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JUNIPER-Europe indicator-specific resource–environment nexus hotspots across six countries against a wider European reference

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Abstract:

Integrated sustainability assessments often compare countries through separate sectoral indicators, limiting diagnosis of cross-sector resource–environment hotspots. We present JUNIPER-Europe, the European implementation of the Joint Use of Nexus Indicators for Policy and Environmental Resilience framework, for Greece, the United Kingdom, Finland, Czechia, Spain and Romania, together with a wider European reference covering the EU-27, Norway, Switzerland and the United Kingdom. Harmonised 2000–2019 data were used to compare 2019 baseline states across water, food, energy, transport, health and biodiversity. Spain recorded the highest Water Exploitation Index (31.23%), whereas Greece had the largest agricultural share of total water withdrawals (77.1%). The Energy-module contribution dominated total simulated greenhouse-gas emissions in all six national implementations, although Food- and Transport-module contributions varied. Simulated biodiversity-risk proxies identified different national profiles: Romania had the lowest Red List Index (RLI, 0.72), whereas Czechia had the lowest Red List Index of Ecosystems (RLIe, 0.57). The calibrated Quality of Life (QoL) proxy produced a distinct cross-country ordering and is interpreted as a comparative living-conditions measure rather than as an observed welfare statistic. The European reference often fell within national ranges but represented no single national profile. JUNIPER-Europe provides a harmonised baseline for country-specific nexus diagnosis and future pathway analysis.

Keywords: resource–environment nexus; WEFTHB nexus; system dynamics; sustainability indicators; biodiversity risk; European benchmarking

1. Introduction

Rapid biodiversity loss, climate change, resource scarcity and public-health pressures increasingly expose the limits of sector-by-sector sustainability assessment. These pressures reflect broader risks to the safe operating space for human development and to the ecological foundations that sustain economies and societies [1,2]. Biodiversity underpins ecosystem services such as pollination, climate regulation and water cycling, with direct implications for food systems, freshwater security and human well-being [3–5].

At the same time, policy interventions designed within one sector can generate unintended effects elsewhere. Agricultural production is a major driver of freshwater withdrawals and land-use pressure, while land-use change remains one of the dominant direct drivers of biodiversity loss [4,6]. Transport links energy demand, greenhouse-gas emissions, air pollution and health outcomes through fuel use, mobility demand and pollutant-exposure pathways [7,8]. Similarly, decarbonisation strategies can reduce emissions while failing to address non-climate biodiversity pressures, particularly those related to land use, habitat fragmentation and ecosystem integrity, if they are not designed within a broader sustainability framework [4,9]. Recent food- and land-system pathway assessments similarly show that food security, greenhouse-gas mitigation, biodiversity conservation and sustainable water use need to be considered jointly because interventions can generate both synergies and trade-offs across sustainability targets [10]. These interdependencies motivate modelling approaches that move beyond isolated indicators and represent pressure–state–impact pathways across coupled human–environment systems [11–13].

The Water–Energy–Food (WEF) nexus has become a widely used framework for analysing cross-sector interdependencies and the unintended consequences of siloed policies [14–16]. Nexus applications span multiple spatial scales, including city-level assessments of water–energy interactions [17]. Reviews of the WEF literature show that nexus studies increasingly combine qualitative, quantitative and model-based approaches, but also highlight persistent challenges in reproducibility, comparability and operational use for policy assessment [12,18,19]. This is particularly relevant for indicator-based nexus modelling, where the choice of indicators, their directionality and their interpretation rules can strongly influence conclusions. Environmental-indicator research has therefore emphasised the need for transparent indicator typologies, coherent pressure–state–impact logic and indicator sets that are relevant, interpretable and comparable across contexts [11,20,21]. The WEF nexus has also been explicitly cross-mapped against the Sustainable Development Goals (SDGs) to identify potential synergies, trade-offs and reciprocal influences between resource-management priorities and the wider 2030 Agenda [22].

More recent nexus research has expanded the traditional WEF framing to include additional interacting sectors and ecological constraints, including health, biodiversity, land use and climate-related pressures [23–25]. This broader framing is reinforced by the IPBES Nexus Assessment, which stresses that biodiversity loss, water availability and quality, food insecurity, health risks and climate change are interconnected challenges that should not be addressed in isolation [13]. Transport is also central to this expanded nexus. It remains a major source of fossil-fuel demand, greenhouse-gas emissions and air pollution, while transport infrastructure and associated land take can place additional pressure on habitats and ecosystem integrity [4,7]. For these reasons, the present study focuses on the Water–Energy–Food–Transport–Health–Biodiversity (WEFTHB) nexus.

Despite this conceptual progress, a key methodological gap remains. Much of the nexus literature remains fragmented across case-study scales, sectoral boundaries and indicator choices. Reviews show that applications frequently focus on individual countries, basins or narrower sub-nexus combinations, while heterogeneity in methods, variables and indicator definitions limits comparability across cases [12,18,19,26]. As a result, it remains difficult to distinguish recurring cross-sector patterns from context-specific dynamics and to compare sustainability hotspots across different policy, hydro-climatic and socioeconomic settings.

This challenge is especially important across European jurisdictions, where sustainability policy is shaped by shared international commitments such as the SDGs and, for EU Member States, by EU-level agendas including the European Green Deal and the EU Biodiversity Strategy for 2030 [27–29]. Yet European jurisdictions differ substantially in water availability, agricultural structure, energy systems, transport profiles, environmental pressures and social resilience [26,30]. At EU level, sustainability progress is already monitored through harmonised indicator systems, including the EU SDG indicator set, but these monitoring frameworks are not designed to simulate cross-sector propagation pathways or diagnose how national nexus hotspots emerge from interacting pressures

[12,13,30]. A harmonised cross-country modelling framework is therefore needed to identify which nexus pressures are shared across countries, which are context-dependent and where EU-level assessments may obscure national heterogeneity.

The Joint Use of Nexus Indicators for Policy and Environmental Resilience (JUNIPER) framework was developed to address this gap. In its first application, JUNIPER was introduced as a data-driven system dynamics model that extends the traditional WEF nexus by explicitly integrating transport, health and biodiversity within a unified indicator framework [31]. That study applied the model to Greece over the 2000–2019 historical baseline, demonstrating how sectoral pressures propagate through the WEFTHB system to generate internally consistent indicators for water stress, energy and emissions, health outcomes and biodiversity risk. It also established the model’s indicator workflow, including fixed indicator definitions, directionality rules, pressure–state–impact mappings and hotspot synthesis.

Building on this foundation, the present study introduces JUNIPER-Europe, a harmonised multi-jurisdiction implementation of the JUNIPER framework for Greece, the United Kingdom, Finland, Czechia, Spain and Romania, together with a wider European reference implementation covering the EU-27, Norway, Switzerland and the United Kingdom, hereafter referred to as the European reference. Harmonised annual data for 2000–2019 are used to configure structurally consistent model instances and compare their 2019 baseline states through a shared WEFTHB indicator portfolio.

This study advances JUNIPER in four respects. First, it extends the framework from a single-country application to six structurally consistent national implementations and a European reference. Second, it establishes a comparable 2019 WEFTHB baseline from harmonised annual data covering 2000–2019. Third, it identifies shared and country-specific profiles across water, energy, food, transport, health and biodiversity without collapsing the results into a single composite ranking. Fourth, it examines whether the European reference implementation captures or obscures important national differences in resource–environment pressures and outcomes.

Accordingly, we assess whether a common WEFTHB indicator framework can support meaningful cross-country benchmarking, identify the indicator-specific nexus hotspots emerging across the six national implementations and determine how far national profiles depart from the European reference. The resulting harmonised baseline also provides the empirical foundation for subsequent comparative pathway analyses to 2030, 2040 and 2050. The JUNIPER-Europe benchmarking workflow is summarised in Fig. 1.

