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Socioeconomic and spatially-explicit assessment of Nature-related risks

The case of South Africa

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Abstract
This study introduces new methods for evaluating nature-related socioeconomic risks in the South African context, anchored on two main contributions. Firstly, it embarks on a multidimensional analysis of the exposure of several macro-financial and social variables to nature-related risks. Based on Environmentally Extended Input-Output tables and socioeconomic satellite accounts, the analysis identifies how physical and transition risks could exert significant impacts on directly and indirectly sectors essential for domestic and international supply chains but also for employment and fiscal revenues. Secondly, the research extends to a more granular spatially-explicit assessment, at the municipality level, of socioeconomic vulnerabilities related to water scarcity and the protection of terrestrial ecosystems. Results localize socioeconomic exposures through key sectors, especially in Mpumalanga. These two intertwined facets underline the importance of a holistic approach to nature-related risks, combining economists and ecologists' knowledge, and able to emphasize the intertwined goals of economic prosperity, social stability, and environmental sustainability.

Keywords
Biodiversity scenarios, Biodiversity-related financial risks, Ecological transition modeling

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Résumé
Cette étude introduit de nouvelles méthodes pour évaluer les risques socioéconomiques liés à la nature dans le contexte sud-africain. Celles-ci sont ancrées sur deux contributions principales. Tout d'abord, nous proposons une analyse multidimensionnelle de l'exposition de plusieurs variables macro-financières et sociales aux risques liés à la nature. Sur la base des Tablex d'entrées-sorties élargis sur le plan environnemental et des comptes satellites socioéconomiques, l'analyse indique comment les risques physiques et de transition pourraient avoir des répercussions importantes sur les secteurs essentiels, directement et indirectement, pour les chaînes d'approvisionnement nationales et internationales, mais aussi pour l'emploi et les recettes fiscales. Deuxièmement, la recherche propose une évaluation plus granulaire, spatialement explicite, au niveau des municipalités, des vulnérabilités socioéconomiques liées à la rareté de l'eau et à la protection des écosystèmes terrestres. Les résultats localisent les expositions socioéconomiques à travers des secteurs clés, en particulier au Mpumalanga. Ces deux aspects étroitement liés soulignent l'importance d'une approche holistique des risques liés à la nature, combinant les connaissances des économistes et des écologistes, et capable de mettre l'accent sur les objectifs étroitement liés de la prospérité économique, de la stabilité sociale et de la durabilité environnementale.

Mots-clés
Scénarios de biodiversité, risques financiers liés à la biodiversité, Modélisation de la transition écologique

Introduction

Nature is vital for our well-being, a healthy planet, and economic prosperity. We rely on it for food, medicine, clean air and water, and protection from natural disasters, as well as for health, cultural and aesthetic values (De Groot, 2002; Diaz et al, 2018). In January 2020, the World Economic Forum estimated that half of the world's GDP (USD 44 trillion) depends directly on the state of ecosystems (WEF, 2020). At the same time, Nature contributes to key ecosystem services for economic activities (Johnson et al, 2021). The global value of ecosystem services in 2011 (USD 125–145 trillion) represents more than 150% of global gross domestic product (GDP) (Costanza et al., 2014). However, human demands are exceeding nature's ability to regenerate, leading to a loss of nature at alarming rates. The biodiversity loss is accelerating and threatens to cause ecosystems' abrupt threshold-dependent changes sooner than anticipated, which will have a cascading impact on the living conditions on Earth for a growing proportion of the population (Willcock et al, 2023; Reichtein et al 2021, Bradshaw et al 2021). This destabilization of the biosphere and the increasing likelihood of the worst-case climate scenarios materializing (Scheffer et al, 2012; Kemp et al 2022) pose greater risks to the stability of economic activity and financial systems (IPBES, 2019; WEF, 2021; Dasgupta, 2021; NGFS 2022; NGFS 2023).

Although the analytical and empirical handling of Nature Related Risks (NRRs)[1] is difficult, if not impossible, due to the non-linear interactions, irreversibility, and tipping-points within and across eco-systems and society (Chenet & al. 2021, NGFS-INSPIRE 2022), an emerging literature started to explore the quantification of NRRs. Several organizations started to assess countries' financial sector exposure to Nature related financial risks and all found substantives amount of assets potentially exposed to nature related physical and transition shocks (Van Toor et al 2020, Svartzman et al 2021, Calice et al 2021, World bank & Bank Negara Malaysia, 2022). Similar to climate risks, financial risks associated with NR shocks can be categorized into two types. Firstly, there are physical risks that arise when the loss of biodiversity negatively affects human capital and economic activities. For instance, a study by Svartzman et al. (2020) revealed that 42% of the value of securities held by French financial institutions is linked to issuers highly or extremely dependent on at least one ecosystem service. On the other hand, transition risks stem from changes in policies, consumer preferences or behaviors, and techno-

[1] The terms "nature" and "biodiversity" related risks will be used interchangeably.

logies aimed at mitigating the impact of human activity on biodiversity. As an example, the aggregated biodiversity footprint of Dutch financial institutions is equivalent to the loss of 58,000 km^2 of untouched nature, which is more than 1.7 times the land area of the Netherlands.

As a result, policymakers, politicians and private sector actors are increasingly aware of the potential risks associated with the loss of nature (WEF, 2020; Power et al, 2022). For example, the Taskforce for Nature-related Financial Disclosures (TNFD) just released a risk management and disclosure framework for public and private corporates and finance institutions to report and act on evolving nature-related risks (TNFD, 2023b). Policymakers of 188 governments have just approved a specific target (#15) in the new Kunming-Montreal Global Biodiversity Framework approved at Biodiversity COP 15, which calls on large corporations and transnational financial institutions to ensure that they monitor, transparently assess and disclose their risks, dependencies and impacts on biodiversity. This decision is supported by the work developed by the Network of central banks and supervisors for the Greening of the Financial System (NGFS) which explored how biodiversity loss poses a potentially significant threat to financial stability (NGFS, 2022a, 2022b). This group has launched a specific 'Biodiversity Loss and Nature Risk Working Group', which aims to develop nature risk scenarios that include links between nature loss and climate change. In addition, private initiatives such as the Finance for Biodiversity Pledge[2] and Nature Action 100[3] recognise the significant consequences of nature loss for the global economy and the systemic financial risk that could result. At the same time, the private sector is increasingly exploiting new business opportunities related to the conservation, restoration and sustainable use of nature. Managing nature-related risks and exploiting opportunities are growing priorities for investors and the financial sector.

Current methods evaluating NRRs are inadequate for a comprehensive strategic management of these risks (Van Toor et al 2020, Svartzman et al 2021, Calice et al 2021, World Bank & Bank Negara Malaysia, 2022). Primarily, they focus solely on the vulnerability of financial assets, overlooking the broader macro-financial and social consequences of biodiversity loss that extend beyond financial stakeholders. Socioeconomic variables such as employment, fiscal revenue, and trade balance are also susceptible to NRRs. Recognizing these extra-financial variables is vital for policymakers, particularly in developing nations. Another significant limitation of current NRR studies is their inability to locally pinpoint potential nature-related shocks and identify the

[2] https://www.financeforbiodiversity.org/

[3] https://www.natureaction100.org/

economic activities that are directly or indirectly at risk. Connecting these shocks to macro-financial and social outcomes is challenging due to constraints in data availability and compatibility issues between ecological and economic data. This makes it arduous to discern holistically the local economic impacts of NRRs.

In this article, we explore new methods for analyzing macroeconomic NRR in South Africa, one of the world's top three biodiverse countries, boasting exceptional biodiversity with diverse ecosystems and high species richness (SANBI, 2019). The National Biodiversity Strategy and Action Plan aims to utilize this natural capital for the well-being of South Africans, providing significant employment opportunities (Government of South Africa, 2015). However, South Africa's unique biodiversity faces numerous threats, with half of assessed ecosystems in 2018 considered threatened due to land use, pollution, and invasive species. Water stress exacerbates these challenges, driven by factors like the semi-arid climate, climate change, and growing water demand (SANBI, 2019).

In this context, the present study proposes a contribution to the literature in the following way. We endeavor to address prevailing limits in the estimation of the likelihood component by conducting spatially-explicit assessments. We engage with the multidimensional nature of biodiversity by independently evaluating several dependencies to ecosystem services and pressures pertinent to biodiversity. We confront the multi-dimensionality of socio-economic exposure by analyzing various forms of socio-economic vulnerabilities. We integrate disparate databases within a structured framework employing an Input-Output methodology to assess indirect impacts of NNRs through value-chain propagations.

The content of the paper is as follows. First, it presents a literature review of recent assessments of NNRs and identifies that they are essentially limited to idiosyncratic risk for financial assets and with limited exploration of likelihood of shocks. In order to overcome the identified limitations, we propose in the second chapter a method of macro-financial analysis combined with spatially explicit assessments that locate and estimate the likelihood of certain NR shocks. In the third chapter, we present examples of results that can be obtained by applying this method to the case of South Africa. In the fourth chapter, we discuss these contributions and explore avenues for further improvement of these methods in the future.

1. Literature review

Existing studies on vulnerability aim at decomposing the concept into distinct dimensions. Such a breakdown is useful to clarify the concept itself and the type of indicators that can be used to approach it empirically. In addition, such a decomposition helps to delimit the scope of NRR studies. Carley & al. (2018) categorize the vulnerability of an entity (or an agent), be it a firm, a sector, or a country, to NNRs into the three following aspects:

- Exposure to NR shocks is approached by the dependencies and impacts of activities on biodiversity. An agent is exposed to a particular physical shock if it depends on the ecosystem service that corresponds to that shock (e.g., an activity dependent on water provision to operate is exposed to water-shortage). An agent is exposed to a transition shock if it exerts one or more pressure(s) threatening the existence of ecosystems (e.g., a water-intensive activity is exposed to transition shocks intended to mitigate water withdrawal).

- Likelihood of NR shocks corresponds to the susceptibility of shocks to occur. It is approached through the state of the ecosystem corresponding to the service on which the agent relies in the case of physical risks (e.g., the surrounding water sources are scarce), and on the willingness of (/likelihood for) the society to protect the ecosystem it impacts (if any) in the case of transition risks (e.g., the pressures exerted by an activity locally affect an ecosystem whose legal protection is likely in the short to medium term).

- The adaptive capacity (or sensibility) is the capability of a given entity to cope with the shock or mitigate its negative effects.

The different aspects of vulnerability[4] have strong relationships with the LEAP (Locate, Evaluate, Assess, Prepare) approach developed by the TNFD framework[5]. The Evaluate phase of the LEAP approach corresponds to the impacts (pressures on ecosystems) and dependencies (on ecosystem services) of the entities considered. It relates precisely to what we call the "exposure" of a sector: a measure of its dependence and impact toward ecosystems. The Locate and Assess phases correspond respectively to the Shock Likelihood and the Adaptive Capacities aspects of vulnerability. The Locate phase focuses on the evaluation of the state of the environment/ecosystem on which a given entity depends or which is impacted by the entity. In a fairly symmetrical fashion, the notion of shock likelihood focuses on the environmental conditions with a view to inferring the susceptibility of a biophysical or socio-political shock. Finally, the Assess phase focuses on the adaptive capacities of the entities under consideration (resilience of a company, financial health, etc.). The main difference between the TNFD framework and the focus of this paper is the

[4] Note that other risk assessment frameworks present likelihood and exposure together under a combined 'susceptibility' of shocks impacting a specific agent and distinguish between coping capacity (i.e. immediate response to a shock) and adaptive capacity (i.e. long-term strategies for change).

[5] https://framework.tnfd.global/the-leap-nature-risk-assessment-process/

scale: while the task force is interested in company-level risks, we are interested in macroeconomic ones.

We will focus principally on the most recent case studies that explicitly intend to assess “Nature” or “Biodiversity”-related risks in Netherlands (Van Toor & al., 2020), France (Svartzman & al., 2021) , Brazil (Calice & al., 2021), Malaysia (World Bank and Bank Negara Malaysia, 2022) and Mexico[6] (see NGFS-INSPIRE Final report[7] and the recent contribution by the coalition of finance ministries for climate action[8] for a brief description of the main results of each study). These studies commonly analyze financial assets’ exposure to NRRs by combining a financial portfolio dataset, containing the sectoral allocation of financial institutions’ portfolios, with biodiversity-related datasets. This second type of data connects productive sectors with their ecosystem service dependencies (often through the ENCORE database, identifying sectors the most at risk using high or very high thresholds) or their impacts on ecosystems (often using consolidated metrics of biodiversity losses including several types of biodiversity-relevant pressures). The exposure of a financial portfolio to NRRs is then estimated based on the dependencies and pressures underlying its constituent assets.

One of the main limitations of these approaches is that exposure does not mean vulnerability as one would have to characterize the likelihood of shocks to emerge. To accurately assess physical risk, it is imperative to characterize the likelihood of disruptions in ecosystem services. This likelihood is intricately tied to the evolving state of ecosystems providing these services (Folke et al, 2004; Dakos et al, 2019; Willcock et al 2023). On the one hand, the likelihood of a physical risk is directly tied to the capacity of the ecosystems to provide ecosystem services. On the other hand, the likelihood of transition shock relates to changes in policies, behaviors, or technological change that could adversely impact prevailing economic activities. As acknowledged by the NGFS and others, scenarios will thus be essential in the analysis of NRRs. Central to these evaluations is the role of spatial analysis. Indeed, the local conditions of an ecosystem not only determine the likelihood of ecosystem service supplies—shaped by the spatial flow of ecosystems as studied by Serna-Chavez et al. (2014)—but also influence the likelihood of the emergence of transition shocks.[9]

In the existing studies, different approaches were used to construct scenarios of physical risks. The Dutch study envisaged the consequences of a loss of pollination via the combination of sectoral production dependency to certain crops and international trade data. The Brazilian study used a global model combining the collapse of different ecosystem

[6] https://www.banxico.org.mx/publicaciones-y-prensa/seminarios/financiamiento-a-las-comunidades-para-la-conservac/%7BA955B369-AD4D-FDF9-A984-D84812F9BB42%7D.pdf

[7] https://www.ngfs.net/node/421191

[8] https://www.financeministersforclimate.org/sites/cape/files/inline-files/Bending%20the%20Curve%20of%20Nature%20Loss%20-%20Nature-Related%20Risks%20for%20MoFs_2.pdf

[9] Note that in contrast to climate concerns, spatial assessments are vital for NRRs, particularly in the case of transition risks. Unlike global nature of climate change, the physical consequences of other types of biodiversity-relevant pressures are typically spatially close, so agents causing environmental stress in distinct areas face varied nature-related transition risks depending on local ecosystem conditions and the subsequent public and authoritative reactions.

services provision (pollination, timber provision fisheries and carbon sequestration) to then determine the evolution of non-performing loans in Brazil. Finally, the Malaysian study constructed scenarios based on ENCORE and expert knowledge to highlight which ecosystem services are more likely to trigger large financial exposition in the country. Note that the Brazilian and Dutch studies assumed a total collapse of ES under consideration, a rather conservative scenario.

