Establishing a reference tool for ecosystem accounting in Europe, based on the INCA methodology

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Abstract

The European Commission developed an amendment to Regulation 691/2011 on European environmental economic accounts to include reporting on ecosystem accounts compliant to the United Nations Statistical Commission System of Environmental-Economic Accounts – Ecosystem Accounts (SEEA-EA) standard. To support Member States implementing this regulation, an open source tool, known as INCA-tool, to generate ecosystem service accounts has been developed, based on the Knowledge Innovation Project on Integrated Systems of Naural Capital and Ecosystem Services Accounting (KIP-INCA) methodologies. The INCA-tool was developed by taking into account the FAIR principle for software and data, as well as existing interoperability standards by the SEEA community. Three types of users were identified with their specific needs, interactions and skills. To meet their needs, the INCA-tool was split into two parts, a python package to perform the calculations and an acessible and easy-to-use user interface in QGIS to integrate national information. With a first version of the toolkit in place, improvements to the existing calculation methods and alignment with the upcoming EU regulation can be achieved. Further, feedback from Member States beta-tests and their experiences is currently collected and implemented and the full public roll-out is planned for the end of 2022. The software packages in the toolkit were already used to extend the existing nine INCA European wall-to-wall account series with the year 2018.

Keywords

INCA, SEEA EA, Natural Capital Accounting, QGIS, FAIR, open source, python

Introduction

The European Union (EU) 7th Environment Action Programme (Commission 2014) and the EU Biodiversity Strategy of 2030 (Commission 2020) included objectives to develop Natural Capital Accounting (NCA) in the EU, with a focus on ecosystems and their services. The Knowledge Innovation Project on an Integrated System of Natural Capital and Ecosystem Services Accounting (KIP-INCA) carried out in the years 2016 – 2020 produced pilot ecosystem accounts for the EU that are largely based on models available at the time the project was conducted and using public datasets from the Statistical Office of the European Commision (EUROSTAT), explicit spatial data and Earth Observation (EO) products (Commission et al. 2018, Commission et al. 2019, Commission et al. 2021). Complementary to this KIP-INCA initiative, the European Commission (EC) supported the development of ecosystem accounting in Member States. Furthermore in 2021, the UN Statistical Commission (UNSC) adopted the System of Environmental-Economic Accounts – Ecosystem Accounts (SEEA EA) as an official standard (UNSD 2021). The SEEA EA constitutes an integrated and comprehensive global statistical framework for organising data about habitats and landscapes, measuring the ecosystem services, tracking changes in ecosystem assets and linking this information to economic and other human activity.

Currently, the EC developed an amendment to Regulation 691/2011 on European environmental economic accounts to include ecosystem accounts compliant with the SEEA EA (European Commission 2022). Therefore, in 2021 Eurostat awarded a grant to revise the methodolgoies of the KIP-INCA service accounting models (Vallecillo et al. 2019) and results to support regulary ecosystem accounting (European Commission - Eurostat 2020). The objectives of this project are the increased harmonisation of accounting methods within the EU, providing a tool - called INCA-tool - to produce ecosystem accounts at national scale, extending the time-series of EU wall-to-wall KIP-INCA accounts and facilitating NCA results in regular reporting (Commission et al. 2021). To assist further development and integration into existing tools, the INCA-tool needs to be open-sourced and follow the FAIR (Findability, Accessibility, Interoperability and Reusability) principles for produced data as described by Wilkinson et al. (2019), as well as for the research software itself as described by Lamprecht et al. (2020). The FAIR principles define a technical standard and, therefore, do not provide any quality control of the software or data itself. The in-depth discussion of the FAIR principles is described in a later section of this article. Nevertheless, since these principles are not a binary concept (Lamprecht et al. 2020), they define the scope of FAIRness of the tool and its output.

The main objective of this article is to introduce the INCA-tool as a reference tool for ecosystem accounting in the EU following the amendment to Regulation 691/2011. This includes the basic concept of the tool, the nine currently integrated and harmonised ecosystem services, as well as its usability. Moreover, we evaluate the FAIRness of the INCA-tool following the 15 principles as described in Lamprecht et al. (2020), as well as of the tool output following the 15 principles as decribed in Wilkinson et al. (2019). In order to showcase the modular build-up of the INCA-tool, one ecosystem service - soil retention - is presented.

Tool and User Requirements

To facilitate Member States in the implementation of Regulation 691/2011 (European Commission 2022) and assist EUROSTAT in the validation of the produced national ecosystem accounts, a reference tool was requested to generate SEEA EA compliant European accounts (European Commission - Eurostat 2020). Therefore, the software package must fulfil different tools, as well as user requirements.