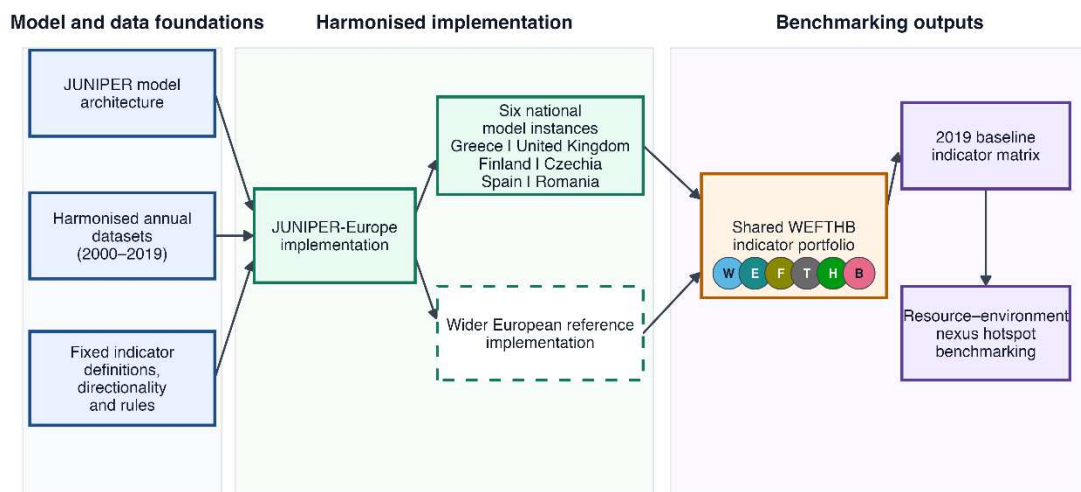


Figure 1. JUNIPER-Europe benchmarking workflow.

2. Results

2.1 Harmonised JUNIPER outputs reveal distinct 2019 nexus profiles

Figure 2 provides an overview of selected 2019 outputs from the JUNIPER Water, Food, Energy, Transport and Biodiversity modules across the six national implementations and the European reference. Original model values are reported within each cell, while colour intensity is scaled separately within each indicator to show the relative cross-jurisdictional position of each implementation. For the RLI and RLIE, the colour scale is reversed because lower index values indicate higher simulated biodiversity risk. For sectoral withdrawal and greenhouse-gas (GHG) shares, darker shading indicates a larger contribution to the corresponding total rather than inherently better or worse performance. The heatmap should therefore be interpreted as a comparison of multidimensional indicator profiles and not as a composite sustainability ranking.

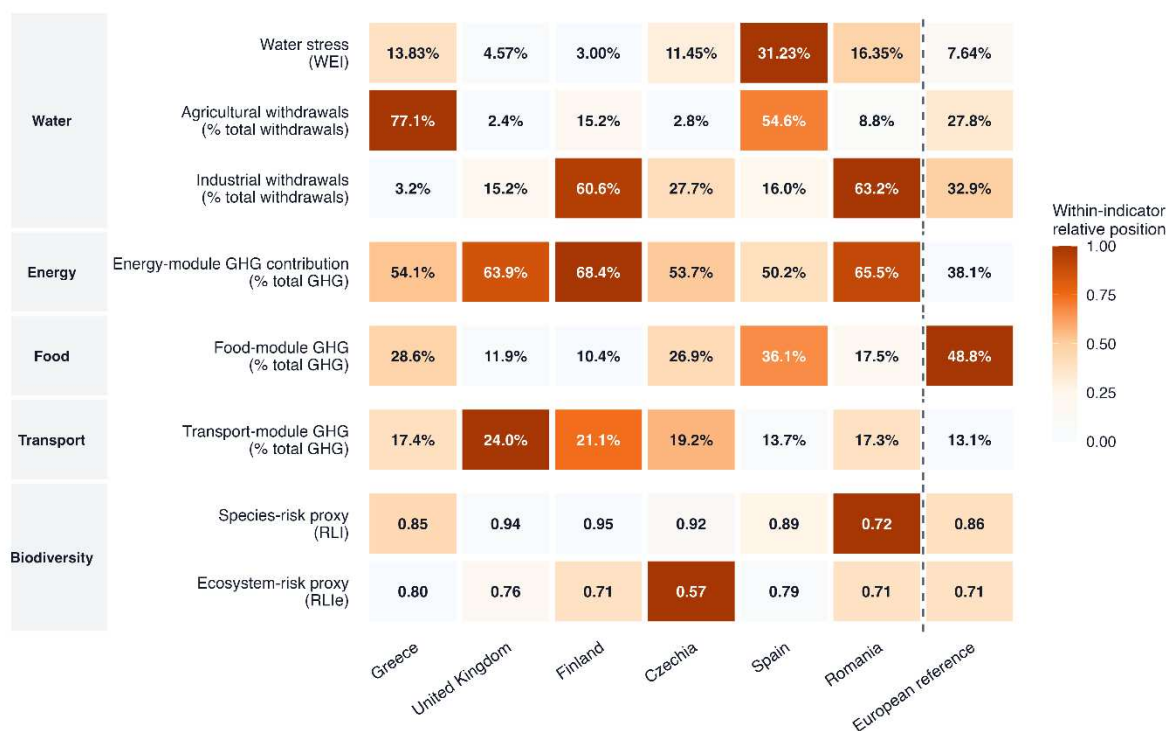


Figure 2. Selected 2019 JUNIPER resource–environment nexus indicator profiles. Cell labels show the original model outputs, whereas colours represent min–max-scaled positions calculated separately within each indicator. For the simulated RLI and RLIE screening proxies, the colour direction is reversed because lower original values indicate higher simulated risk. No composite score is calculated.

The overview reveals marked differences in both the magnitude and composition of resource–environment pressures. Spain recorded the highest Water Exploitation Index (31.23%), whereas Greece had the largest agricultural share of total water withdrawals (77.1%). Finland and Romania showed the largest industrial withdrawal shares, at 60.6% and 63.2%, respectively. The Energy-module contribution formed the largest component of total simulated GHG emissions in all six national implementations, ranging from 50.2% in Spain to 68.4% in Finland. Spain had the largest Food-module contribution among the national cases (36.1%), while the Transport-module contribution was proportionally highest in the United Kingdom (24.0%) and Finland (21.1%).

Biodiversity indicators produced a different cross-country pattern. Romania recorded the lowest species-based Red List Index (RLI = 0.72), whereas Czechia had the lowest Red List Index of Ecosystems (RLIe = 0.57). The European reference fell within the national range for several indicators but did not reproduce any single national configuration. These differences support the domain-specific analyses that follow, which retain the original units and interpretation of the water, GHG and simulated biodiversity-risk screening proxies. Human-system quantities are examined separately because they require distinct interpretation.

2.2 Water stress and selected withdrawal shares reveal contrasting pressure structures

Water pressure varied markedly across the six national implementations in the 2019 baseline (Fig. 3). Spain recorded the highest Water Exploitation Index (WEI), at 31.23%, followed by Romania (16.35%), Greece (13.83%) and Czechia (11.45%). The European reference had a WEI of 7.64%, while the United Kingdom and Finland showed the lowest values, at 4.57% and 3.00%, respectively.

The selected withdrawal shares reveal contrasting demand profiles. Agricultural withdrawals accounted for 77.1% of total withdrawals in Greece and 54.6% in Spain, indicating a prominent agricultural contribution among the selected modelled withdrawal components. Industrial withdrawals accounted for 60.6% in Finland and 63.2% in Romania, while Czechia had the largest domestic contribution among the national implementations, at 42.7%. The European reference showed a more mixed pattern, with domestic, agricultural and industrial withdrawals accounting for 15.1%, 27.8% and 32.9% of total withdrawals, respectively.