Regarding transition risks, most of the studies concentrate on scenarios expanding protected areas with the hypothesis that economic activity would have to be (partially) interrupted in those areas. The authors first identified locations that are likely to be included in protected areas, either via global scenarios/datasets (Kok et. Al (2020) in the Dutch study, IBAT[10] in the Malaysian study, the World Data Base of Protected Areas[11] in the Mexican study) or via domestic scenarios (Fonseca and Venticinque (2018) in the Brazilian study). They then localized economic activities using different datasets (Labor survey in Brazil, proprietary business localization dataset in the Dutch study, unpublished banking dataset in Malaysia, unpublished regulatory data containing detailed credit registry and securities holding of various financial institutions) and assumed different rules to determine the percentage of economic activities and/or financial portfolio that are at risk in each location. Interestingly, the Mexican study combines this approach with the Natural Capital Index to monitor and assess the quantity and quality of biodiversity and ecosystem services in Mexico to see the exposition of financial assets according to the state of biodiversity in the municipality they are located.

Aside from the specification of the likelihood of shocks, another aspect that is worth considering in the analysis of NRRs is their multidimensional nature. First, biodiversity is inherently multidimensional, as biodiversity has to be regarded through different lenses such as genetic and community composition, species population, and ecosystem structures and functions (see Peirera & al., 2013). Furthermore, economic activities both impact and rely on various ecosystems, leading to a myriad of sources of NRR. This complexity makes standardizing and comparing nature-related data challenging. For instance, how does one compare the usage of a hectare of land for cattle to the emission of a ton of nitrate or the usage of a liter of water for cooling? The same questions apply to dependencies to ecosystem services. While indices like the Mean Species Abundance (MSA) (see Alkemade & al. (2009) used in the Dutch and French studies, or the Potentially Disappeared Fraction (Huijbregts & al., 2017) attempt to consolidate pressures through synthetic indices (Verones et al., 2020; NGFS, 2022), no such index exists for dependencies. Nonetheless, relying solely on such consolidated indicators might not be the most effective approach to analyze NRRs, as they may not elucidate the specific channels of risks. Knowing that a company has a certain footprint in terms of, say, MSA does not indicate whether it is vulnerable to policies focusing on land use or pollutant regulations, for instance (unless the total MSA value can be disaggregated for each pressure). Therefore, it can be more

[10] IBAT - Integrated Biodiversity Assessment Tool. https://www.ibat-alliance.org/

[11] https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA

informative to study different types of shocks independently. This is what has been done in Malaysia and Mexico using multidimensional pressures from the ENCORE database.

The multidimensionality of NNRs not only lies in the diverse sources of biodiversity-related sources of shocks, but also in the diversity of economic vulnerabilities these shocks can originate. Because the literature emerged in the analysis of NRR financial risks, existing studies often look only at the risks pertaining to specific financial portfolios. Nonetheless, financial stability at the company level also depends on the stability of the macro level, and the macro-financial level is of interest in itself for policymakers (Campiglio & al., 2023). The broader socio-economic landscape is indeed also influenced by NR shocks hence indicating a double feedback loop between micro and macro-financial stability (Guzman & al., 2019 ; Carney, 2019). Magacho et al. (2022) introduced a framework applied to the low-carbon transition where climate-related shocks can lead to a restructuring of the production network resulting in various economic tensions and imbalances. These disturbances are measurable through indicators like employment and wage income, consumption prices, fiscal revenues, international trade, production, and profits. These are variables that decision-makers follow regularly to ensure sustainable development and macro-financial stability (Borio & al., 2023), and which are potentially vulnerable to NRRs.

Last but not least, an important feature of climate and nature-related risks lies in their propensity to restructure entire industrial networks, rendering numerous sectors indirectly vulnerable to supply or demand effects due to their relations with sectors that are directly at risk (Godin & Hadji-Lazaro, 2022 ; Cahen-Fourot & al., 2021). Wilting & van Oorschot (2017) pioneered a systematic quantification of biodiversity footprints within supply chains. Their findings revealed that over 50% of biodiversity losses pertaining to the Dutch economy's supply chains originated abroad and that more than 45% of the biodiversity losses attributed to the food and chemical sectors took place further upstream than their immediate suppliers. This highlights not only the extensive realignment of value chains necessitated by a transition to a nature-positive economy but also the multiple pathways through which nature-related risks can permeate economies. All existing studies overlook such indirect value-chain implications, except for the French study.[12]

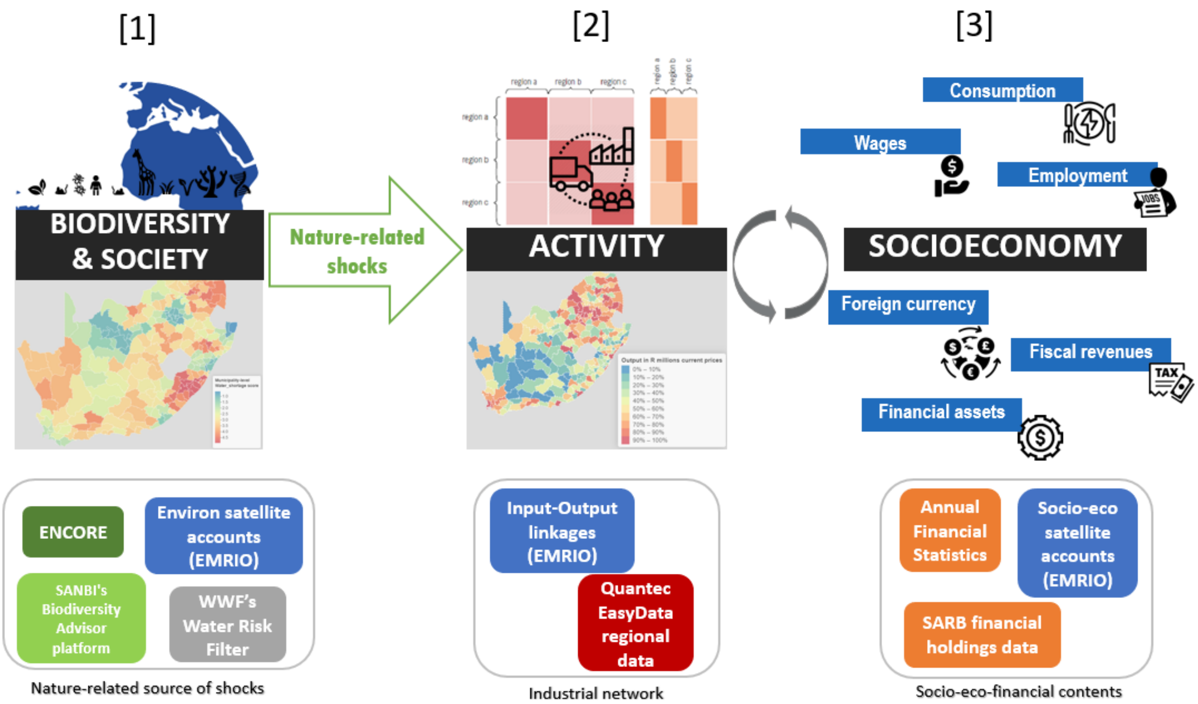
[12] Although the Brazilian study uses a global computable general equilibrium model that includes supply-chain effects, the study only uses global results and does not delve into the specific channels of shocks' propagation throughout value-chains.

2. Methodology

As illustrated in figure 1, the framework's central objective is to track the propagation of nature-related shocks (NRS) from the biophysical or social environment embedding the economy, throughout the industrial network, to socio-economic and financial outcomes.

The core of the method consists of evaluating the transmission channels from NRS to socio-economic and financial outcomes via, on the one hand, the extent to which economic activities are impacted by physical or transition shocks[13], and on the other hand how impacted activities generate socio-economic and financial outcomes. To do this, we connect three modules: a "source of shock" module (indicated by [1] in figure 1), an activity module [2], and a socioeconomic module [3]. The "source of shock" module contains information related to the biodiversity-related perturbations, either physical or transitional. The activity module contains the network of economic activities being impacted by the disturbances and within which will propagate the initial perturbations along value chains. The socio-economic module contains the socio-economic indicators (SEI) affected by the shock along the value chain. For example, a company facing too much water stress (source of shock) will close or relocate (impact on the activity) hence failing to export its goods and services (external balance exposure).

Figure 1. Scheme of the general approach



Note: Numbers on the top indicate the different methodological modules presented in this section)

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13 We are using the notion of "shock" to capture any disruption in production, both direct and indirect, emerging from either a collapse of biodiversity and ecosystem services (i.e. physical shocks), or policies and/or technological and/or behavioral changes to mitigate pressures on biodiversity (i.e. transition shocks).

As depicted in figure 1 and explained with details below, several databases are connected in order to characterize and link the three modules (source of shock, economic activities, socioeconomic indicators). Each database will be detailed in the next sections.

- The sources of shocks module uses:
  - ✓ the ENCORE database to delineate sector dependencies on 21 ecosystem services;
  - ✓ environmental satellite accounts from the EMRIO[14] table to highlight sectors' impacts on biodiversity;
  - ✓ the WWF's water-risk filter to provide municipality-level data on water-related shock risks; and
  - ✓ SANBI's Biodiversity Advisor platform data to present potential area protection and information on threatened ecosystems at the municipal level.
- The economic activity module uses:
  - ✓ the EMRIO table to depict sectoral production, value-added, and intersectoral input-output relationships; and
  - ✓ the Quantec-EasyData, which provides a distribution of economic activities by sectors at the municipality level.
- The socioeconomic module integrates data from EMRIO to cover production, household final demand, profits, wages, employment, tax revenues, and exports on a country scale.

2.1 Sources of Nature-related shocks

As highlighted above, physical risks refer to an implicit scenario of biophysical shocks reducing ecosystems' capacity to provide ecosystem services, whereas transition risks refer to an implicit scenario of policy, technological or behavioral changes aiming to mitigate the pressures humans exert on biodiversity.

2.1.1 Exposure to Nature-related shocks

We follow the literature and evaluate the exposure of industrial sectors to physical risks by assessing their dependencies on ecosystem services, and their exposure to transition risks through their impact on biodiversity.

[14] Environmentally-extended MRIO table, see III.2.A for details.

2.1.2 Exposure to physical shocks through dependencies analysis

The dependency analysis is based in the ENCORE database, which assigns to several production processes "dependency scores" related to 21 ecosystem services (definitions of these services are provided in appendix A):

- **Provisioning**: Ground water, Surface water, Genetic materials, Fibers and other materials, Animal-based energy

- **Regulation and Maintenance**: Bioremediation, Buffering and attenuation of mass flows, Climate regulation, Dilution by atmosphere and ecosystems, Disease control, Filtration, Flood and storm protection, Genetic materials, Maintain nursery habitats, Mass stabilization and erosion control, Mediation of sensory impacts, Pest control, Pollination, Soil quality, Ventilation, Water flow maintenance, Water quality

Encore proposes a materiality score to assess the degree of dependence of business processes on ecosystem services, ranging from very low to very high. This score indicates the level of non-substitutability of the ecosystem service for the continuity of the production process, based on evidence from studies on functional losses in business processes. For example, the production process "Large-scale irrigated arable crops" has a high dependency score on the ecosystem service "Water flow maintenance" (among others). These production processes are then connected to economic sectors through the assignment of processes to specific business activities (sectors) based on the Global Industry Classification Standard (GICS). We use a concordance table linking sectors in the input-output database to the 86 ENCORE production processes to assign dependency scores to all IO sectors for each of the 21 ecosystem services listed in ENCORE (see Svartzman et al. (2021), p.29, for an explanation of how a unique dependency score is assigned by pairs of sector-ESS) .

In this study, we apply the ENCORE methodology in a binary manner, categorizing sectors as either dependent (exposed) if their dependency score is considered as high (equal or greater than 0.6) - the score at which the ecosystem service is considered as non-substitutable for the operations of an economic process by ENCORE experts.

2.1.3 Exposure to transition shocks through pressures analysis

Our study investigates an implicit scenario pertaining to domestic changes in South Africa, specifically those related to national policies or behavioral changes aiming to lessen the footprint of domestic agents, hence excluding any imported shocks. This could serve as preliminary work in evaluating how South Africa might explore policy options to meet the targets set out in the new CBD Global Biodiversity Framework, excluding the consideration of exposure to external transition shocks.

We use the environmental satellite accounts available in the MRIO table to measure biodiversity-relevant pressures exerted by economic sectors. We base the impact analysis on the multi-dimensional assessment of the main pressures that human activity exerts on biodiversity. The compilation of "drivers" outlined by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)[15] and the "threats" indicated by the International Union for Conservation of Nature (IUCN)[16] provides substantial insights into the principal pressures that warrant consideration. The pressures we will consider in this study (see Table 1) relates to climate change, land use change, pollution and resource extraction.

Table 1. Biodiversity-relevant pressures covered in the study

Pressure category	Pressure type	Unit
Climate change (Climate change & severe weather)[17]	carbon dioxide (CO_2)	kt
	greenhouse gas (GHG)	kt ($eqCO_2$)
Land-use (Agriculture)	Crop land-use	km^2
	Pasture land-use	km^2
	Forestry land-use	km^2
Pollution (Pollution)	Ammonia (NH_3)	kt
	Nitrogen oxides (NO_x)	kt
	Sulfur oxides (SO_x)	kt
Resource extraction (Natural system modifications & Biological resource use)[18]	Water-use (withdrawal)[19]	m^3
	Fish	kt

15 https://ipbes.net/global-assessment

16 https://www.iucnredlist.org/resources/threat-classification-scheme

17 Before the parenthesis we use the IPBES lexicon, inside the parenthesis we use the IUCN lexicon.

18 While this can seem unsatisfactory, we include water abstraction and fish extraction in the resource extraction category as does IPBES. This is only a matter of presentation and has no implications for the results as we always differentiate between each pressure.

19 Water *withdrawn* is the total volume removed from a water source such as a lake or river. Often, a portion of this water is returned to the source and is available to be used again. Water *consumed* is the amount of water removed for use and not returned to its source.

We focus on a range of biodiversity-related pressures without integrating them into a consolidated biodiversity impact metric such as Species Threat Abatement and Restoration (STAR), Potentially Disappeared Fraction (PDF), or Mean Species Abundance (MSA). In this context, we adopt a neutral standpoint concerning the nature of the pressure that is targeted for mitigation efforts. This approach enables us to scrutinize the socio-economic implications associated with mitigation strategies targeting specific pressures – an examination of the socio-economic trade-offs for targeted stressors. However, we recognize that different pressures do not result in uniform impacts, and even identical pressures may induce dissimilar effects on biodiversity in varied geographical contexts. It is plausible that societal inclination may be towards mitigating impacts rather than the pressures themselves. In such scenarios, the indicator of exposure to transition shock might not be the direct pressure from sectors, but rather the pressures translated into an impact metric. The spatially-explicit assessment described below partially overcomes this limitation by localizing threatened ecosystems.

In our analysis, we define "key exposed sectors", for each pressure, via two distinct indicators: the absolute pressure that sectors exert and the pressure intensity relative to sectors' production levels.[20] Sectors are deemed key either if they account for at least 5% of the national level of a particular pressure or if they are, for a specific pressure, highly intensive (i.e. their footprint intensity exceeds the third quartile for that pressure) and contribute at least 2% to the country's footprint. The advantage of pinpointing highly intensive sectors is that it offers policymakers the opportunity to reduce ecological footprints in a more economically efficient manner (per unit of output in this case). Figure 19 in the appendix presents the distribution of pressure intensities across different sectors for each type of pressure considered in the study.