A user requirements analysis was performed to identify all possible stakeholders (e.g. EU Institutions and Member States) and to determine their requirements and considerations through interviews. We identified three main users for the INCA-tools: EUROSTAT, Joint Research Centre (JRC) and EU Member States. Furthermore, the analysis showed a large variation of experience in the usage of NCA within the EU Member States. Some EU Member States have little to no experience in integrating NCA in their reporting, where others have expressed no needs for additional tools. Therefore, the INCA-tool has to support the following needs: (1) consultation and use of the results at national level, (2) integration of national data sources in existing KIP-INCA accounting models, (3) using the models as a starting point to develop methods more tailored to regional characteristics. The analysis unveiled that, to support the three main users, the INCA-tool needs to support three different levels of expertise (see Table 1).

The tool requirements are based on an analysis of existing modelling platforms and the requirements from the European Commission. Table 2 highlights the main features of existing ecosystem accounting tools, their potential use in SEEA EA and their compliance with EU Regulation 691/2011. This analysis shows that the ESTIMAP (Zulian et al. 2014) tool, developed by the JRC, was a potential candidate, but is tightly linked to the GRASS database concept (Neteler et al. 2012) and, hence, limited the adaptation, based on user requirements. Currently, it only supports four out of nine mandatory service accounts by the EU Regulation and does not include monetary valuation. Additional requirements were gathered through analysing technical descriptions of IT environments, user requirements gathered during other processes, such as the System of Environmental-Economic Accounts – Experimental Ecosystem Accounts (SEEA-EEA) revision process (UN et al. 2014), an independent expert review report of KIP-INCA ecosystem service accounts and the Mapping and Assessment for Integrated ecosystems (MAIA) project (Hein 2019) complements this information.

Therefore, we decided to build on the existing knowledge of the KIP-INCA models and decided to redesign the tool according to the following tool requirements:

- harmonisation of the existing models (Commission et al. 2018, Commission et al. 2019, Commission et al. 2021) in both processing and data formats;

- validation and enhancement of the quality of the existing models and introduction of compliance with the SEEA EA EU guidelines;
- open-sourced and following the FAIR (Findability, Accessibility, Interoperability and Reusability) principle for research software (Lamprecht et al. 2020);
- output of the tool (maps and tables) should be compliant with the FAIR principle for data (Wilkinson et al. 2019).

The INCA tool

Taking into account the user requirements (Table 1) and tool requirements, the INCA tool is designed in a modular way to allow automated processing, as well as human induced processing through a user-friendly graphical interface. The modularity of the INCA-tool is given by two main components:

- a core library, which can run independently via a command line interface and contains all processing routines for the different accounting modules and
- a front-end library, currently a QGIS (QGIS Development Team 2022) plug-in, to enable users to easily set up processing runs and inspect the results.

Fig. 1 shows both components, implemented in the open source repository (GIT) and licensed under European Union Public Licence (EUPL).

The command line interface provided by the core library, allows advanced users to set up batch runs or scripted sensitivity analyses. The core library supports integration into larger processing frameworks, either using the command line tool or through python Application Programming Interface (API). In this sense, the QGIS plug-in interface is just one example of such an integration.

The core INCA-tool library was set up with extensibility and flexibility in mind (see Fig. 2). The library was developed, based on the KIP-INCA prototypes (Vallecillo et al. 2019) for five of the current implemented services, amongst which some of them are derived from ESTIMAP (Zulian et al. 2014). All models were harmonised and validated against references in order to ensure the functional correctness of the software. The harmonisation also included, next to the map generation, the statistical tabular outputs and interoperability with other software. We want to stress that, therefore, the FAIR principles were not only applied on the software itself, but also on its output data. The different ecosystem services are implemented as independent modules, which are then included in a processing framework that deals with basic tasks, such as command line parsing, configuration files, input data and log files. The package also contains a few shared general utility modules containing routines for common processing steps related to Graphical Information Systems (GIS) data or other frequently used input data formats and exporting tables in a standardised way. This modular structure makes it convenient to include other ecosystem services in the future.

The current implemented front-end (QGIS plug-in) takes away the complexity of having to know how to operate a programming language for the end user, by restricting its input to specifiying the necessary parameters and input data to run a calculation procedure. These can be selected via convenient drop-down menus. After completion of the automatic calculations, the users can inspect the tabular data and maps in the QGIS desktop. The integration of the plug-in in the official QGIS repository is planned.

