MISSIONE 4
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Deliverable 8.16 – WP8 – Task 6

OPERATIONAL VERSION OF THE CARBON VRE SERVICE AND THE ASSOCIATED USER GUIDE

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

Deliverable number:	D8.16
Work package:	WP8
Intermediate Objective:	
Deliverable type:	X Document, report
•	☐ Websites, patent filings, videos, etc.
•	• ☐ Other: please specify .....
Dissemination level:	X Public
•	• ☐ Restricted
Estimated delivery (bimester):	B13
Actual delivery date:	December 2024
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Reviewed by:	ITINERIS Executive Board
Note:	•

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System - CUP B53C22002150006 (D.D. n. 130/2022)
Funded by EU - Next Generation EU
Mission 4 "Education and Research" - Component 2: "From research to business" - Investment 3.1: "Fund for the realisation of an integrated system of research and innovation infrastructures"

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1 The "Carbon Virtual Research Environment"

The progressive intensification of anthropic activities has resulted in an increase in the emission of greenhouse gases (GHGs), e.g. from burning of fossil fuels or intensive livestock, with a net warming effect on our Earth's atmospheric temperatures and a shift in weather patterns that is referred to as Climate Change (CC). CC stands as one of the most critical issues human societies face nowadays, with far-reaching consequences that embrace all aspects of human life. CC interacts with on-going global megatrends such as urbanization, globalization, population growth, etc., with deep environmental and socio-economic implications. Finding solutions to promote adaptation to and mitigation of CC is thus fundamental to support the health and well-being of populations worldwide and achieve a sustainable future.

The study of the carbon balance, namely the equilibrium between carbon sources (emissions) and carbon sinks (removals) is critically important, because it is central to understanding and mitigating CC. It allows for the identification of CC drivers, and consequently for the targeting of emission reductions and enhancement of carbon sinks. The dynamics of carbon in terrestrial ecosystems reflect their and ability to function as carbon sinks; similarly, oceans are major sinks, though they are progressively threatened by acidification. Atmospheric carbon, usually estimated by inverse modeling, is the other compartment to be considered.

The main focus of ITINERIS WP 8 Task 8.6 is the setup of the Carbon Virtual Research Environment (VRE), the first digital environment dedicated to the Italian Carbon balance and cycle. It stores national data and promotes sharing, analysis, and innovative research, useful for both the research community and national authorities or local managers in charge of reporting activities The Carbon VRE stores and documents multiple carbon-related data, such as outputs of large scale models, ground observations from Research Infrastructures and national/international facilities, and outputs from specific and local modelling efforts. Most data are spatially explicit, and the aim is to provide national information down to the provincial level. All the compartments are documented, including Land, Atmosphere, and Marine, and Emissions from national records. The Carbon VRE integrates:
(a) the geoportal that allows to navigate, visualize and explore data based on location;
(b) the Metadata Catalog that reports information on the datasets;
(c) the Analysis Tool that allows to perform user-specific processing, with links to an R-Studio environment and dedicated code.

1.1 The Virtual Research Environment and the D4Science e-Infrastructure

The aim of a VRE is to enhance collaboration among researchers to find adequate solutions and address specific scientific and/or management issues (Assante et al., 2019, 2023). The principles of Open Science and data FAIRness (data which meet the principles of findability, accessibility, interoperability, and reusability) are at the basis of a Virtual Research Environment (VRE). VREs require the collection and harmonization of data, and the collection and development of analysis tools, modelling solutions and graphical tools. Rather than a simple "repository", a VRE is a dynamic research facility, that is built-up on the following premises:

- involvement of stakeholder to identify questions (and/or gaps) concerning the main issues underlying the VRE;
- harmonization and collection of validated datasets, modelling solutions, analysis and graphical tools;
- identification of specific scientific and/or management questions and development of new data, knowledge and solutions;
- application of FAIRness principles.

D4science, used to implement the Carbon VRE, is an organization hosted by the *Istituto di Scienza e Tecnologie dell'Informazione* "A. Faedo" of the National Research Council of Italy (ISTI, CNR), which has offered data infrastructures for the past 10 years.
The D4science e-Infrastructure (https://www.d4science.org, last access: 07/12/2024) consists of a network of hardware and software resources (e.g., databases, services, machines) and is managed by a team of Information and Communication Technology (ICT) professionals and researchers having as main objective the infrastructure maintenance, updating, operation and support for users. The infrastructure relies on the gCube technology (https://gcube.wiki.gcube-system.org/gcube/About_gCube, last access: 07/12/2024), that is an open-source software toolkit specifically conceived for the construction and development of VREs (Assante et al., 2019). Currently, D4Science hosts 20 different gateways (https://services.d4science.org/thematic-gateways, last access: 07/12/2024) and 176 active VREs with a total of more than 24k users worldwide (Aug. 2024). Based on the needs of stakeholders and the scientific community, the D4Science facility supports researchers on the implantation and/or development of new packages, functions and tools.

1.2 The design of the "Carbon VRE"

Task 8.6 of the ITINERIS WP 8 project, funded by EU – Next Generation EU PNRR, Mission 4 "Education and Research" – Component 2: "From research to business" – Investment 3.1:

"Fund for the realization of an integrated system of research and innovation infrastructures", is focused on the design and setup of a VRE dedicated to Carbon data, balance, and dynamics. Different infrastructures contribute to the Carbon VRE, first of all the Integrated Carbon Observation System (ICOS), part of the European Research Infrastructure Consortium (ERIC), main responsible for collection, storage and dissemination of Carbon flux data in Europe.

Different stakeholders of the Carbon VRE were identified:
(i) scientists from the global community interested in the analysis of data related to the complex processes involved in Carbon dynamics, Carbon balance and Carbon modelling;
(ii) national authorities responsible for Carbon accounting and reporting;
(iii) local authorities responsible for monitoring Carbon stocks and emissions at the local level;
(iv) Organizations of the Civil Society (OCS) interested in raising awareness among citizens.

In general, the main sources (in terms of data and metadata) feeding the Carbon VRE are (a) national public authorities; (b) research infrastructures; (c) research projects.

The main datasets included in the Carbon VRE are as follows:

a) "GHG_Emissions_Italy": Italian government CO_2, CH_4, NO_2+NO, and CO emission data from 1990 to 2019, spatialized at the provincial scale and assembled per region, as vector layers; Emissions Database for Global Atmospheric Research (EDGAR) 2022 Total CO_2 emission product of the Joint Research Center (JRC);
b) "Carbon_Fluxes_Models_Italy": flux-based estimates of Net Ecosystem Exchange (NEE), Gross Primary Productivity (GPP), Gross Ecosystem Exchange (GEE), Total Ecosystem Respiration (TER, RTot) for Italy, derived by different international modeling efforts, at different spatial and temporal resolutions, provided as raster layers;
c) "Atmospheric_inversion_models": based on in situ observations, provide estimates of atmospheric CO_2
d) "SOCAT_Ocean_data": quality-controlled in situ surface ocean fCO2 (fugacity of CO2) from Surface Ocean CO_2 Atlas
e) "Above_Ground_Biomass": includes maps of Aboveground Biomass (ABG) for different environmental contexts and at different spatial resolutions;
f) "Local_Research_Projects": datasets, methods, and products of specific studies.

2 "Carbon VRE" User Guide

2.1 Access to the VRE

Within the ITINERIS Project website, ITINERIS Hub has a specific section (https://itineris.cnr.it/itineris-hub/, last access: 07/12/2024), representing the access point to all the services, facilities, tools and datasets provided by the Italian Research Infrastructures (RIs) in the environmental domains (Figure 1).
The ITINERIS Hub is a "unique comprehensive catalogue" that includes the access to the ITINERIS VREs Gateway.

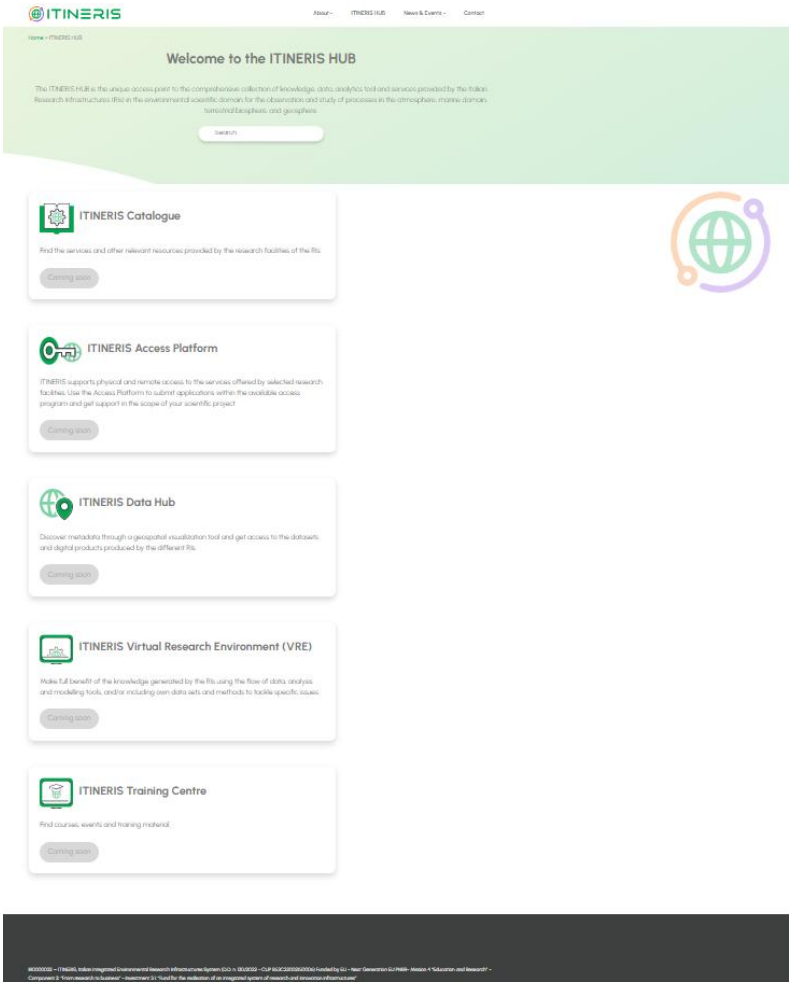


Figure 1. Main page of the ITINERIS Hub (https://itineris.cnr.it/itineris-hub/, last access: 07/12/2024).

Clicking on the "ITINERIS Virtual Research Environments" (VREs) provides access to the ITINERIS VRE Gateway (https://itineris.d4science.org/, last access: 09/12/2024; Figure 2a), providing access to multiple VREs, with an Identity and Access Management (IAM) system.

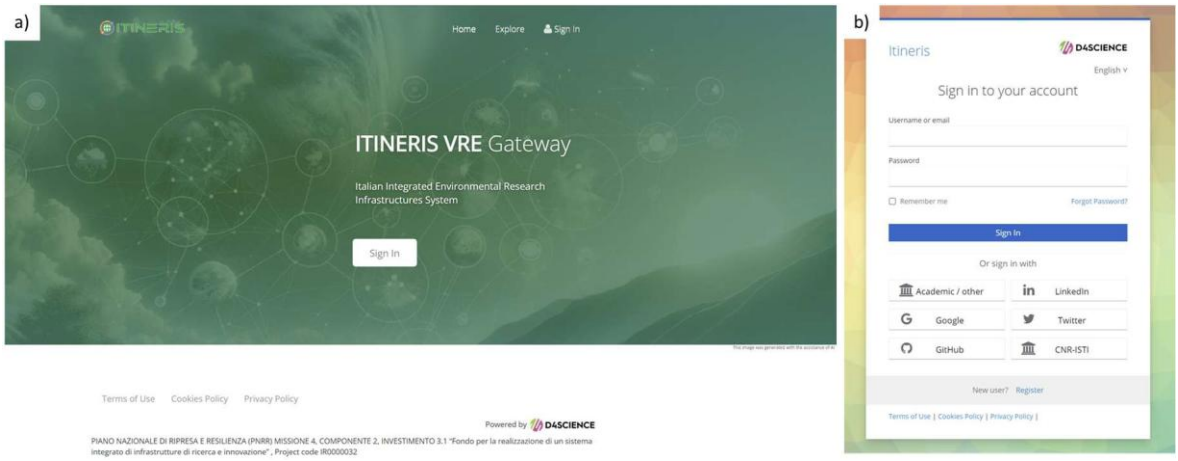


Figure 2. a) Main page of the ITINERIS VREs Gateway. b) Sign-in page: here the user can insert username and password or select one of the different methods available for login. For the creation of a new D4Science account, the users can select the "Register" button and proceed.