2.1.4 Spatially-explicit assessment of the likelihood of shocks

We evaluate the relative likelihood of shocks through spatially-explicit assessments, using the definition of Sun & al (2018).[21] In our case, we will identify "sensitive municipalities", i.e. municipalities for which ecosystems threatened by economic activities are very degraded (transition risk) or for which there is a high risk of failure of provision of ecosystem services (physical risk). Although the biophysical data capturing the sources of shocks are usually available at a finer spatial resolution, the economic data restrict the analysis to the municipality level.[22]

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[20] Unlike physical risk assessments which use absolute dependency scores, transition risks identify exposed sectors based on their relative biodiversity footprints, given the different nature of both shock types. Relative thresholds seem more suitable for transition risks as decision-makers seeking to protect biodiversity may prioritize reducing impacts from companies with the highest biodiversity footprint.

[21] Sun & al. (2018) define a spatially-explicit assessment as involving a result where the spatial information available from the study is at a spatial scale greater than the available IO data itself.

[22] There are 234 municipalities in South Africa under the pre-2016 boundaries.

We then define vulnerable activities as those simultaneously located in a sensitive municipality and exposed to the given risk. For example, an activity reliant on water resources is considered vulnerable to water scarcity only if it is located in a water-scarce municipality. Similarly, activities exerting high pressure on biodiversity are deemed vulnerable to potential protective measures if they adversely affect a locally threatened ecosystem.

2.1.5 Likelihood of water-related physical risks

While there are many different physical risks possible in South Africa, we will concentrate on water scarcity but the proposed methodology can be applied to other physical risks. Water scarcity presents a significant economic challenge in South Africa due to high water stress and limited access to clean sources. Factors include the semi-arid climate, climate change impacts, and growing water demand. Droughts worsen scarcity, such as the 2022 severe drought in the Western Cape and Northern Cape (CSIR[23] ; SARVA[24]). This issue has wide-reaching consequences, for example affecting agriculture with crop failures and reduced yields due to hydric stress, or hydroelectric power and coal-fired plants, dependent on water for cooling. Water scarcity leads to production cuts, economic decline, job losses, and reduced incomes. The Cape Town droughts from 2015 to 2018 showcased these impacts, causing job losses, increased poverty, and income reduction.

We identify water-sensitive municipalities based on the WWF's Water Risk Filter (WRF). The WRF investigates various spatial data sets on water issues. Detailed data processing method descriptions for each indicator are available with WRF methodology documentation.[25] Once the data was extracted, a risk score of between 1 and 5 was allocated to each quaternary catchment, reflecting risk levels of Very Low to Very High for different types of risks. The WRF team provided municipality-level area-based weighted means of those risk scores, enabling us to comply with the geographic scale of the local economic data at hand. Our use of the WRF is therefore more aggregated than the original tool.

We then combine municipal-level risk scores with the dependencies of economic activities on water provision (derived from ENCORE) to determine the prevalence of activities heavily reliant on water provision within municipalities where the condition of water provisioning appears to be compromised, as indicated by the WRF indicators.

2.1.6 Likelihood of threatened ecosystem-related transition risks

Our spatially-explicit assessment of transition risks centers on the potential impact of protective measures on economic activities related to specific threatened terrestrial ecosystems, primarily vegetation types. Using a classification system that hierarchically organized vegetation types within biomes and bioregions, we draw on South Africa's extensive experience with ecosystem threat status assessments, which have culminated in

23 https://greenbook.co.za/

24 https://sarva.saeon.ac.za/

25 https://cdn.kettufy.io/prod-fra-1.kettufy.io/documents/waterriskfilter.org/WaterRiskFilter_Methodology.pdf

a national list of threatened ecosystems crucial for land-use decision-making (Botts et al., 2020; Skowno & Monyeki 2021). Out of 458 cataloged vegetation types in South Africa, 120 are deemed threatened, with classifications such as "vulnerable," "endangered," and "critically endangered" based on the IUCN Red List. These designations rely on quantitative evaluations of spatial configuration and remaining ecosystem extent, indicative of various threat levels. The data further includes information on the main pressures contributing to ecosystem threats. Such pressures include loss of natural habitat due to agriculture, timber plantations, human settlements, mining, overgrazing, invasive species, and disrupted fire regimes (Skowno and Monyeki 2021).[26]

The spatially-explicit assessment of transition shock looks at the geographical distributions of biodiversity pressures within South Africa to identify sectors impacting ecosystems located in municipalities where they are threatened. The rationale is to consider that economic activities are more exposed to a transition risk linked to hypothetical regulatory measures, technological innovation or consumer behavior changes targeting a reduction of the pressures exerted on ecosystems where these ecosystems are more threatened. In this study, we consider the case of mining activities but the methodology could be applied to other activities such as agriculture.[27] We define a municipality as sensitive to the protection of ecosystems if 20% of its area is covered by threatened ecosystems or if 20% of a specific threatened ecosystem type is located in the municipality. We call these municipalities, “mining pressures-sensitive municipalities”.

2.2 Economic activities

2.2.1 National scale EMRIO framework

In this study, we analyze economic activities through the recently released GLORIA Multi-regional Input-Output (MRIO) database[28] - see Lenzen & al. (2022). It contains 164 regions and 120 sectors from 1990 to 2020. The table provides information on the exchange of intermediate goods, enabling the evaluation of linkages within sectors and across regions. The MRIO table also includes data on the supply of final goods by each sector and captures

[26] The assessment of critical pressures for each threatened ecosystem is based on historical and ongoing observations of the role of these pressures (using geographic and expert derived data). We are however interested in the current and future threat that economic activities pose to ecosystems. Despite this, we will consider that only the activities corresponding to these pressures are at risk of transition, but if activities exert "new" pressures impacting the ecosystems considered, then they too could be considered at risk. In this sense, our assessment is underestimating the set of activities vulnerable to the protection of these threatened ecosystems.

[27] The main reason why we did not get into the spatially-explicit assessment on agriculture is that the local economic data consolidates agriculture into one same sector, which prevents us from deriving results as relevant as those for mining sectors.

[28] https://ielab.info/analyse/gloria

the value-added components such as wages and taxes. Additionally, satellite accounts are integrated, accounting for social factors like employment details and environmental aspects such as resource usage and waste emissions. The combination of MRIO and satellite accounts forms an Environmentally-extended MRIO (EMRIO) table. We are aware that country-specific IO tables should be preferred to MRIO datasets for country analysis. The rationale behind our selection of an MRIO table for analyzing a country-specific case resides in the inherent advantages offered by EMRIO tables such as GLORIA to encompass an exhaustive collection of both environmental and socio-economic indicators, a depth of information that typically extends beyond the content of national Input-Output (IO) tables.

2.2.2 Indirect exposure

In addition to the activities that are directly vulnerable to physical or transition shocks, a range of other activities are indirectly vulnerable due to the direct and indirect links they have with directly vulnerable sectors (Acemoglu & al. 2012). Sectors higher in the value chain (i.e. upstream) of sectors directly vulnerable are exposed to demand shocks, while sectors further down in the value chain (i.e. downstream) of sectors directly vulnerable are exposed to supply shocks. It is worth noting that the TNFD framework also emphasizes the importance of looking at both direct and indirect (upstream and downstream in the value chain) vulnerabilities (TNFD, 2023a). The input-output framework is the most commonly used to study such indirect effects (Miller & Blair, 2009).

Demand effects (exposure to a demand shock) on output refer to the decrease in demand experienced by an industry when its customers reduce production and therefore do not demand as many inputs as before. Demand effects are easily evaluated through the Leontief demand-pull quantity model (Oosterhaven, 1996). The model calculates Leontief multiplier coefficients used to measure the sequence of demand declines across sectors throughout the economy following a shock (see details in Godin & Hadji-Lazaro (2022), for example). The gross effect of a shock equals the Leontief multipliers times the initial change in output experienced by the directly exposed sectors. First round effects are the effects incurred by the direct sellers of the directly vulnerable sectors. All indirect effects include all rounds of production decline due to an initial shock (using the famous Leontief inverse matrix to calculate). Although useful and informative, this way of approaching demand-related effects faces limitations. Among others, it assumes a fixed input-output relationship, which means it does not account for changes over time ; it does not incorporate price information which can be a significant limitation when analyzing the impact of price shocks ; it assumes linear relationships between inputs and outputs, which may not accurately represent the complexities of real-world production processes.

Supply effects (exposure to a supply shock) are more difficult to evaluate. As shown in the Input-Output literature (Oosterhaven, 1988), it is unclear how to calculate the impact of a reduction in the supply of input from another industry because of input substitution possibilities (Galbusera & Giannopoulos, 2018). The choice we make in this study is to consider an industry as exposed to supply constraints as soon as the monetary share of the physical inputs supplied by directly exposed sectors in the total physical inputs the industry uses is sufficiently high.[29] For instance, if we observe that the value of inputs produced by industries highly dependent on pollination exceeds 20% of the value of physical inputs an industry uses, then this industry will be considered as indirectly exposed to supply constraints from a shock on the pollination ecosystem service.

Physical inputs are intermediate goods supplied by the manufacturing, construction, electricity, gas and water as well as agriculture, forestry and fishing sectors. Focusing on physical inputs allows to mitigate the weight of services in the evaluation of a sector's supply chain and hence to avoid as much as possible the monetary evaluation bias in the description of physical input requirements (i.e. giving to much weight, because of their monetary value, to goods and services that are not essential to the production process). Nevertheless, this approach is still biased by monetary valuation within the set of physical inputs. We view the method as an exploratory tool designed to highlight the potential chains of tensions that a decline in the supply of certain goods could generate. Note that in order to avoid double counting direct and indirect exposures, we will consider only the indirect effects on the not directly exposed sectors (which prevents us from identifying intra-sector indirect supply effects). In other words, in each sub case study, we exclude the sectors already directly exposed in the calculation of indirect exposures to supply effects.

2.2.3 Local scale economic activities

Raw spatial data on economic activity are from the RSA Standardized Regional Income & Production from Quantec EasyData.[30] The database maps economic activities of 50 sectors (50 SIC - Standard Industrial Classification categories - most manufacturing and business services are down to 3-digit level and the rest down to 2-digit level) within 234 South African municipalities (based on the pre-boundary reform of 2016). Indicators included in the database are Gross value added at basic prices, Value added at factor cost, Compensation of employees, Gross operating surplus, Tax on production, Subsidies on production and Output at basic prices. Unlike the IO data, these data do not include trade between sectors, but only the production of each sector in each municipality. This is still useful in that it gives an idea of the location of a particular type of activity in South Africa with a quite high geographic granularity.

In order to make the results found at the national scale comparable with the results at the municipal scale, we need consistent data at both scales. In order to get consistent data at both scales, we extrapolate some values from the Input-Output data at the local level because municipal data has 40 SIC sectors while GLORIA has 120 sectors. Specifically, we distribute at the municipality level the national-level sectoral production from IO data based on the sectoral distribution of production among and within municipalities indicated in the local economic data. In this allocation process, we assume a homogeneity of production-level within sub (IO) sectors in each municipality. This means that inside each SIC-40 sector, the relative distribution of the production of the corresponding sub (IO) sectors is the same

29 We will discuss specific thresholds for each case study.

30 https://www.quantec.co.za/easydata/regional-subscription/

across each municipality.[31] Municipalities then differ in the amount of production, in the SIC-40 sectors distribution of their production structure, but not in the IO sub-sectors relative distribution within each SIC-40 sectors.

This approach has a significant drawback as it introduces discrepancies between the original and transformed geographical distribution of activities due to discrepancies in the national-level production distribution of sectors between local economic and IO data. If a sector is underestimated in the IO data for instance, the municipalities in which the sector is important will artificially see their production level underestimated after the extrapolation.[32] However, as shown in the appendix C, at the province level, the impact of this discrepancy is negligible. Still, the transformed data allows us to (i) make the national-level analysis comparable with the spatially explicit analysis, and (ii) assign some national-level socioeconomic and environmental sectors' information at the municipality level - the underlying assumption being that the unitary environmental and socio-economic characteristics of each sector are the same in all municipalities (e.g., the transportation sector requires the same amount of work and emits the same amount of pollution per unit of production in two different municipalities).

2.3 Socioeconomic indicators

Once exposed or vulnerable economic activities have been identified both directly and indirectly, we assess how their perturbation could impact social, macroeconomic, and financial indicators. Several categories of socio-economic indicators could be considered. We expand on the proposition of Magacho et al. (2022) who developed a framework for the case of a low-carbon transition. Their framework is based on the idea that the tensions and instabilities generated by the fundamental restructuring of the production network that are climate-related dynamics can be of different nature (social, economic, fiscal or financial) and can be measured by several indicators. These indicators (described in Table 2) correspond to channels of macro-financial instabilities and are commonly used by decision makers to manage sustainable development policies or macro-financial stability. They are directly derived from the EMRIO table and its socioeconomic satellite accounts.

[31] The 50 SIC sectors of the local economic dataset are aggregated into 40 SIC sectors for each of the 120 Gloria sectors to be assigned to only one of the 40 SIC sectors. In this way, each SIC-40 sector "contains" the corresponding IO sub sectors, and we do not need to find an allocation rules for assigning parts of IO sub sectors to SIC-40 sectors.

[32] Indeed, we force the production levels from Gloria database and distribute them within municipalities according to the proportions represented by each sectors indicated in the Quantec database.

Table 2. Socioeconomic indicators (SEIs) covered in the study

SEI name	Nature of instability	Description
Employment	Social	Number of jobs impacted
Wages	Social	Total amount of wages impacted (in million Rands)
Final Demand	Social and Economic	Total amount of final consumption of households impacted (in million Rands)
Production	Economic	Total amount of production impacted (in million Rands)
Profits	Economic	Total amount of profits, or gross operating surplus, impacted (in million Rands)
Net taxes	Economic and Fiscal	Total amount of net taxes (i.e. taxes net of subsidies) impacted (in million Rands)
Net exports	Economic and External	Total amount of net exports (i.e. exports net of imports needed to produce these goods and services) impacted (in million Rands)

The inclusion of these indicators is justified as they provide insights into macro-financial stability and economic development implications. Decline in fiscal revenues can make it more difficult for the government to fund key social and economic programs, which can further undermine the country's economic stability and growth prospects (Beirne, 2021; Mallucci, 2022; Mauro & Zilinsky, 2016). Employment is another key area where economic shocks can have negative macroeconomic consequences, as a decline in employment can lead to a decrease in household wage income and a reduction in consumer spending (Saget & al., 2020). This can further contribute to a slowdown in economic activity and a decline in GDP. Furthermore, high unemployment levels can generate social tensions and political turmoil. Difficulties in sectors supplying goods and services to households can lead to a decline in the availability of these goods and services, which can have negative impacts on the overall standard of living in the country through shortages and/or through price inflation, which can be another source of social tensions and political turmoil. Decline in a country's exports can lead to a decline in the value of its currency and a reduction in the competitiveness of its exports on the global market. This can further undermine the capacity of the country to import intermediate or final goods, and to attract foreign capital (Kling & al., 2021). Profits are an important source of funding for businesses, and a decline in profits can make it more difficult for firms to invest in new projects or expand their operations (Fazzari & al., 1988). This can further undermine economic growth and development.