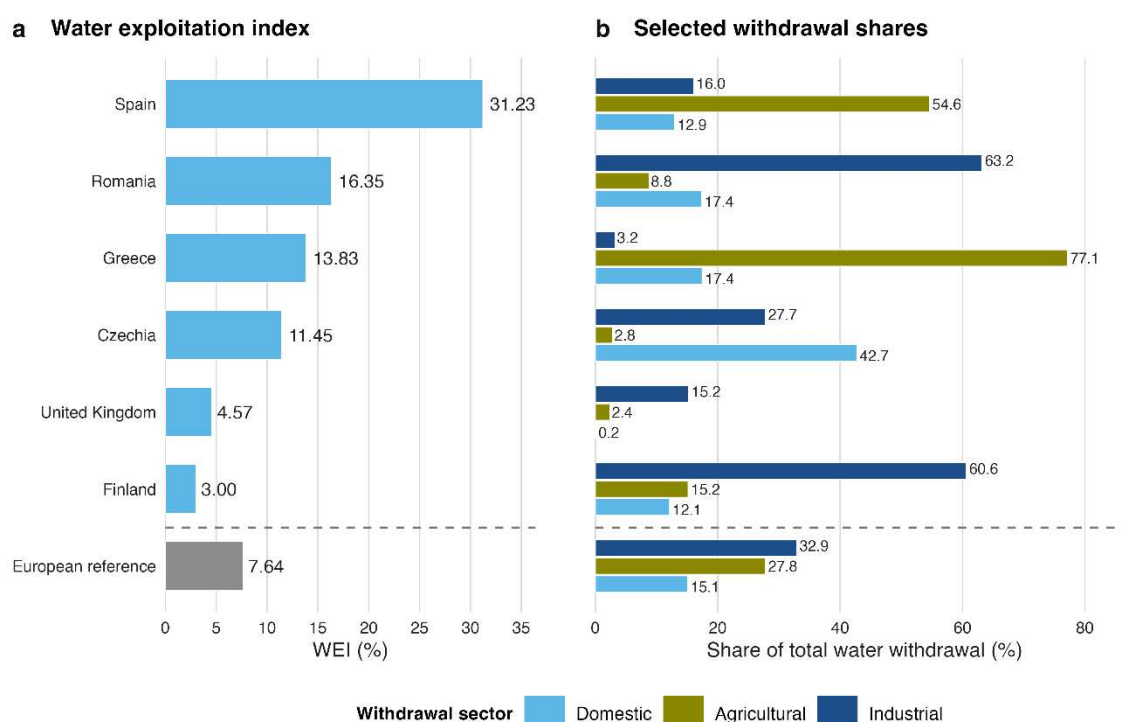


Figure 3. Water stress and selected withdrawal shares in the 2019 JUNIPER baseline. a, Water Exploitation Index. **b,** Domestic, agricultural and industrial withdrawals expressed independently as percentages of total water withdrawal. The displayed components do not constitute an exhaustive decomposition of total withdrawals in every implementation.

The three displayed components (Domestic, agricultural and industrial withdrawals) were selected because they were available under common definitions in the comparative JUNIPER output template.

They do not constitute an exhaustive decomposition of total withdrawals in every implementation, as additional water components are represented within the underlying national models. The reported shares should therefore be interpreted independently as selected model-output components rather than as a complete water-use composition.

These results show that WEI alone does not identify the source of water pressure. The selected withdrawal outputs nevertheless distinguish implementations in which agricultural, industrial or domestic demand forms a prominent component of the modelled water balance and identify priority areas for subsequent scenario testing.

2.3 Module-level GHG composition differs across national implementations

The composition of the total simulated greenhouse-gas output differed substantially across the six national implementations (Figure 4). To compare emissions structure without conflating it with country size, the GHG outputs of the JUNIPER Food, Energy and Transport modules were expressed as shares of the corresponding total GHG output from the Climate Change module. The three module-level contributions summed to within 0.4 percentage points of the exported total simulated GHG output, with the small differences attributable to rounding. These shares describe the internal accounting structure of JUNIPER and should not be interpreted as equivalent to official national inventory categories.

Module-level Contributions to Total Simulated GHG Output

Shares are calculated against the JUNIPER total GHG output; small departures from 100% reflect rounding.

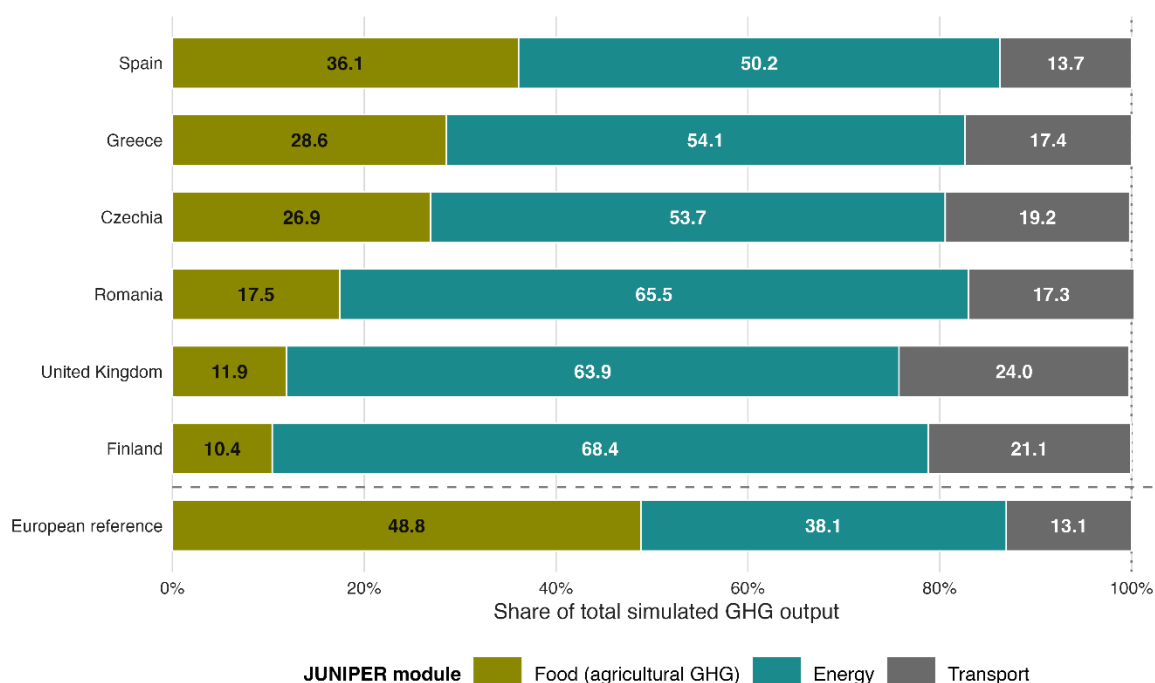


Figure 4. Module-level contributions to the total simulated GHG output in the 2019 JUNIPER baseline.

The Energy-module contribution was the largest in all six national implementations. It ranged from 50.2% in Spain to 68.4% in Finland, with intermediate values in Czechia (53.7%), Greece (54.1%), the United Kingdom (63.9%) and Romania (65.5%). Spain had the largest Food-module contribution among the national cases, with agricultural GHG emissions accounting for 36.1% of its total simulated output. In the European reference, the Food-module contribution was the largest component (48.8%), followed by the Energy module (38.1%).

The Transport-module contribution was proportionally highest in the United Kingdom (24.0%) and Finland (21.1%), followed by Czechia (19.2%), Greece (17.4%), Romania (17.3%) and Spain (13.7%). The European reference recorded a Transport-module share of 13.1%. These differences show that the national implementations have distinct module-level GHG profiles, even where the same modelling structure is applied. The comparison describes the composition of the 2019 JUNIPER baseline and should not be interpreted as a measure of mitigation potential, policy effectiveness or official sectoral emissions performance.

2.4 Simulated biodiversity-risk screening proxies reveal different national patterns

The JUNIPER Biodiversity module generates model-normalised, pressure-derived species- and ecosystem-risk screening proxies, reported here as simulated RLI and RLIE. These outputs are not official national IUCN index time series. The biodiversity indicators reveal distinct species- and ecosystem-level risk patterns across the six national implementations (Figure 5). Both indices range from zero to one, with lower values indicating higher simulated risk. The species-based RLI ranged from 0.72 to 0.95 across the national cases, whereas the RLIE ranged from 0.57 to 0.80. The two indicators are presented separately and are not combined into a composite biodiversity score.