Adopting the FAIR principles

The KIP-INCA accounts have been developed over the past years through the implementation of spatial models and integrating a variety of geospatial and other data not originally designed for statistical purposes (Vallecillo et al. 2019). Even though the results were published in several reports (Commission et al. 2018, Commission et al. 2019, Commission et al. 2021), researchers or statisticians were not able to replicate these results and were obliged to search through these reports to extract important information (e.g. account results or model parameters). This fact limits the usage of the KIP-INCA methodologies to reproduce regular ecosystem accounts.

To facilitate harmonisation of the services and usability of the tool, we adopted the FAIR (Findability, Accessibility, Interoperability and Reusability) principles for both the research software and the output data. The FAIRness of the software and the data is not limited to the fulfilment of all fifteen principles (Wilkinson et al. 2019, Lamprecht et al. 2020).

FAIRness assessment of the INCA-tool

The FAIRness of the INCA-tool was assessed by following the guideline by Lamprecht et al. (2020) as shown in Table 3. The assessment shows that the current version of the INCA-tool fully fulfils eight out of fifteen principles. It is planned to complement the five partially fulfilled and two unfulfilled principles by assigning a Digital Object Identifier for the software and each version, further align the metadata vocabulary to ARIES (Balbi et al. 2022) and advocate it as community vocabulary (Balbi and Bagstad 2021) and register the software in a searchable software registry.

Application of the FAIR principles for output data

Since the output from the INCA-tool is considered as a product, it is of equal importance to assess the application of the FAIR principles for this output data. The level of FAIRness of the output data was assessed by following the guidelines by Wilkinson et al. (2019) and is shown in Table 4. The assessment reveals that the current version of the INCA-tool provides output data that fully fulfils six out of fifteen principles. It is planned to complement the five partially fulfilled and three unfulfilled principles by aligning the metadata with a standardised vocabulary (from SEEA EA and GEO EO4EA) as soon as it has been provided. Furthermore, it is foreseen that the protocols, as implemented on the website for the European continental accounts, are further improved to facilitate uptake.

Currently, we see that 'Interoperability' is probably the most difficult principle to achieve and requires data compatibility, metadata compatibility and common APIs. The INCA-tool produces cloud-optimised geotiff (COG) raster images which are commonly recognised as an interoperable format that is supported by many platforms (Anonymous 2022). Tabular data are written in machine-accessible formats (like Comma-Separated Values - CSV format) where standard API can be defined (e.g. OpenSearch) to retrieve this information. Another important aspect of interoperability in the accounts is to harmonise the reporting across all EU Member States according to the SEEA EA standard. The standard, however, leaves room for interpretation and, therefore, the European Commission (EUROSTAT) has established a taskforce to have joint discussions for this harmonisation through developing EU guidelines to implement the SEEA EA standard. These EU guidelines are applied in the updates of the INCA-tool, making the tool more interoperable.

The assessment for the FAIRness of the software and the output data showed that our current implementation of the INCA-tool provides a certain degree of FAIRness. Nevertheless, the FAIR principles only describe the technical standard and do not provide any information on the functional correctness of the software itself. To ensure this correctness, we implemented a detailed evaluation and validation scheme for the models (unit tests), as well as the output data (cross-checks between table and map data, plausibility checks).

Example of integrating an ecosystem service in the INCA-tool

To demonstrate the integration of modular ecosystem services into the INCA-tool, the soil retention model was chosen. Soil retention, also known as sediment retention, requires a biophysical model and is an ecosystem service frequently included in ecosystem accounting. The service accounts for the value of the ecosystem to minimise soil erosion and, hence, contribute to the maintenance of soil quality and, therefore, of ecological processes. The Revised Universal Soil Loss Equation (RUSLE) model (Renard et al. 1991), as implemented in the KIP-INCA (Commission et al. 2021) is used for the biophysical calculations. RUSLE requires several spatial data inputs, such as the digital elevation model (DEM), land use - land cover, soil information, rainfall erosivity data and several coefficients. The INCA on-site soil retention account calculates the amount of soil retained by the ecosystem (use) as an interaction between the potential of ecosystems to reduce soil erosion by rain (the ecological side) and the demand (or need) for soil retention by ecosystems (the socio-economic side). The amount of soil erosion taking place at a higher rate than the soil formation rate (net losses) are provided in a complementary mismatch dataset. The monetary value is only calculated for cropland and expressed in 'real' values and 'nominal' values deflated to the reference year 2000. Cropland is considered a socio-economic flow contribution to the agricultural sector, while other ecosystem types are considered intra-ecosystem flows and, hence, not valuated. The soil retention module can be used to generate ecosystem accounts at different reporting levels (EU level, national level, regional level).