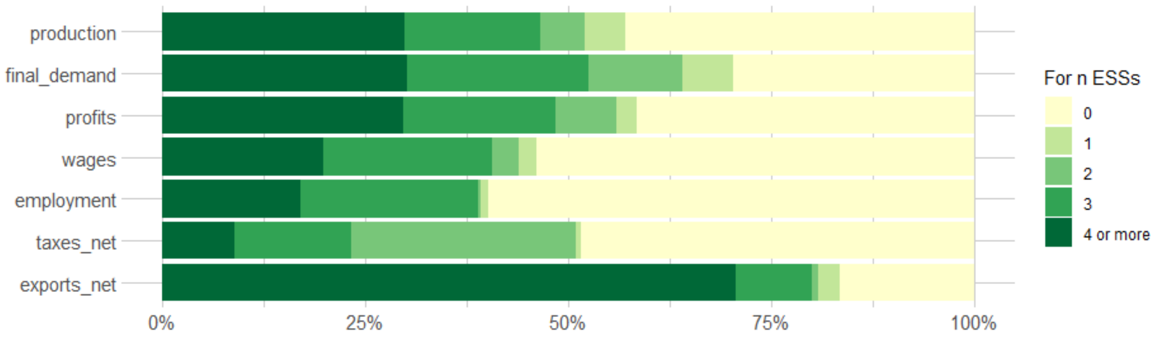
3. Results

3.1 Physical risks

3.1.1 National-scale exposure to physical risks

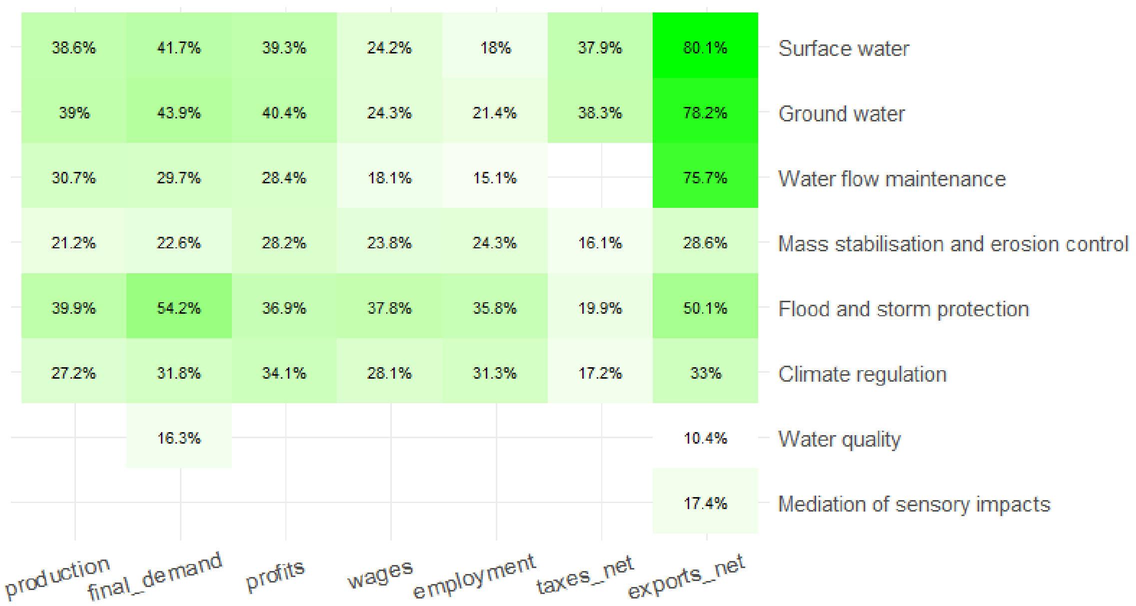
We find that half of the country's output is produced by economic activities exposed to (i.e. highly dependent on) at least 2 different ecosystem services (see Figure 2). Concerning the other Socio-Economic Indicators, 70% of final demand, 58,5% of profits, 46% of wages, 40% of employment, 51,6% of taxes and 83,4% of net exports appear to be generated in sectors highly dependent on at least one ecosystem service.

Figure 2. Shares of SEIs
generated in sectors highly dependent on one or more ecosystem services (ESS)



Disaggregating the results by ecosystem services, we derive that more than 30% of South Africa's production is generated by activities which are highly dependent on water provision and flood and storm protection, 20-30% is highly dependent on climate regulation and mass stabilization, 8% is highly dependent on water quality, and 6.5% on mediation of sensory impacts (see Figure 3). Significant shares of SEIs are generated in sectors highly dependent on Surface and Ground water provision as well as on Water flow maintenance and Water quality. For instance, more than 25% of all the considered socioeconomic variables are generated by sectors highly dependent on Surface and Ground Water provision. Nonetheless, other types of ecosystem services also appear as important for many SEIs. Around or more than 25% of all SEIs is generated in sectors highly dependent on climate regulation. Around or more than 30% of exports, employment, gross operating surplus and production are generated in sectors highly dependent on flood and storm protection. And mass stabilization and erosion control is also an ecosystem service on which depend sectors that generate important amounts of socioeconomic variables.

Figure 3. Shares of SEIs
generated in sectors highly dependent on specific ecosystem services

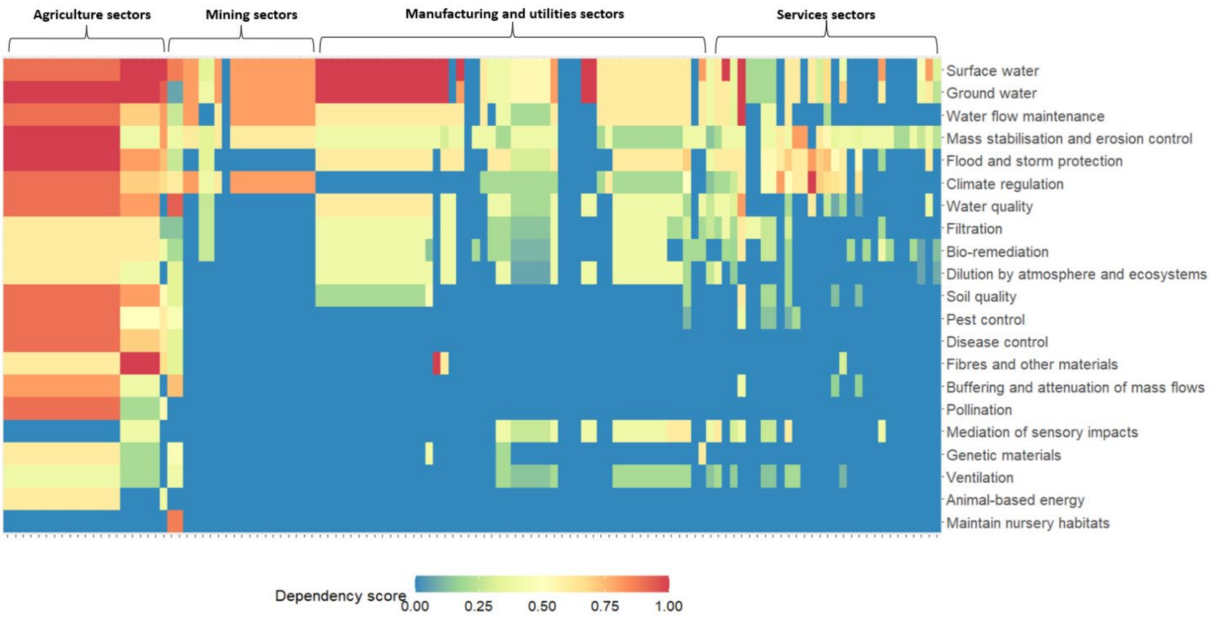


Net exports appear to be the socioeconomic variable the most exposed to physical shocks. Indeed, 83,4% of net exports are generated in sectors highly dependent on at least one ecosystem service, including 80% of net exports depend on at least 3 ESSs, and 70% dependent on at least 4 ESSs. It is therefore highly likely that ecosystem degradation will severely affect the export capacity of the South African economy. The degradation of ecosystem services would therefore degrade the country's balance of trade, its ability to generate foreign currencies and thus its ability to import goods and services. The socioeconomic exposure of export to physical risk is explained by the sectors structure of exports, which are mainly generated in the mining or manufacturing sectors - while other SEIs are more concentrated in service sectors less directly dependent on ecosystem services. More than 80% of exports are generated in sectors highly dependent on surface water, 78% of exports are generated in sectors highly dependent on ground water, 75,7% are generated in sectors highly dependent on water flow maintenance and 50% are generated in sectors highly dependent on flood and storm protection. The degradation of one of more water-related services would then significantly affect South African exports. The securing of water supply capacity (of good quality) thus appears to be a key issue for the South African trade balance. Also, 33% and 28,6% of exports are dependent on the regulation services climate regulation and mass stabilization and erosion control, respectively.

The sectors supplying final goods to households also appear particularly dependent on ecosystem services and thus exposed to nature-related physical shocks. Indeed, 70% of household demand is supplied by sectors directly highly dependent on at least one ecosystem service, and 53% by sectors highly dependent on at least three ecosystem services. This means that ecosystem degradation would make it difficult for these sectors to produce the goods and services directly needed by households. Ecosystem degradation would therefore lead to price inflation of household consumption goods. The sectors producing the goods and services supplied to households are exposed to shocks from the degradation of water provision, water quality, flood and storm protection, as well as climate regulation.

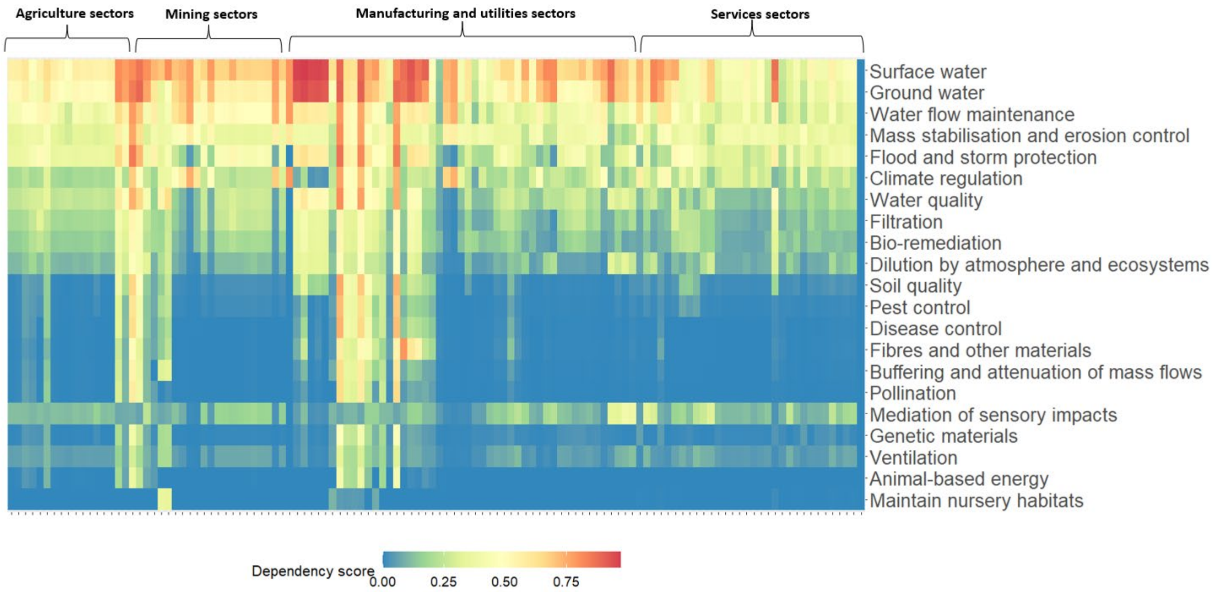
The results previously shown portray the direct exposure of socioeconomic variables to physical shocks. The heatmap in Figure 4 illustrates these dependencies by drawing the direct dependency scores of the 120 economic sectors (x-axis) to the 21 ecosystem services (ESSs) (y-axis). Primary sectors such as crop farming and livestock operations are the most dependent sectors on ESSs, both in terms of dependency intensity (score levels) and number of dependencies. Certain other (non-primary) sectors also appear as highly dependent on several types of ESSs and thus exposed to physical shocks, especially some utility sectors, manufacturing sectors, transport sectors and mining sectors. Some ESSs appear particularly important for many sectors of the economy, especially water-related services (such as ground and surface water) - the good state of those ESSs is important for almost all sectors of the economy.

Figure 4. Heatmap of dependency scores by sectors and ecosystem services



Nonetheless, because sectors are interconnected through productive linkages, a shock on a sector directly dependent on an ESS could have effects propagating throughout the whole industrial network, and some SEIs are for this reason indirectly exposed to physical shocks. In the event of an ecosystem degradation, the industries dependent on the corresponding ecosystem may cease production, resulting in a decline in demand addressed to the sectors that furnish goods and services to dependent sectors (demand effects), as well as supply constraints for the sectors that source from dependent sectors (supply effects from price inflation or quantity shortage).

Figure 5. Heatmap of indirect (first round upstream) dependency scores by sectors and ecosystem services in South Africa



Before turning to a case study on a specific ecosystem services, let us illustrate the indirect dependencies assessment for the totality of ecosystem services in the case of South Africa economic productive linkages. In the heatmap of Figure 5 are shown indirect (upstream) dependency scores. These indirect scores are here computed as averages of the direct scores weighted by the importance (in value) of the physical inputs provided to the sectors to which they are assigned (only considering the first suppliers, or first round, here).[33] Two main features emerge. First, all sectors become at least slightly dependent on all ecosystem services. This is because almost all industries are directly or indirectly connected to each other through productive linkage. It illustrates the systemic scale that physical risks could reach through cascading effects across industries. Second, the agri-food sectors seem particularly indirectly dependent (compared to the first heatmap shown at the beginning of the section, the reddest cells move to the right toward agri-food sectors). This is explained by their important linkages with agriculture sectors, which are themselves directly highly dependent on many ESSs.

As a case study, we consider the indirect effects of a shock affecting the pollination service. Eight agriculture sectors are directly highly dependent on pollination. Despite contributing to 3.5% of employment and 3.6% of exports, these sectors demonstrate relatively limited generation of socio-economic indicators. The question now is to determine the amounts and channels through which indirect effects would arise from the deterioration of the ecosystem service of pollination.

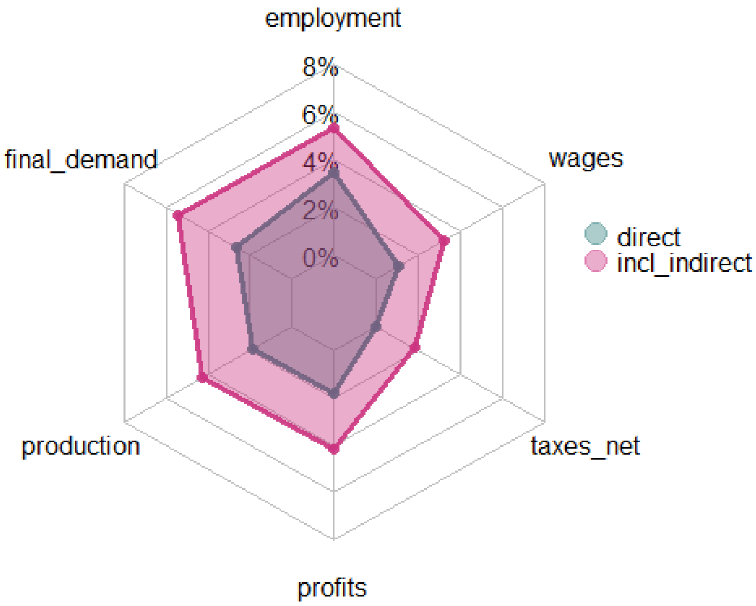
[33] Note that this mapping is country specific: because the supply chain of SA sector is specific to SA sectors, the weights assigned to each direct score to compute indirect scores depend on the specific supply chain of SA sectors.