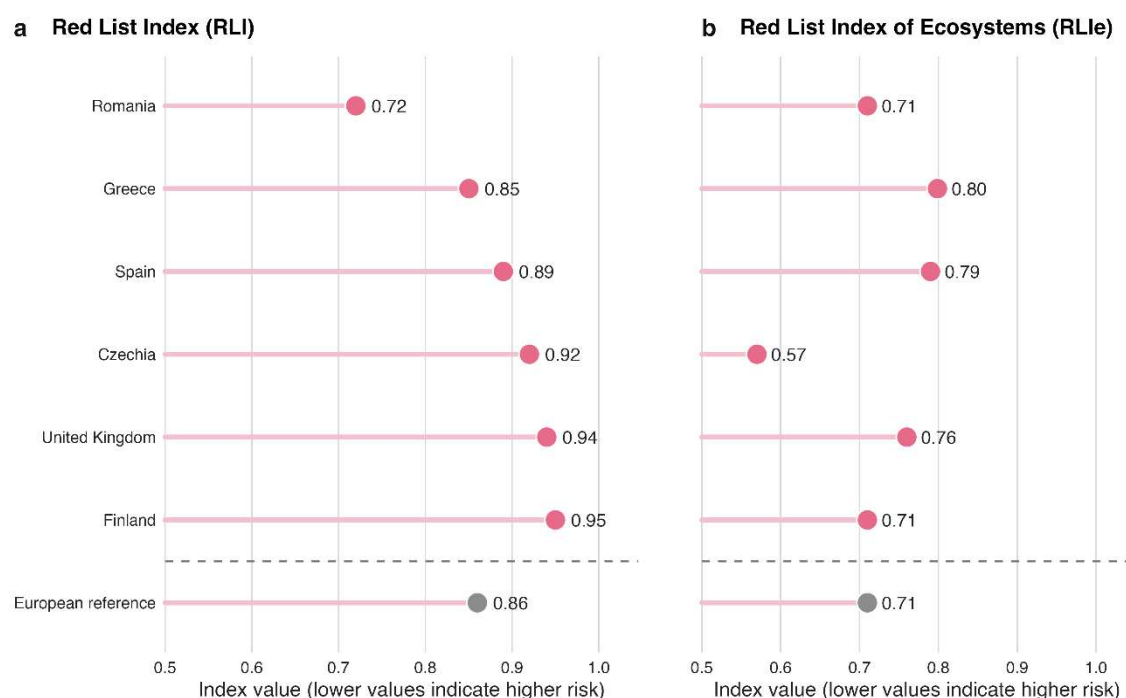


Figure 5. Simulated biodiversity-risk screening proxies in the 2019 JUNIPER baseline. a, Species-based RLI screening proxy. b, Ecosystem-based RLIE screening proxy. Lower values indicate higher simulated pressure-derived risk; the outputs are not official national IUCN index time series.

Romania recorded the lowest RLI (0.72), followed by Greece (0.85) and Spain (0.89), while Finland (0.95) and the United Kingdom (0.94) had the highest species-based index values. The ecosystem-based results produced a different ordering. Czechia recorded the lowest RLIE (0.57), followed by Finland and Romania (both 0.71), while Greece had the highest RLIE value (0.80), followed by Spain (0.79).

The divergence between the two rankings shows that species- and ecosystem-based indicators capture complementary dimensions of biodiversity risk. Czechia, for example, combined a relatively high RLI (0.92) with the lowest RLIE, whereas Romania had the lowest RLI but an RLIE equal to those of Finland and the European reference (0.71). The European reference remained within the national range for both indicators but did not reflect the most pronounced national hotspots. These results describe relative biodiversity conditions in the 2019 baseline and do not, on their own, establish causal attribution or temporal change.

2.5 Contextual life-expectancy reference values and calibrated living-conditions profiles differ across national implementations

The human-system comparison reports two distinct quantities for the 2019 baseline: the national life-expectancy reference-series values embedded in the six national implementations, presented only as external contextual data, and the calibrated Quality of Life (QoL) proxy retained as the JUNIPER human-system output (Fig. 6). No directly equivalent life-expectancy reference value was defined for the wider European reference. QoL is a semi-endogenous composite of eight socioeconomic, environmental, health-care and mobility-related components and is interpreted as a calibrated national living-conditions proxy rather than as an observed or absolute welfare measure [31,32]. The two quantities are therefore presented separately and are not combined into a composite score. The corresponding 2019 values and analytical roles are summarised in Supplementary Table S1.

The 2019 national life-expectancy reference-series values shown in Fig. 6a ranged from 75.60 years in Romania to 84.00 years in Spain. Finland recorded a value of 82.10 years, followed by Greece (81.70), the United Kingdom (81.30) and Czechia (79.30). These values provide contextual information on the national reference series embedded in the model configurations. They are not simulated JUNIPER outputs, are not included in the national-to-European-reference deviation dashboard and do not constitute an independent validation exercise.

The calibrated QoL proxy shown in Fig. 6b produced a different cross-country ordering.

Finland recorded the highest value (201.20), followed by the United Kingdom (195.73), Czechia (189.01), the European reference (184.97) and Spain (174.24). Lower values were obtained for Romania (131.62) and Greece (114.24). Because the calibration period spans a documented change in the Numbeo aggregation formula, and because the proxy includes both imported and model-reconstructed components, these values are interpreted comparatively within the common JUNIPER framework rather than as directly observed or methodologically homogeneous national welfare statistics.

The contrast between the national life-expectancy reference values and the calibrated QoL proxy reflects the different constructs represented by the two quantities. The former provides external contextual information on longevity, whereas the latter represents broader calibrated living conditions. Neither quantity is used to construct an overall country ranking or to infer causal effects of individual nexus pressures.

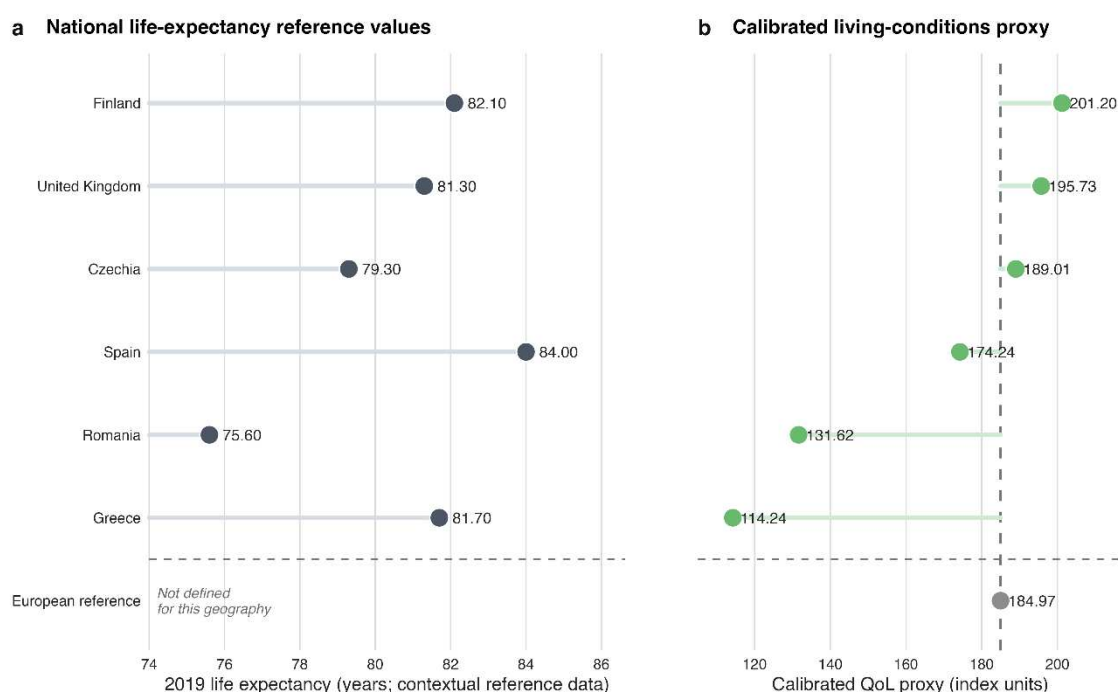


Figure 6. Contextual life-expectancy reference values and calibrated living-conditions outputs in the 2019 JUNIPER baseline. **a**, 2019 values from the national life-expectancy reference series embedded in the six national implementations; no directly equivalent value was defined for the wider European reference. These values are external contextual data and are not simulated JUNIPER outputs or independent validation statistics. **b**, Calibrated Quality of Life (QoL) proxy, interpreted as a comparative national living-conditions measure rather than as an observed or absolute welfare indicator. Horizontal segments in panel b indicate numerical differences from the European-reference QoL value and do not represent temporal change.

