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Monitoring, Reporting and Verification procedures for soil health: Current landscape, stakeholder dynamics and future pathways

Authors: Camille Imbert[1], Antonio Bispo[2], Sophia Götzinger[3], Peter Hoebe[4], Taru Sandén[3], Sambit Shome[1], Lucile Rabeau[5] and Kilian Walz[6]

Affiliations:

[1] Leibniz-Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, D-15384 Müncheberg, Germany

[2] INRAE Info&Sols, 2163, avenue de la Pomme de Pin, CS 40001 Ardon, 45075 Orléans cedex 2, France

[3] Austrian Agency for Health and Food Safety – AGES, Institute for Sustainable Plant Production, Department for Soil Health and Plant Nutrition, Spargelfeldstraße 191, A-1220 Wien, Austria

[4] Earthwatch Europe, 102-104 St Aldates, Oxford, OX1 1BT, United Kingdom

[5] Independent researcher, 24 cité des fleurs, 75017 Paris, France

[6] Commonland Foundation, Kraanspoor 26, 1033 SE Amsterdam, Netherlands

Correspondence to: Camille Imbert camille.imbert@zalf.de

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Abstract

To counteract green washing, the effects of the activities that lead to an intended outcome should be quantified and monitored in a scientifically robust way and results should be transparently reported and verified. With this objective, Monitoring, Reporting and Verification (MRV) procedures were developed and studied in the context of soil carbon credits. However, no broader overview, including other aspects of soils, exists to date. The objective of this study was to fill this gap of knowledge by gathering, describing and classifying the MRV procedures including soil parameters, across the world. As the term MRV seems to be sparsely used by scientists, we combined three methodologies to collect information about MRV procedures: the classical use of scientific article database, web scraping and Artificial Intelligence browsers. We found 96 MRV procedures and partial information was available. Most of the available MRV procedures were applied on a local scale, in agricultural areas, responding to the methodological requirements of voluntary carbon markets standards, which illustrates the hegemony of carbon markets in the soil MRV context. Results were mainly gathered in a classical report and result-based verified. We classified the MRV procedures into six groups. Group 1 was only characterized by the lack of information and thus reflected the main limitation of our study. The five other groups addressed different stakeholders. Four of them targeted stakeholders of the agricultural sector and the last one project developers for peatlands and wetland restoration. The two largest groups

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demonstrated different strategies: more accurate monitoring and verification methodologies or cheaper ones. We also highlighted the lack of transparency from companies offering MRV procedures. In complement, we developed a decision tool to help future users of MRV procedures to navigate our dataset and select the most adequate MRV procedure, adapted to their context. The next steps are 1) to strengthen the collaboration between scientists and MRV providers and to 2) understand how to transition from carbon-focused MRV procedures to more holistic, soil health-focused MRV procedures.

Short summary

We classified 96 Monitoring, Reporting and Verification (MRV) procedures including soil parameters. They were applied on a local scale, in agriculture, focusing on soil carbon, using a classical report and result-based verification. The six groups differed by available information, targeted stakeholders, monitoring and verification strategies. We also developed a decision tool. Next steps are to strengthen scientists-MRV providers collaboration and to transition to soil health MRV procedures.

1. Introduction

Numerous measures to preserve or restore soil health are applied by stakeholders such as adopting agro-ecological practices, de-sealing or planting trees (Altieri et al., 2015; Bárcena et al., 2014; Vieillard et al., 2024). Healthy soils correspond to soils that are in good chemical, biological, and physical conditions, and which can therefore provide ecosystem services vital to humans and the environment, such as a safe, nutritious and sufficient food, biomass, clean water, nutrient cycling, carbon storage, and a habitat for biodiversity (Directive 2025/2360, 2025, Vasquez et al., 2025). To create an incentive for land managers to preserve and restore soil health, few instruments are currently available. On a global level, voluntary carbon markets have been evolving as one of the major market-based instruments allowing to generate and trade credits as certified units that help to finance the adoption of more sustainable agricultural practices (Batjes et al., 2024, Regulation EU 2024/3012, 2024). A carbon credit is a certificate that represents one ton of CO2-equivalent and is the common trading unit on carbon markets (**https://www.offsetguide.org/understanding-carbon-offsets/what-is-a-carbon-offset/**). However, in several cases, carbon offsetting projects were deemed to under deliver on the expected climate mitigation outcomes leading to numerous situations for which actions to preserve the environment (like the mitigation of climate change) did not attain what the stakeholder had claimed (Trouwloon et al., 2023). These scandals led to allegations of green washing and discredited the effectiveness of carbon credits as means to achieve climate mitigation (Probst et al., 2024; Schreefel et al., 2023; Trencher et al., 2024). A prominent example is the non-commensurate use of carbon credits to achieve greenhouse gas reductions beyond offsetting solely residual emissions as is prescribed in voluntary best-practice guidance (Trouwloon et al., 2023).

To counteract green washing, the effects of the activities that lead to an intended outcome should be quantified and monitored in a scientifically robust way and results should be transparently reported and verified. This is the main purpose of Monitoring, Reporting and Verification (MRV) procedures (Smith et al., 2020). They are transparent and accurate frameworks giving

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indications in the way to assess the impact of an action on an object. Regarding soils, the main objective of the MRV procedures is to demonstrate the effect of land management (mainly, e.g. moving to agro-ecological practices or reforestation), on soil parameters (such as organic matter content or biodiversity). Moreover, MRV procedures not centered on soils but on other topics such as forest conservation can include the assessment of soil parameters.

The term MRV seems to be sparsely known by soil stakeholders except to those active on the carbon markets (Batjes et al. 2024). In the soil scientific community, this term has been promoted by the two recent EU projects BENCHMARKS and MARVIC (https://soilhealthbenchmarks.eu/, https://www.project-marvic.eu/). Until now, scientists mainly described carbon-focused MRV procedures and no classification targeting a larger spectrum of purposes exists (Batjes et al. 2024).

Thus, there is a need to go beyond carbon and identify all the MRV procedures including soil parameters. Indeed, MRV procedures can be applied in all the contexts dealing with soils. The main involved stakeholders are land managers as farmers, foresters or public administration but also scientists, NGOs and companies are concerned because they encourage practices enhancing soil health. Within soil monitoring, biological, physical and chemical soil parameters can be assessed via sampling, proximal (site images) or remote sensing, modelling or several of these methodologies combined (Batjes et al., 2024). Land management information, collected with questionnaires and provided by land managers, can also be used as proxy for soil parameters (Batjes et al., 2024). Result uncertainty is computed with probabilistic methods (Markov chain Monte Carlo and Bayesian inference), a sensitivity analysis or basic quantile distribution (with the representation and/or consideration of the quantiles in the result interpretation (Ceschia et al., 2025). Data are compared to reference values to determine if the implemented action is beneficial to soil health. Matson et al., 2024 describes four methodologies for computing these reference values 1) fixed value i.e. a static value based on the literrature, 2) reference value i.e.a static value from a reference site, mainly natural areas, 3) data distribution i.e. based on regional data, or 4) relative change i.e. a comparison to the data previously collected on the same site. Results are gathered in a document or entered on an online platform (Andries et al. 2021). The verification could take two forms: result-based i.e. doubling soil measurements with the same or a different methodology than for the monitoring step, or action-based i.e. the implementation of the actions is verified during a site visit, a second soil sampling, by remote sensing or with a phone application (Andries et al., 2021, Batjes et al., 2024). The auditor can be part of the organization implementing the soil monitoring or act as an independent entity.

