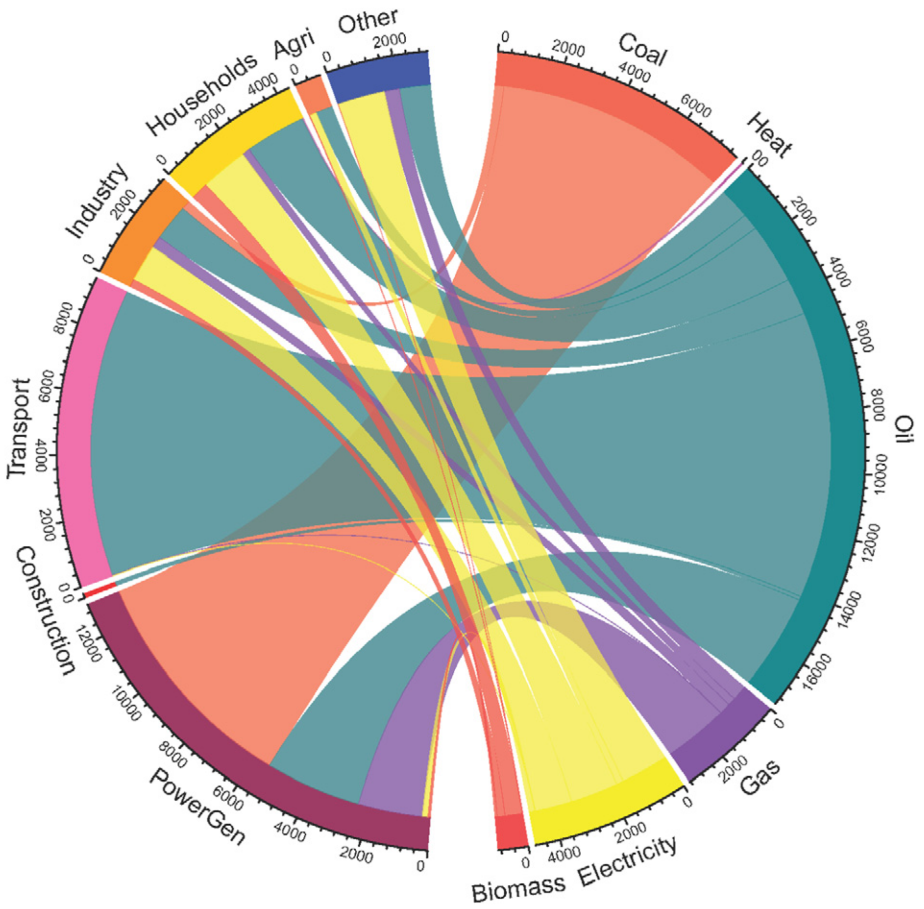


Fig. 15. Analysis of the energy sector at a national level, linking energy sources to energy uses. All units shown are in Mtoe.

which becomes highly dependent to water security, when intensely irrigated crops form the basis of food production in a nation. Strong interlinkages place resource securities at risk and are to be minimized by promoting the efficient use of resources in sustainable systems. Nexus Chord plots help stakeholders identify where the potential for improvement exists and how to prioritise spending and interventions. An investment in a sector that has synergistic effects with other sectors will have multiplicative effects on its impact. Recognising the areas that have the biggest impact across all sectors helps authorities rank their priorities in spending and in setting their agendas.

4. Conclusions

This paper describes a modeling platform that maps data from various sectors and quantifies the links between Water, Energy, Food, Land and Climate. As resource scarcity increases and societies and institutions are getting stressed, especially under the pressure of climate change, abandoning silo-thinking and institutional fragmentation becomes even more urgent. Nexus-coherent policies are at the core of achieving the SDGs and securing resources; even though this fact is widely recognised, governments still have a lot of progress to make in that