2.6 National profiles depart substantially from the European reference

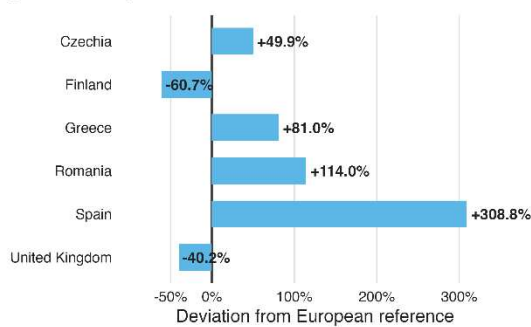
The indicator-specific comparison shows that the European reference implementation does not represent the full range or composition of the selected national resource–environment profiles (Figure 7). Each national output is expressed as a percentage deviation from the corresponding European-reference value. The zero line therefore represents the European reference, while bars extending to the right or left indicate numerically higher or lower national values, respectively. These deviations should not be interpreted uniformly as favourable or unfavourable because the indicators differ in directionality and meaning.

Water stress showed the widest national dispersion. Spain’s Water Exploitation Index was 308.8% above the European reference, followed by Romania (+114.0%) and Greece (+81.0%), whereas Finland

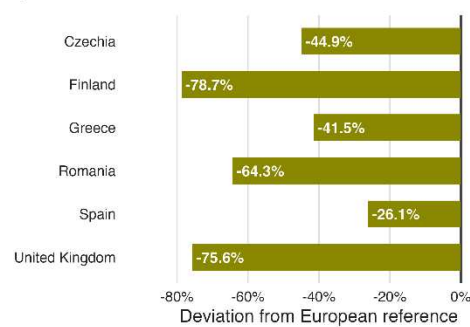
and the United Kingdom were 60.7% and 40.2% below it, respectively. The module-level composition of the total simulated GHG output showed a different pattern. The Food-module contribution was lower in all six national implementations than in the European reference, with deviations ranging from -26.1% in Spain to -78.7% in Finland. By contrast, the Energy-module contribution was higher than the European reference in every national case, ranging from +31.8% in Spain to +79.5% in Finland. The Transport-module contribution was also higher in all six countries, although Spain remained close to the European reference (+4.9%), while the United Kingdom showed the largest departure (+83.4%).

The calibrated QoL proxy produced a distinct national pattern. Finland (+8.8%), the United Kingdom (+5.8%) and Czechia (+2.2%) recorded values numerically above the European reference, whereas Spain (-5.8%), Romania (-28.8%) and Greece (-38.2%) were below it. These deviations describe a calibrated comparative living-conditions proxy and should not be interpreted as differences in observed or methodologically homogeneous national welfare. Biodiversity indicators also identified different national hotspots. Romania's RLI was 16.3% below the European reference, whereas Czechia's RLIE was 19.7% lower. Conversely, Greece and Spain recorded RLIE values above the European reference.

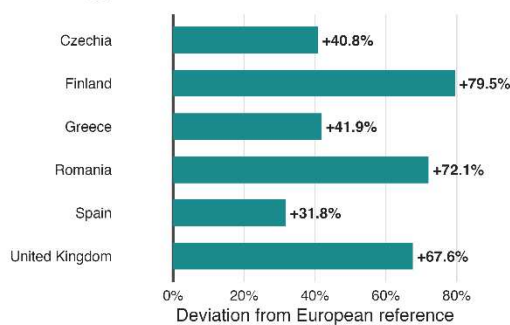
a Water exploitation index



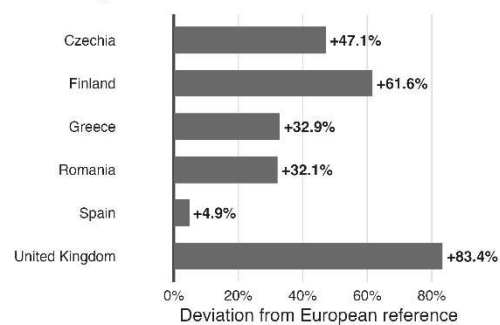
b Food-module contribution



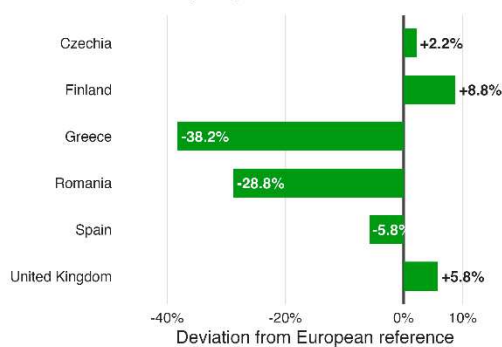
c Energy-module contribution



d Transport-module contribution



e Calibrated QoL proxy



f Biodiversity

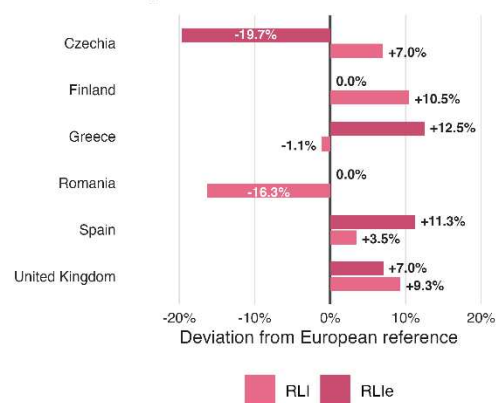


Figure 7. Indicator-specific national deviations from the European reference in the 2019 JUNIPER baseline. **a**, Water Exploitation Index. **b**, Food-module contribution to total simulated GHG output. **c**, Energy-module contribution. **d**, Transport-module contribution. **e**, calibrated Quality of Life (QoL) proxy, interpreted as a comparative living-conditions measure. **f**, simulated RLI and RLIE screening proxies. Positive values indicate numerically higher outputs than the European reference and should not necessarily be interpreted as more favourable outcomes, because indicator directionality differs.

The dashboard confirms that a European-reference value can fall within the national range without representing the structure or extremes of the individual country profiles. It is therefore most appropriately interpreted as a regional benchmark rather than as a substitute for national hotspot assessment. Country-specific analysis remains necessary when identifying intervention priorities and developing differentiated pathways to 2030, 2040 and 2050.

3. Discussion

The JUNIPER-Europe analysis shows the value of applying a common modelling and indicator framework across national systems that differ substantially in their resource use, sectoral structures and environmental outcomes. Although the six national implementations were constructed using the same WEFTHB logic, indicator definitions and 2019 baseline year, they did not produce a common European hotspot profile. Instead, each country was characterised by a distinct combination of water pressure, module-level GHG composition, biodiversity status and human-system profiles. This supports earlier calls for nexus assessments that move beyond isolated sectoral indicators and represent multiple interacting pressures within a coherent analytical framework [11,12,18]. It also extends the single-country JUNIPER implementation by demonstrating how the model can support harmonised comparison without collapsing national systems into a single sustainability score [31].

Water provides the clearest example of why both aggregate and sector-specific indicators are needed. Spain recorded the highest Water Exploitation Index, whereas Greece had the largest agricultural contribution among the selected reported withdrawal components. Finland and Romania had larger industrial contributions among the selected reported components. These differences would be obscured if countries were compared using WEI alone. An aggregate water-stress indicator identifies the overall intensity of pressure, but sectoral withdrawal data are needed to understand its source and the type of intervention that may be relevant. Agriculture-dominated systems may require irrigation efficiency, crop-management or allocation measures, whereas industrial-water profiles point towards different efficiency, reuse and production-system interventions. This distinction illustrates a broader nexus principle: similar aggregate outcomes can emerge from different underlying system structures and should not automatically lead to identical policy responses.