The different VREs are available and accessible after login with the D4Science's username and password; alternatively, one can select a different login method, including ORCID, GitHub, Google, LinkedIn (Figure 2b).

After registration and login, the user is directed to the ITINERIS Gateway homepage (Figure 3a), where VREs are displayed (top right corner); here access to VREs can be requested clicking on the "Add More" button. This will redirect the user to a page where all the available ITINERIS VREs are displayed (Figure 3b): users can gain access by clicking on the "Request Access" button, providing a brief motivation (Figure 4). Each VRE has moderators and managers who can review the access requests. Typically within a few hours the user receives a notification via email about the outcome of the request.

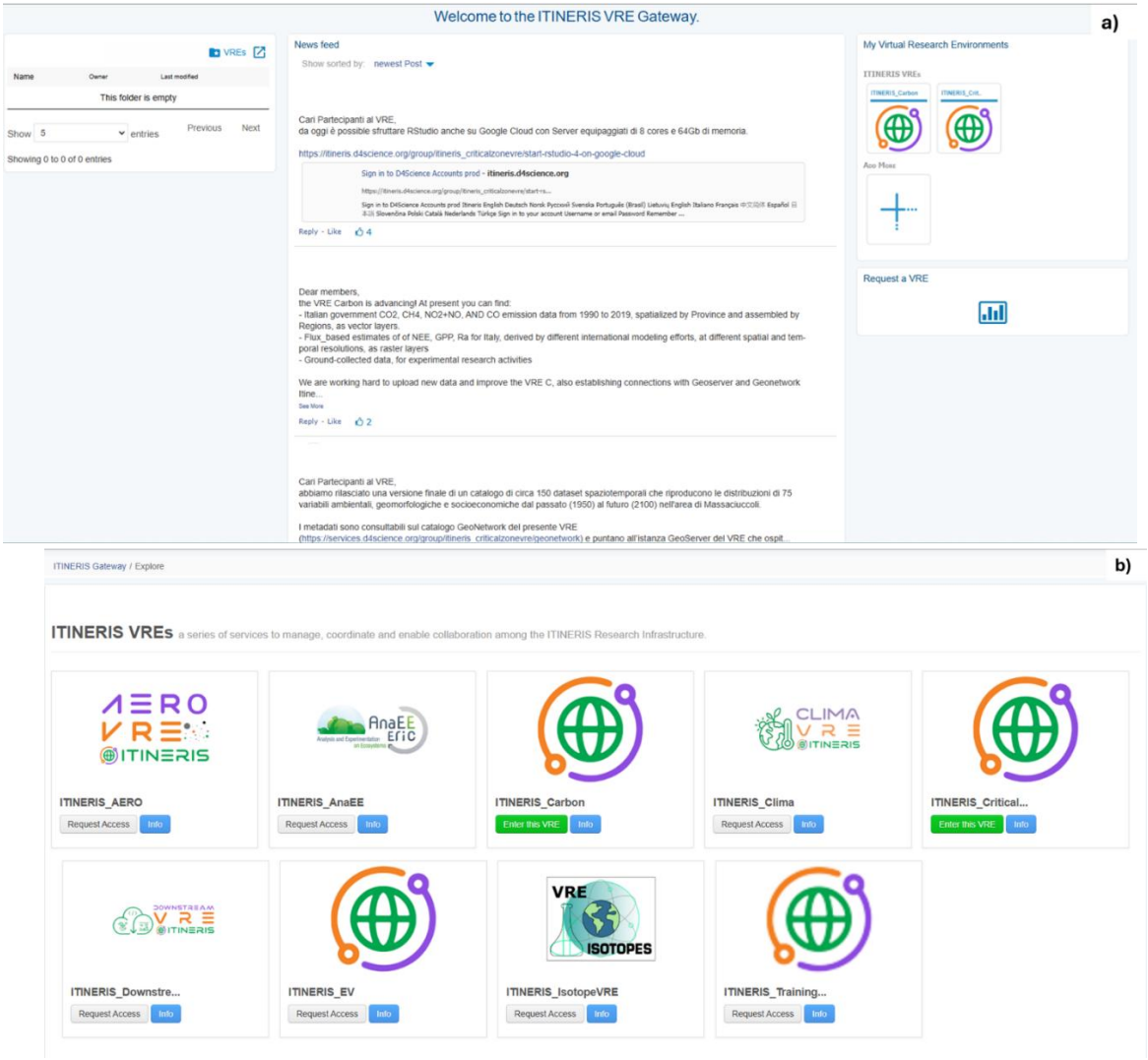


Figure 3. a) Panel on the top shows how users see their gateway after login. On the left, the panel "My Virtual Research Environments" allows to add one or more VREs by clicking on the button "+" ("Add More"). b) Once users have identified the VRE they are interested in, they can click the grey button "Request Access" and confirm the request after stating a motivation for accessing the VRE.

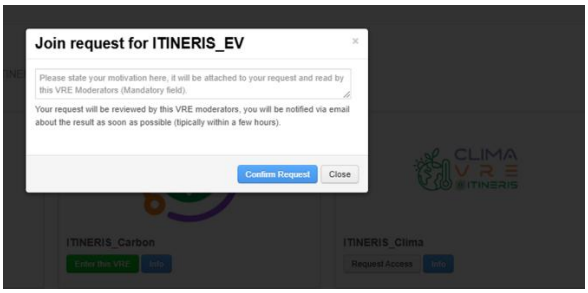
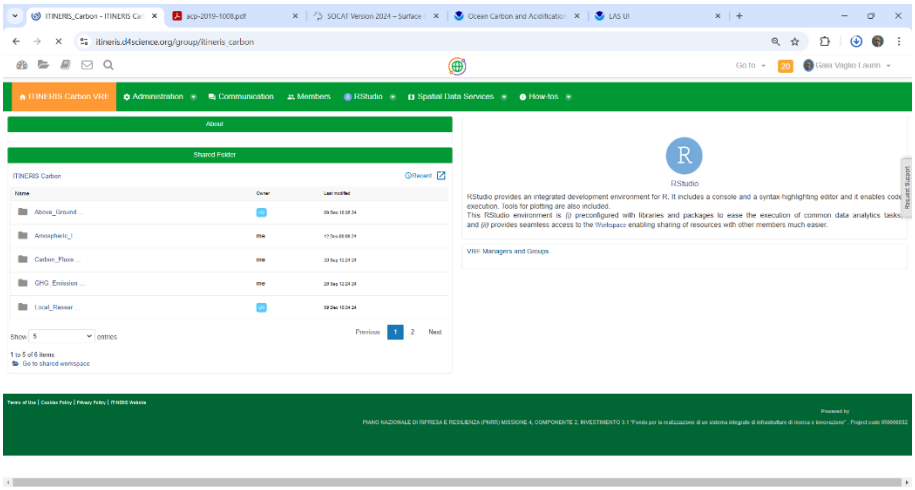


Figure 4. View of the window where users must provide a short statement to motivate their request for access to a VRE.

The thematic VREs include: Critical Zone (CZ VRE); Essential Variables (EV VRE); Aerosol-biosphere (AERO VRE); Carbon Cycle services (CARBON VRE); Indicators and Impacts of Climate Change (CLIMA VRE); Downstream Effects of Environmental Change (DOWNSTREAM VRE); Isotope Database (ISOTOPE VRE); Analysis and Experimentation on Ecosystems (AnaEE VRE).
Additionally, a Training-Platform dedicated to ITINERIS is also present, providing training courses about VREs, notions on the Digital Objects, the FAIR principles for research products and the scientific data repositories, the VRE usability (from data collection, to data analysis up to results publication), the practical sessions on data analyses, and the Cloud Storage principles.

2.2 The "Carbon VRE" homepage and the primary services: Communication and Administration

Once users have gained access to the Carbon VRE, they will be directed to its homepage (Figure 5a). At the top is a menu bar where all the provided services are displayed.
By clicking on "Communication" (Figure 5b), users can access a social networking board that supports the exchange of messages. The board (also called "News Feed") is open to discussions and allows for the sharing of updates, links and files (Figure 5c). Using "@" symbol it is possible to mention other participants, while the tag ("#") can be used to identify topics and keywords. Members of the VRE can also reply to a specific post or add a "Like" as reaction, and set specific options to receive notifications.
In the "Communication" page users can also check out "Trending Topics", invite members, and view managers and groups. The "Administration" button in the menu bar (Figure 5d) manages memberships and specific roles.



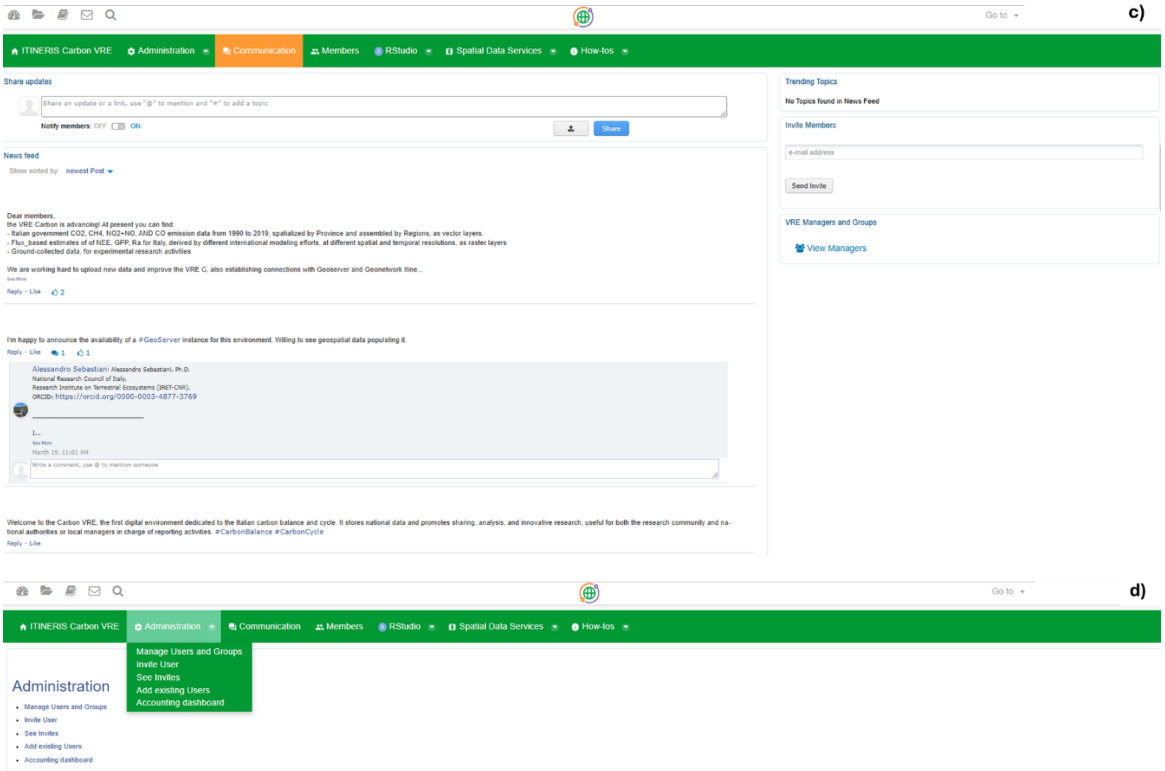


Figure 5. a) View of the ITINERIS Carbon VRE homepage; b) View of the homepage menu bar with the main services provided within the VRE; c) Social network board displaying the "News Feed", "Trending Topics", and "VRE Managers and Groups"; d) Drop-down menu for the "Administration" options.