In this study, we reviewed and classified the adoption of MRV procedures for assessing soil health and, assessed whether they are used beyond the context of carbon markets. We also identified the involved stakeholders, as well as the soil management practices. We proposed a decision support tool to help future users to select the right MRV procedure, corresponding to their context.

As we suspected that few scientific articles would be written on the topic of soil MRV procedures, we decided to combine three review methods: the traditional literature review using a database of scientific articles and the recent ones web scraping and AI browsers (Perplexity and Elicit). While traditional literature review has been the common method for any academic researcher, web scraping allowed for accessing grey literature from websites in a more systematic manner (Sayles et al., 2022).

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Most recently, Artificial Intelligence has emerged providing a wide array of search capabilities and in particular, browsers as Perplexity and Elicit trained for the scientists.

Our findings are very relevant for future stakeholders that wish to develop or simply implement MRV procedures for assessing their soil health status and will enable to identify existing approaches or build upon them, with a view to adapting existing practices to their needs and context.

2. Materials and methods

2.1. Data search

As MRV procedures on soils seem to be not well studied, we decided to use a very broad search string: **Monitor* AND Report* AND Verif* AND MRV AND soil***.

We used it for the three methods we combined to scientific articles and websites presenting MRV procedures: a search on the database of scientific articles Scopus, webscraping and the use of Artificial Intelligence browsers Elicit (**https://elicit.com/**) and Perplexity (**https://www.perplexity.ai/**). The search was done in Scopus in March 2025 and includes article titles, abstracts and keywords. It resulted in 18 articles (primary studies, reviews and book chapters). We recorded the name of the first author, the title, the publication year, the DOI and the type of document i.e.if it was a primary study, an editorial article or a review. Then, we developed a web scraping script using Python 3.9.7 and Selenium web driver (Fig. A2, **https://www.selenium.dev/documentation/webdriver/**). We ran the script to scrap the first 20 pages on Google Search Engine Results Page (SERP). We manually handled reCAPTCHA images. As results provided by Google varied according to the country location, the date and the IP address, we decided to run the script during Autumn 2025, from different countries and different computers in Europe (See Code and data availability). We recorded the URL link, webpage title and URL domain in a database for further analysis. We used the Artificial Intelligence browsers Perplexity and Elicit in December 2025 with the following prompt: "*I would like to investigate existing Monitoring, Reporting and Verification Systems for soil parameters. Please find the documents for this contextual focus and give a table that I can copy, listing these documents, with for each of them, a URL link to download them.*" We recorded the document title and the URL link in a dataset for further analysis.

2.2. Data extraction

2.2.1. Inclusion rules

To be included in the study, the collected articles and websites should at least, indicate one of the required information for each step of the MRV procedure i.e. one information for monitoring, one for reporting and one for verification. For example, if only information about monitoring was given, such as the assessed soil parameters, and no information about reporting nor verification, the document was excluded from the analysis. Moreover, the MRV procedure was required to include at least one

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soil parameter. For example, MRV procedures about greenhouse gas emissions in forest, focusing on parameters related to the vegetation, without considering a single soil parameter, were excluded.

2.2.2. Duplicate management

The same document or the same MRV procedure could be collected several times. For example, several scientific articles could include the same MRV procedure, or a website could appear several times. We considered any new mention of an already mentioned MRV procedure as duplicate. Thus, we avoided counting twice the same MRV procedure.

2.2.3. Data collection

We considered the land uses and land covers were the MRV procedures are applied, the geographical scale (i.e. local such as a field, a farm or a forest area, regional corresponding to several sites or farms, national, continental and global scale). We categorized occupations of stakeholders implementing the MRV procedures as farmers, foresters and forester associations, public administrators, educational and research institutions, NGOs, agroindustry, forestry companies, consultants and others (Chowdhury et al., 2023; Eggers et al., 2020; Pachón Maldonado et al., 2024; Strauss et al., 2023; Vanino et al., 2023). We indicated the purpose of the MRV procedure i.e.the reason why it was developed : 1) voluntary carbon market i.e. a carbon market in which members are not legally compelled to reduce their emissions but do so voluntarily, 2) compliance carbon markets also known as mandatory markets, governed by national, regional, or provincial law and 3) certification i.e.a procedure to attribute a label (Batjes et al., 2024; Ceschia et al., 2025). We recorded the actions that were implemented.
Monitoring methodologies were divided in : 1) information about land management, 2) spatial images, 3) on-site images with photos, 4) soil samples and 5) modelling (Batjes et al., 2024). In the case of soil samples, we collected information about the sampling design: 1) the plot area and 2) the monitoring frequency i.e. duration between two monitoring sessions (less than every 5 years, between 5 and 10 years, between 10 and 15 years or more than 15 years as in Batjes et al. 2024). Soil parameters required in each MRV procedures were listed. We also recorded if sampling and/or analytical methods comply to existing standards (e.g. ISO). We described the format of the report (classical document or online platform, Andries et al. 2021) and the statistical methodology employed to compute the uncertainty of the results: 1) probabilistic methods corresponding to Markov chain Monte Carlo (MCMC) and Bayesian inference, 2) sensitivity analysis, i.e.the effect of the explanatory variables on the uncertainty of the results and 3) quantile distribution, with the representation and/or consideration of the quantiles in the result interpretation (Ceschia et al., 2025). We recorded the methodology used to compute the reference values : 1) fixed value, 2) reference value, 3) data distribution, or 4) relative change (Matson et al. 2024) Regarding verification, five information were listed : the scheme i.e. action-based or result-based (Batjes et al. 2024), the methodology i.e. soil sampling, satellite data, phone application or site inspection, its automatization, the auditor independance and the data access (Batjes et al., 2024). Finally, we recorded if the MRV procedure was already implemented or under development and the country where the MRV procedure was implemented or tested.

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2.3. Data analysis

2.3.1. Management of missing information

Once the data collection was completed, we noticed a large part of missing information. As missing information could bias the results, in particular with categorical variables, we decided to keep only variables that presented more than 70% MRV procedures with information in the analysis.

2.3.2. Description and typology of MRV procedures

We pooled the data collected from the three search methods. We used the software R 4.3.0 for data analysis building the figures. We designed with the package ggplot2 (Wickham et al., 2016) bar plots for each variable and a co-occurrence matrix between stakeholder' and MRV procedure' s characteristics.