The module-level GHG results reveal a second form of structural heterogeneity. The Energy-module contribution constituted the largest component in all six national implementations, although its relative importance varied considerably. Spain had a more balanced profile, with a larger Food-module contribution than the other national cases, while the Transport-module contribution was comparatively large in the United Kingdom and Finland. These differences are relevant because mitigation priorities depend not only on total emissions but also on Food-, Energy- and Transport-module contributions. Profiles with larger Energy- or Transport-module contributions identify electrification, efficiency and mobility as priority areas for subsequent scenario testing, whereas a larger Food-module contribution highlights agricultural production practices as a domain for further pathway analysis. These baseline profiles indicate where interventions merit examination but do not, by themselves, demonstrate mitigation effectiveness [6,7]. The values presented here should nevertheless be interpreted as the internal module-level composition of the JUNIPER baseline rather than as substitutes for official national greenhouse-gas inventories. The Food, Energy and Transport modules use their respective modelling and accounting procedures; their comparison is intended to reveal simulated nexus structure under a common framework, not to redefine formal inventory categories.

The simulated biodiversity-risk screening outputs further demonstrate why a single environmental endpoint is insufficient. Romania recorded the lowest species-based RLI, whereas Czechia had the lowest ecosystem-based RLLe. The two indicators therefore did not generate the same ordering of countries. This is not an inconsistency: species and ecosystem indicators describe related but distinct dimensions of biodiversity condition and can respond differently to the pressures represented in the model. Presenting them separately avoids concealing these differences through aggregation and is consistent with indicator research that recommends retaining complementary measures where a single index cannot represent the full structure of environmental change [11,21]. It also reflects the broader nexus perspective advanced by IPBES, in which biodiversity outcomes emerge from interacting water, food, climate, infrastructure and human-system pressures rather than from a single environmental driver [4,13].

The human-system comparison adds a complementary perspective but requires strict separation between external contextual data and model outputs. The national life-expectancy reference-series values shown in Fig. 6a are embedded reference data for the six national implementations; they are not simulated JUNIPER outputs, causal estimates or independent validation targets. They provide descriptive longevity context only, and the absence of a directly equivalent value for the wider European reference prevents their inclusion in the deviation dashboard.

The calibrated QoL proxy shown in Fig. 6b represents a broader semi-endogenous living-conditions construct and produced a distinct cross-country ordering.

Finland and the United Kingdom recorded the highest values, whereas Greece and Romania recorded the lowest. Because the calibration period spans a documented change in the Numbeo aggregation formula and combines imported with model-reconstructed components, the absolute values are not treated as observed or methodologically homogeneous welfare statistics [32]. Reporting the contextual life-expectancy values and the QoL proxy separately avoids conflating national longevity context with a calibrated living-conditions measure.

Comparison with the European reference shows that a regional benchmark can be informative without representing the full range or composition of the selected national profiles. The European-reference value lay within the national range for several biodiversity and human-outcome indicators, but aggregate values alone could not identify national extremes or the mechanisms producing them. The European reference should therefore be interpreted as a regional benchmark rather than as a substitute for national assessment. National nexus profiles remain necessary for differentiated policy design [30].

Several limitations frame the interpretation of these results. First, the comparison covers six countries selected to represent contrasting European contexts and should not be treated as statistically representative of Europe as a whole. Second, the analysis focuses on the 2019 baseline generated from harmonised 2000–2019 datasets; it describes cross-sectional differences and does not establish temporal causality, transition speed or policy effectiveness. Third, a common model architecture and shared indicator definitions improve comparability but do not eliminate differences in the availability, resolution and uncertainty of national input data. Fourth, the module-level GHG comparison reflects the internal accounting structure of JUNIPER and should not be interpreted as equivalent to official national inventory categories. Fifth, biodiversity outputs depend on the mapping of simulated pressures to species and ecosystem risk. The national life-expectancy values are external contextual reference data rather than model outputs, while the QoL proxy is a calibrated semi-endogenous indicator rather than a direct epidemiological estimate or an observed welfare statistic. Its cross-country interpretation is constrained by perception-based calibration data, the combination of imported and model-reconstructed components, and the methodological change in the Numbeo aggregation formula within the 2013–2019 reference period. Finally, the present analysis does not propagate input or parameter uncertainty across implementations; the results should therefore be interpreted as deterministic baseline outputs under the harmonised model assumptions.

Despite these limitations, the harmonised baseline provides a consistent foundation for comparative scenario analysis. The country profiles suggest that common European interventions may not produce uniform outcomes, a proposition that will be tested explicitly in the comparative 2030, 2040 and 2050 pathway simulations. The next stage of JUNIPER-Europe will examine how alternative pathways to 2030, 2040 and 2050 alter these profiles, whether countries converge or diverge over time, and which interventions generate cross-domain co-benefits without transferring pressures between water, food, energy, transport, health and biodiversity systems.

4. Methods

4.1 Study design and JUNIPER-Europe implementation

JUNIPER-Europe extends the system dynamics framework introduced previously [31] from a single-country application to six national implementations: Greece, the United Kingdom, Finland, Czechia, Spain and Romania. A wider European implementation covering the EU-27, Norway, Switzerland and the United Kingdom was used as a regional reference and is hereafter referred to as the European reference.

The core Water–Energy–Food–Transport–Health–Biodiversity (WEFTHB) structure, indicator definitions and cross-module relationships established in the model-introduction study were retained

across all implementations. Jurisdiction-specific datasets and parameters were introduced while preserving a common model logic, annual time step and indicator-calculation workflow. This design supports comparison under a shared analytical structure while retaining differences in national resource use, sectoral activity and environmental pressures.

The six national cases correspond to the JUNIPER implementations for which complete harmonised WEFTHB datasets were developed for 2000–2019 within the BIONEXT modelling work. They were retained to span Northern, Southern, Western and Central–Eastern European contexts and contrasting resource-system structures. The selection was purposive and data-availability driven rather than statistically representative of Europe.

4.2 Harmonised datasets and baseline definition

Each national and European reference implementation was populated with harmonised annual datasets covering 2000–2019. Data were compiled from public European, international and national statistical sources and aligned by definition, unit and reference year before being incorporated into the corresponding JUNIPER modules. The harmonised national input datasets and their associated source documentation are publicly archived in Zenodo [33,34].

The historical simulation period was used to establish internally consistent model states and to evaluate the behaviour of selected outputs against available reference series. The cross-country comparison presented in this study uses the final simulation year, 2019, as the common baseline. The term *baseline* therefore refers to the simulated 2019 state generated from the harmonised 2000–2019 historical implementation; it does not refer to a future business-as-usual scenario.

Where source coverage differed among jurisdictions, the module-specific data-treatment and calibration procedures established in the original JUNIPER application were retained. Annual national life-expectancy reference series were retained as external contextual data for the six national implementations. The 2019 values shown in Fig. 6a are not simulated JUNIPER outputs or independent validation targets, and no directly equivalent value was defined for the wider European reference geography; accordingly, they were excluded from the national-to-European-reference deviation analysis. The QoL proxy was calibrated against the available Numbeo reference series for 2013–2019 [32]. Because Numbeo reports that different aggregation formulas were used before December 2017, the historical reference series is used for calibration and benchmarking rather than as an independent or methodologically homogeneous validation dataset [31,32]. All baseline results were extracted for the common simulation year 2019.

The 2019 JUNIPER-Europe benchmarking indicator portfolio is summarised in Table 1.

Table 1. JUNIPER-Europe 2019 benchmarking indicator portfolio.

Domain	Indicator	Unit/transformation	Interpretation
Water	Water Exploitation Index	%	Higher values indicate greater water pressure
Water	Selected withdrawal shares	% of total withdrawals	Selected reported components; not an exhaustive decomposition of total withdrawals
Food	Food-module GHG contribution	% of total simulated GHG	Internal module contribution
Energy	Energy-module GHG contribution	% of total simulated GHG	Internal module contribution
Transport	Transport-module GHG contribution	% of total simulated GHG	Internal module contribution
Biodiversity	Simulated RLI screening proxy	0–1	Lower values indicate higher model-derived species risk
Biodiversity	Simulated RLIE screening proxy	0–1	Lower values indicate higher model-derived ecosystem risk
Human-system context	National life-expectancy reference value	years	External contextual data for the six national implementations; not a simulated output or European-reference comparison
Health	Calibrated QoL proxy	index units	Comparative living-conditions proxy; not an observed welfare statistic
Cross-module	Total GHG output	kg CO ₂ e yr ⁻¹	Denominator for module-level contributions

The final analytical portfolio comprises selected outputs from the JUNIPER Water, Food, Energy, Transport, Health and Biodiversity modules, together with the total GHG output of the Climate Change module used for cross-module accounting and the national life-expectancy reference values presented only as contextual information in Fig. 6a.