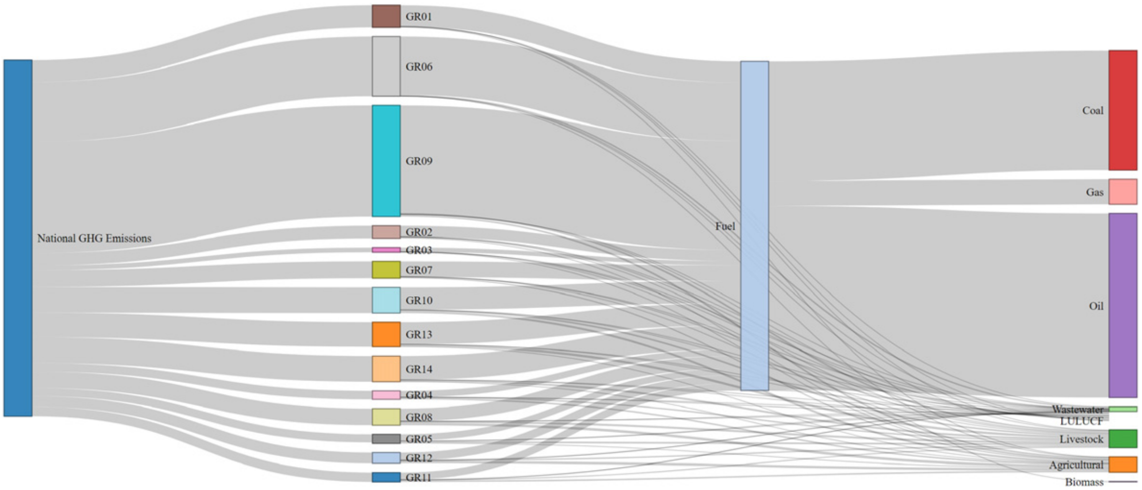


Fig. 16. Analysis of Climate Impact by quantifying GHG emissions at national and RBD scale. It should be noted that LULUCF emissions are negative.

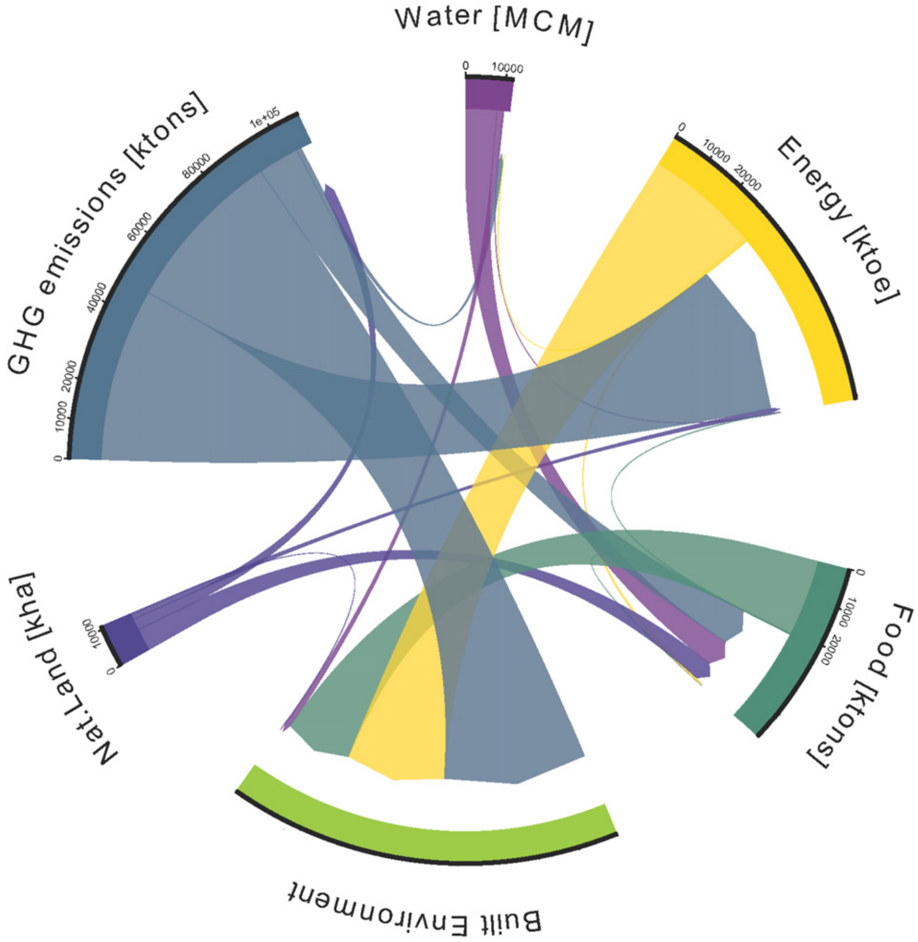


Fig. 17. Nexus Chord plot for the national case study of Greece. Note that units should be read at the point where the arc originates.