We implemented multiple component analysis (MCA, function MCA, package R FactomineR, Lê et al., 2008) and a Hierarchical Clustering on Principle Components (HCPC, function HCPC, package FactoMineR) to identify the groups of MRV procedures and the particular elements characterizing them. We computed a v-test and its p-value (Husson et al., 2017). We focused our analysis on the categories with 1) v-test>2 and 2) a p-value<0.05 (Husson et al., 2017).

2.3.3. Building the decision tool

We built a user-friendly interface to access our dataset, with Python 1.29 with the package Streamlit (https://streamlit.io) . The outputs are the MRV procedures with a playing card format, fitted to the context of the user. All the codes and datasets needed to run the decision tool are available (See Code and data availability).

3. Results

All sources pooled, nine scientific articles and 32 websites were selected (of 28 articles collected and 1211 websites screened, see Code and data availability). In total, we found 96 MRV procedures. Only little information was provided in the documents we collected (Fig. A2). We removed from the analysis, variables with information missing for more than 30% of the MRV procedures : 1) regarding the monitoring, sampling frequency, standard methodologies, cost and plot area, 2) regarding the reporting, uncertainty measurement and threshold methodology, 3) considering the verification, methodology, automatization, auditor type and data sharing.

MRV procedures mainly took place in America, Oceania and Europe. Only few countries were covered in Africa and Asia (Fig.1).

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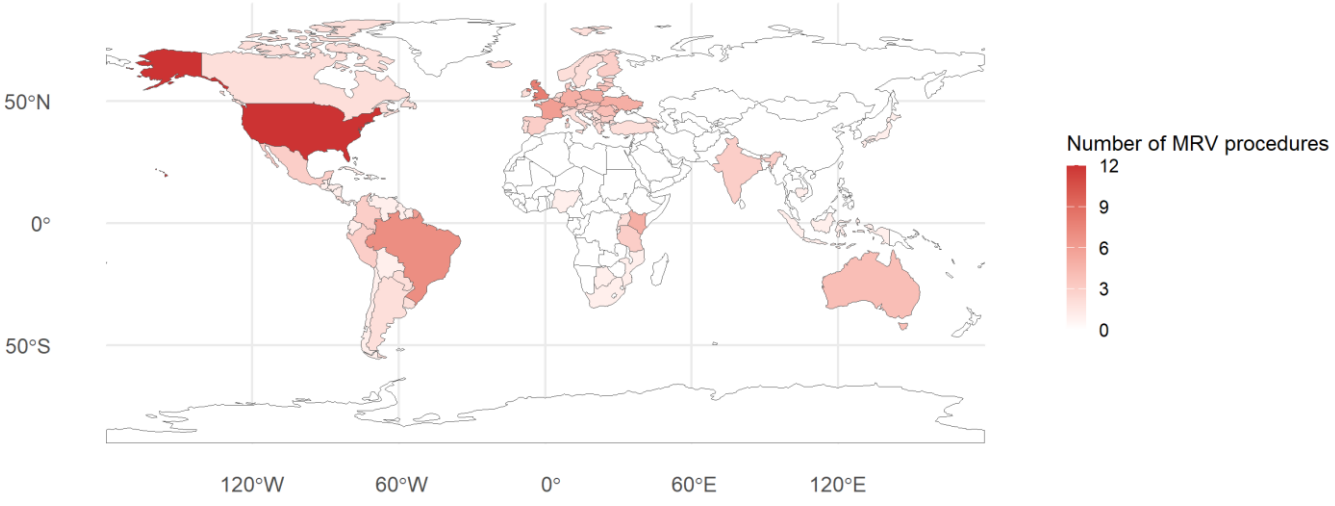


Figure 1. Map of the number of MRV procedures taking place in each country

More than 80% of the MRV procedures were already implemented, leaving the remaining 20% as purely conceptual procedures (Fig. A3).

3.1. Data description

Seventy-nine MRV procedures took place in agricultural areas (Fig. 2 a.). The other land uses and land covers were forests (22), peatlands or wetlands (9) and degraded lands (1, Fig. 2 a.).

MRV procedures took place mainly at local scale (62 MRV procedures) and then at regional scale (45) and national scale (18, Fig. 6). Only two MRV procedures was applied at continental or at global scale.

A large diversity of occupations were involved in the MRV procedures. The majority targeted farmers (59 MRV procedures) and then consultants (40). At a lesser extend, MRV procedures also included other occupations as public administrators (25), agroindustry (19), NGO (16), academia (15), project developers (12), foresters (11), forest companies (3), software developers (1) and other companies (5, Fig. 2 d.).

Five purposes were found: voluntary and compliance carbon markets, certification and sustainability measures (Fig. 2 c.).

The main purpose of the MRV procedure was by far, voluntary carbon market with 84 MRV procedures with 84 MRV procedures.

The main actions were related to the change in agricultural practices (59 MRV procedures). They could be specified as mineral weathering, irrigation, grazing practices and biochar application. We found other very rare actions (less than five MRV

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200 procedures) as: afforestation and reforestation, restoration measures, deforestation, rewetting of peatlands and wetlands, forest management, fire management and land conversion (Fig. 2 e.).