Quantities were retained where definitions, units and analytical roles were sufficiently consistent across the six national implementations and, where applicable, the European reference. The portfolio distinguishes pressure indicators, compositional indicators, simulated screening outputs, a calibrated living-conditions proxy and external contextual reference data, which require different interpretations. Water pressure was represented by the Water Exploitation Index (WEI), total water withdrawal and domestic, agricultural and industrial withdrawals. Sectoral withdrawal shares were calculated by equation (1):

$$WS_{i,s} = 100 \times \frac{W_{i,s}}{W_{i,\text{total}}} \quad (1)$$

where $W_{i,s}$ is water withdrawal by sector s in implementation i , and $W_{i,\text{total}}$ is total water withdrawal in that implementation. Domestic, agricultural and industrial shares were reported independently. They were not assumed to exhaust all components of total withdrawal, and no residual category was inferred.

Module-level GHG composition was described using agricultural emissions from the Food module, energy-module contribution from the Energy module and transport emissions from the Transport module. Each contribution was expressed relative to the total GHG output of the JUNIPER Climate Change module by equation (2):

$$GS_{i,m} = 100 \times \frac{G_{i,m}}{G_{i,\text{total}}} \quad (2)$$

where $G_{i,m}$ is the simulated GHG output of JUNIPER module m in implementation i and $G_{i,\text{total}}$ is the corresponding total simulated GHG output. These ratios describe the internal module-level composition of the JUNIPER baseline and should not be interpreted as official national inventory-sector shares. The module-level contributions were checked against the corresponding total GHG output, with minor differences attributed to rounding of the reported values.

Biodiversity was represented by the simulated RLI and RLIE. Both indicators range from zero to one, with lower values indicating higher simulated risk. They were retained as separate endpoints because species- and ecosystem-level conditions represent complementary dimensions of biodiversity and do not necessarily produce the same country ordering. The simulated RLI and RLIE values were calculated internally by each JUNIPER implementation from the harmonised national pressure pathways using the implemented pressure-to-risk mappings. No observed country-level RLI or RLIE time series was used as an external model input.

The human-system comparison distinguished external contextual data from model outputs. The 2019 national life-expectancy reference-series values were reported only for the six national implementations as descriptive longevity context; they were not treated as simulated outputs, independent validation targets or inputs to the European-reference deviation dashboard. The calibrated QoL proxy was retained as the comparative JUNIPER human-system output.

QoL is a semi-endogenous calibrated composite of purchasing power, property-price-to-income ratio, cost of living, safety, health care, traffic commute time, pollution and climate components [31,32]. Some component trajectories are reconstructed from JUNIPER drivers, whereas others are supplied as external series. QoL is therefore treated as a calibrated national living-conditions proxy and is interpreted comparatively rather than as an absolute measure of welfare. The national life-expectancy reference values and the QoL proxy are presented separately and are not combined into a composite score. Definitions and interpretive boundaries for both quantities are provided in Supplementary Table S2. The eight QoL components and their implemented contributions are summarised in Supplementary Table S3.

4.4 Cross-country benchmarking

Cross-country benchmarking was profile-based and indicator-specific rather than based on an overall country ranking. In this study, a nexus hotspot denotes a national implementation that either occupies a comparatively high-pressure or high-risk position for an indicator with a defined adverse direction, or shows a pronounced structural departure from the European reference for a compositional indicator. The first category includes indicators such as the Water Exploitation Index and biodiversity risk, for which directionality can be interpreted explicitly. The second includes indicators such as sectoral withdrawal shares and module-level GHG contributions, which describe differences in system structure rather than inherently favourable or unfavourable performance. Hotspots are therefore defined separately for each indicator; no universal threshold, composite score or overall country ranking is calculated. Original JUNIPER values were retained in all domain-specific figures and tables.

For the overview heatmap, each indicator was min–max scaled separately across the six national implementations and the European reference, as described by equation (3):

$$z_{i,k} = \frac{x_{i,k} - \min(x_{j,k})}{\max(x_{j,k}) - \min_j(x_{j,k})} \quad (3)$$

where $x_{i,k}$ is the value of indicator k for implementation i , and the minimum and maximum are calculated across the six national implementations and the European reference. The scaled values indicate only the relative position of each implementation within the corresponding indicator distribution. They are not comparable across indicators and are not summed or averaged.

For RLI and RLle, the visual scale was inverted because lower original values indicate higher biodiversity risk as described by equation (4):

$$z_{i,k}^{\text{risk}} = 1 - z_{i,k} \quad (4)$$

The original RLI and RLle values were retained in the cell labels. The scaled values were not summed or averaged, and no composite sustainability score was calculated.

Domain-specific figures were used to examine the mechanisms underlying the overview profiles. Water results combined WEI with selected withdrawal shares. Greenhouse-gas results compared the relative contributions of the Food, Energy and Transport modules. Biodiversity outputs, the calibrated QoL proxy and the contextual national life-expectancy reference values were reported separately because their scales and analytical roles differ.

Country differences are reported as 2019 baseline contrasts in model outputs, selected withdrawal shares, module-level GHG contributions and deviations from the European reference. National life-expectancy reference values are presented separately as contextual data. No inferential statistical tests were applied, and the comparisons are not used to establish causal relationships, temporal effects or policy effectiveness.

4.5 Comparison with the European reference

For the indicator-specific dashboard, each national result was expressed as a percentage deviation from the corresponding European-reference output as described by equation (5):

$$D_{i,k} = 100 \times \frac{x_{i,k} - x_{\text{REF},k}}{x_{\text{REF},k}} \quad (5)$$

where $x_{\text{REF},k}$ is the value of indicator k for the European reference implementation. The European reference is therefore represented by zero, with positive and negative values indicating numerically higher or lower national outputs, respectively.

The sign of the deviation was not interpreted uniformly as favourable or unfavourable. For pressure indicators such as WEI, a positive deviation indicates greater pressure. For the calibrated QoL proxy, a positive deviation indicates a numerically higher proxy value but not necessarily better observed welfare. For RLI and RLle, a positive deviation indicates a higher index value and therefore lower simulated risk. For module-level GHG contributions, deviations describe differences in emissions composition rather than overall performance. National life-expectancy reference values were excluded from this transformation because no directly equivalent value was defined for the wider European reference geography. The dashboard was used to visualise national heterogeneity around the European reference and not to produce a country ranking. Because each of the six national cases is included within the wider European reference geography, national-to-reference deviations are descriptive rather than statistically independent contrasts. Inclusion within the reference may slightly attenuate the magnitude of some national departures.

4.6 Data quality assurance and cross-implementation consistency

All outputs retained for cross-country benchmarking were reviewed for unit consistency, missing values, plausible numerical ranges and common definitions across the six national implementations and the European reference. Derived water-withdrawal and module-level GHG shares were recalculated directly from the corresponding raw JUNIPER outputs. The Food-, Energy- and Transport-module GHG contributions were also compared with the total GHG output from the Climate Change module to identify transcription or accounting inconsistencies. Minor differences between the summed components and the reported total were accepted only where they could be attributed to rounding of the exported values.

Cross-implementation consistency was further assessed by confirming that the same indicator definitions, equations, directionality rules and baseline year were applied across all model instances. The model architecture and historical evaluation approach were established in the original JUNIPER application to Greece [31]. In the present study, the emphasis is on the consistency and comparability of the harmonised 2019 outputs rather than on claiming independent external validation for every model variable in every jurisdiction. The underlying final benchmark matrix and figure-source values are available from the corresponding author on reasonable request. The national life-expectancy reference values shown in Fig. 6a were checked for completeness, positive values and consistent treatment as external contextual data; they were excluded from the European-reference deviation calculations. The QoL proxy was retained as the only human-system output in that dashboard. The evidence role and intended interpretation of each benchmark-output class are summarised in Supplementary Table S4, while the cross-implementation quality-control checks are reported in Supplementary Table S5.