Fig. 3 depicts the workflow diagram for the soil retention model which consists of four specific modules, following the INCA architecture structure: the potential, the demand, the biophysical flow and the monetary flow for cropland. The fifth module is a generic module to calculate statistics and generate the tabular output. The INCA core soil retention model provides a python3 compliant API to configure the 13 input datasets and five configuration settings, next to some generic features as logging file, start run etc. Each module is further broken down and programmed into separate python sub-modules to ease integration and reuse with other accounts (e.g. mapping of Ecosystem Types to land-cover map).

The 13 input datasets and five configuration files necessary to generate the soil retention account are represented in the QGIS graphical interface. A set of default input datasets at EU level were prepared for the accounting years 2000, 2006, 2012 and 2018 and can be used by users to reproduce the results. Nevertheless, each of these datasets can be replaced by MS using the INCA tool interface to create their optimised national accounts. Fig. 4 shows the graphical interface of the QGIS tool for the Soil Retention account for 2018 in Austria. The left window depicts the selection of the input datasets. The bottom left window shows the actual execution (run) button. The geospatial maps for the ecosystem flow are automatically ingested into the QGIS project as shown in the right window. Users can further add other geospatial data to their QGIS accounting project for analysis.

The statistical reporting module is a generic module that not only calculates zonal statistics (provided as CSV files), but also automatically formats the tabular output in Supply-Use ecosystem accounting tables (provided as EXCEL files). Fig. 5 shows an example of this tabular output for the soil retention of 2018 over Europe (Austria is indicated with AT).

Summary & outlook

Currently, nine ecosystem services, based on the KIP-INCA methodology (Commission et al. 2021), are integrated in a toolkit, based on the python programming language and the open QGIS tool. This new toolkit, named INCA-tool, was used to update the EU wall-2-wall KIP-INCA service accounts - published by JRC on the INCA website (Joint Research Centre 2021) - and is ready to generate yearly accounts. The tool is currently also in beta test by several European Member States to generate national accounts and is planned to be publicly released by the end of year 2022 as free and open source. The INCA-tool provides baseline methods for ecosystem accounts, but Member States are not limited to these methods. Nevertheless, the implemented methods will be the baseline for EU validation. The tool will be further extended in the coming years with more service accounts to support the amendment to Regulation 691/2011 on European environmental economic accounts. This tool facilitates the generation of SEEA-EA accounts compliant with the EU guidelines on ecosystem accounting for European Statistical Offices.

In a step forward for open science, we decided to implement the FAIR principles for software, as well as output data in the INCA-tool. The FAIRness concept is a relatively new topic to the ecosystem accounting community, well received, but requires more standardisation and integration. Despite the fact that we achieved a high level of FAIRness and plan to further raise this level, currently, the INCA-tool cannot be fully compliant with all principles until the community has decided on a standard vocabulary and registry.

Nevertheless, due to the modular design of the INCA-tool, it can be integrated into other tools, if the platforms support and can bind with python3. For that, we plan to further improve the tool to achieve semantic interoperability aligning with the SEEA interoperability strategy (Balbi and Bagstad 2021). This prepares for seamless ingestion in modelling approaches centred on interoperability like the Artificial Intelligence for Environment & Sustainability (ARIES) platform (Villa et al. 2014), while still being available for more commodity practices, such as using Geographic Information System tools (QGIS or ArcGIS).

The new INCA-toolkit is the next step in harmonising ecosystem accounting within the European Union. By Regulation 691/2011, the INCA-tool will be the reference for ecosystem accounting in Europe. Thanks to its modular design, its appliance of FAIR principles and its free and open-source licence, expert users in the community have the ability to improve existing services or add new services to the toolkit.

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Author contributions

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Conflicts of interest

No conflict of interests.

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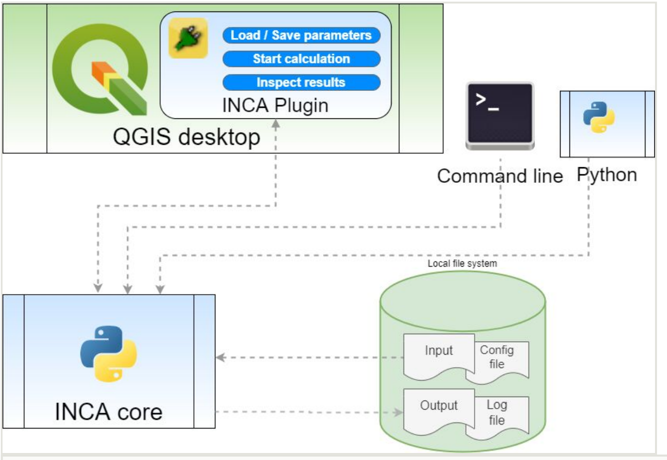

Figure 1.