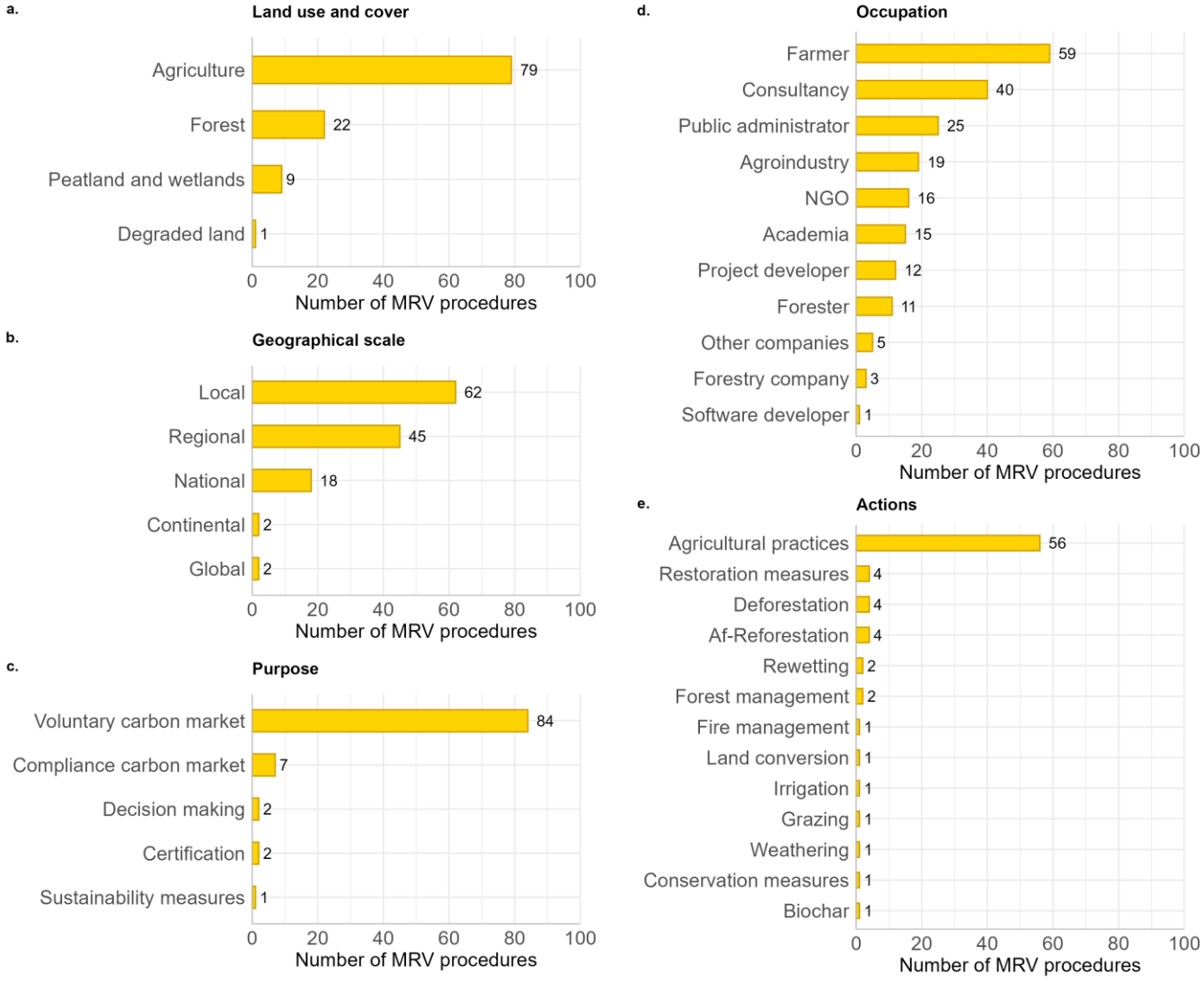


Figure 2. Frequency of MRV procedures according to stakeholders' characteristics: land uses and land covers (a.), geographical scales (b.), occupation (c.), purpose (d.) and the implemented actions (e.)

205 Regarding monitoring, a total of 22 soil parameters were identified in the MRV procedures (Fig. 3 a.). Physical, chemical and biological parameters were assessed. The most frequent was soil organic matter and carbon, monitored in almost all of them (93 MRV procedures, Fig. 3 a.). In average, two parameters were assessed by MRV procedure. The minimum number was one parameter, and the maximum was nine for the procedure MRV WE020 (measurements include pH, soil organic matter

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and carbon, texture, bulk density, nutrient availability, green house gases, soil type, calcium carbonates, electrical conductivity and water holding capacity, see Code and data availability).

The most frequent monitoring methodology was modelling with 75 MRV procedures. Soil samples, spatial images and management information are also used in more than 50 MRV procedures. We also found a MRV procedure (MRV WE011) based on site images taken with a smart phone (see Code and data availability).

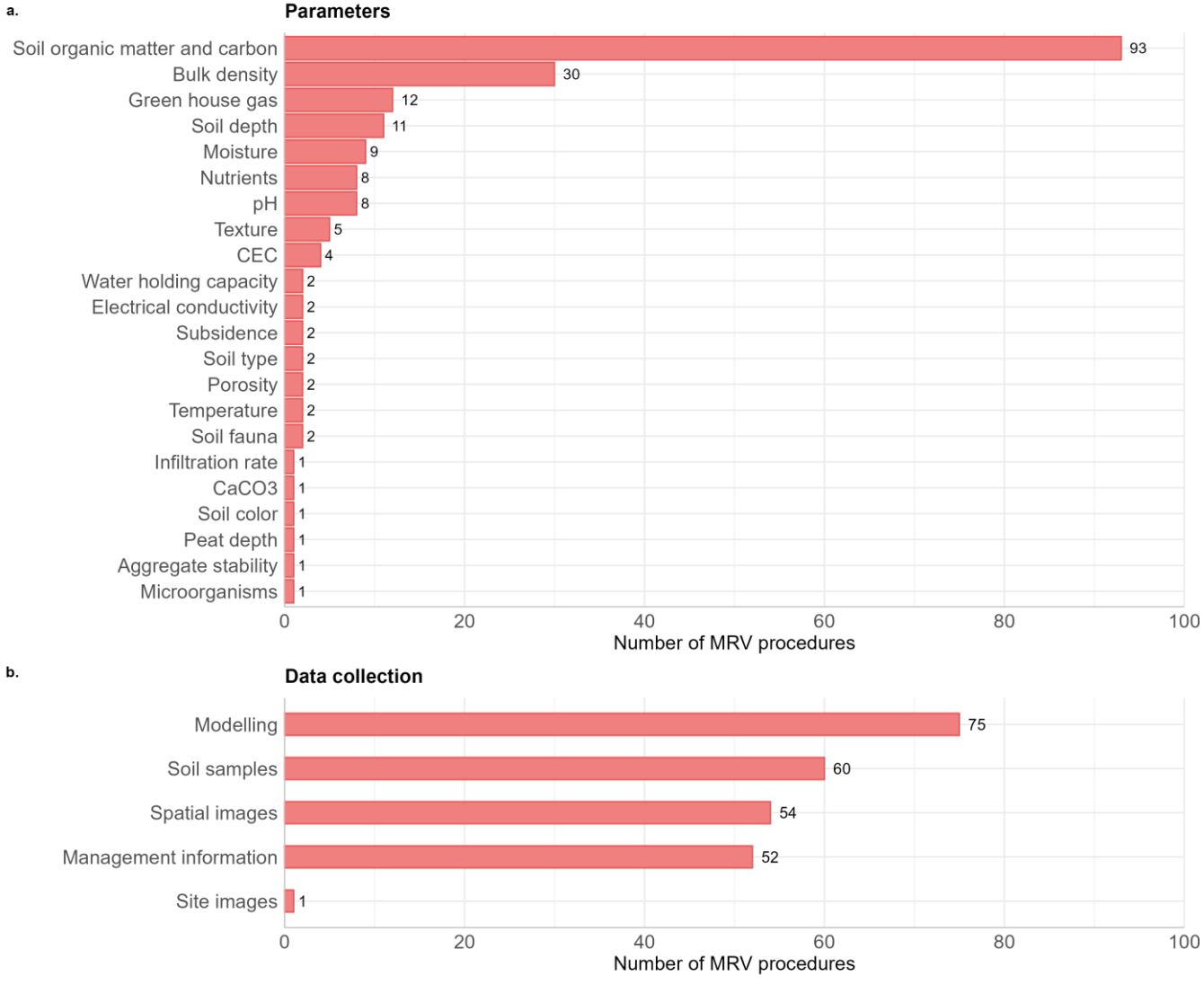


Figure 3. Number of MRV procedures according to the included soil parameters (a.) and the type of data used for monitoring (b.)