Simulations were performed in Stella Architect version 3.7, build 3335. Data quality checks, derived-indicator calculations and figure generation were conducted in R version 4.4.3 using ggplot2 3.5.2, dplyr 1.2.0, tidyr 1.3.1 and patchwork 1.3.2. During manuscript preparation, ChatGPT (OpenAI) was used to support language editing, structural refinement and the drafting of selected text. All outputs were critically reviewed, tested and verified by the authors, who take full responsibility for the final content.

Author contributions

A.I. and C.L. conceptualized the study. A.I., D.K. and K.Z. developed the methodology. A.I. and D.K. curated the data. A.I. implemented the model and prepared the visualizations. A.I. wrote the original draft. A.I., D.K., K.Z. and C.L. reviewed and edited the manuscript. C.L. supervised and administered the project and acquired funding. All authors reviewed and approved the final manuscript.

Data Availability

The harmonised national input datasets are publicly available in Zenodo [33,34]. The final quality-controlled 2019 national and European-reference output matrix, together with the source and derived data underlying Figs. 2–7, is available from the corresponding author on reasonable request. The native Stella Architect model files are not publicly available because of institutional intellectual-property restrictions.

Code availability

The native Stella Architect implementations and associated analysis scripts are subject to institutional intellectual-property restrictions and are not publicly available. The equations, indicator definitions, calculation rules and quality-controlled input and output data required to verify the reported comparisons are provided in the manuscript, Supplementary Information and cited repositories.

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Competing interests

The authors declare no competing interests.

References

1. Rockström, J. et al. A safe operating space for humanity. *Nature* **461**, 472–475 (2009).
2. Steffen, W. et al. Planetary boundaries: guiding human development on a changing planet. *Science* **347**, 1259855 (2015).
3. Millennium Ecosystem Assessment. *Ecosystems and Human Well-being: Synthesis* (Island Press, 2005).
4. IPBES. *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (eds Brondizio, E. S., Settele, J., Díaz, S. & Ngo, H. T.) (IPBES Secretariat, 2019). <https://doi.org/10.5281/zenodo.3831673>
5. Dasgupta, P. *The Economics of Biodiversity: The Dasgupta Review* (HM Treasury, 2021).
6. Food and Agriculture Organization of the United Nations. *The State of the World's Land and Water Resources for Food and Agriculture 2021: Systems at Breaking Point* (FAO, 2021). <https://doi.org/10.4060/cb7654en>
7. IPCC. *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) (Cambridge University Press, 2022). <https://doi.org/10.1017/9781009157926>
8. World Health Organization. Ambient (outdoor) air pollution. *WHO Fact Sheet* <https://www.who.int/en/news-room/fact-sheets/detail/ambient-%28outdoor%29-air-quality-and-health> (2024).
9. Pörtner, H.-O. et al. *Scientific Outcome of the IPBES–IPCC Co-sponsored Workshop on Biodiversity and Climate Change* (IPBES Secretariat, 2021). <https://doi.org/10.5281/zenodo.4659158>
10. Douzal, C. et al. Transforming food and land systems to achieve the SDGs. In *The SDGs and the UN Summit of the Future: Sustainable Development Report 2024* (eds Sachs, J. D., Lafortune, G. & Fuller, G.) 50–82 (Dublin University Press, 2024). <https://doi.org/10.25546/108572>
11. Niemeijer, D. & de Groot, R. S. Framing environmental indicators: moving from causal chains to causal networks. *Environ. Dev. Sustain.* **10**, 89–106 (2008).
12. Albrecht, T. R., Crootof, A. & Scott, C. A. The water–energy–food nexus: a systematic review of methods for nexus assessment. *Environ. Res. Lett.* **13**, 043002 (2018).
13. IPBES. *Thematic Assessment Report on the Interlinkages among Biodiversity, Water, Food and Health of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (eds Harrison, P. A., McElwee, P. D. & van Huysen, T. L.) (IPBES Secretariat, 2024). <https://doi.org/10.5281/zenodo.13850054>
14. Hoff, H. *Understanding the Nexus: Background Paper for the Bonn2011 Conference* (Stockholm Environment Institute, 2011).
15. Bazilian, M. et al. Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* **39**, 7896–7906 (2011).
16. Kurian, M. The water–energy–food nexus: trade-offs, thresholds and transdisciplinary approaches to sustainable development. *Environ. Sci. Policy* **68**, 97–106 (2017).
17. Ioannou, A. E. & Laspidou, C. S. The water-energy nexus at city level: the case study of Skiathos. *Proceedings* **2**, 694 (2018). <https://doi.org/10.3390/proceedings2110694>
18. Endo, A., Tsurita, I., Burnett, K. & Orenco, P. M. A review of the current state of research on the water, energy, and food nexus. *J. Hydrol. Reg. Stud.* **11**, 20–30 (2017).
19. D'Odorico, P. et al. The global food–energy–water nexus. *Rev. Geophys.* **56**, 456–531 (2018).

20. Smeets, E. & Weterings, R. *Environmental Indicators: Typology and Overview*. EEA Technical Report No. 25 (European Environment Agency, 1999).
21. Hák, T., Janoušková, S. & Moldan, B. Sustainable Development Goals: a need for relevant indicators. *Ecol. Indic.* **60**, 565–573 (2016).
22. Ioannou, A. E. & Laspidou, C. S. Cross-mapping important interactions between water-energy-food nexus indices and the SDGs. *Sustainability* **15**, 8045 (2023). <https://doi.org/10.3390/su15108045>
23. Hirwa, H. et al. Insights on water and climate change in the Greater Horn of Africa: connecting virtual water and water-energy-food-biodiversity-health nexus. *Sustainability* **13**, 6483 (2021).
24. Nuwayhid, I. & Mohtar, R. H. The water, energy, and food nexus: health is yet another resource. *Front. Environ. Sci.* **10**, 879081 (2022).
25. Moreno Vargas, D. C., Quiñones Hoyos, C. P. & Hernández Manrique, O. L. The water-energy-food nexus in biodiversity conservation: a systematic review around sustainability transitions of agricultural systems. *Heliyon* **9**, e17016 (2023).
26. Rezaei Kalvani, S. & Celico, F. The water–energy–food nexus in European countries. *Sustainability* **15**, 4960 (2023).
27. United Nations General Assembly. *Transforming Our World: The 2030 Agenda for Sustainable Development*. A/RES/70/1 (United Nations, 2015).
28. European Commission. *The European Green Deal*. COM(2019) 640 final (European Commission, 2019).
29. European Commission. *EU Biodiversity Strategy for 2030: Bringing Nature Back into Our Lives*. COM(2020) 380 final (European Commission, 2020).
30. Eurostat. *Sustainable Development in the European Union: Monitoring Report on Progress Towards the SDGs in an EU Context—2026 Edition* (Publications Office of the European Union, 2026). <https://doi.org/10.2785/9931334>
31. Ioannou, A. E., Kasiteropoulou, D., Ziliaskopoulos, K. & Laspidou, C. S. JUNIPER: Joint use of nexus indicators for policy and environmental resilience—case study of Greece. Revised SSRN preprint at <https://doi.org/10.2139/ssrn.6863181> (2026).
32. Numbeo. Understanding quality of life indexes. https://www.numbeo.com/quality-of-life/indices_explained.jsp (accessed 10 June 2025).
33. Ioannou, A. E., Kasiteropoulou, D., Ziliaskopoulos, K. & Laspidou, C. S. WEFTH nexus data 2000–2019 for six European countries (JUNIPER model). *Zenodo* <https://doi.org/10.5281/zenodo.16947695> (2025).
34. Ioannou, A. E., Kasiteropoulou, D., Ziliaskopoulos, K. & Laspidou, C. S. Water–Energy–Food–Transport–Health–Biodiversity input dataset for JUNIPER model in Greece. *Zenodo* <https://doi.org/10.5281/zenodo.15993325> (2025).

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