direction, with lack of suitable information, that is easy to comprehend and appreciate probably playing an important role. In this direction, a methodology for analysing and assessing the Nexus for a national case study is presented. The Nexus modeling platform, the Nexus_SDM, showcases how data-intensive the process of making the Nexus operational for policymakers and stakeholders is and how it can help identify Nexus hotspots, i.e. areas where the security of one sector (e.g. energy) relies on the availability of another (e.g. water). The complexity of a highly-interlinked Nexus system, the plethora of data to be considered and the importance of scale make it challenging to communicate modeling outcomes to stakeholders. To this end, the development of advanced visualisation diagrams, the Directional Nexus Chord plots that can

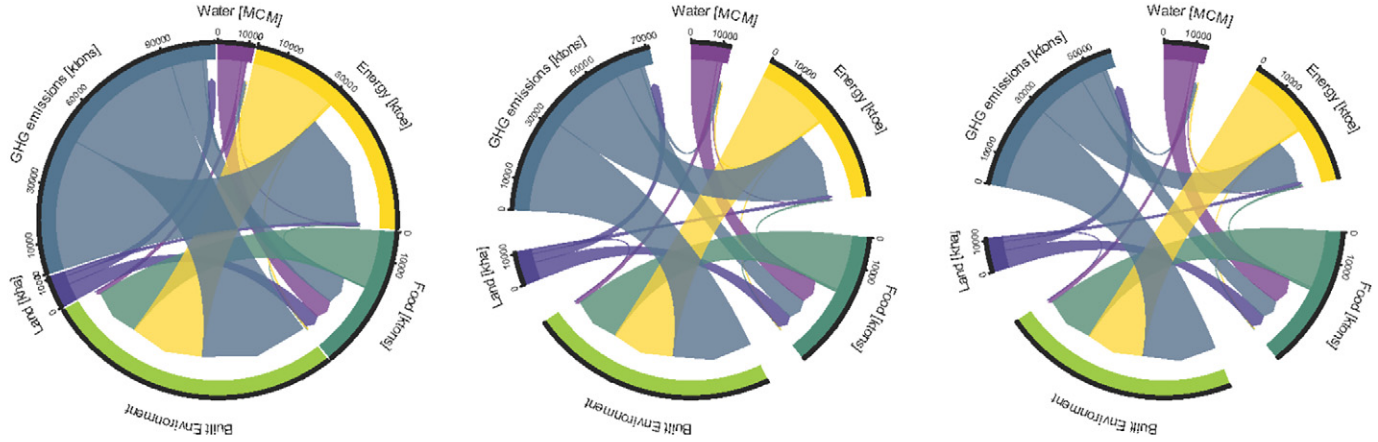
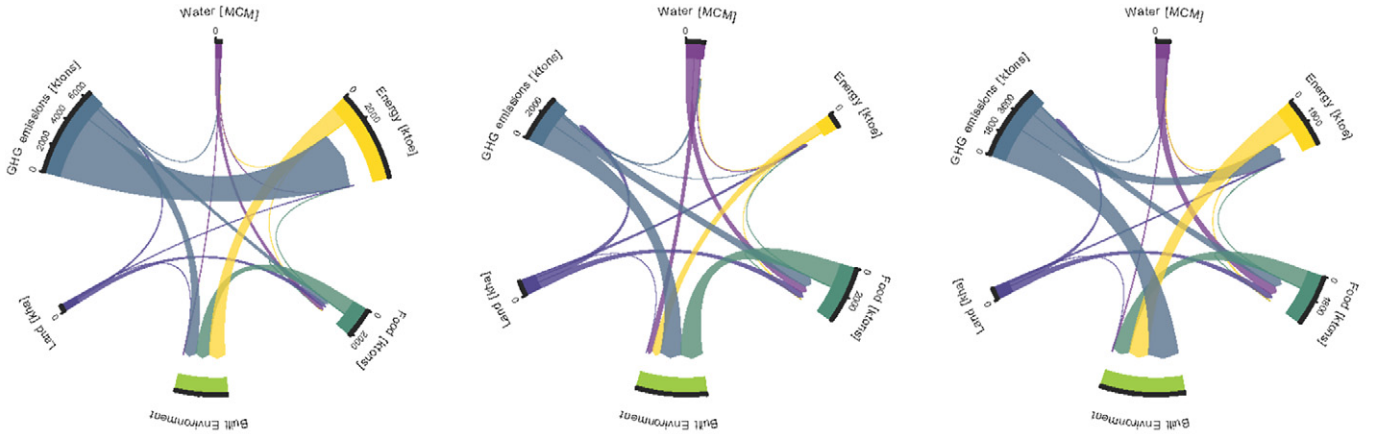
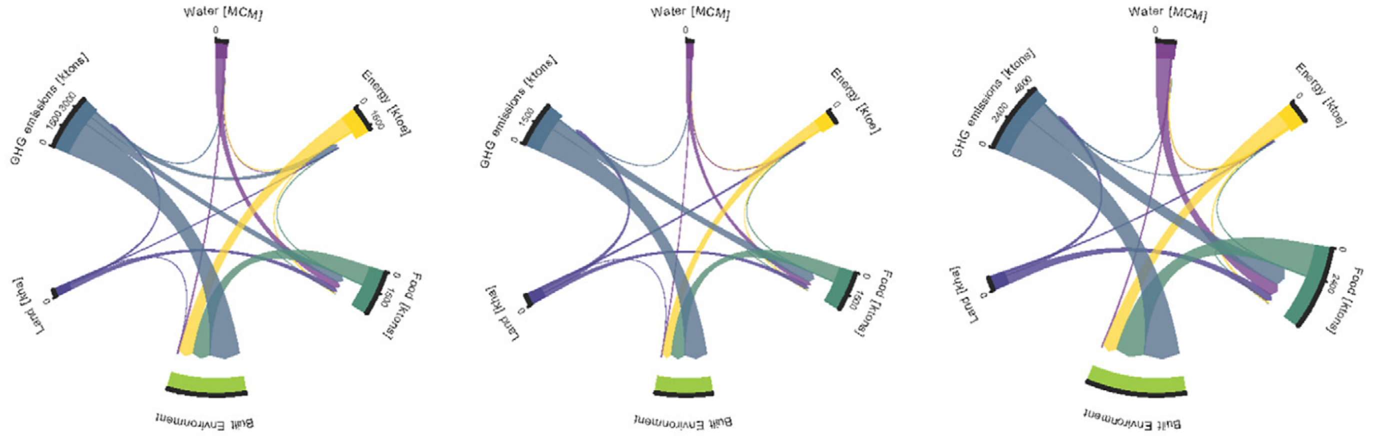