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Results were for 52 MRV procedures gathered in a classical report. An online platform was used for 29 MRV of them (Fig. 4 a.).The verification was mainly based on the results (61 MRV procedures) and on the implementation of the actions for 20 MRV procedures (Fig. 4 b.).

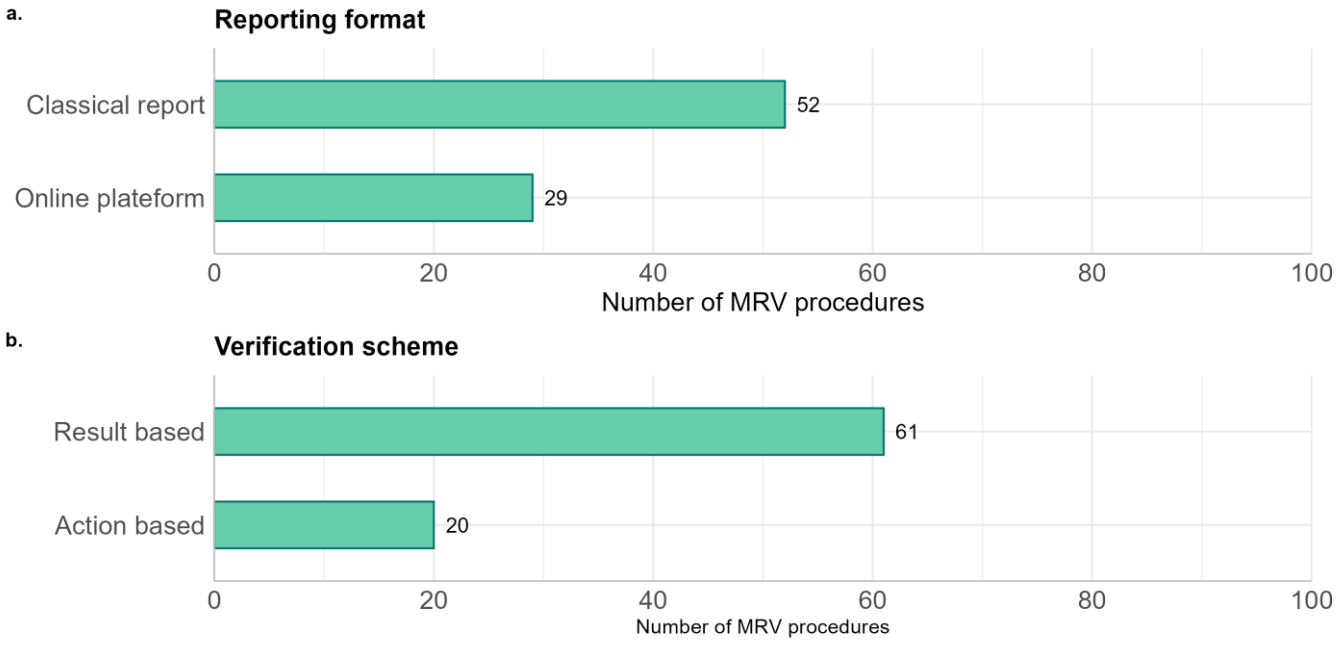


Figure 4. Number of MRV procedures according to the reporting format (a.) and the verification scheme (b.)

3.2. Co-occurrence between stakeholders' and MRV procedures' characteristics

We looked more precisely at the link between the characteristics of the stakeholders and the MRV procedures, by focusing on the main co-occurrences between stakeholders' and MRV procedures' characteristics (i.e. more than 25 MRV procedures, Fig. 5).

In agricultural areas, organic matter and carbon was the only soil parameter included in more than 25 MRV procedures. All monitoring methodologies were very frequent, except on-site images. Both ways of result reporting were used in more than 25 MRV procedures. Verification was result-based for more than 25 MRV procedures.

At both local and regional scale, we noticed the same pattern for the monitoring i.e. focused on soil organic matter and carbon, using a diversity of methodologies. Results were gathered in a classical report and the verification was result-based. For more than 25 MRV procedures, consultants monitored soil organic matter and carbon with modelling, using result-based verification. Concerning farmers, they also focused on soil organic matter and carbon, without any preference for the methodology (except site images). Results were gathered in a classical report and the verification was result-based. As expected, regarding the voluntary carbon market, more than 25 MRV procedures included soil organic matter and carbon. More than 50 were based

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on soil sampling and modelling and more than 25 on land management information or spatial images. Logically, when this implemented action was the change in agricultural practices, MRV procedures' characteristics were the same as for farmers. At a larger picture, a lot of combination stakeholders x MRV procedures did not exist or were not communicated yet.



Figure 5. Co-occurrence between the characteristics of stakeholders and MRV procedures

3.3. Typology of stakeholders and MRV procedures

We classified the MRV procedures into six groups and highlighted their particular characteristics (Fig. 6, Tab. A1).

Group 1, including two MRV procedures, was only characterized by missing information for stakeholder occupation (Fig. 6 a.). Group 2 included ten MRV procedures. It stood out from the other groups by covering local (all the MRV procedures), national (7),continental (2) and global (2) scales and five occupation types that are public administrators (7), academia (7), NGOs (7), agroindustry (7) and consultancy (8, Fig. 6 a.). This group was focused on the change in agricultural practices (9 MRV procedures, Fig. 6 a.). Another particularity was that, for a part of the MRV procedures, pH (8 MRV procedures), cationic exchange capacity (CEC, 3) soil moisture (6), water holding capacity (2), soil type (2), soil depth (4), nutrients (7), porosity (2), texture (3) and temperature (2) were monitored (Fig. 6 b.).

Group 3 was also very small with three MRV procedures (Fig.6). Its particularity was the absence of information regarding the geographical scale the MRV procedures took place and the presence of a MRV procedure assessing the impact of the change in grazing rate (Fig. 6 a.).