We firstly look at demand effects (Table 3). We find that a shock affecting pollination-dependent sectors would have slight demand consequences because the agriculture sectors involved use mainly labor and few intermediate goods. Some manufacturing sectors would endure demand decline, such as the nitrogenous fertilizers and the refined petroleum products sectors, which lose 21% and 8% of their demand respectively as a result of the shock on pollination-dependent activities. The demand addressed to the trade, finance, and transport sectors are also affected. In terms of socioeconomic impacts (Figure 6), the relative effects on wages is particularly important (from 1% in the direct case to 3,2% with the demand effects). In fact, the initial shock directly affects low-paid activities that indirectly affect higher-paid activities.

Table 3. Indirect exposure of sectors to demand effects from a shock affecting the pollination service

Sector	Indirect effects in billion Rand	Indirect effects to production
Wholesale and retail trade Repair of motor vehicles and motorcycles	1 762 793	2.46 %
Finance and insurance	1 650 471	3.14 %
Refined petroleum products	877 275	8.24 %
Nitrogenous fertilizers	498 604	21.53 %
Rail transport	489 984	7.02 %
Electric power generation, transmission and distribution	452 575	2.6 %
Fabricated metal products	396 588	4.76 %
Human health and social work activities	373 062	2.53 %
Road transport	363 182	3.22 %
Transport via pipeline	336 012	2.66 %

Figure 6. Socio-economic exposure to demand effects from a shock on pollination



Note: Direct (blue), Indirect (pink)

Much more important appear to be the supply implications of a perturbation of the pollination service (Table 4). Such perturbation could imply strong food and raw material security issues. Indeed, more than 40% of all (including indirect) inputs to the alcohol, cereal products, food products and feeds, and raising of swine/pigs sectors are composed of goods produced by sectors directly highly dependent on pollination. More than 30% of the inputs to the raising of poultry, vegetable products, fruit products, raising of cattle, and vegetable products sectors are from pollination-dependent sectors. Interestingly, the hospitality sector is exposed to indirect rounds of effects, through its use of food products especially. While less than 0.001% of its direct supply-chain is composed of goods produced by sectors highly dependent on pollination (not shown), almost 8% of its total requirements embed pollination-dependent agricultural products.

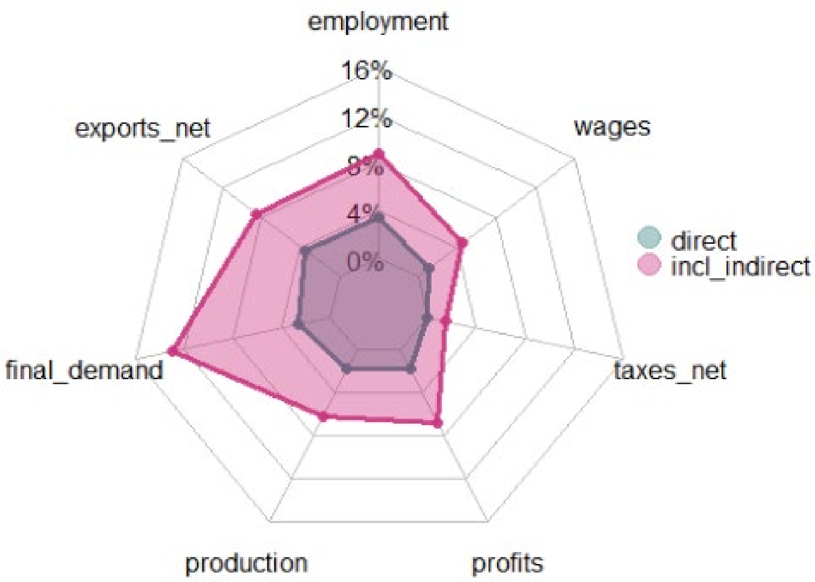
Table 4. Indirect exposure of sectors to supply effects from a shock affecting the pollination service (physical inputs threshold=5%)

Sector	Share in total physical requirements	Production (ZAR billion Rand)	Sector group
Cereal products	51%	7 123 800	Manufacturing
Alcoholic and other beverages	51%	5 814 000	Manufacturing
Raising of swine/pigs	46.5%	100 210	Agriculture, forestry and fishing
Food products and feeds n.e.c.	44.1%	3 356 400	Manufacturing
Raising of poultry	34.1%	420 470	Agriculture, forestry and fishing
Raising of cattle	25.9%	960 740	Agriculture, forestry and fishing
Vegetable products	22.9%	317 730	Manufacturing
Fruit products	21.1%	385 470	Manufacturing
Vegetable oils and fats	19.8%	346 940	Manufacturing
Raising of sheep	11.6%	4 117 900	Agriculture, forestry and fishing
Growing vegetables, roots, tubers	11.2%	3 649 100	Agriculture, forestry and fishing
Sugar refining Cocoa, chocolate and confectionery	8.2%	1 722 000	Manufacturing
Hospitality	7.7%	6 462 500	Trade, catering and accommodation
Raising of animals n.e.c. Services to agriculture	7.3%	44 513	Agriculture, forestry and fishing

3.1.2 The type of scenarios

While only 3% of household demand is supplied by pollination-dependent sectors, more than 12% is supplied by sectors heavily reliant on intermediate goods supplied by pollination-dependent sectors. The effects of the degradation of the pollination service on prices for final consumers could thus be substantial, especially for low-income households whose consumption basket is largely composed of food products. The effects on net exports and employment are also significant. While only 3% of net exports and employment are generated by sectors directly dependent on pollination, more than 8% of both are generated by sectors whose production is indirectly and significantly dependent on goods produced by sectors directly dependent on pollination. While the effect on exports is driven mainly by the alcohol, food and sugar industry, the employment effects are for their part mainly driven by the hospitality sector.

Figure 7. Socio-economic exposure to supply effects from a shock on pollination

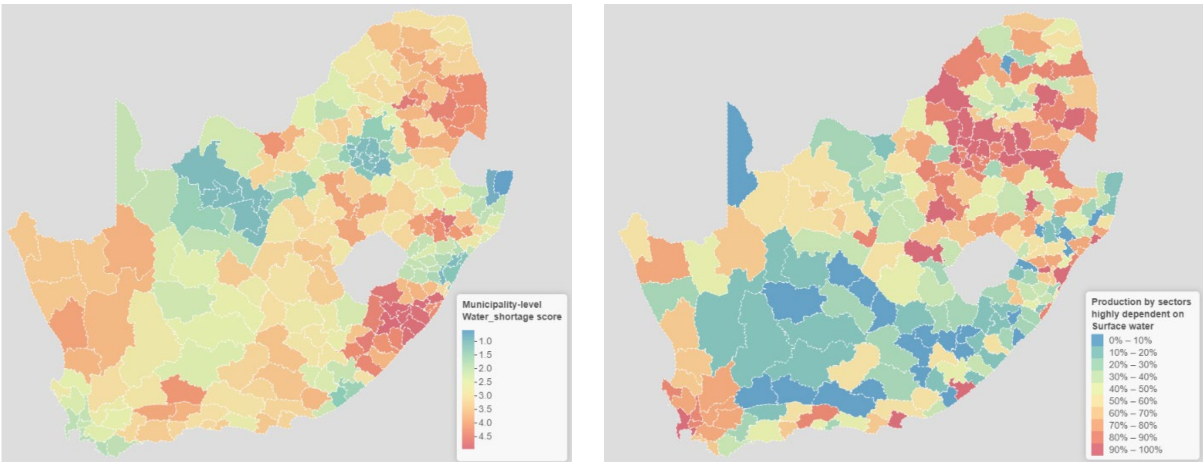


Note: Direct (blue), Indirect (pink)

3.1.3 Spatially explicit assessment of surface water related physical risks

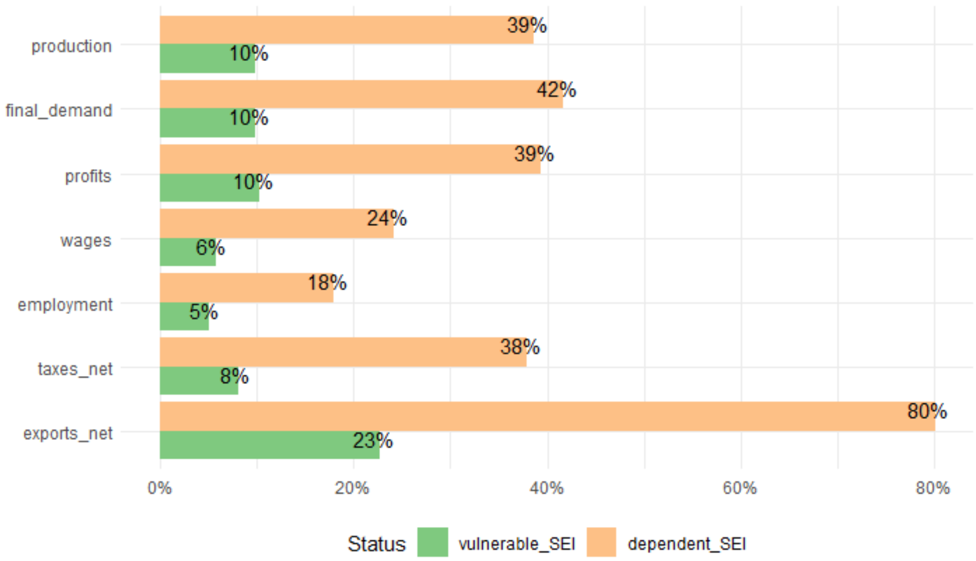
Water shortage-sensitive municipalities are not evenly distributed across South Africa. The left map of Figure 8 shows the water shortage risk scores of the 234 municipalities. This score corresponds to the Water scarcity risk (ranging from 1 with low risk to 5 with very high risk) extracted from South Africa WWF Water Risk Filter itself constructed from Water Shortage indicator based on the Water Resources of South Africa, 2012 Study (WR2012). With the threshold we have set at 3 on the risk score, 113 municipalities emerge as water-sensitive. 23 sensitive municipalities are located in the provinces of Eastern Cape, 21 in KwaZulu-Natal, 19 in Limpopo, 13 in Free State, 12 in Western Cape, 9 in Mpumalanga, 8 in Northern Cape, and 8 in North West. Across these provinces, the 113 critical municipalities produce 24% of SA output, 23.1% of final demand, 24.9% of profits, 24.7% of wages, 24.4% of employment, 23.2% of tax revenues, and 26.3% of net exports.

Figure 8. Water-shortage municipal risk scores (left), Activities highly dependent on surface water, by decile of production value (right)



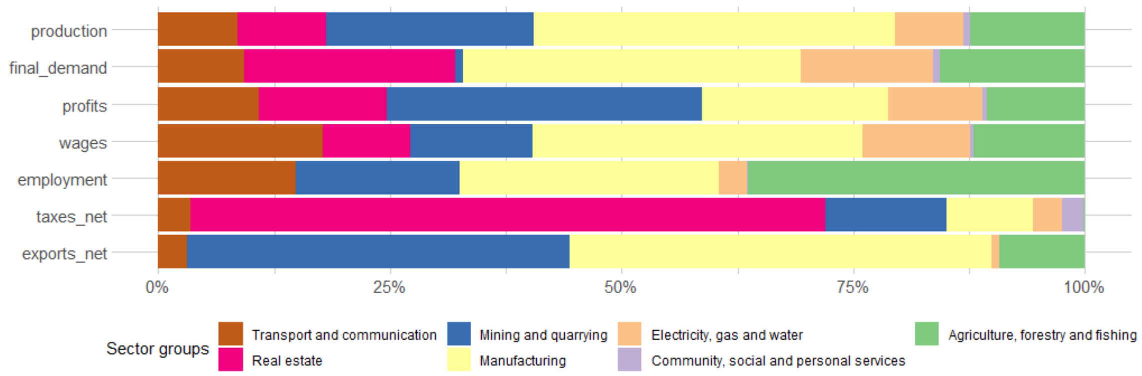
The right map in Figure 8 shows deciles of the production level generated by activities highly dependent on surface water per municipality. Vulnerable SEIs are the SEIs generated in water-sensitive municipalities by highly water-dependent sectors. As shown in Figure 9, production directly vulnerable to water-shortage amounts to 9.8% of South African total production, against 38.6% of exposed production identified in the previous chapter (output generated by all activities highly dependent on surface water, regardless of their location). As shown in Figure 9, 8-10% of profits, household goods, production, and tax revenues emerge as vulnerable to water-shortage. Wages and employment are vulnerable to water-shortage at about 5-6%. Exports emerge again as the SEI the most threatened by physical shocks. While 80.1% of South African exports are generated in activities highly dependent on surface water, 22.7% are generated in such activities located in water-scarce municipalities. In other words, almost a quarter of net exports appears directly vulnerable to water shortage. Therefore, there are high risks of trade imbalances and foreign exchange shortages due to water shortages.

Figure 9. Shares of SEIs generated by highly dependent sectors in orange and by highly dependent sectors in sensitive municipalities (that are thus vulnerable SEI) in green



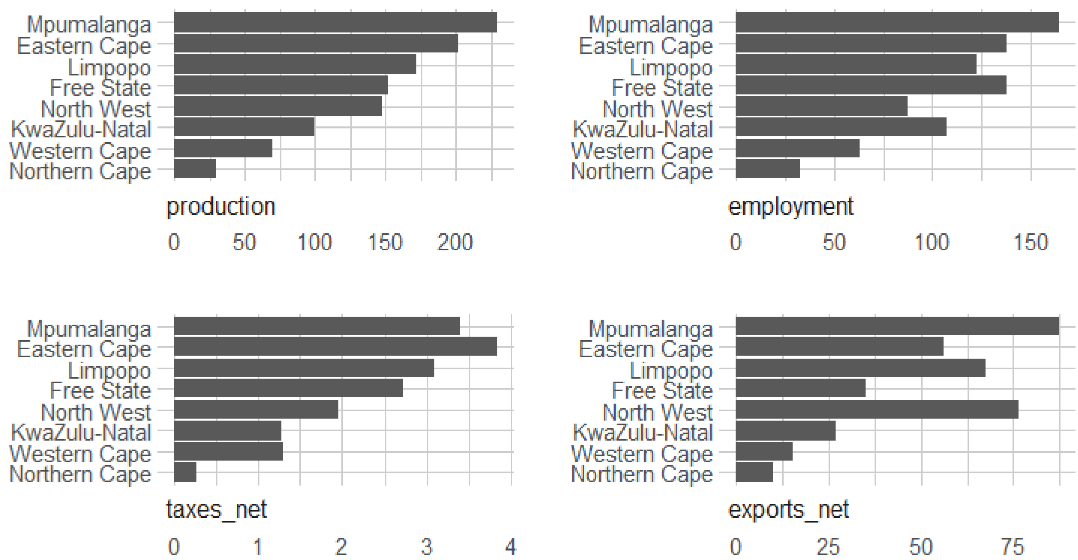
Various sectors are potential to be vectors of socio-economic imbalances related to water scarcity. The set of sectors involved in the vulnerability of SEIs depend on (i) whether they are highly dependent or not on surface water, (ii) their distribution within sensitive municipalities, and (iii) the amounts of SEIs they generate. Figure 10 shows the distribution of vulnerable SEIs across sectors. Mining, manufacturing, agriculture and real estate activities are important vectors of socio-economic vulnerabilities related to water scarcity. There are however important differences among types of socioeconomic indicators. The 22% of exports vulnerable to water-shortage is principally and almost equally distributed across manufacturing sectors (10%) and mining sectors (9%). Agriculture sectors contain 40% of the employment considered vulnerable to water shortage, the rest of water shortage induced unemployment being located in manufacturing, mining and transport sectors. Almost the entire 8.2% of fiscal revenues vulnerable to water-shortage is generated in the real estate sector. Water-related tensions on household consumer goods activities would be through manufacturing, agriculture and real estate sectors.