Flow chart diagram showing the architecture of the INCA-tool.

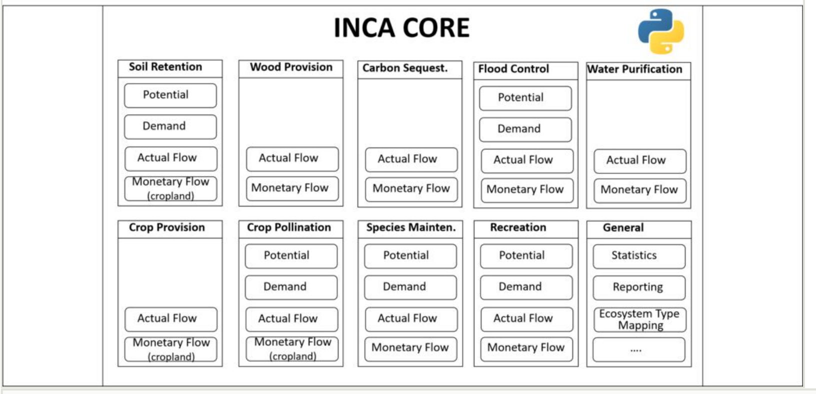

Figure 2.

Flow chart diagram showing the modular setup of the INCA core library.

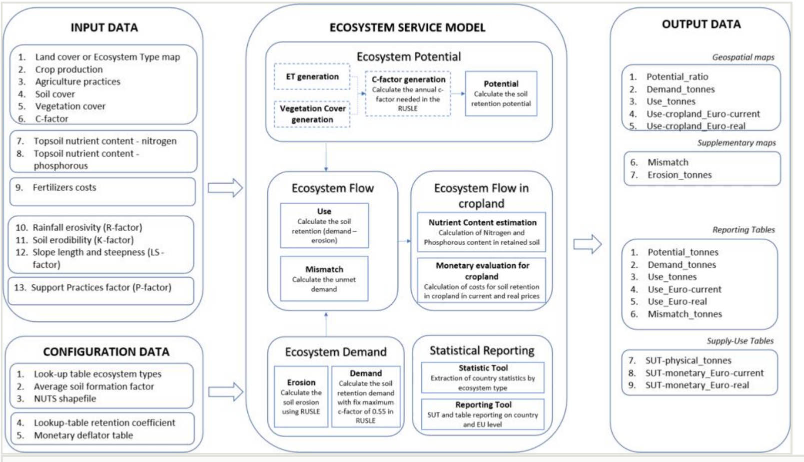

Figure 3.

Flow chart diagram showing the modular setup of the soil retention ecosystem service as implemented in the INCA-tool.

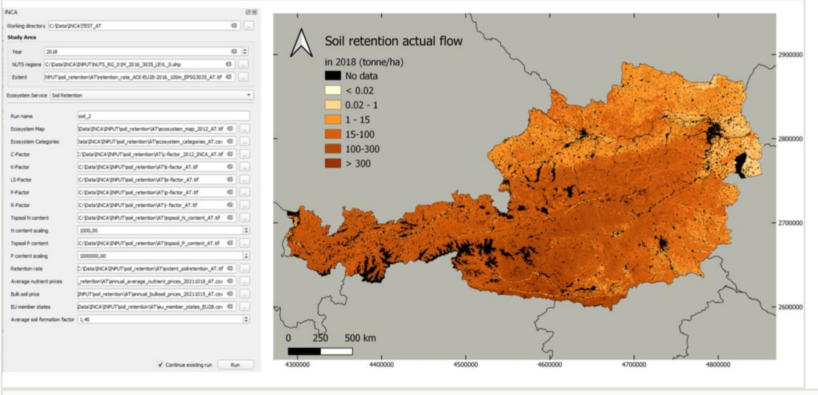

Figure 4.

Screenshot of the QGIS front-end of the INCA-tool for the soil retention ecosystem service account - example shows the Graphical User Interface and ecosystem flow result for Austria in 2018.