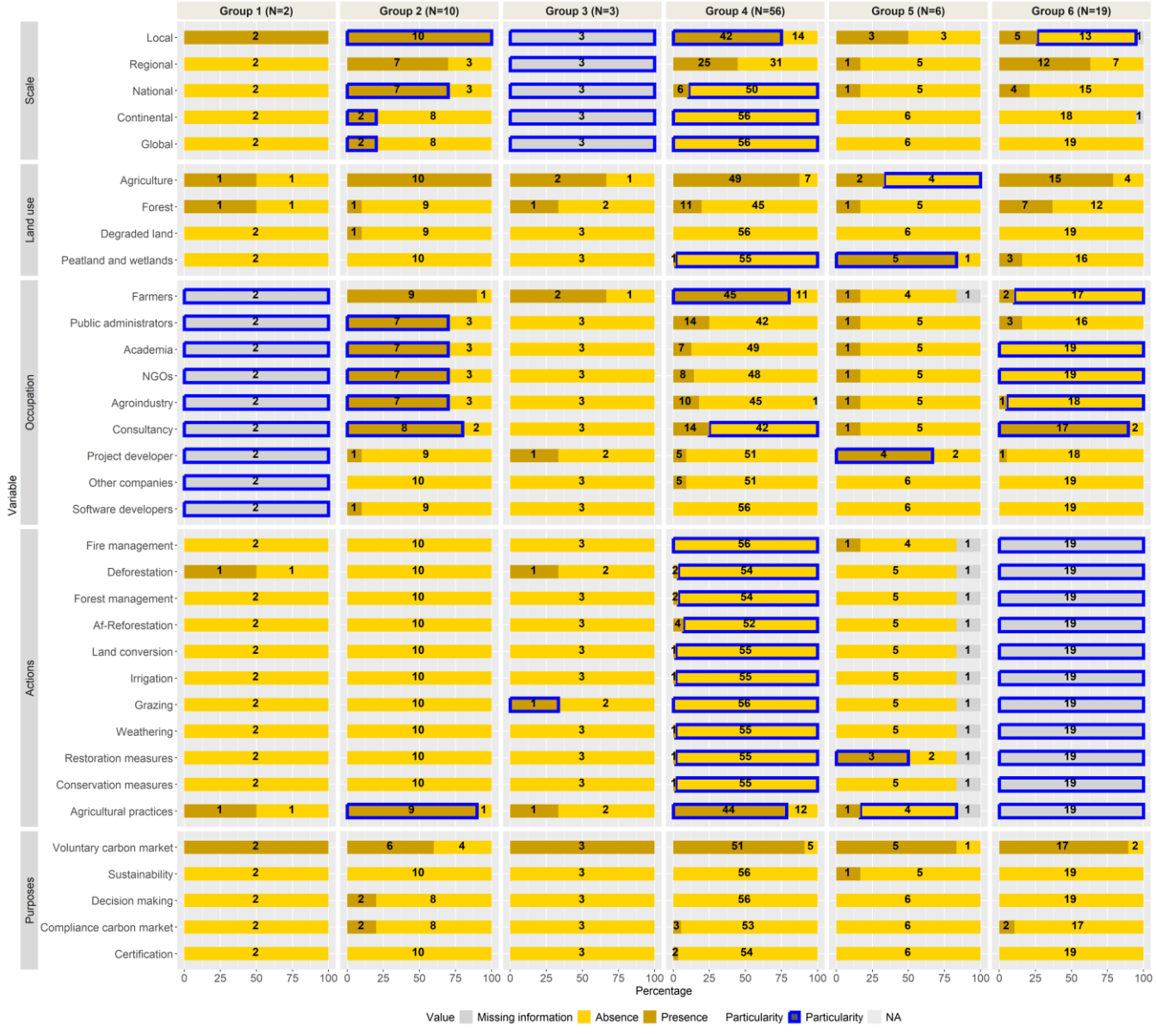
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The largest group was the fourth with 56 MRV procedures (Fig. 6). It was characterized by a high specificity : the particularities were the implementation at local scale (for 42 MRV procedures) and nor at national, continental neither at global scale (almost all the MRV procedures are not implemented at those scales, Fig. 6 a.). Another particularity was that these MRV procedures did not take place in peatlands or wetlands (55 MRV procedures). This group stand out by targeting farmers (45 MRV procedures) and not consultancy (42). Regarding implemented actions it was also focused on the change in agricultural practices (44). The absence of rarer actions were also group 4's particularities. Regarding monitoring, a particularity was that almost all the MRV procedures did not include pH (56), moisture (54), soil depth (53) nor nutrient (55, Fig. 6 b.). Different methodologies appeared as group 4's particularities : soil sampling, spatial images and land management information (Fig. 6 b.). The use of online platform (for 22 MRV procedures) and not a classical report (22) to display the results was also a particularities of the group (Fig. 6 c.). The last one was that the verification was result-based (43) and not action-based (37, Fig. 6 c.).

Group 5 included only six MRV procedures (Fig. 6). Most of them focused on peatlands and wetlands (5 MRV procedures) and excluded agricultural areas (4), targeting project developers (4) for land restoration (3) and not change in agricultural practices (4, Fig. 6 a.). Another particularity was the monitoring of rare soil parameters that are subsidence (2) and soil depth (4, Fig. 6 b.). This group was also defined by missing information regarding monitoring methodology (Fig. 6 b.) and verification scheme (Fig. 6 c.).

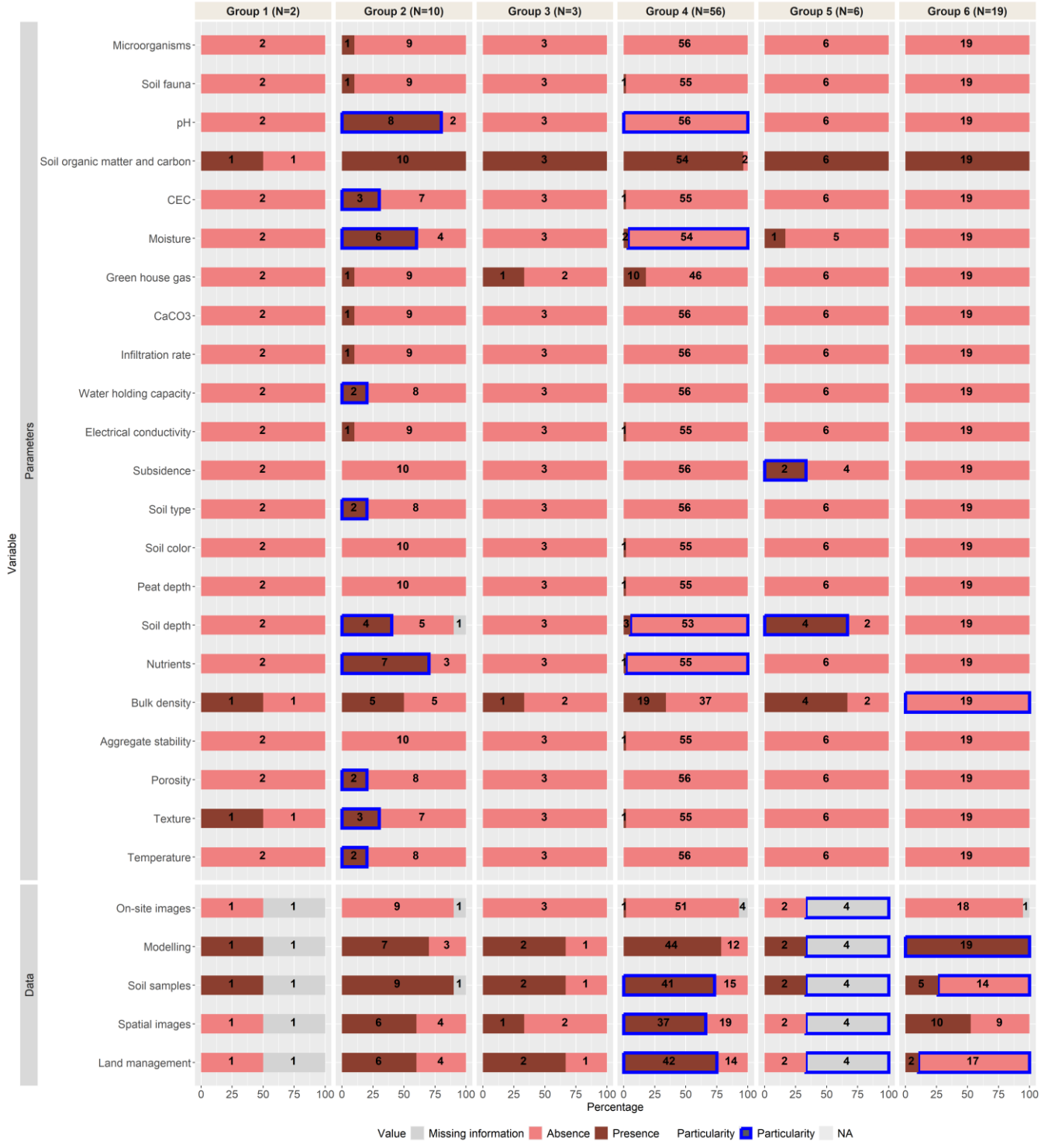
The sixth group, with 19 MRV procedure was the second largest group. One of its particularities is to include 13 MRV procedures not taking place at local scale (Fig. 6 a.). It is also targeting consultancy (for all the MRV procedures) and not farmers (17), academia (all), NGOs (all) nor the agroindustry (18, Fig 6 a.). The implemented actions are not known for all of them (Fig. 6 a.). Regarding monitoring, bulk density was never assessed and the methodology was always modelling (Fig. 6 b.). The absence of soil sampling nor land management information was also a particularity of the group (Fig. 6 b.). It was also characterized by the absence of information regarding reporting format for 18 MRV procedures (Fig. 6 c.). Regarding verification, it was action-based (9) and not result-based (10).