2.3 The Carbon VRE workspace

The Carbon VRE **workspace** is a shareable folder system for data collection, allowing to upload files, create and share folders, and publish data in a catalogue. The folders are visible in the VRE's homepage in the "Shared Folder" box (Figure 6a). The shared workspace can be accessed clicking on the "Go to shared workspace" link (black square in Figure 6a).

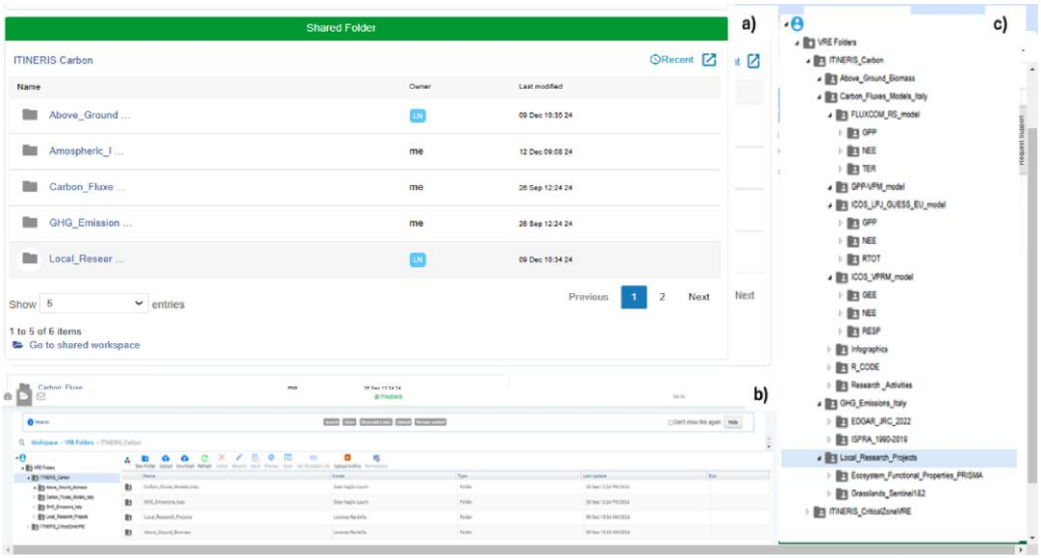


Figure 6. a) The "Shared Folder" box, presenting the folders inside the workspace; inside the black square the link to go to the dedicated page of the shared workspace; b) Main page of the Carbon VRE shared workspace. c) Main folders and relative subfolders of the Carbon VRE shared workspace.

In the workspace main page, users will find (as "USER's workspace") a space named "VRE Folders" (Figure 6b); files and digital objects added to the VRE folders are shared with the other VRE's members.

The **Carbon VRE workspace** includes six main folders (Figure 6c) with datasets continuously added or updated:

1) **"Above_Ground_Biomass"**, including raster maps of aboveground biomass (AGB) and related metadata (Figure 7):
   a) "*IFAC_CyGNSS_Pantropical_AGB.tif*": a pantropical AGB map based on 1 year data of the NASA's CyGNSS constellation and artificial neural networks (ANN) modeling developed, calibrated and validated at CNR-IFAC (Santi et al., 2020);
   b) "*AGB_trento_ALOS_S2.tif*" and "*ABG_UMA_ALOS_S2.tif*", local AGB maps at 14 m spatial resolution from the European Alpine Space: (Trento and Unione Montana Agordina - UMA in Northern Italy (Vaglio Laurin et al., 2021);

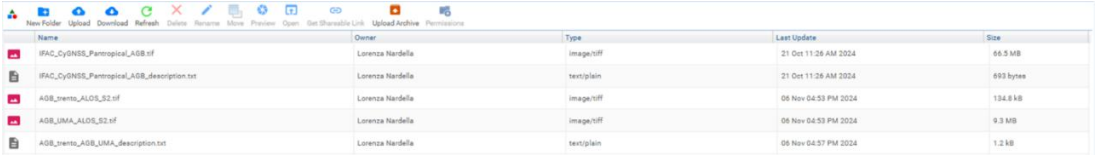


Figure 7. Content of the "Above_Ground_Biomass" folder.

2) **"Atmospheric_Inversion_Models"** including results from different models from EUROCOM in the 2005-2016 period (upload ongoing from https://www.icos-cp.eu/data-products/G068-1T09 referred to Montail et al. 2019)

3) **"Carbon_Fluxes_Models_Italy"**, with seven subfolders, four of which (2a-d) include spatially explicit carbon flux data over Italy in raster formats:

   a) *FLUXCOM_RS_model*: 2001-2015 average monthly raster stacks (12 layers, one for each month) for GPP, NEE and TER provided by elaboration and aggregation of FLUXNET ensemble products (Tramontana et al., 2016; Jung et al., 2020), with metadata (Figure 8a-c);

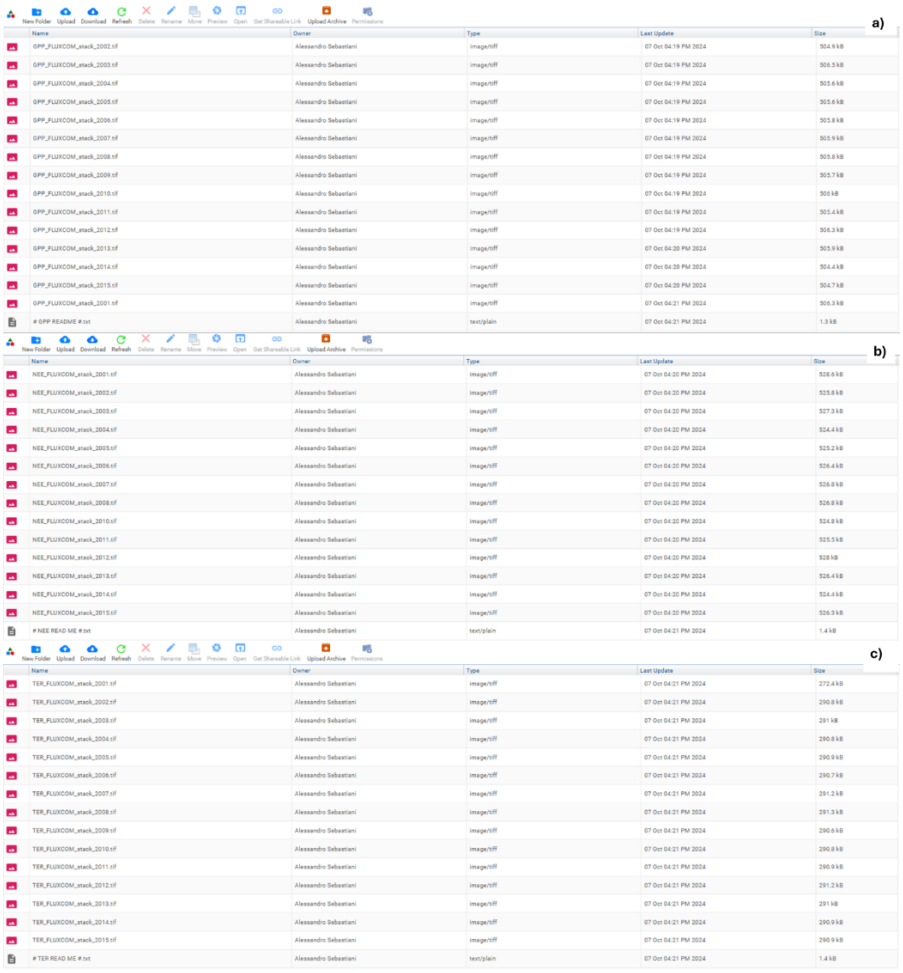


Figure 8. a) Content of the "Above_Ground_Biomas/FLUXCOM_RS_model/GPP" folder; b) Content of the "Above_Ground_Biomas/FLUXCOM_RS_model/NEE" folder; c) Content of the "Above_Ground_Biomas/FLUXCOM_RS_model/TER" folder.

   b) *GPP_VPM_model* : 2000-2016 average monthly raster stacks (12 layers, one for each month) of GPP by elaboration and aggregation of Vegetation Photosynthesis Model (VPM) products (Zhang et al., 2017), with metadata (Figure 9);

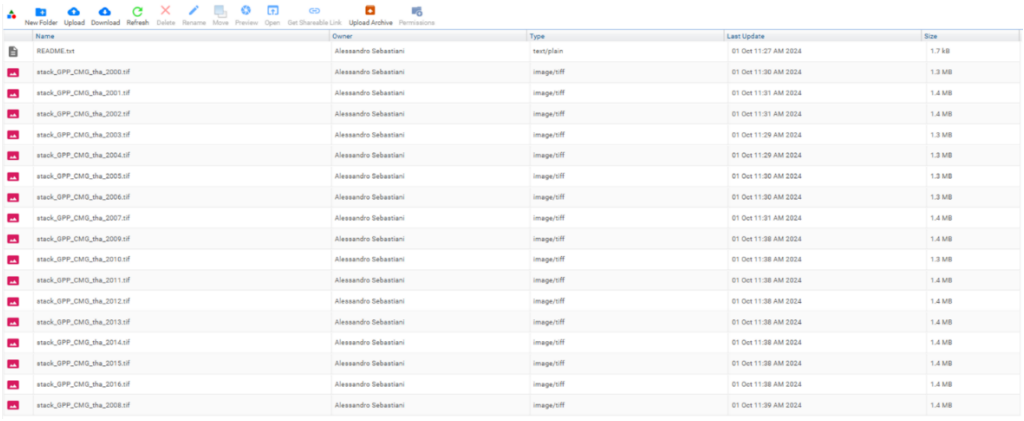


Figure 9. Content of the "Above_Ground_Biomas/FLUXCOM_RS_model/GPP_VPM_model" folder.

c) *ICOS_LPJ_GUESS_EU_model*: 2010-2022 average monthly raster stacks (12 layers, one for each month) of GPP, NEE and RTot from elaboration and aggregation of the Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS) products, and metadata (Figure 10a-c);

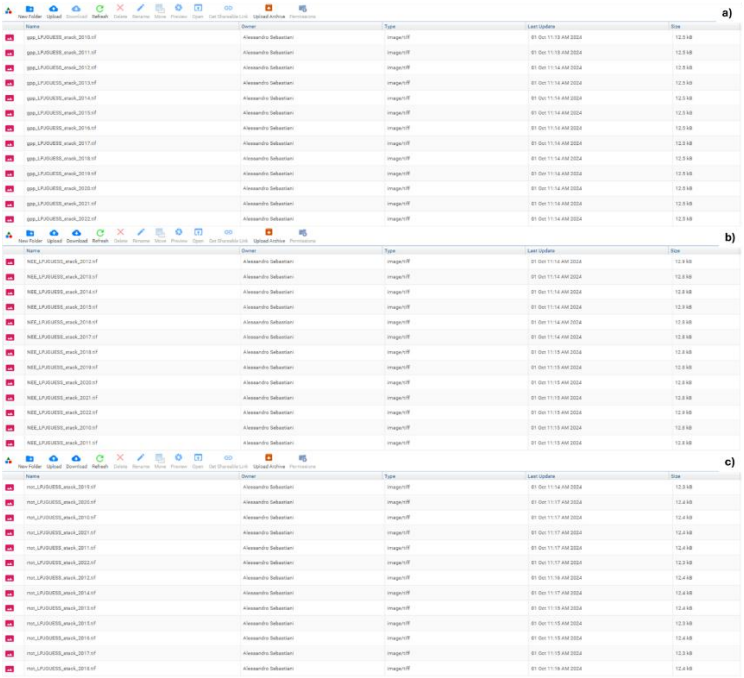


Figure 10. a) Content of the "Above_Ground_Biomas/ICOS_LPJ_GUESS_EU_model/GPP" folder; b) Content of the "Above_Ground_Biomas/ICOS_LPJ_GUESS_EU_model/NEE" folder; c) Content of the "Above_Ground_Biomas/ICOS_LPJ_GUESS_EU_model/RTOT" folder.