SUPPLY 2018															
	Economic Unit						Type of ecosystem unit								Total
	Primary sector														
	Agriculture	Forestry	Secondary Sector	Tertiary sector	Households	Global Society	Urban	Cropland	Grassland	Woodland and forest	Heathland and shrub	Sparsely vegetated land	Wetlands	Rivers and lakes	Coastal / intertidal	
soil retention *1000 metric tonnes year 2018*															
AT							59	24,567	151,224	421,934	33,939	22,162				653,885
BE							35	6,135	2,759	12,073	76	-				21,080
BG							38	39,437	17,618	166,707	1,555	842				226,198
CY							3	3,778	489	12,039	4,426	132				20,868
CZ							69	22,945	9,597	61,654	72	9				94,346
DE							189	52,048	61,132	228,480	2,656	351				344,857
DK							23	3,519	105	1,364	42	0				5,053
EE							7	1,777	456	5,408	7	0				7,655
EL							32	76,885	58,604	273,746	143,865	8,691				561,823
ES							295	253,485	171,261	878,506	367,371	16,879				1,687,797
FI							18	2,694	97	43,305	2,340	65				48,519
FR							304	162,799	228,743	701,118	73,146	31,294				1,197,404
HR							54	23,996	22,594	179,619	8,712	2,111				237,086
HU							35	14,166	4,262	38,696	-	2				57,162
IE							8	4,413	21,807	11,068	6,475	2,182				45,952
IT							366	423,922	117,678	1,433,935	122,597	67,948				2,166,446
LT							45	5,112	1,010	7,795	4	1				13,968
LU							8	1,167	494	3,294	-	-				4,963
LV							16	3,386	1,472	10,896	-	1				15,771
MT							4	223	-	3	87	2				319
NL							27	1,148	786	656	50	-				2,666
PL							85	39,492	7,821	74,667	323	33				122,421
PT							60	41,548	2,476	107,043	26,021	2,245				179,393
RO							42	74,933	86,824	434,439	7,141	300				603,680
SE							109	7,547	7,622	185,066	44,047	5,058				249,449
SI							23	30,311	13,045	234,019	9,950	850				288,197
SK							12	15,542	7,843	97,875	1,480	271				123,024
EU							1,968	1,336,974	997,819	5,625,405	856,382	161,429	-	-	-	8,979,978

USE 2018															
	Economic Unit						Type of ecosystem unit								Total
	Primary sector														
	Agriculture	Forestry	Secondary Sector	Tertiary sector	Households	Global Society	Urban	Cropland	Grassland	Woodland and forest	Heathland and shrub	Sparsely vegetated land	Wetlands	Rivers and lakes	Coastal / intertidal	
soil retention *1000 metric tonnes year 2018*															
AT	24,567						59		151,224	421,934	33,939	22,162				653,885
BE	6,135						35		2,759	12,073	76	-				21,080
BG	39,437						38		17,618	166,707	1,555	842				226,198
CY	3,778						3		489	12,039	4,426	132				20,868
CZ	22,945						69		9,597	61,654	72	9				94,346
DE	52,048						189		61,132	228,480	2,656	351				344,857
DK	3,519						23		105	1,364	42	0				5,053
EE	1,777						7		456	5,408	7	0				7,655
EL	76,885						32		58,604	273,746	143,865	8,691				561,823
ES	253,485						295		171,261	878,506	367,371	16,879				1,687,797
FI	2,694						18		97	43,305	2,340	65				48,519
FR	162,799						304		228,743	701,118	73,146	31,294				1,197,404
HR	23,996						54		22,594	179,619	8,712	2,111				237,086
HU	14,166						35		4,262	38,696	-	2				57,162
IE	4,413						8		21,807	11,068	6,475	2,182				45,952
IT	423,922						366		117,678	1,433,935	122,597	67,948				2,166,446
LT	5,112						45		1,010	7,795	4	1				13,968
LU	1,167						8		494	3,294	-	-				4,963
LV	3,386						16		1,472	10,896	-	1				15,771
MT	223						4		-	3	87	2				319
NL	1,148						27		786	656	50	-				2,666
PL	39,492						85		7,821	74,667	323	33				122,421
PT	41,548						60		2,476	107,043	26,021	2,245				179,393
RO	74,933						42		86,824	434,439	7,141	300				603,680
SE	7,547						109		7,622	185,066	44,047	5,058				249,449
SI	30,311						23		13,045	234,019	9,950	850				288,197
SK	15,542						12		7,843	97,875	1,480	271				123,024
EU	1,336,974						1,968	-	997,819	5,625,405	856,382	161,429	-	-	-	8,979,978

Figure 5.