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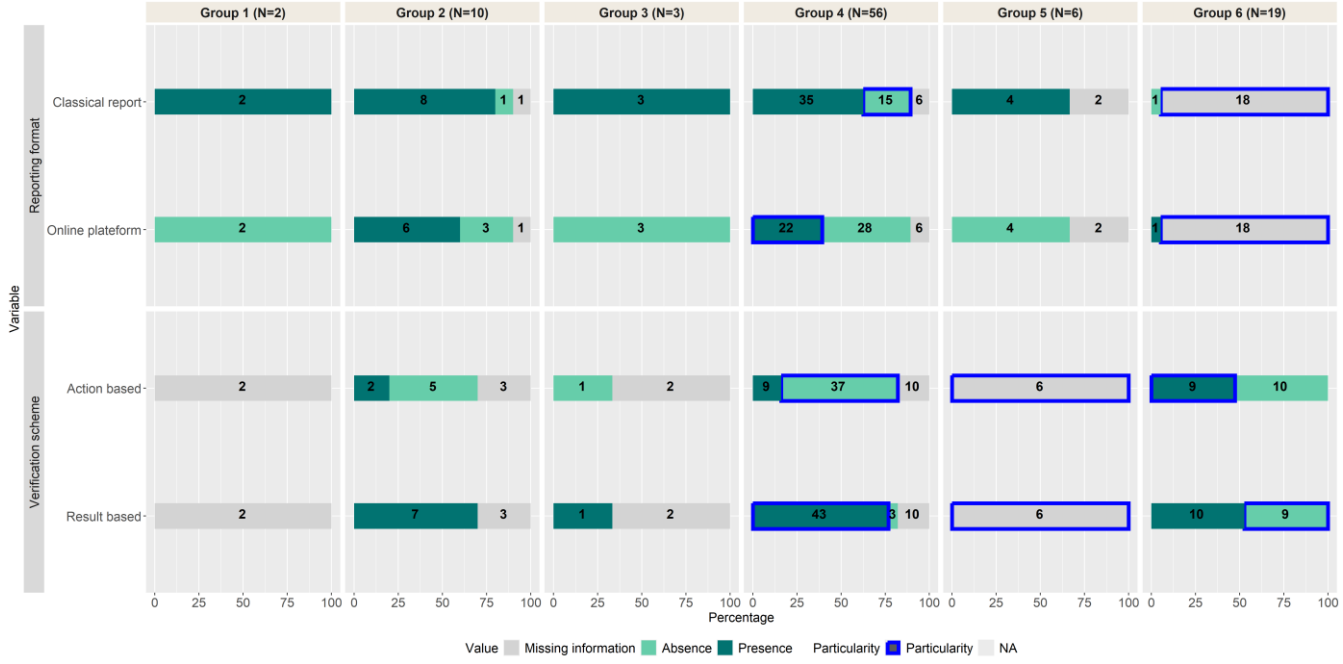
a. Stakeholder'characteristics

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b. Monitoring characteristics

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c. Reporting and Verification characteristics

Figure 6. Number of MRV procedures per category in each group and of MRV procedures per category in each group and groups' particularities

3.4. Decision tool

To encourage knowledge transfer between scientists and non-scientists, we developed a decision tool to help users in the choice of an adapted MRV procedure for soil health. It is available online: https://mrv-procedures-soil-health.streamlit.app/. We used the playing card format to summarize the collected information. The welcome page explains the purpose of the tool and the information presented on each MRV card. Then, the user selects its context`s characteristics and the tool provide the MRV procedures with a level of similarity higher than 80%. The MRV procedures are presented with the format of cards.

The first page of the decision tool corresponds to the user (i.e. the stakeholder)'s characteristics : 1) On which land use do you want to apply the MRV procedure?, 2) At which geographical scale do you want to apply the MRV procedure?, 3) What is the purpose of the MRV procedure?, 4) Which type of actions do you want to implement? and 5)What is your occupation? After answering the previous questions, the MRV cards corresponding to these criteria are suggested. The tool will present all the MRV cards with a percentage of similarity as the number of items fitted with user' wishes divided by the total number of items.

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4. Discussion

With only nine scientific articles included in our literature review, the term MRV seems to be rarely used by soil scientists. A large part of scientific articles when mentioning MRV only focus on the monitoring part. The term MRV is more common in the private sector as shown by the higher number of MRV procedures coming from company websites, collected with web scraping. Our study illustrates the difference in terminology between academia and the private sector. These differences can lead to communication difficulties (Weninger et al., 2024). However, scientists implement MRV procedures without calling them like this: they monitor soils, verify their data and report the results in the form of scientific articles. National soil monitoring networks are good examples of these "hidden" MRV procedures (Imbert et al., 2024).

Major characteristics of MRV procedures were discarded from the analysis due to lack of information. We are missing knowledge on: sampling designs (plot area, sampling frequency), costs, uncertainty reporting, verification provider and data sharing or availability. A recent study in Wallonia, Belgium tried to develop a cost model for three MRV systems namely decision support tools, process-based models, and direct soil measurements. They suggest that their generic cost model development can be extrapolated across various context to estimate MRV costs of carbon farming (Vanderheyden et al. 2026). Again, we encourage the providers of MRV procedures to clearly communicate about those later points to avoid suspicion of green washing.