d) *ICOS_VPRM_model*: 2006-2022 average monthly raster stacks (12 layers, one for each month) of GPP, NEE and RESP from elaboration and aggregation of the Vegetation Photosynthesis and Respiration (VPRM) products (Jung et al. 2006;

Mahadevan et al., 2008; Gerbig et al., 2023), and metadata (Figure 11a-c);

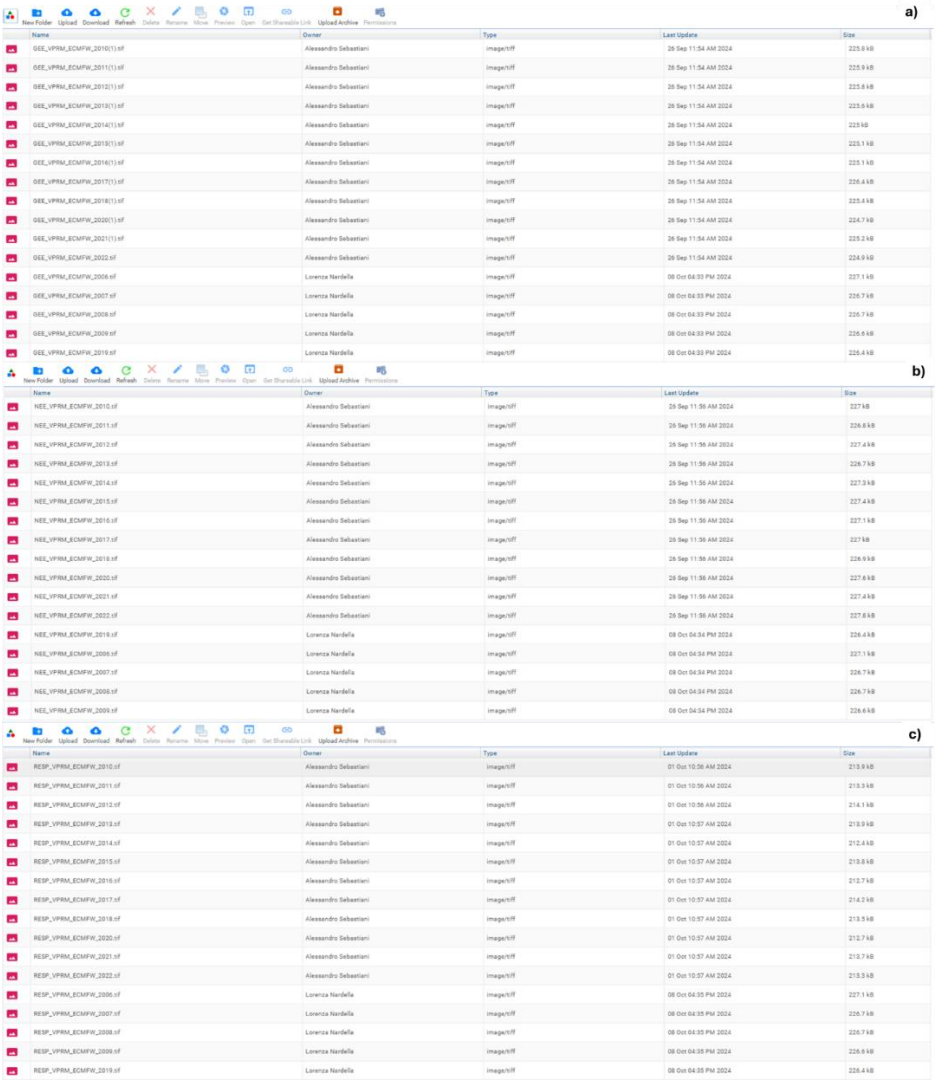


Figure 11. a) Content of the "Above_Ground_Biomas/ICOS_VPRM_model/GEE" folder; b) Content of the "Above_Ground_Biomas/ICOS_VPRM_model/NEE" folder; c) Content of the "Above_Ground_Biomas/ICOS_VPRM_model/RESP" folder.

e) *Infographics*: a .ppt document presenting the four flux products, metadata and example maps;

f) *R_CODE*: four folders, one for each of the models described above (2a-d), to perform some or all the following actions:

- aggregate half-hourly flux data on a monthly basis
- reprojects rasters into Universal Transverse Mercator (UTM), zone 32 projected Coordinate Reference System (CRS)
- grouping monthly data into yearly stacks;

-aggregate data into tons/ha, and group monthly data into one year stack

- clip rasters on the Italian national administrative limits

g) *Research_Activities*: at present including a research thesis ("Analisi sul flusso di CO2 (1).pdf"), and its presentation ("TESI_SCHIAVI_PPPA(L-21).pdf");

4) **"GHG_Emissions_Italy"***:* two subfolders:

a) *"ISPRA_1990_2019"* (Figure 12a):

- subfolder ("emissions_regions_rawData") the 1990-2019 provincially aggregated emission data are stored by region, also available in the file "REGIONI_EMISS_TOT.xlsx";
- subfolder with regional administrative limits in shapefile format; five R script files (.R format) allowing to map 1990-2019 emissions at the provincial level; a "READ_ME.txt";

b) *"EDGAR_JRC_2022"* (Figure 12b):

- a "READ_ME.txt" file with a description of the content and use of the folder;
- shapefile of Italian provincial administrative limits with total and pro-capita GHG emissions (tons) per province, derived from EDGAR v8 2022 data (Muntean et al. 2018) and elaborated using the script "EMISSIONS_ITALY_EDGAR_v8.R" (https://github.com/milos-agathon/carbon-emissions-per-capita/blob/main/R/main.r); an image with total GHG emission (tons) pro capita obtained running the script described above;

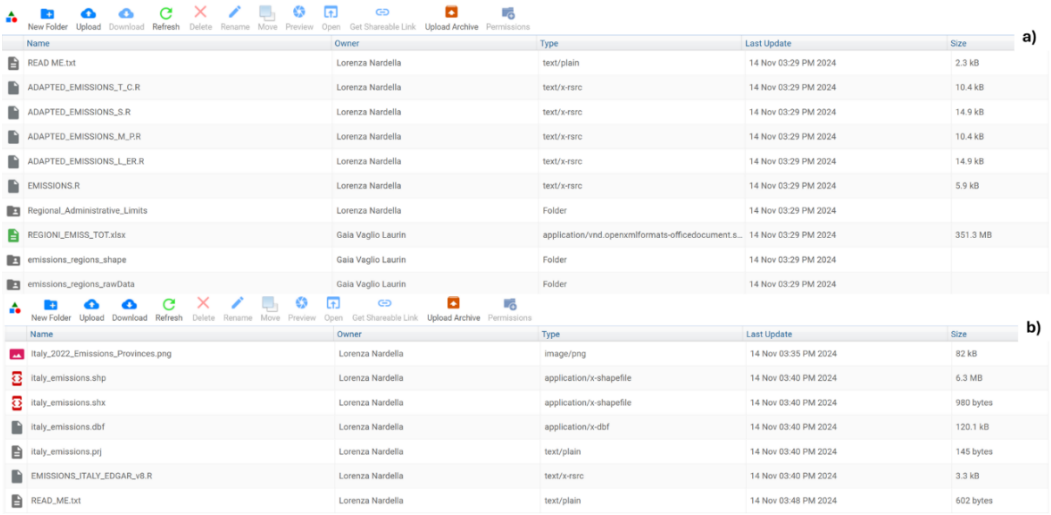


Figure 12. a) Content of the "GHG_Emissions_Italy/ISPRA_1990_2019" folder; b) Content of the "GHG_Emissions_Italy/EDGAR_JRC_2022" folder.

5) **"Local_Research_Projects"**: local research activities (conference papers presented at

the 2024 Society of Photographic Instrumentation Engineers, SPIE, Edinburgh):

a) *"Grasslands_Sentinel1&2"* (Figure 13a) to evaluate remote sensing data (multispectral and SAR) in supporting Natura 2000 habitat conservation, including:

- ground data subfolder with grassland structural parameters (fresh and dry weight, average and maximum height) collected in Apulia region, southern Italy;
- "RS_data" 26 Vegetation Indices from Sentinel-1 and Sentinel-2 imagery;
- conference paper (Sebastiani et al., 2024), and slideshow;

b) *"Ecosystyem_Functional_Properties_PRISMA"* (Figure 13b), investigating the capacity of hyperspectral PRISMA-derived vegetation indices to predict EFPs at 15 ICOS sites in Europe, including:

- Vegetation Indices from hyperspectral PRISMA data for two Italian ICOS sites ("PRISMA_VIs")
- Ecosystem Functional Properties (EFP) measured at the same two sites
- "Processing_steps" subfolder, including the script "SUBSET_group_EFPs_function.R" inside "Flux_tower" to import flux tabular data and extract only half-hourly values overlap with image acquisition time
- conference paper (Vaglio Laurin et al., 2024), and slideshow investigating the capacity of hyperspectral PRISMA-derived vegetation indices to predict EFPs at 15 ICOS sites in Europe;

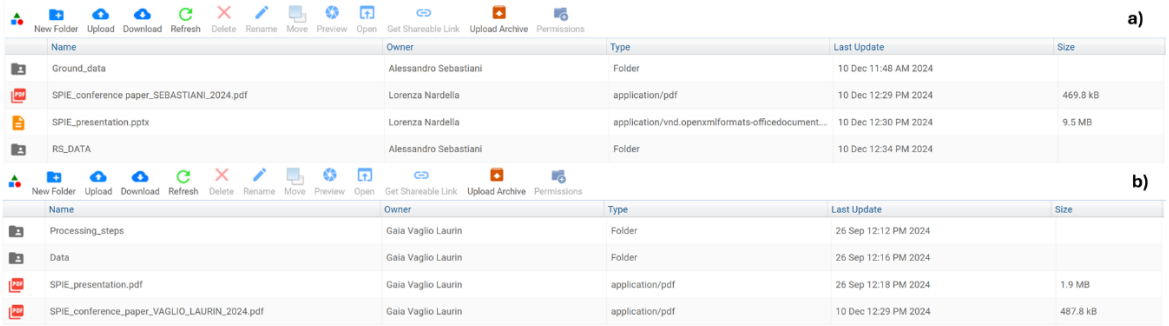


Figure 13. a) Content of the "Local_Research_Projects/Grasslands_Sentinel1&2" folder; b) Content of the "Local_Research_Projects/Ecosystem_Functional_Properties_PRISMA" folder.

6) **"SOCAT_Ocean_Data"**: includes quarter-degree monthly coastal (nc) measures of coastal fCO_2 (upload ongoing from https://socat.info/index.php/data-access/ and refererred to Bakker et al., 2016) A multi-decade record of high quality fCO_2 data in version 3 of the Surface Ocean CO_2 Atlas (SOCAT). Earth System Science Data, 8: 383-413. doi:10.5194/essd-8-383-2016

2.4 The Spatial Data Services and the Metadata Catalogue of the "Carbon VRE"

From the menu bar at the top of the ITERIS Carbon VRE homepage, two **Spatial Data Services** can be accessed (Figure 14), namely the **GeoNetwork** and the **GeoServer**.

The **GeoNetwork** provides a spatial data catalogue (available at https://itineris.d4science.org/group/itineris_carbon/geonetwork, last access: 10/12/2024) where VRE users can create and edit metadata.