Fig. 18. Nexus Directional Chord Plot for the national case study of Greece with baseline forecasts for 2030 and 2050. Note that part (a) is identical with Fig. 7 and is repeated here for comparison purposes. Note that units should be read at the point where the arc originates.

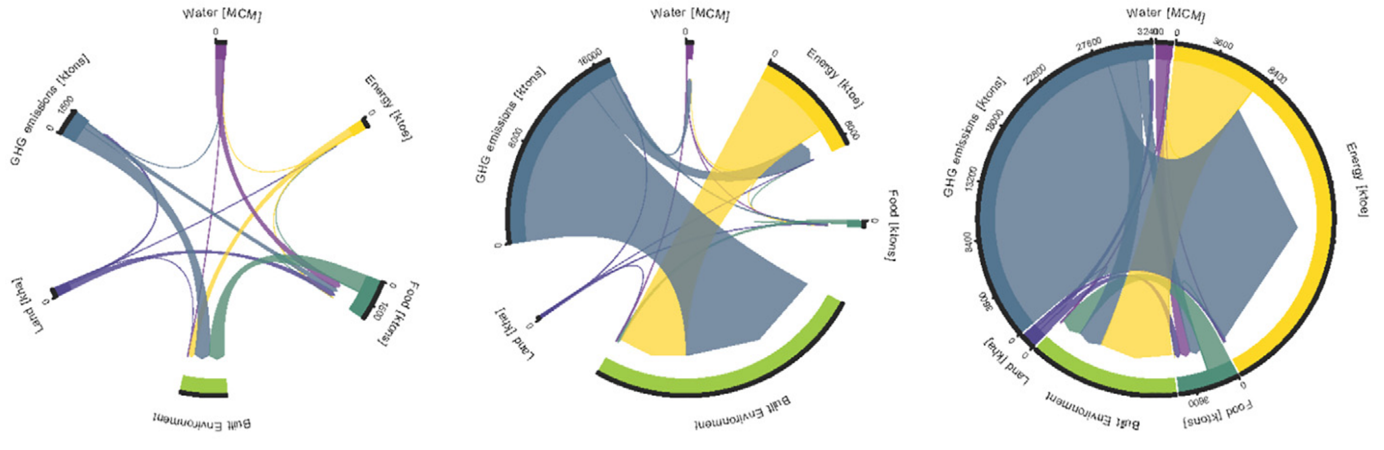
present the complex Nexus data coming from robust modeling analysis to stakeholders in a comprehendible way is an important innovation. The Nexus plots are presented for the national case of Greece for 2010 and forecasted plots for 2030 and 2050 are shown, implementing the baseline, European Commission Reference Scenario. In order to support sustainable development at a national level, it is imperative to recognise the need to implement greener solutions in power generation that include reduction of coal use and enhancement of renewables. At the same time, the BE can improve with more sustainable resource use, while the excessive amount of water required for food production results in a threatened food security under the pressure of climate change and water scarcity. Policies that recognize the trade-offs between saving energy and water, reducing GHG emissions and intensifying food production would be the ones with the most sustainable outcomes.