Figure 10. Sectors distribution of vulnerable SEIs



As shown in Figure 11, SEIs vulnerable to water shortages are mainly located in Mpumalanga, Eastern Cape, Limpopo, and Free State. More than others, these four provinces harbor sources of socioeconomic instability related to water scarcity. Mpumalanga contains the highest amounts of production, profits, employment and net exports generated by activities vulnerable to water shortage, but Eastern Cape contains the highest amounts of vulnerable wages and taxes generated by such activities. In other words, Mpumalanga concentrates vulnerable labor-intensive activities, but that employs low-paid workers and contributes relatively little to tax revenues compared to Eastern Cape.

Figure 11. Provincial amounts of SEIs generated by activities vulnerable to water shortage (in ZAR billion Rand or k jobs)

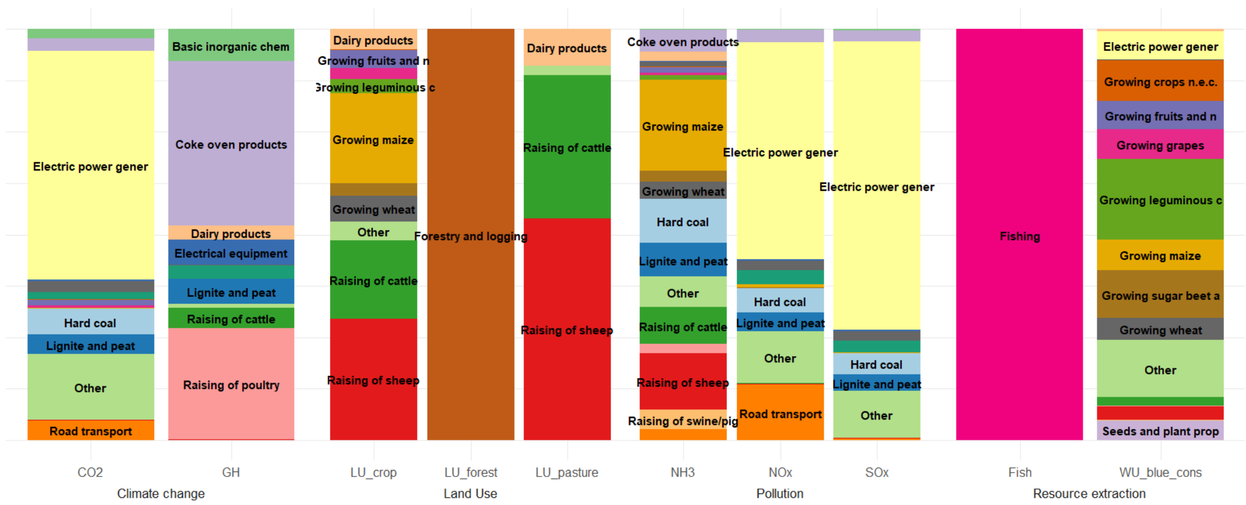


3.2 Transition risks

3.2.1 National-scale exposure to transition risks

Figure 12 provides a graphical representation of the contribution of various economic sectors to the array of biodiversity-related pressures in South Africa. The vertical axis quantifies the respective contribution of each sector to the country's specific pressures, which are delineated along the horizontal axis. The diagram clearly shows that different economic sectors contribute to distinct types of biodiversity-relevant pressures.

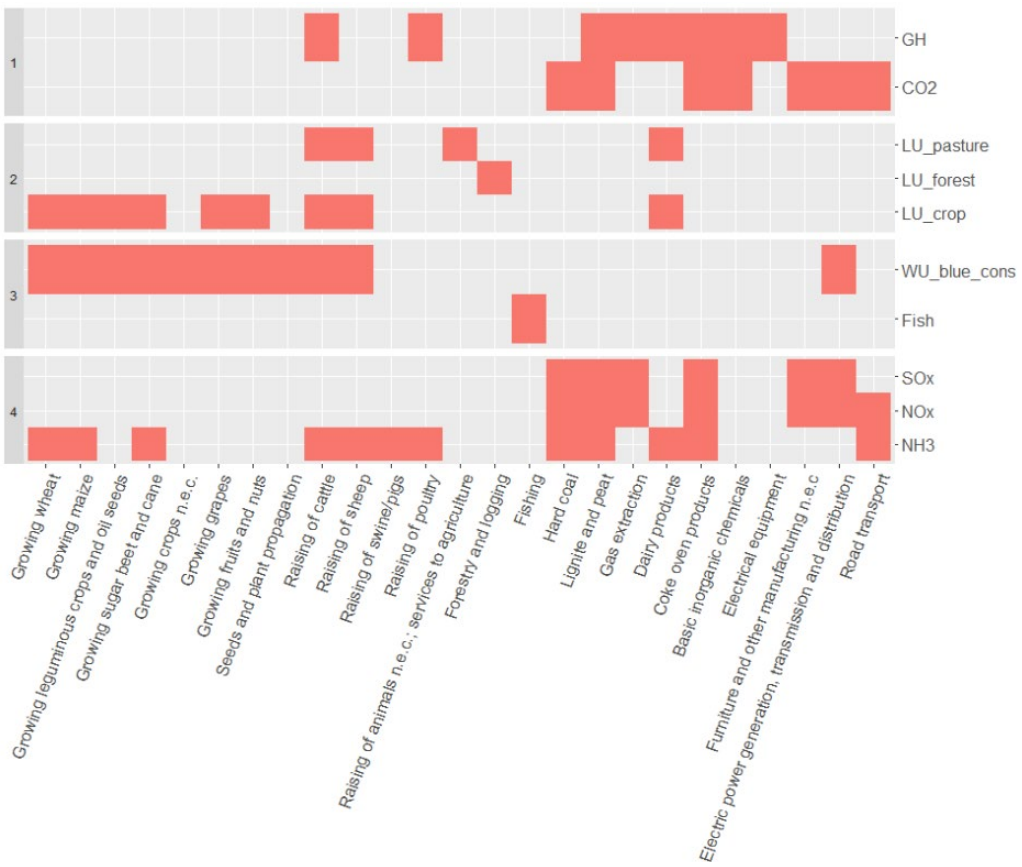
Figure 12. Distribution of economic sectors corresponding to each biodiversity-related pressure



For climate change, the main sectors contributing to CO2 emissions are electricity production (primarily coal), coal mining, and road transport, along with manufacturing sectors such as coke oven products, dairy products, inorganic chemical products, and electrical equipment; and livestock raising. Land-use change is segmented into crop production, forestry, and pasture, with key sectors such as maize, wheat, cattle, sheep, and dairy products being prominent in crop and pasture land-use, while the forestry and logging sector dominates forest land-use. Pollution at the origin of acidification and eutrophication is measured through NOx, SOx emissions for the former (essentially generated by the electricity and coal mining sectors), and NH3 emissions for the latter (generated by a diverse set of agricultural sectors). Resource extraction includes the pressures from fishing and blue water consumption, with the fishing sector predominantly responsible for fish resources extraction and agriculture (mostly harvesting) sectors primarily contributing to blue water consumption.

Key sectors, i.e. those that have a large pressure and/or a high intensity pressure (see the methodology section), are represented in Figure 13.[34] Key sectors for pasture- and crop-related land use are mostly agriculture sectors complemented by the dairy products sector. These sectors also are the key sectors for NH3 pollution, complemented by the coke oven products, the furniture and the road transport sectors. SOx- and NOx-key sectors generating acidification pressures are composed of the hard coal, lignite and peat, gas extraction, textile, coke oven products, furniture, electricity and civil engineering sectors. Key sectors exerting high water extraction pressures are mostly agriculture sectors (especially harvesting sectors), food products sectors and the electricity sector. Climate change pressure-related key sectors are dispersed among several agriculture, manufacture, utility and transport sectors. Fish-extraction and forest land use pressures- key sectors are represented by the fishing and the forestry sectors respectively. Note that some sectors emerge as key for several types of transition risks (coke oven products, dairy products, sheep rising…).

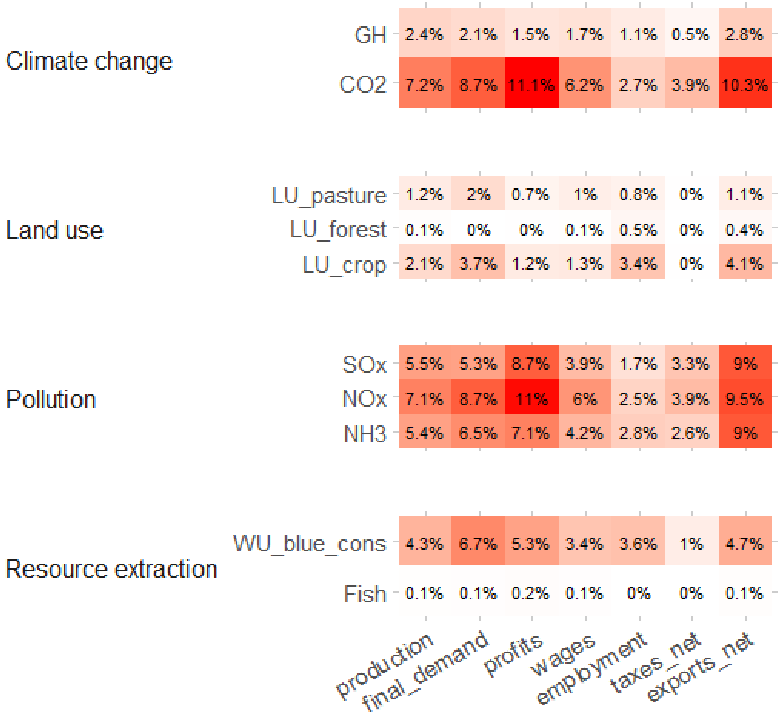
Figure 13. Key sectors for each biodiversity-relevant pressure



[34] Note that except for CO2, the +5% sectors represent around or more than 70% of each national footprint.

The macroeconomic implications of mitigating biodiversity-related pressures vary, depending on the specific pressure being addressed (Figure 14). The production generated by key sectors diverges considerably based on the type of pressure. Land-use pressures related sectors contribute 1-2% of the total production value in South Africa, while carbon emissions pressures-related sectors account for 2-7%. The contribution ranges from 5-7% for pollutant-related sectors, 4% for water-extraction pressures related sectors, and 0.1% for the fishing sector.

Figure 14. Percentage shares of SEIs generated annually by key sectors for each biodiversity-relevant pressures



Exports, final demand, and profits emerge as the SEIs the most at risk from biodiversity transition impacts. Transition shock affecting these sectors to reduce their pressures on biodiversity (i.e. Nature related transition shock) could primarily affect the trade balance, investment trends, and consumer goods' prices and availability if not properly accompanied by support measures to facilitate their transition or reconversion. Nature-related transition shocks could adversely influence the trade balance in multiple ways. Nearly 10% of South Africa's net exports come from pollution-related key sectors, 10.3% from CO2-related sectors, 4% from crop land use-related sectors, and 5% from water use-related sectors. These transition shocks could create price or quantity stresses in household consumer goods markets. For instance, water-related key sectors constitute almost 7% of household demands. Hence, constraints on water use could trigger market unrest, especially in the electricity and food markets. Food markets would also be impacted by shocks on land use-related key sectors as they directly fulfill nearly 4% of household demands.

However, employment, wages, and tax revenues are also vulnerable to specific transition shocks. Tackling land-use and water-related pressures could strain the job market as these key sectors employ a considerable number of workers. Crop land-use related sectors house 3.4% of employment, predominantly in harvesting sectors such as grapes, fruits, and nuts. However, wage exposure is lower than job exposure, indicating that these are generally low-paid jobs. On the fiscal front, transition shocks' financial impact appears minimal for most pressures. However, pollution- and CO_2-related sectors, contributing 3-4% of net corporate taxes in South Africa, could potentially cause some public revenue losses. This financial burden would primarily arise from the coal mining and the electricity sector.

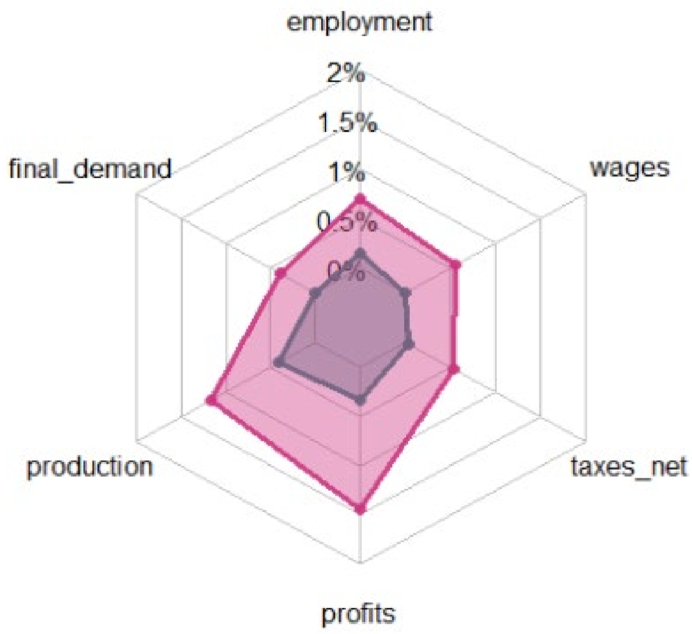
Comparable to the case of physical risks, indirect effects of transition shocks can affect the entire economic structure, further amplifying effects on SEIs. As a case study, we consider the indirect effects of a shock affecting the coke oven products sector. The main reason why we choose to focus on this case is that the coke oven products sector has been identified as a key sector for five different environmental pressures, associated with climate change and pollutants (CO_2, GHG, NH_3, SO_x, and NO_x). Any ambitious policy intended to mitigate these biodiversity-relevant pressures would thus affect this sector. The coke oven products sector does not significantly contribute to SEIs generation on its own, but as we will see, the socioeconomic implications of disturbances along its value-chain are worth considering.

A decline in the coke oven products sector would decrease demand, particularly addressed to mining, quarrying, transport, and trade sectors. Sectors such as stone, sand, and clay quarrying, as well as hard coal mining would experience sharp demand drops of roughly 10% and 5% respectively (see Table 5). The socioeconomic variables primarily impacted by these demand effects are above all profits and production (see Figure 15).