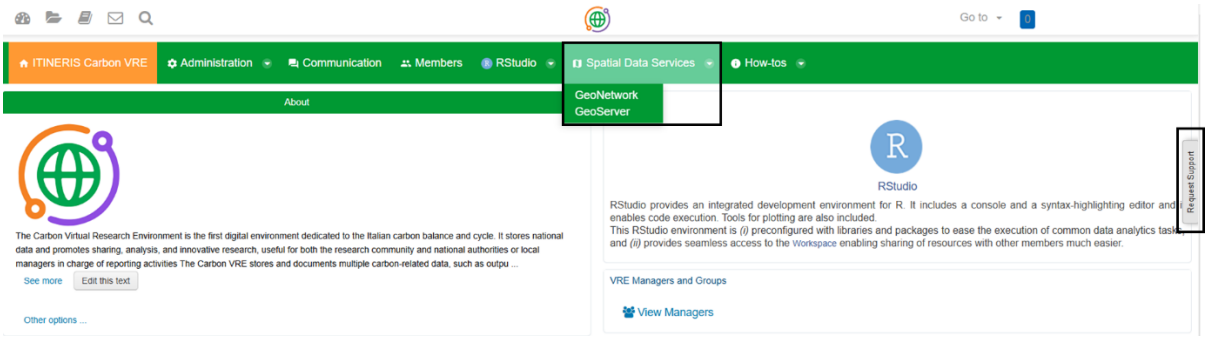


Figure 14. Spatial Data Services in the ITINERIS Carbon VRE homepage menu.

All metadata are compliant with the relevant standards, i.e. the INSPIRE (Infrastructure for Spatial Information in Europe) Directive, and the ISO19139 XML scheme implementation. Moreover, metadata are compliant with the Italian guidelines as from RNDT 2.0 (Repertorio Nazionale dei Dati Territoriali 2.0; https://geodati.gov.it/geoportale/manuale-rndt, last access: 08/12/2024). Considering these metadata standards, the RNDT 2.0 is necessarily compliant with INSPIRE, but the opposite may not be true (so it is better to stick to RNDT 2.0 in order to have metadata "automatically" compliant with the INSPIRE Directive). A set of information that should be included in the metadata record to be compliant with the standards EU INSPIRE Directive and ISO19139 is reported at the link https://docs.geonetwork-opensource.org/4.2/annexes/standards/iso19139/ (last access: 08/12/2024). At this link, a description of the fields that should be compiled can be found.

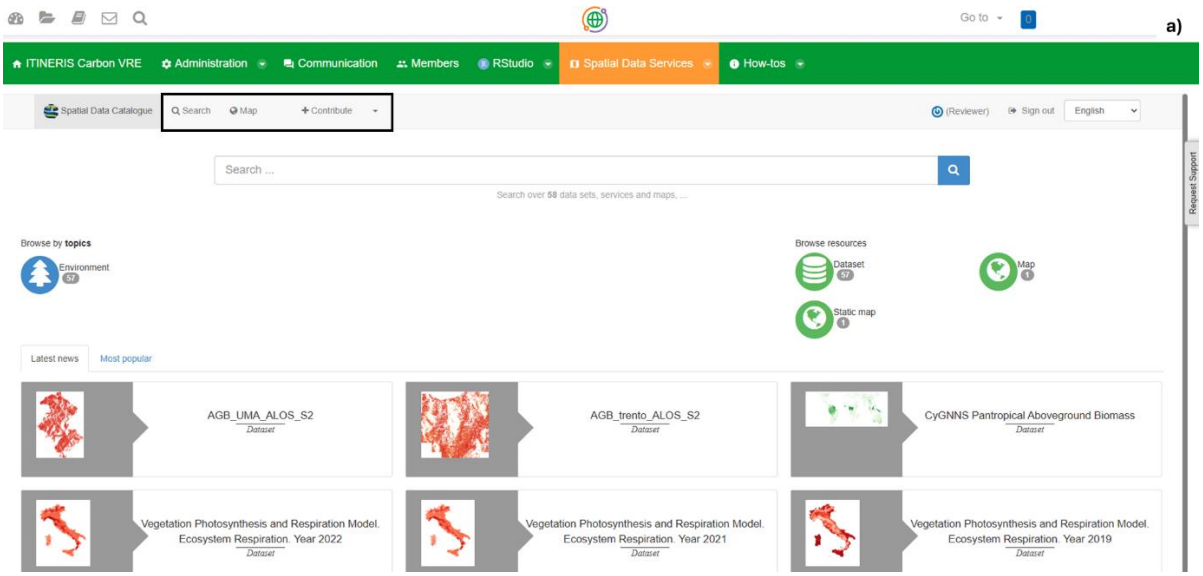


Figure 15. The box in the top highlights the three tools available in the GeoNetwork Spatial Data Catalogue (i.e., "search", "makeYourMap" and "contribute").

The GeoNetwork main page includes the layers available in the Spatial Data Catalogue, (Figure 15) and provides three tools:

1. The "search" function, by keywords and/or applying filters (Figure 16);

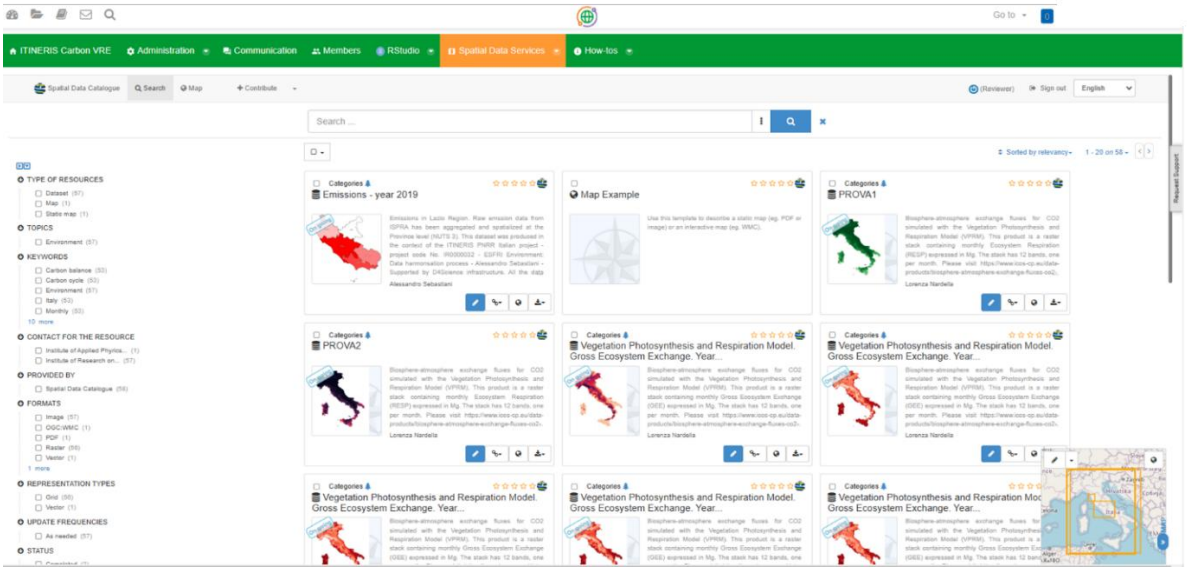


Figure 16. View of the "searching" tool of the GeoNetwork Spatial Data Catalogue.

2. The "Map" tool, to visualize geospatial data by clicking on the "+" sign in the menu on the right-hand side, and then selecting the desired layer to be added (Figure 17). . In order to visualize a layer from the spatial data catalogue (Figure 18c), users must first

click on the desired product (Figure 18a), and then add it to the map (Figure 18b).

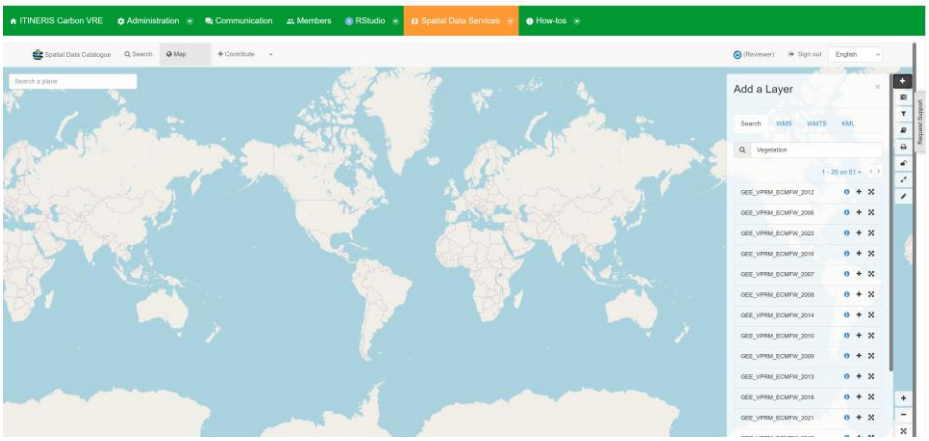


Figure 17. View of the screen once the "Map" tool is selected. Layers can be visualized in the map by clicking on the "+" sign in the menu on the right-hand side, and then selecting the desired layer to be added.

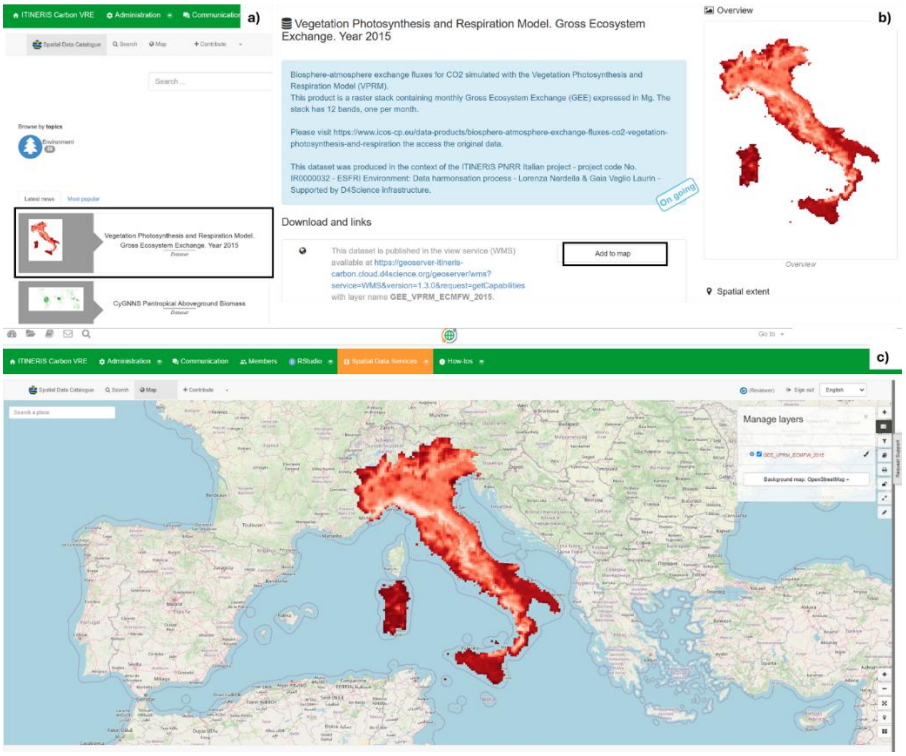


Figure 18. a) Selection of a layer from the spatial data catalogue; b) View of the selected product, with the "Add to map" option which allows to visualize it in the map; c) Geospatial data viewer, with an example of January 2015 GEE from VPRM product

3. The "contribute" button, to edit and add new metadata and records. The same functions are in the menu on the right-hand side (Figure 19a). From the metadata template list, VRE users should first select a template from the dropdown menu, click "create", and then fill-in the

fields to create an image that illustrates the record (Figure 19b).