Supply and Use tables (SUT) for the soil retention ecosystem service for the year 2018. Note: the unit is in 1000 metric tonnes carbon.

Table 1.

Needs, interactions and skills for different types of users.

Type of User	Needs	Tool interaction	Required skills
Basic User	Only source for national accounts / Cross validation of national models	Consultation and use of final results at national level (tabular data)	Consultation and processing of tabular data (e.g. MS Excel)
Proficient User	Starting point to develop improved national accounts	Operate the tools on a national level and replace input data with national data sources	Consultation and processing of spatial data (e.g. GIS software – QGIS, ArcGIS)
Expert User	Starting point to develop national accounting procedures and perform R&D (e.g. JRC)	Operate the tools to replace formulae (open source code) and input data	Programming skills (e.g. python)

Table 2.

Overview of existing modelling platforms with potential use in SEEA EA to support EU Regulation 691/2011, adapted from SEEA EA Guidelines (United Nations 2022) and comparison with the INCA tool.

Modelling platform	**Primary goal of the platform**	**Annual timestep feasible**	**Spatial explicit**	**Scalable**	**Economic valuation**	**EU Regulation compliancy**	**Coverage**
INCA	*Flagship tool of the European Union to support Member States in developing SEEA EA accounts. It includes all models in the EU legislation and is extendible according to the FAIR principles.*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Extent, Ecosystem services*
ESTIMAP (Zulian et al. 2014)	ESTIMAP is a collection of models for mapping ecosystem services in a multi-scale perspective.	Yes	Yes	Yes	No	Partly	Ecosystem services
ARIES (Villa et al. 2014)	ARIES provides easy access to data and models through a web-based explorer and using Artificial Intelligence to simplify model selection, promoting transparent reuse of data and models in accordance with the FAIR principles.	Yes	Yes	Yes	Yes	No	Extent, Condition, Ecosystem services

InVEST (Sharp 2018)	A compilation of open-source models for mapping and valuing ecosystem services. InVEST is the flagship tool of the Natural Capital Project and has been the most widely used ecosystem service modelling tool globally.	Yes	Yes	Yes	Yes	No	Condition, Ecosystem services
Data4Nature (D4N 2022)	Data4Nature is a decision support tool that is designed to answer questions about where organisations should invest in their natural resources.	Yes	Yes	Yes	No	No	Extent, Ecosystem Services
i-Tree (i-Tree Canopy 2021)	i-Tree is a tool developed by the USDA Forest Service with capabilities of modelling ecosystem services related to trees, particularly in urban settings.	Yes	Yes	Yes	Yes	No	Ecosystem services (forest related)
Nature Braid/LUCI (Jackson et al. 2013)	The Nature Braid provides a suite of high spatial resolution ecosystem services models designed to improve decision-making around restoration and land management.	Yes	Yes	Yes	No	No	Condition, Ecosystem Services (hydrological, soil)

Table 3.

FAIRness assessment of the INCA-tool following the guidelines by Lamprecht et al. (2020)

Principle	Description	Fulfilled	Comment
F1	Software and its associated metadata have a global, unique and persistent identifier for each released version.	Yes (partially)	Identifier is 'INCA' plus version in X.x in all metadata sources. Currently no specific DOI is assigned, but can be easily found across GitHub repository. In the future, a concept DOI (resolved to the latest stable version) and version DOI (allows traceability to every version) will be assigned through Zenodo.
F2	Software is described with rich metadata.	Yes (partially)	Metadata covers the description, usage and accessibility of the software. Metadata is available in XML format, but does not yet use a structured controlled vocabulary. In the future, metadata will be updated to conform to the community vocabulary.
F3	Metadata clearly and explicitly include identifiers for all the versions of the software it describes.	Yes	All metadata include the version they apply to, for the core module as well as all ecosystem service models.
F4	Software and its associated metadata are included in a searchable software registry.	No	In future, the software and its metadata will be included in an appropriate software library in agreement with the ecosystem accounting community (SEEA EA and/or GEO EO4EA).
A1	Software and its associated metadata are accessible by their identifier using a standardised communications protocol.	Yes	Both software and metadata are accessible through HTTP/S:GitHub, webpage, INCA-tool publication.
A1.1	The protocol is open, free and universally implementable.	Yes	All software and associated metadata are available using HTTP/s across various sites: GitHub (public source code repository), webpage (open), INCA-tool publication (open).
A1.2	The protocol allows for an authentication and authorisation procedure, where necessary.	NA	Not necessary.
A2	Software metadata are accessible, even when the software is no longer available.	Yes	Metadata is independent of software accessibility in GitHub and on a webpage.