Table 5. Indirect exposure of sectors to demand effects of a shock on the coke oven products sector

Sector	Indirect effects (in ZAR billion Rand)	Indirect effects to production ratio	Sector group
Quarrying of stone, sand and clay	483 802	10.08 %	Mining and quarrying
Hard coal	426 107	4.54 %	Mining and quarrying
Wholesale and retail trade Repair of motor vehicles and motorcycles	356 055	0.50 %	Trade, catering and accommodation
Chemical and fertilizer minerals	222 992	6.09 %	Mining and quarrying
Finance and insurance	166 679	0.32 %	Finance and insurance
Services to transport	113 469	1.60 %	Transport and communication
Electric power generation, transmission and distribution	111 975	0.64 %	Electricity, gas and water
Rail transport	101 905	1.46 %	Transport and communication
Professional, scientific and technical services	92 897	0.37 %	Business services
Uranium ores	92 659	2.08 %	Mining and quarrying

Figure 15. Socio-economic exposure to demand effects from a shock on the coke oven products sector



Note: Direct (blue), Indirect (pink)

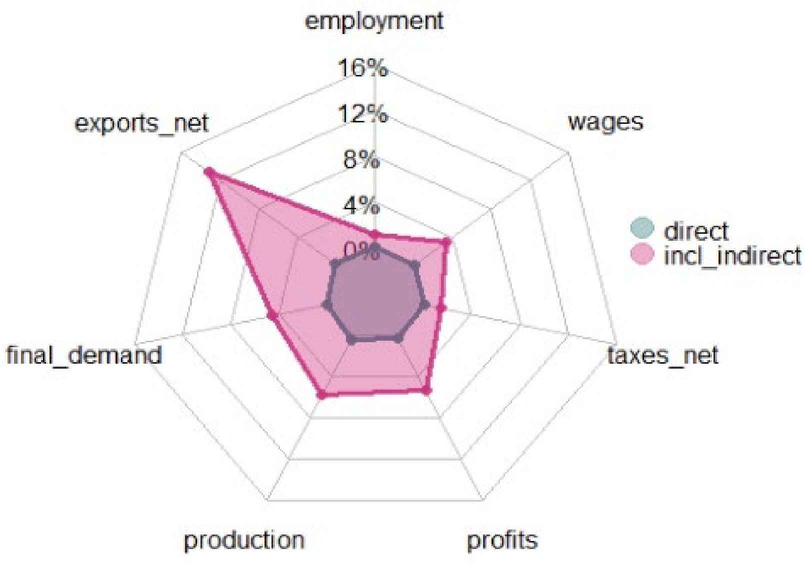
Supply-side effects are also substantial and concentrated on other manufacturing industries, mostly basic ones, and the electric power generation sector, due to their dependency on coke oven products (see figure 16). For example, more than 30% of the value of all the physical inputs used by the basic petrochemical products sector, and more than 20% of physical inputs used by the basic organic and inorganic chemical sectors, are composed of coke oven products (see Table 6). The basic metals manufacturing and fertilizer sectors would encounter severe supply challenges in the event of difficulties to buy coke oven products.

In terms of socioeconomic effects, it is primarily exports that would suffer from these supply constraints. Despite the coke oven sector representing only 0.02% of South African net exports, sectors exposed to indirect supply effects generate more than 13% of South African exports (see Figure 16). For instance, sectors such as basic gold, and basic organic chemicals, inorganic chemicals, and petrochemicals, all of which derive more than 10% of the value of their physical inputs from coke oven products, account for 11% of South African exports.

Table 6. Indirect exposure of sectors to supply effects of a shock on the coke oven products sector (threshold=10%)

Sector	Share in total physical requirements	Production (in ZAR billion Rand)	Sector group
Basic petrochemical products	31.9%	1501600	Manufacturing
Basic organic chemicals	24.6%	4589700	Manufacturing
Basic inorganic chemicals	20.8%	1439500	Manufacturing
Nitrogenous fertilizers	14.8%	2315500	Manufacturing
Basic Gold	14.4%	8750500	Manufacturing
Basic nickel	12.8%	569280	Manufacturing
Basic Copper	11.3%	378480	Manufacturing
Basic lead/zinc/silver	10.8%	80937	Manufacturing

Figure 16. Socio-economic exposure to supply effects from a shock on the coke oven products sector



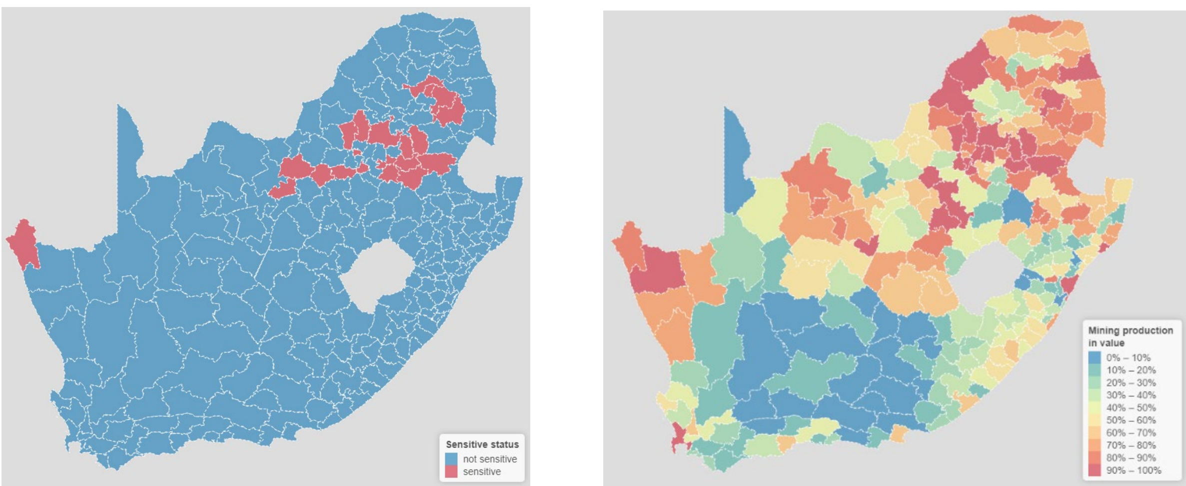
Note: Direct (blue)
Indirect (pink)

4. Spatially explicit assessment of threatened ecosystem-related transition risks

Here, we focus on the location and the likelihood of economic activities to be affected by measures intended to protect particular threatened terrestrial ecosystems: vegetation types. A vegetation type is a category of terrestrial ecosystem and their mapping has a long history in South Africa (Botts et al, 2020; Skowno et al 2021). Indeed, the new Kunming-Montreal Global Biodiversity Framework set new 2030 ambitions to reduce ecosystem degradation and species extinction risks (cf. target 3 and 4) and some new transition measures could be taken in the near future.

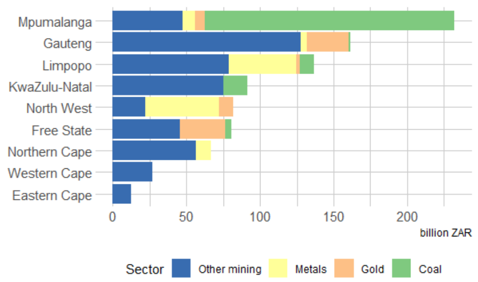
Terrestrial ecosystems threatened by mining activities are principally located in the provinces of Gauteng, Mpumalanga, and North West; and marginally in Free State, Limpopo, Eastern Cape and Northern Cape. No terrestrial ecosystems threatened by mining activity are located in Western Cape or KwaZulu-Natal. But 13.8% and 12.8% of the areas of Gauteng and Mpumalanga are covered by ecosystems threatened by mining activities, respectively. The figure amounts to 7% in North West, 3% in Free State and 1.3% in Limpopo. Under the criteria described in Section III.1.B.b, 21 municipalities are considered as sensitive to the protection of vegetation threatened by mining (shown on Figure 17, left). These are the “mining pressures-sensitive municipalities”. They are principally located in Mpumalanga (containing 7 mining-sensitive municipalities), in North West (containing 6 mining-sensitive municipalities), in Gauteng (4) and in Limpopo (3), the last one being located in Northern Cape.

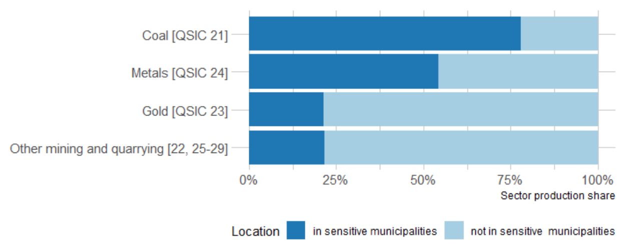
Figure 17. Map of mining pressures-sensitive municipalities (left)
Mining production in value (municipality deciles) (right)



On the economic side (see Figure 17, right), mining production is not evenly distributed in South Africa. In production value, 30% of mining activity is located in Mpumalanga, 16% in Gauteng, 15% in Limpopo, 10% in North West, 9% in Free State, another 9% in KwaZulu-Natal and the rest in Northern, Western and Eastern Cape. In addition, each province locates different types of mining activities (see Figure 18, left). Despite the high aggregation of mining sectors that offers the spatial economic data, it highlights that coal mining prevails in Mpumalanga, while gold and other mining (such as gold and precious metals) prevails in Gauteng. We thus expect that the more the vegetation threatened by mines are located in Mpumalanga for instance, the more the coal sector will be specifically vulnerable to measures to protect threatened vegetation.

Figure 18. Sectoral distribution of mining activities among provinces (left) Mining sectors' production share in or not in mining pressures-sensitive municipalities (right)





Overall, the 21 mining pressures-sensitive municipalities produce ZAR 303.8 billion from mining sectors, representing almost 3% of the country's production level and 43.2% of mining production. Because there are disparities among the types of mining sectors located in such municipalities, there are differences in vulnerability between types of mining activities. As shown on Figure 18 (right), less than 25% of the activity of the quarrying of stones and the mining of chemicals sector is located in mining pressure-related sensitive municipalities, but around 80% of coal mining activities and 55% of metal mining activities are located in sensitive municipalities. The protection of terrestrial ecosystems threatened by mining activity in South Africa would therefore primarily affect coal and metals mining activities among the different mining activities. The important role of coal mining reveals a clear overlap with the low-carbon transition challenge. Closing coal mines could therefore produce a double dividend by contributing to South Africa's climate change reduction objectives and also to achieving the targets of the new global biodiversity framework.

Table 7 indicates the amounts of SEI generated by mining activities located in mining pressures-sensitive municipalities. Mining activities located in such sensitive municipalities furnish ZAR 3.4 billion of household demand (0.1% of the country's total), generate ZAR 111.5 billion of profits, pay ZAR 33.8 billion of wages, contain 175.1 thousand of jobs, pay ZAR 4 billion of taxes and export ZAR 180.2 billion of goods. Given the capital-intensive nature of mining activities, the national share of profit vulnerable to the protection of the concerned ecosystems (4.3%) is significantly larger than the national share of wages and employment vulnerable to such transition shocks (1.5% and 1%). Protecting the concerned ecosystems by closing the concerned mines would nevertheless expose approximately 175 thousand jobs, mainly located in Mpumalanga. In addition, despite the significant share of production generated by mining sectors located in sensitive municipalities (2.7% of the country total), these activities provide a small amount of final goods to households (0.1%). In general, mining activities provide goods to other industries and few directly to households. Exports emerge as highly vulnerable to the protection of ecosystems threatened by mining activities. Indeed, almost 50% of exported mining products are extracted in mining-sensitive municipalities, representing almost 11% of the total net exports value of South Africa. Therefore, closing the corresponding mines in order to preserve the ecosystems threatened by those activities would have significant effects on South Africa's trade balance.

Table 7. SEI generation in mining sectors located in mining-sensitive municipalities

SEI	Value generated by mining activities in mining pressures-sensitive municipalities	Country share	Share in mining activities
Production	ZAR 303.8 billion	2.7%	43.2%
Final demand	ZAR 3.4 billion	0.1%	43.4%
Profits	ZAR 111.5 billion	4.3%	43.5%
Wages	ZAR 33.8 billion	1.5%	35.6%
Employment	175 thousand jobs	1%	42.8%
Taxes net	ZAR 4 billion	1.8%	56.7%
Exports net	ZAR 180.2 billion	10.9%	48.9%

We identify only one scenario suitable to analyze physical shocks, the exploratory scenario of Johnson et al. (2021). It corresponds to a narrative where biodiversity tipping points are crossed. Indeed, they analyzed how the partial decline of three ESs (pollination, marine production, and timber production) would impact the economy. The study does not specify the nature of the shock that would lead to such degradation, probably because it is challenging to scientifically explain the causes and likelihood of triggering the collapse or regime shift of ES (Turner et al., 2020).

4.1 Results conclusion

Table 8 and 9 summarize the main outcome of our NRR assessment for South Africa. A few conclusions can be drawn from our study. First, these results highlight the systemic nature of NRRs: the sectors dependent on at least one ecosystem service represent a significant share of production and generate an important share of SEIs. When moving away from exposure only and looking at vulnerabilities these shares of SEIs, albeit lower in value, remain significant, posing possible threat to macroeconomic stability (e.g. 22.7% of exports produced in municipalities vulnerable to water shortage or 11% of exports produced in municipalities vulnerable to mining activities).

Second, NRRs stress the importance of providing multidimensional analyses: there are multiple dependencies and multiple pressures exerted by economic activities producing directly or indirectly multiple socio-economic indicators. Given the complexity of these interactions, it is important to be able to systematically filter the most probable source of NRRs and to identify the sectors and locations that are the most likely to be affected by these NRRs and their importance for socio-economic stability or development, to design and implement more in-depth sectoral/geo-localized analyses. In our case, the dependency to water provisioning emerges as a candidate for physical risk analysis while mining and agriculture are candidates for transition risks analyses. The identified sectors are important mostly for exports and final demand production in the case of South Africa.

Finally, the results have shown the importance to consider both direct and indirect impacts of NRRs. We have proposed methodologies to (1) identify key sectors from a direct point of view and then (2) quantify indirect impacts both upstream and downstream the value chain. The approach has been applied to the case of pollination for physical risks and the case of coke oven products for transition risks. These methodologies ought to be improved, notably by being able to determine the level of dependency of certain sectors to goods and services produced by other sectors to produce their own goods or services.

Table 8. Main results for physical risks

Indicator	Impacts
Economic Activities Exposure	50% of South Africa's output from activities exposed to ≥2 ecosystem services.
SEIs Dependency	70% final demand, 58.5% profits, 46% wages, 40% employment, 51.6% taxes, 83.4% net exports from sectors dependent on ≥1 ecosystem service.
Dependency on Ecosystem Services	Over 30% production reliant on water provision, flood/storm protection; 20-30% on climate regulation/mass stabilization; 8% on water quality, 6.5% on sensory impacts mediation.
Indirect Exposure (Pollination Shock)	Only 3% net exports, household goods, employment from directly pollination-dependent sectors; around 10% indirectly. Nitrogenous fertilizers, refined petroleum sectors lose 21%, 8% demand, respectively.
Vulnerability to water shortage (municipality)	113 sensitive municipalities: 9.8% production vulnerable to water shortage; 8-10% profits, household goods, tax revenues; 5-6% wages, employment; 22.7% exports from water-scarce areas.
Sector involved	Manufacturing (10%), mining (9%) for exports vulnerability; 40% of the employment exposed are in agriculture sectors; 8.2% fiscal revenues especially from real estate vulnerable activities.

Table 9. Main results for transition risks

Indicator	Impacts
Biodiversity Pressures	Electricity production, coal mining, road transport, specific manufacturing sectors for climate change; crop production, forestry, pasture (maize, wheat, cattle, sheep) for land-use change; NOx, SOx emissions (electricity, coal mining), NH3 (agriculture) for pollution.
Macroeconomic Implications	Land-use (1-2%), carbon emissions (2-7%), pollutant-related (5-7%), water-extraction (4%), fishing (0.1%) key sectors' production value impact; exports, final demand, profits most at-risk; 3.4% workforce in low-paid jobs in crop land-use sectors; 3-4% net corporate taxes from pollution- and CO2-related sectors.
Indirect Exposure (Coke Oven Products Shock)	Demand decrease in quarrying (10.08%), hard coal (4.54%); impacts profits, production; Supply constraints in manufacturing, electric power sectors; more than 13% of exports from sectors with indirect exposure.
Ecosystems Threatened by Mining	Predominantly in Gauteng (16% mining production), Mpumalanga (30%); 21 sensitive municipalities; 80% of coal mining activities and 55% of metal mining activities are located in these municipalities ; 2.7% national production, 0.1% household demand, 4.3% profits, 1.5% wages, 1% employment, 11% net exports from mining activities in sensitive municipalities.