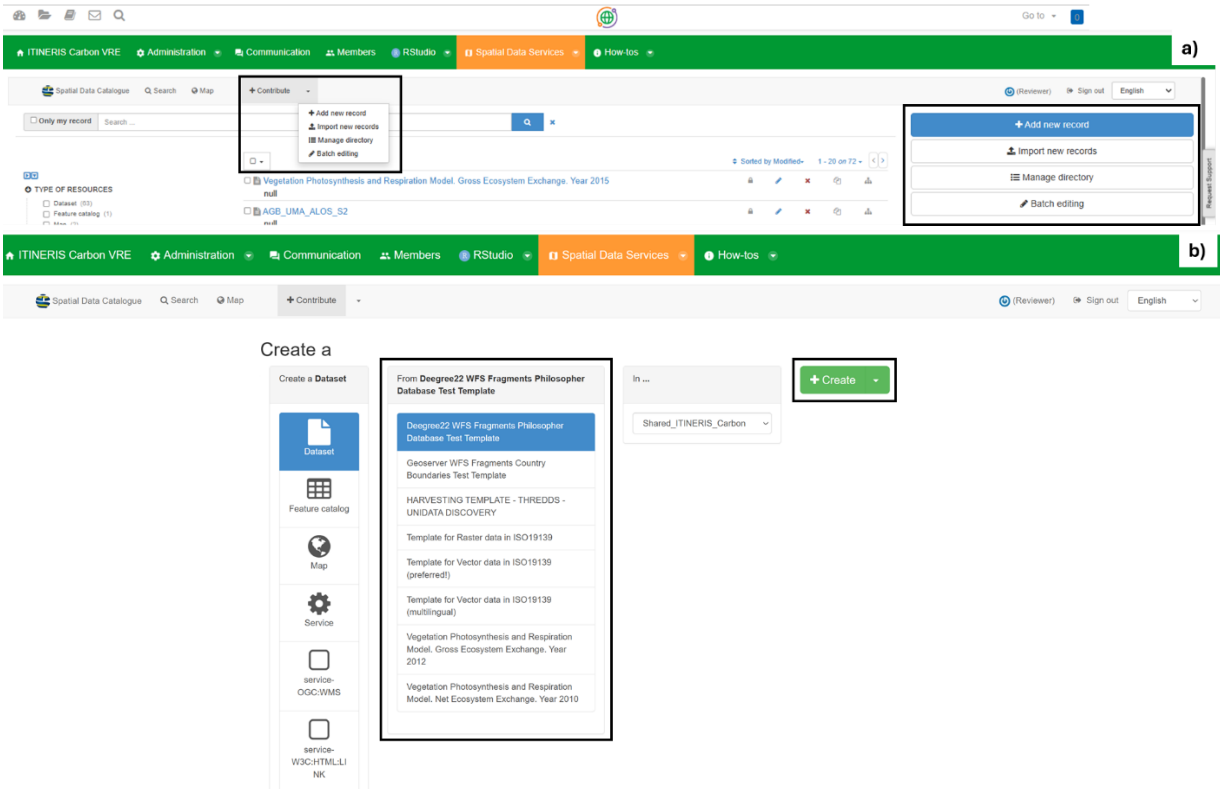


Figure 19. How to create a new metadata record operationally. a) The boxes highlight the two available options to create, import or edit metadata in the GeoNetwork; b) Creation of new metadata.

VRE users may import metadata using pre-existing templates. In order to do so, they must click on "contribute" and then "import new records", which will open the screen in Figure 20. Here, as highlighted in the box on the left, users can browse to the desired folder and import the relevant resource; after clicking on the "+ import" at the bottom, a successful import will be reported as in the box on the right (Figure 20). Metadata can also be directly edited by clicking on a product in the spatial data catalogue, and then clicking on the pencil button (Figure 21a), which will redirect users to the metadata editing page (Figure 21b).

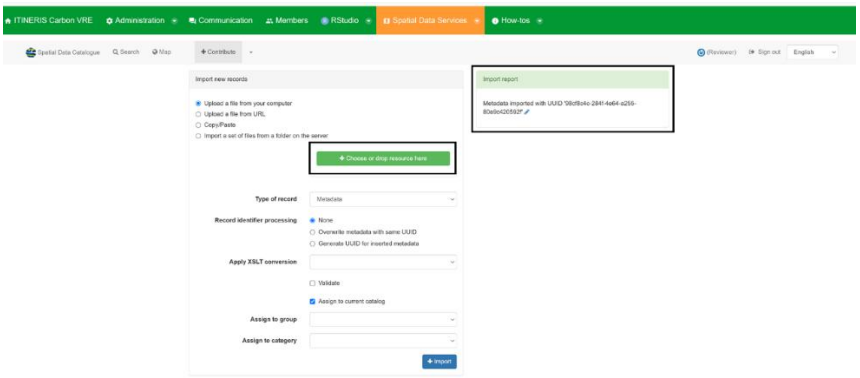


Figure 20. How to import metadata resources.

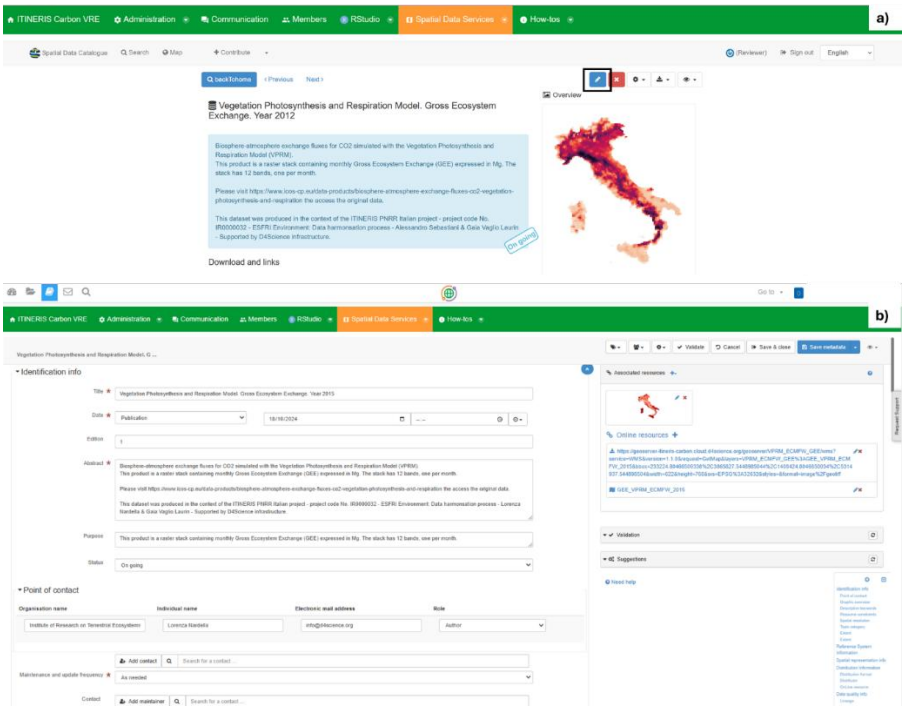


Figure 21. a) The pencil symbol allows users to edit a product's metadata. b) View of the editing metadata record panel.

The **GeoServer** (https://itineris.d4science.org/group/itineris_carbon/geoserver, last access: 10/12/2024) is an open-source Java software server which allows users to publish and share geospatial data using open standards within the Open Geospatial Consortium (OGC) protocols (e.g., Web Map Service - WMS, Web Feature Service - WFS). Metadata records can also be created and added in the GeoNetwork Spatial Data Catalogue by using the GeoServer instance, that is not open to all the VRE members, but it is accessible through a specific login. Enabled VRE members can group similar data via the GeoServer interface configuring specific workspaces. Documentation on the GeoServer software interface is available at https://docs.geoserver.org/latest/en/user/ (last access: 08/12/2024). From the GeoServer main page (Figure 22), all the available layers (Figure 23) and workspaces can be navigated. The

"Styles" option in the menu bar on the left allows to view and edit styles for individual layers in xml format. In case GeoServer layers are used to import metadata records into the GeoNetwork spatial data catalogue, the styles associated to individual layers inside the GeoServer will be maintained and visualized in the GeoNetwork map view.

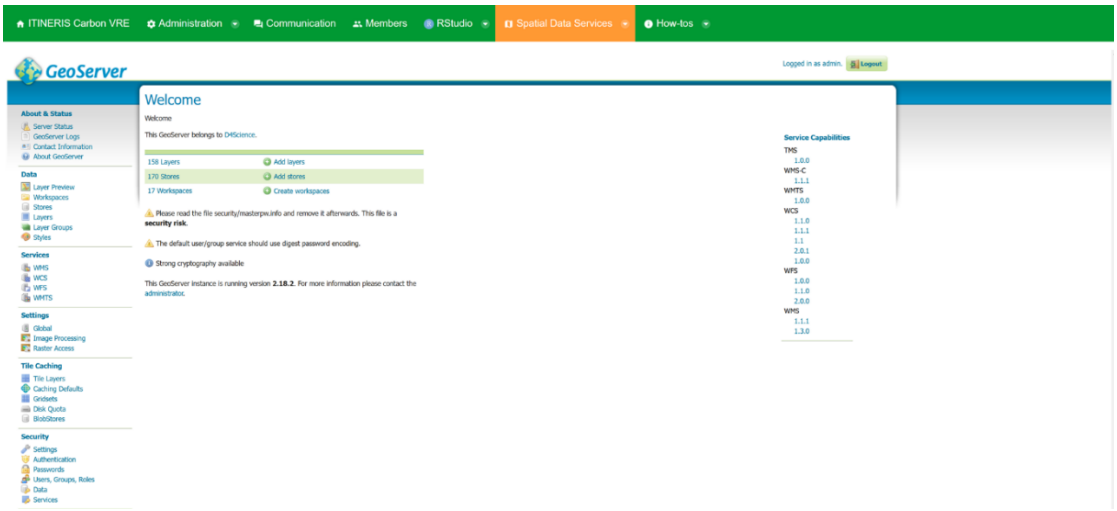


Figure 22. The Geoserver main page.

Figure 23. Layers uploaded to the Geoserver.

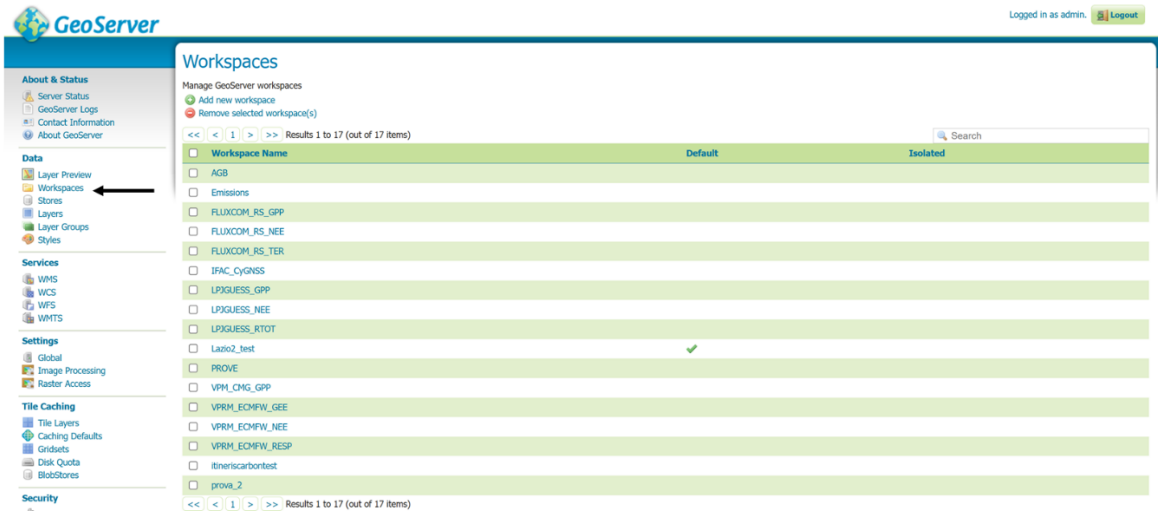


Figure 24. Workspaces present in the Geoserver.