I1	Software and its associated metadata use a formal, accessible, shared and broadly applicable language to facilitate machine readability and data exchange.	Yes	Software is written in python3, a formal machine-readable and widely used language. Metadata is available in XML format.
I2S.1	Software and its associated metadata are formally described using controlled vocabularies that follow the FAIR principles.	No	In the future, we opt to use the same vocabulary as ARIES and advocate the adoption of this vocabulary by the ecosystem accounting community. Note: adaptations to integrate INCA vocabulary will be needed.
I2S.2	Software use and produce data types and formats that are formally described using controlled vocabularies that follow the FAIR principles.	Yes (partially)	Input datasets in raster format follow the STAC (SpatioTemporal Asset Catalogue) format and (GML) Geography Markup Language metadata, input datasets in tabular format follow the Eurostat TSV (Tab Separated Value) format. Output raster formats follow STAC and GML, output tabular formats follow CSV and XLSX supply-use tables.
I4S	Software dependencies are documented and mechanisms to access them exist.	Yes	Stated in GitHub DESCRIPTION. Automatically downloadable and installable through INCA-tool installer.
R1	Software and its associated metadata are richly described with a plurality of accurate and relevant attributes.	Yes (partially)	See comments for R1.1.
R1.1	Software and its associated metadata have independent, clear and accessible usage licences compatible with the software dependencies.	Yes (partially)	Software follows EUPL (EUROPEAN UNION PUBLIC LICENCE v. 1.2) Metadata attributes are described as key value pairs, according to the Climate and Forecast Convention (CF, version 1.6)
R1.2	Software metadata include detailed provenance, detail level should be community agreed.	Yes	Provenance of metadata is given by GitHub versioning, including history of releases.
R1.3	Software metadata and documentation meet domain-relevant community standards.	NA	Currently no domain-relevant community standards are available. In the future, standardisation from SEEA EA and GEO EO4EA is expected to become available and will be applied.

Table 4.

FAIRness assessment for INCA-tool output data, following Wilkinson et al. (2019)

Principle	FAIR for data	Fulfilled	Comments
F1	(Meta)data are assigned a globally-unique and persistent identifier.	Yes (partially)	An internal identifier is used, based on software version and date, but no unique registered identifier (e.g. DOI) is assigned yet.
F2	Data are described with rich metadata.	Yes	Output raster formats follow GML (Geography Markup Language), output tables (csv, xlsx) are accompanied with an XML (eXtensible Markup Language) file.
F3	Metadata clearly and explicitly include the identifier of the data it describes.	Yes	Output rasters do include metadata inside the raster file. Output tables and accomplished metadata file (XML) use same identifier.
F4	(Meta)data are registered or indexed in a searchable resource.	No	It is envisioned to add this information on the webpage in the future.
A1	(Meta)data are retrievable by their identifier using a standardised communications protocol.	Yes	For rasters, the GML protocol is used. For tables, the XML protocol is used.
A1.1	The protocol is open, free and universally implementable.	Yes	Rasters are provided in COG (Cloud Optimised Geotiffs), a commonly used standard in the OGC (Open Geospatial Community). GML and XML are open and free protocols, used by several tools.
A1.2	The protocol allows for an authentication and authorisation procedure, where necessary.	NA	
A2	Metadata are accessible, even when the data are no longer available.	No	See F4
I1	(Meta)data use a formal, accessible, shared and broadly applicable language for knowledge representation.	Yes	GML and XML are broadly applicable languages.
I2	(Meta)data use vocabularies that follow FAIR principles.	Yes (partially)	A non-standard vocabulary is currrently used. See R1.3.
I3	(Meta)data include qualified references to other (meta)data.	Yes	Raster datasets include references to all input datasets and derived children.
R1	(Meta)data are richly described with a plurality of accurate and relevant attributes.	Yes (partially)	See R1.1 to R1.3

R1.1	(Meta)data are released with a clear and accessible data usage licence.	Yes (partially)	All data are free and openly accessible through the website. A general statement is provided, but currently no reference to a data usage licence is included.
R1.2	(Meta)data are associated with detailed provenance.	Yes (partially)	See I3, but not following a standardised vocabulary.
R1.3	(Meta)data meet domain-relevant community standards.	No	No standard vocabulary is available. In agreement with the ecosystem accounting community (SEEA EA and/or GEO EO4EA).