5. Discussion

This study highlights the significance of integrating socioeconomic indicators and spatial assessments to assess nature-related risks via a case study for South Africa. The proposed approach helps identify leverage points and intervention opportunities, hence enhancing policy design and decision-making related to nature. Indeed, by integrating multidimensional socioeconomic vulnerabilities and spatial assessments, a valuable framework emerges to understand trade-offs and complementarities between ecological and economic objectives relative to nature-related risks. Such integrated approach assists policymakers in prioritizing actions by identifying key sectors and regions for detailed study, thereby enabling the effective distribution of resources and targeted interventions. It offers a nuanced understanding of trade-offs between ecological conservation and economic development, facilitating investments in resilience-building, nature conservation, and sustainable development. The methodology also promotes equity and social inclusion by directing resources to communities disproportionately affected by these risks, thereby advocating for a "Just Ecological Transition." To refine these preliminary analyses, consultations with a diverse set of stakeholders—ranging from public agencies to interested citizens—are essential. Subsequent in-depth studies leveraging national sectoral data can then be conducted for each prioritized sector or region, allowing decision-makers to make informed choices without being overwhelmed by the subject's complexity.

In addition to combining macroeconomic indicators with spatial data, this study integrates economic data with ecological data, emphasizing the need for continuous interactions between these two domains in the future. It highlights that creating a common lexicon, consistent methodologies, and interpretable data for both ecological and economic perspectives is crucial to effectively understand and address nature-related risks. For instance, we were confronted with the fact that SANBI's identification of the pressures responsible for endangering species is difficult to reconcile with the way economists and even IUCN/IPBES identify the drivers of biodiversity degradation. Because of this difficulty, our spatially-explicit assessment of transition risks is not 'homogeneous' with the national-exposure. Indeed, while for physical risks we use a homogeneous method where both the national and the spatially explicit analysis use ENCORE's dependency scores, it is not the case for transition risks analysis which, in the national exposure is based on GLORIA's environmental stressors, while the spatially-explicit assessment assimilates sectors (mining sectors) with a category of pressure identified as a driver of biodiversity loss by the Red List of Ecosystem assessments process ("mining"). To achieve a better integration of ecologists' and economists' frameworks, it is advised that academics actively foster interdisciplinary collaboration, facilitating knowledge exchange and integration between ecological and economic disciplines. This convergence would allow for a more comprehensive assessment of the complex interactions between ecosystems, economic activities, and risks, leading to informed decision-making and policy development.

The development of such approaches is especially contingent upon the availability of datasets detailing the geographic distribution of economic activities. Therefore, it necessitates a concerted effort from the agencies responsible for economic statistics. Typically, while biophysical data capturing the sources of shocks are available at a finer spatial resolution, economic data often pose limitations in terms of geographic granularity. The municipality-level economic data used in this study is a relatively rare resource, albeit already more aggregated than numerous ecological datasets. It is hopeful that the adoption of the TNFD framework by a growing number of countries will catalyze government agencies, companies and financial institutions to support the collection of localized data on their economic operations.

Furthermore, we call upon decision-makers to endorse and promote the generation of more comprehensive ecological datasets. Currently, datasets concerning the condition of ecosystems, derived from direct observations rather than solely relying on modeled estimates, remain fragmented. Even today, a comprehensive global assessment of ecosystem health remains elusive. There exists a pressing imperative to give support to initiatives such as the expansion of the IUCN Red List of Ecosystems to encompass all countries worldwide (as it currently covers only 60 countries) or the periodic updating of assessments for the world's ecoregions (Keith et al, 2013; Bland et al 2017). In addition, datasets pertaining to the provisioning of specific ecosystem services also exhibit gaps. It is challenging to ascertain the status of the supply of certain ecosystem services, such as forest biomass or fish, as well as regulatory and maintenance services, notably waste decontamination and recycling. Furthermore, data on aesthetic services, which hold significant relevance in service-oriented sectors like tourism and real estate, remain inadequately documented (Serna Chavez et al. 2014, Chaplin-Kramer et al. 2019, Pereira et al. 2020, Balvanera et al. 2022).

One of the strengths of the approach proposed here is that it relies solely on existing databases with very few modeling assumptions. This is also due to the fact that we are not proposing a dynamic analysis, and are focusing on exposure and vulnerability as they appear in the latest data available. Given the observed weaknesses of global scenarios on biodiversity dynamics, such as too little disaggregation of relevant sectors, the lack of feedback loops of damages linked to biodiversity loss, the too low level of integration of dynamics linked to biodiversity and ecosystem services in narratives (Maurin et al. 2022) and observed weaknesses of nature-economy models such as the under-representation of physical and transitional risks, and the underestimation of the magnitude of the economic consequences of nature-related risks (Kedwards, Salin and Nepumuk, forthcoming), a data-driven approach, such as the one presented in this paper, presents a directly mobilizable alternative that is less prone to these criticisms (NGFS, forthcoming[35]).

We also hope to promote greater awareness of economic opportunities associated with addressing environmental challenges. These economic prospects are intricately linked to two primary areas: adapting the economy to biophysical changes, which involves reducing

[35] Recommendations toward the development of scenarios for assessing nature-related economic and financial risks. NGFS Technical Document.

dependency on vulnerable ecosystem services and constructing systems to safeguard against natural disasters, and mitigating biodiversity degradation, which includes adopting energy-, land-, and water-efficient production processes and engaging in restoration and protection activities. Furthermore, conducting risk analysis can facilitate the identification of such opportunities. A priority lies in examining each sector of activity to identify companies or organizations that have already implemented commendable practices. Subsequently, various measures can be devised to support and encourage the adoption of a well-organized biodiversity-friendly development.

In conclusion, the integration of multidimensional socioeconomic vulnerabilities and spatially explicit assessments is crucial for a comprehensive understanding of nature-related risks, as exemplified in the case of South Africa. By considering socioeconomic indicators alongside spatial analysis, policymakers gain insights into the broader socioeconomic implications and localized impacts of these risks. This knowledge facilitates the development of tailored interventions, the effective allocation of resources, and the promotion of equitable and sustainable approaches to managing nature-related risks. By incorporating both dimensions, policymakers can enhance resilience, promote social inclusion, and ensure the long-term stability and sustainability of the economy in the face of nature-related challenges.

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Appendix A

Definitions of ecosystem services listed in the ENCORE tool (NATURAL CAPITAL FINANCE ALLIANCE, 2021).

Animal-based energy

Physical labour is provided by domesticated or commercial species, including oxen, horses, donkeys, goats and elephants. These can be grouped as draught animals, pack animals and mounts.

Bio-remediation

Bio-remediation is a natural process whereby living organisms such as micro-organisms, plants, algae, and some animals degrade, reduce, and/or detoxify contaminants.

Buffering and attenuation of mass flows

Buffering and attenuation of mass flows allows the transport and storage of sediment by rivers, lakes and seas.

Climate regulation

Global climate regulation is provided by nature through the long-term storage of carbon dioxide in soils, vegetable biomass, and the oceans. At a regional level, the climate is regulated by ocean currents and winds while, at local and micro-levels, vegetation can modify temperatures, humidity, and wind speeds.

Dilution by atmosphere and ecosystems

Water, both fresh and saline, and the atmosphere can dilute the gases, fluids and solid waste produced by human activity.

Disease control

Ecosystems play important roles in regulation of diseases for human populations as well as for wild and domesticated flora and fauna.

Fibres and other materials

Fibres and other materials from plants, algae and animals are directly used or processed for a variety of purposes. This includes wood, timber, and fibres which are not further processed, as well as material for production, such as cellulose, cotton, and dyes, and plant, animal and algal material for fodder and fertiliser use.

Filtration

Filtering, sequestering, storing, and accumulating pollutants is carried out by a range of organisms including, algae, animals, microorganisms and vascular and non-vascular plants.

Flood and storm protection

Flood and storm protection is provided by the sheltering, buffering and attenuating effects of natural and planted vegetation.

Genetic materials

Genetic material is understood to be deoxyribonucleic acid (DNA) and all biota including plants, animals and algae.

Ground water

Groundwater is water stored underground in aquifers made of permeable rocks, soil and sand. The water that contributes to groundwater sources originates from rainfall, snow melts and water flow from natural freshwater resources.

Maintain nursery habitats

Nurseries are habitats that make a significantly high contribution to the reproduction of individuals from a particular species, where juveniles occur at higher densities, avoid predation more successfully, or grow faster than in other habitats.

Mass stabilisation and erosion control

Mass stabilisation and erosion control is delivered through vegetation cover protected and stabilising terrestrial, coastal and marine ecosystems, coastal wetlands and dunes. Vegetation on slopes also prevents avalanches and landslides, and mangroves, sea grass and macroalgae provide erosion protection of coasts and sediments.

Mediation of sensory impacts

Vegetation is the main (natural) barrier used to reduce noise and light pollution, limiting the impact it can have on human health and the environment.

Pest control

Pest control and invasive alien species management is provided through direct introduction and maintenance of populations of the predators of the pest or the invasive species, landscaping areas to encourage habitats for pest reduction, and the manufacture of a family of natural biocides based on natural toxins to pests.

Pollination

Pollination services are provided by three main mechanisms: animals, water and wind. The majority of plants depend to some extent on animals that act as vectors, or pollinators, to perform the transfer of pollen.

Soil quality

Soil quality is provided through weathering processes, which maintain bio-geochemical conditions of soils including fertility and soil structure, and decomposition and fixing processes, which enables nitrogen fixing, nitrification and mineralisation of dead organic material.

Surface water

Surface water is provided through freshwater resources from collected precipitation and water flow from natural sources.

Ventilation

Ventilation provided by natural or planted vegetation is vital for good indoor air quality and without it there are long term health implications for building occupants due to the build-up of volatile organic compounds (VOCs), airborne bacteria and moulds.

Water flow maintenance

The hydrological cycle, also called water cycle or hydrologic cycle, is the system that enables circulation of water through the Earth's atmosphere, land, and oceans. The hydrological cycle is responsible for recharge of groundwater sources (i.e. aquifers) and maintenance of surface water flows.

Water quality

Water quality is provided by maintaining the chemical condition of freshwaters, including rivers, streams, lakes, and ground water sources, and salt waters to ensure favourable living conditions for biota.

Appendix B

Table 10. Production share of each province in the original VS the extrapolated data

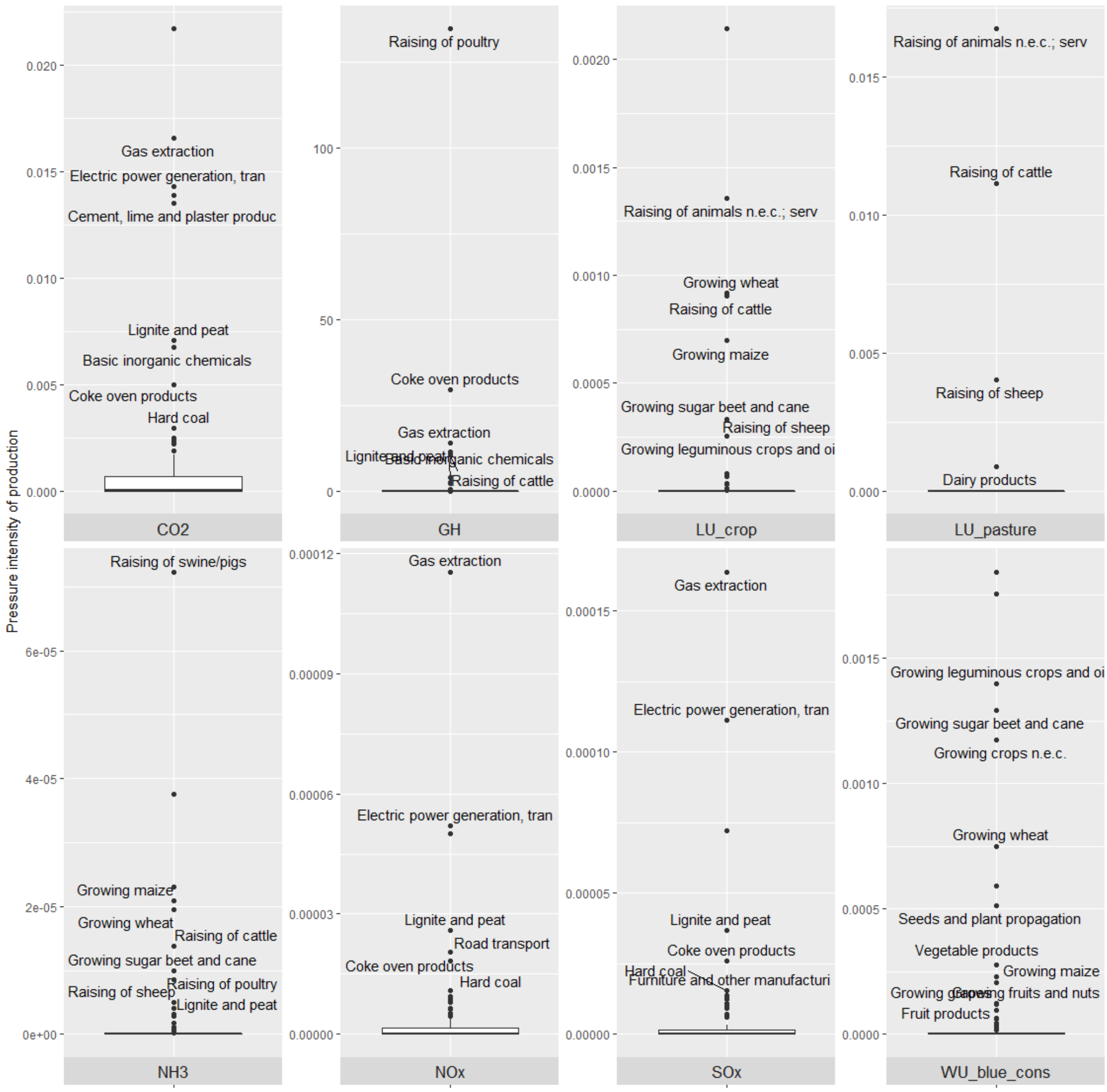
Province	Original shares	Extrapolated
Gauteng	0,346	0,347
KwaZulu-Natal	0,168	0,176
Western Cape	0,141	0,145
Eastern Cape	0,076	0,075
Mpumalanga	0,076	0,082
Limpopo	0,064	0,054
North West	0,059	0,05
Free State	0,05	0,052
Northern Cape	0,02	0,02

Reading note: the original (Quantec) regional data indicate that 34,6% of the gross output of South Africa is generated in the Gauteng province, while the extrapolated data indicate 34,7%.

Appendix C

Figure 19 presents the distribution of pressure intensities across different sectors for each type of pressure considered in the study, displayed as boxplots. The distributions are highly skewed with numerous potential outliers for each pressure type. Typically, sectors that are most intensive in terms of biodiversity-relevant pressures are also those that are highly responsible, although there are a few exceptions. Gas extraction, Electric power generation and several agricultural productions are the main sectors with high intensity of pressures relative to their production output. Every effort to help these sectors to reduce their pressures will thus generate more pressure reductions than other economic sectors, per unit of production.

Figure 19. Boxplot of sectors' biodiversity-relevant pressures intensity of production



Source: author computation.

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