Figure 25. a) Layer styles present in the Geoserver; b) Xml style definition for the layer "AGB_UMA_ALOS_S2".

2.5 RStudio integrated in "Carbon VRE"

The Carbon VRE offers the opportunity to use an integrated web-based Interactive Development Environments, namely RStudio, with an integrated importer software on a virtual machine connected to the workspace folder system. Two versions of RStudio are integrated: Standard (4 Cores / 8G RAM) and Large (8 Cores / 32G RAM) on a RStudio Server (2023.03.0, Build 386, © 2009-2023 Posit Software, PBC) (Figure 26).

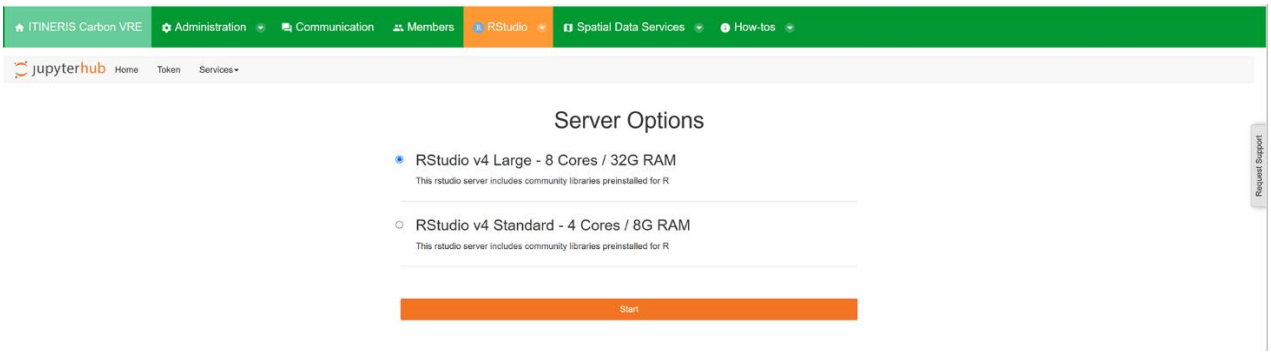


Figure 26. The two available versions of RStudio integrated in the Carbon VRE.

3 Demonstrators

Below are three operative examples using the provided R scripts to quantify and map: a) Italian emission (3.1 and 3.2) and b) carbon fluxes (3.3).

3.1 Mapping Total CO_2 emissions from the EDGAR dataset at the provincial level

Upon starting the RStudio virtual environment, VRE users will be able to directly access code and data present in the workspace. The first scrip presented is a re-adaptation from https://github.com/milos-agathon/carbon-emissions-per-capita/blob/main/R/main.r (last access: 10/12/2024). By running the script "CODE_TEST_popovic_2023.R" (Figure 27), users will:

1. Download and load Italian population data from the Global Human Settlement Dataset provided by the Joint Research Center (https://jeodpp.jrc.ec.europa.eu/ftp/jrc-opendata/GHSL/GHS_POP_GLOBE_R2023A/GHS_POP_E2020_GLOBE_R2023A_4326_30ss/V1-0/);
2. Aggregate population data at the provincial level;
3. Download CO_2 emission data provided by the 2022 EDGAR product (v80_FT2022_GHG) provided by the JRC (https://jeodpp.jrc.ec.europa.eu/ftp/jrc-opendata/EDGAR/datasets/v80_FT2022_GHG/CO2/TOTALS/);
4. Calculate emissions per capita;
5. Map per capita emissions at the provincial level for Italy for the year 2022 (Figure 28).

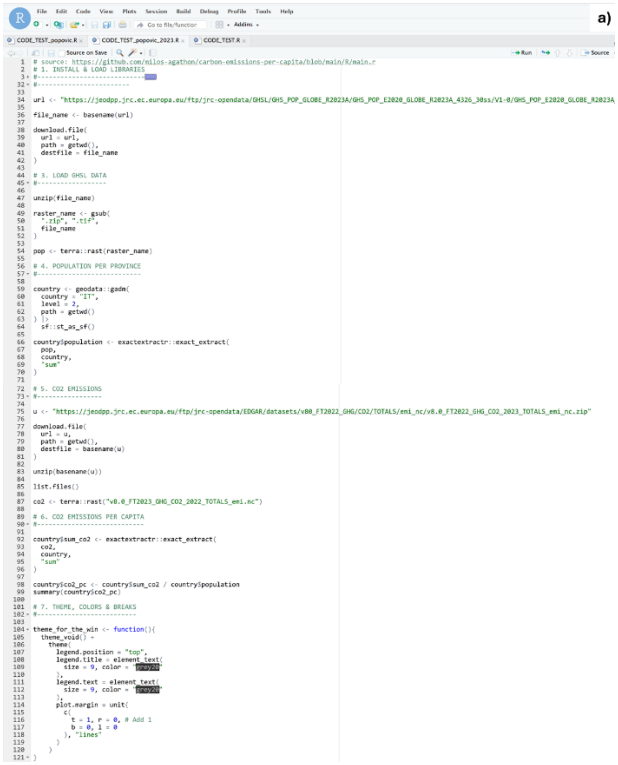


Figure 27. Example of the "CODE_TEST_popovic_2023.R" script available in the virtual RStudio environment;

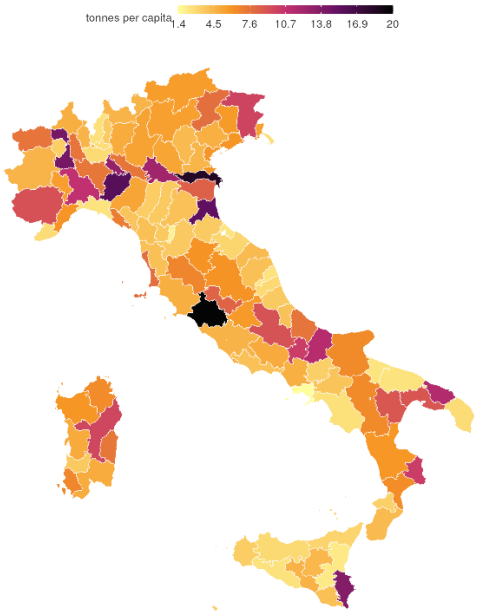


Figure 28. Map of 2022 Total CO_2 emissions (tons/capita) for Italian provinces for the year 2022. Source: 2022 EDGAR v80_FT2022_GHG dataset provided by the JRC.

3.2 Mapping 1990-2019 GHG emissions from the ISPRA national emission inventory at the provincial level

The script "CODE_TEST_ISPRA_EMISSIONS.R" (Figure 29) allows users to import from the workspace ISPRA emission data (ISPRA 2024) and provincial administrative limits, and generate a map of GHG emissions (tons) by province for each year included in the original datasets (1990, 1995, 2000, 2005, 2010, 2015, 2019), and for each GHG reported in the raw data files (CO_2, CH_4, CO, $NO+NO_2$). In the example below, the scripts outputs corresponds to GHG emissions per province of the Lazio region (Figures 30-33).

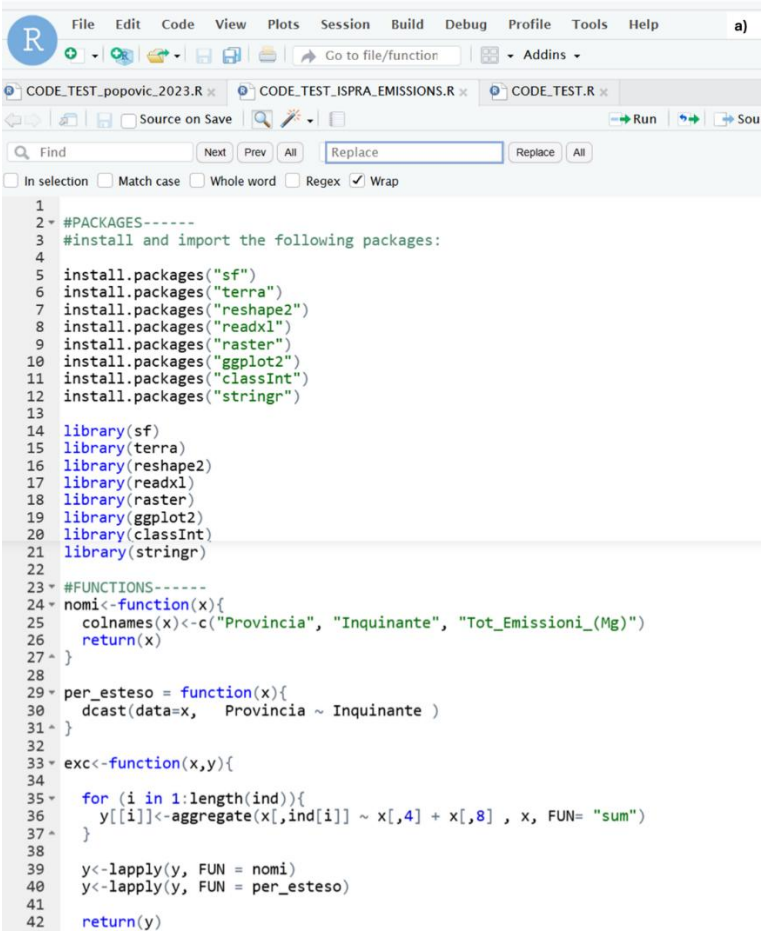


Figure 29. Example of "CODE_TEST_ISPRA_EMISSIONS.R" script.

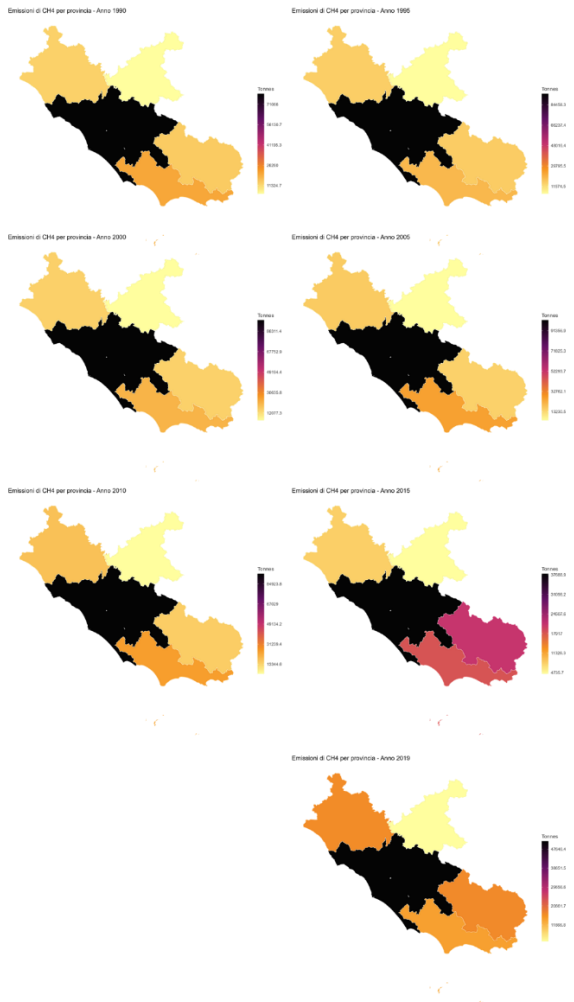


Figure 30. 1990-2019 CH_4 emissions per province in the Lazio region.