GR01-W. Peloponese GR04-W. Central Greece GR07-E. Central Greece

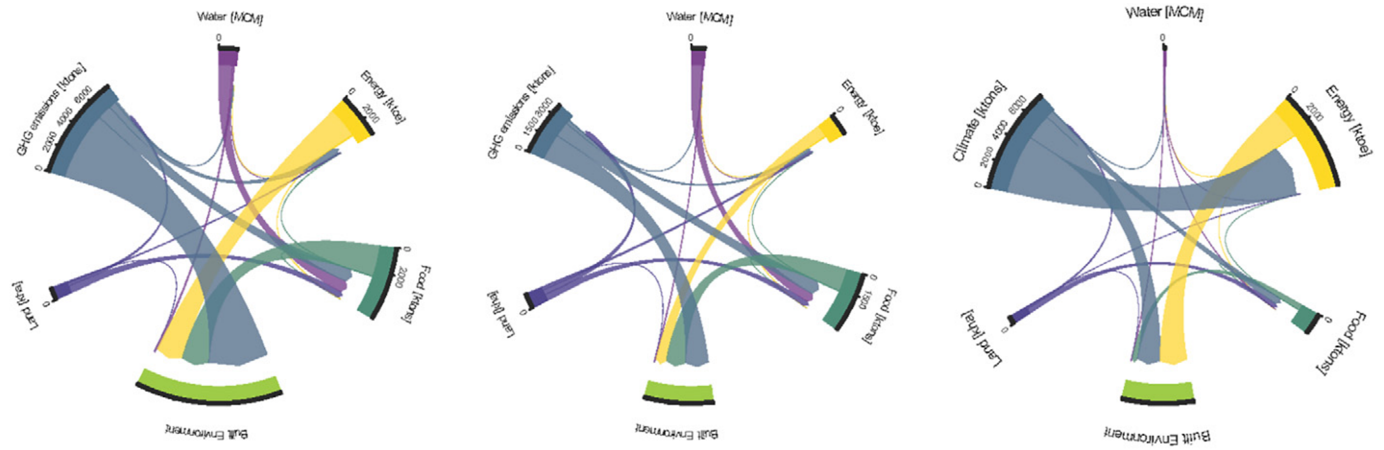


GR02-N. Peloponese GR05-Epirus GR08-Thessaly



GR03-E. Peloponese GR06-Attica GR09-W. Macedonia

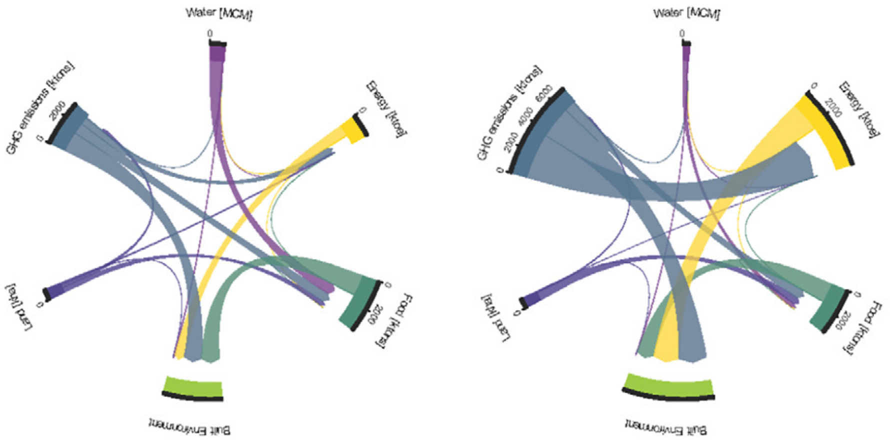
Fig. 19. Nexus Directional Chord plots for all RBDs in Greece. Note that units should be read at the point where the arc originates.



GR10-Central Macedonia

GR11-E. Macedonia

GR12-Thrace



GR13-Crete

GR14-Aegean Islands

Fig. 19 (*continued*).

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Declaration of competing interest

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