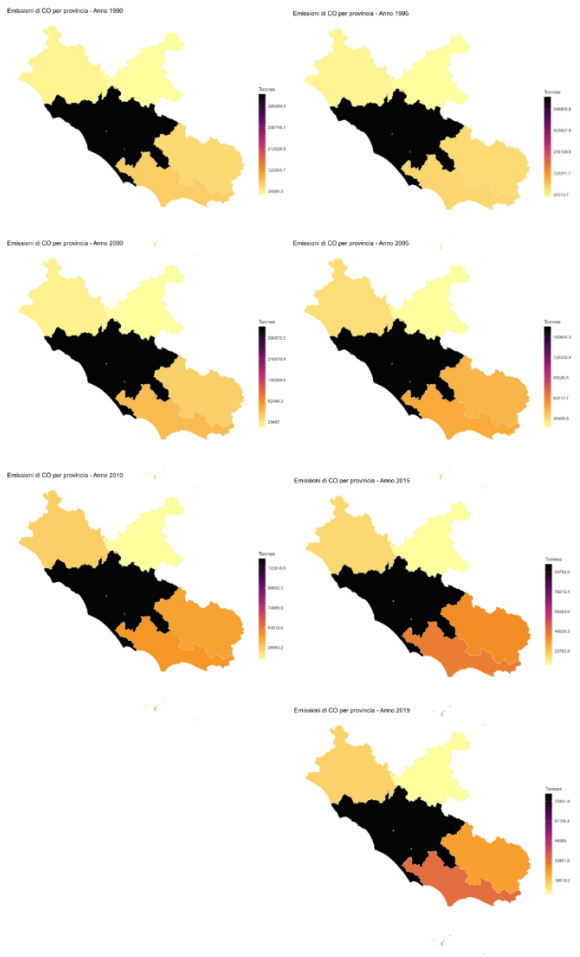


Figure 31. 1990-2019 CO emissions per province in the Lazio region.

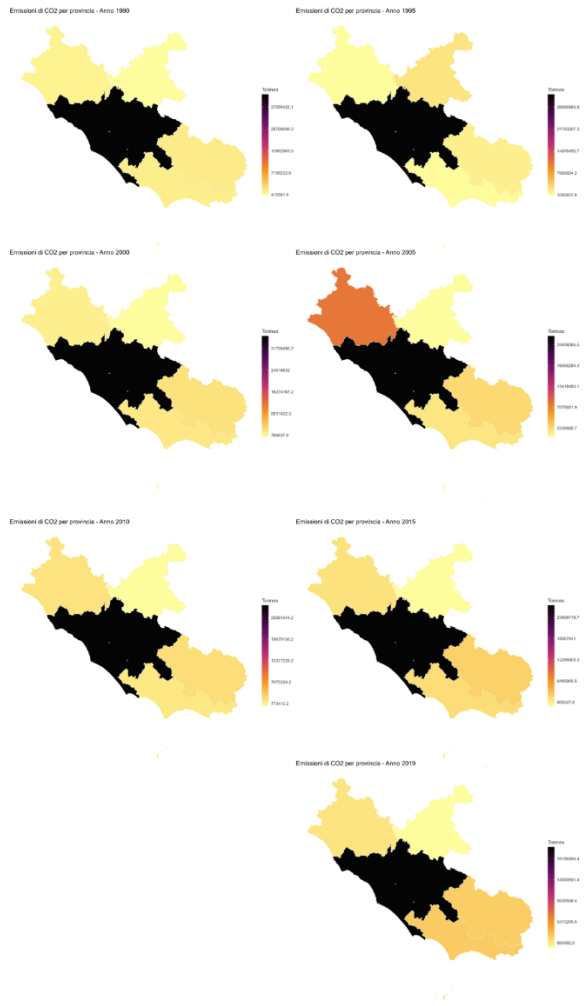


Figure 32. 1990-2019 CO_2 emissions per province in the Lazio region.

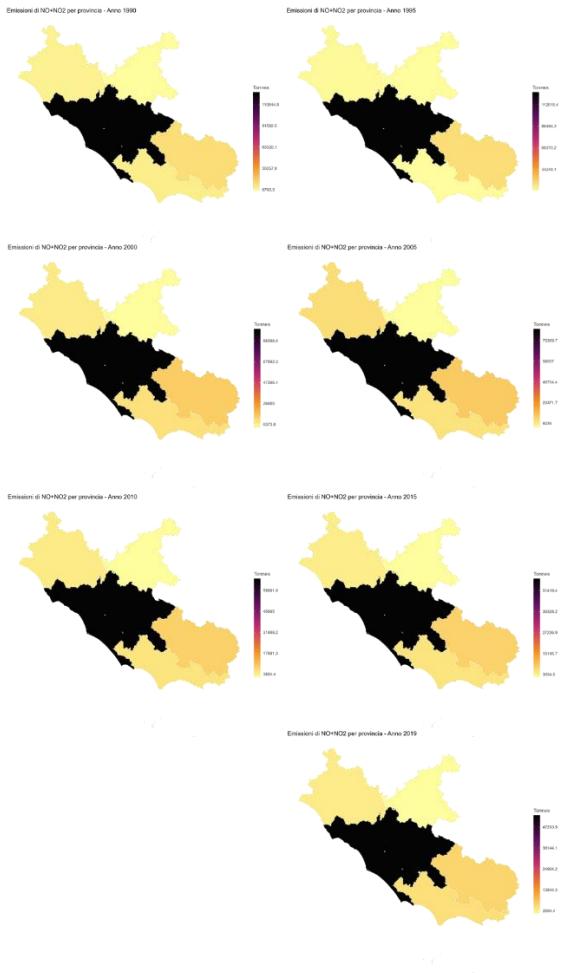


Figure 33. 1990-2019 $NO+NO_2$ emissions per province in the Lazio region.

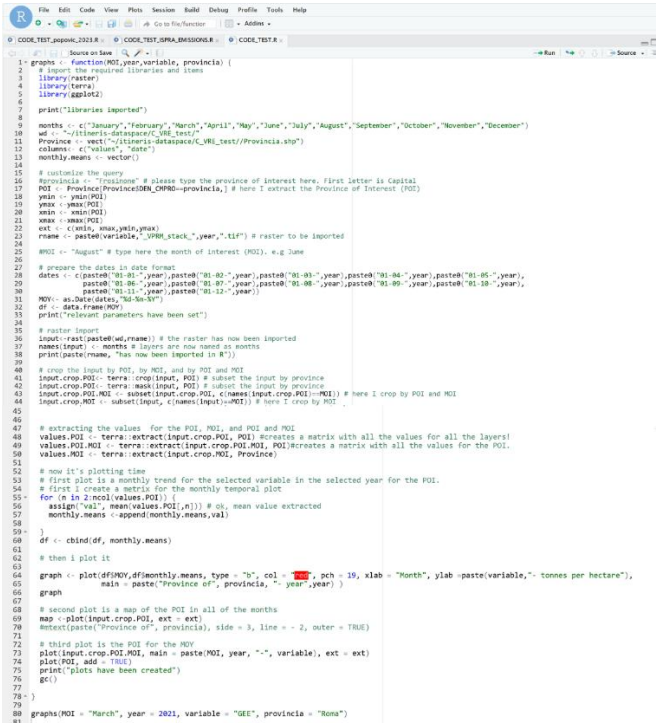
3.3 Mapping monthly average Gross Ecosystem Exchange for the Metropolitan City of Rome

The third example shows how to custom map carbon flux date. More specifically, by running the script "CODE_TEST.R", which can be found inside the folder "Home/itineris-dataspace/C_VRE_test" (Figure 34), users will:

1. Import the required libraries;
2. Set a query for a specific year, month, province and carbon flux product; queries can be customized by users (see line 80 in Figure 31), selecting a carbon flux model from those available in the workspace (see section 2.3 for the description of the **"Carbon_Fluxes_Models_Italy"** folder content);

Figure 35 reports an example run by selecting GEE as the desired flux variable, march as the

month, 2021 as the year, and Rome as the province.



```
graphs <- function(MOI,year,variable, provincia) {
 # import the required libraries and items
 library(raster)
 library(terra)
 library(ggplot2)

 print("libraries imported")

 months <- c("January","February","March","April","May","June","July","August","September","October","November","December")
 wd <- "~/itineris-dataspace/C_VRE_test/"
 Province <- vect("~/itineris-dataspace/C_VRE_test//Provincia.shp")
 columns<- c("values", "date")
 monthly.means <- vector()

 # customize the query
 #provincia <- "Trosinone" # please type the province of interest here. First letter is Capital
 POI <- Province[Province$DEN_CMPRO==provincia,] # here I extract the Province of Interest (POI)
 ymin <- ymin(POI)
 ymax <- ymax(POI)
 xmin <- xmin(POI)
 xmax <- xmax(POI)
 ext <- c(xmin, xmax,ymin,ymax)
 rname <- paste0(variable,"_VPRM_stack_",year,".tif") # raster to be imported

 #MOI <- "August" # type here the month of interest (MOI). e.g June

 # prepare the dates in date format
 dates <- c(paste0("01-01-",year),paste0("01-02-",year),paste0("01-03-",year),paste0("01-04-",year),paste0("01-05-",year),
            paste0("01-06-",year),paste0("01-07-",year),paste0("01-08-",year),paste0("01-09-",year),paste0("01-10-",year),
            paste0("01-11-",year),paste0("01-12-",year))
 MOY<- as.Date(dates,"%d-%m-%Y")
 df <- data.frame(MOY)
 print("relevant parameters have been set")

 # raster import
 input<-rast(paste0(wd,rname)) # the raster has now been imported
 names(input) <- months # layers are now named as months
 print(paste(rname, "has now been imported in R"))

 # crop the input by POI, by MOI, and by POI and MOI
 input.crop.POI<- terra::crop(input, POI) # subset the input by province
 input.crop.POI<- terra::mask(input, POI) # subset the input by province
 input.crop.POI.MOI <- subset(input.crop.POI, c(names(input.crop.POI)==MOI)) # here I crop by POI and MOI
 input.crop.MOI <- subset(input, c(names(input)==MOI)) # here I crop by MOI


 # extracting the values  for the POI, MOI, and POI and MOI
 values.POI <- terra::extract(input.crop.POI, POI) #creates a matrix with all the values for all the layers!
 values.POI.MOI <- terra::extract(input.crop.POI.MOI, POI)#creates a matrix with all the values for the POI.
 values.MOI <- terra::extract(input.crop.MOI, Province)

 # now it's plotting time
 # first plot is a monthly trend for the selected variable in the selected year for the POI.
 # first i create a matrix for the monthly temporal plot
 for (n in 2:ncol(values.POI)) {
   assign("val", mean(values.POI[,n])) # ok, mean value extracted
   monthly.means <-append(monthly.means,val)
 }
 df <- cbind(df, monthly.means)

 # then i plot it

 graph <- plot(df$MOY,df$monthly.means, type = "b", col = "red", pch = 19, xlab = "Month", ylab =paste(variable,"- tonnes per hectare"),
               main = paste("Province of", provincia, "- year",year) )
 graph

 # second plot is a map of the POI in all of the months
 map <-plot(input.crop.POI, ext = ext)
 #mtext(paste("Province of", provincia), side = 3, line = - 2, outer = TRUE)

 # third plot is the POI for the MOY
 plot(input.crop.POI.MOI, main = paste(MOI, year, "-", variable), ext = ext)
 plot(POI, add = TRUE)
 print("plots have been created")
 gc()
}

graphs(MOI = "March", year = 2021, variable = "GEE", provincia = "Roma")
```

Figure 34. View of the "CODE_TEST.R" script.

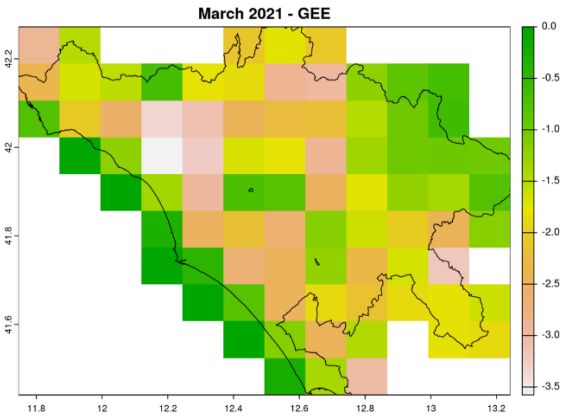


Figure 35. Map of average march 2021 GEE for the Metropolitan City of Rome.

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