In our study, very few MRV procedures took place in Africa or in Asia. This result was surprising because compensation using carbon credits by reforestation mainly takes place in the countries of the Global South i.e. Africa, Asia, Oceania (Australia and New Zealand excluded) and Latin America (Cheong, 2025). Possible explanations would be that the term MRV is not used by all the actors of the private sector or that these MRV procedures do not include soil parameters. Thus, this might be a limitation of our study.

The majority of the MRV procedures involved farmers willing to get involved in the voluntary carbon market, by changing their agricultural practices. In this way, our study illustrates the dominance of the voluntary carbon market in the MRV context. In parallel to carbon markets, certain MRV procedures were designed to help stakeholders in decision making (MRV WE019 and MRV WE040). The aim of these MRV procedures is to give indications to farmers to improve farm management. The farmer chooses to spend money on soil monitoring and compensate this investment with better management (more efficient use of intrants mainly).

Organic matter and carbon was the soil parameter the most frequently monitored. The next step is to understand how to pass from a (mainly) carbon-focused MRV procedure to a broader one, assessing soil health. Several strategies are used to assess soil health but they can give contradictory results (Zwaan et al., 2026). A recent study, based on expert knowledge, advised the monitoring of around thirty parameters, related to soil, topography and climate to accurately assess soil health (Vazquez, et al., 2025). Thus, with a maximum of nine parameters assessed, existing MRV procedures do not currently cover soil health. Regarding monitoring methodology, there is a trade-off between costs and accuracy (Ihasusta et al., 2026). In general, soil sampling is more accurate than modelling (Batjes et al., 2024). However, modelling is more frequently used because it is faster

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and cheaper to implement. Empirical or process-based modelling is associated with soil sampling that is called a "measure-remeasure model" approach to calibrate and validate the model. Soil sampling could also be used alone in a "measure and re-measure" approach, and based on values from other locations and specific sampling design.

Surprisingly, verification was more often result-based than action-based. We could think that action-based would be the most frequent, as it requires only a simple, rapid field visit to check management changes, far more cheaper than result based, requiring a new soil assessment including sampling and measurement. As requiring a second monitoring session, result-based verification is more accurate than action-based.

To synthesize our results, we built a typology of soil MRV procedures (Fig. 7).

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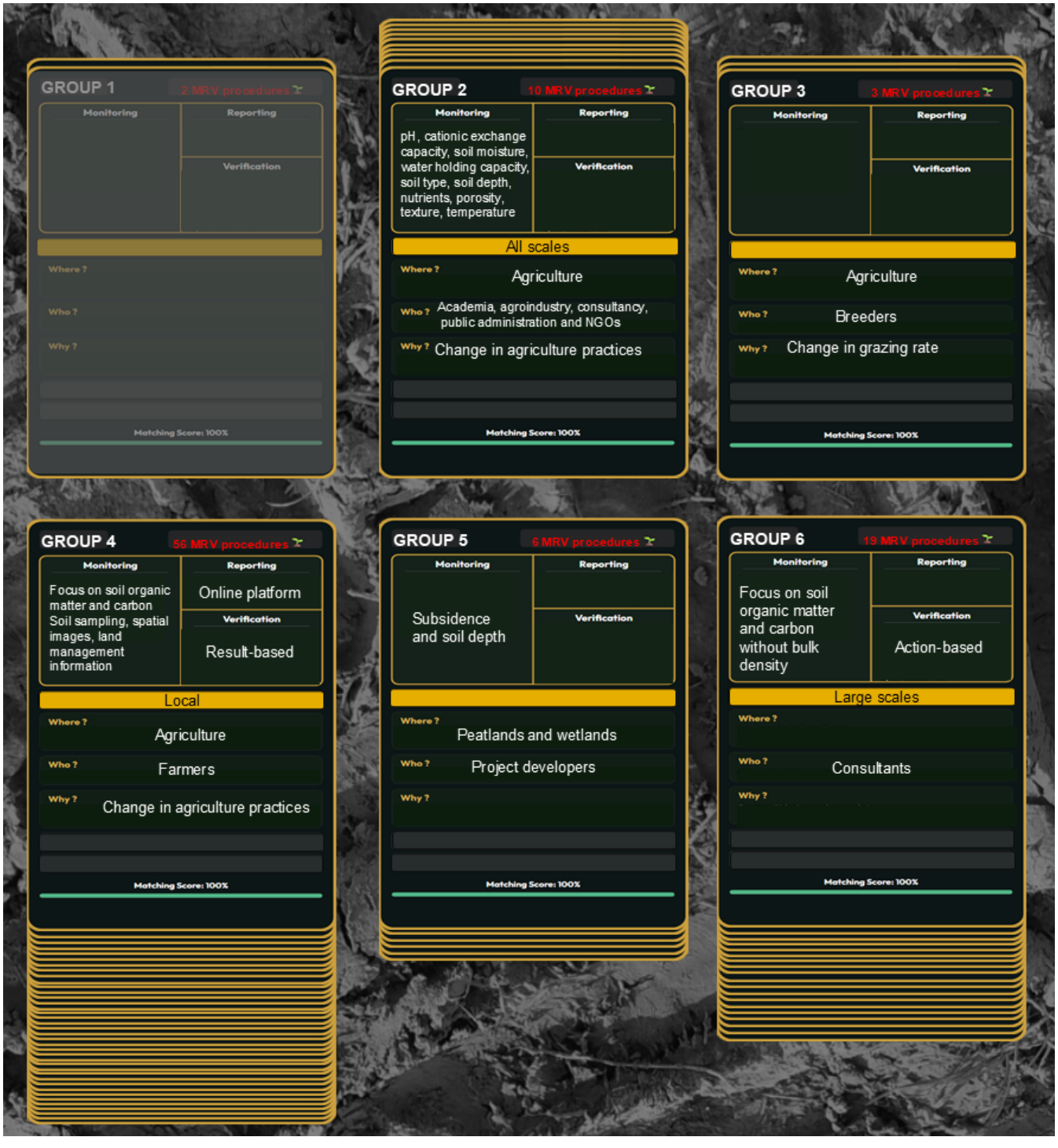


Figure 7. Typology of soil MRV procedures

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We classified them into six groups including from two to 56 MRV procedures. Group 1 was only characterized by the lack of information and thus reflected the main limitation of our study. The five other groups addressed different stakeholders. Four of them targeted stakeholders of the agricultural sector: farmers (group 4) specifically breeders (with changes in grazing rate for the group 3), consultants (group 6) or rarer and more diversified stakeholders (i.e. scientist, agroindustry, public administration and NGOs for the group 2). The last one (group 5) targeted project developers for peatlands and wetland restoration. The two largest groups (group 4 and 6) demonstrated different strategies: more accurate monitoring and verification methodologies for group 4, cheaper ones for group 6. Group 6 was characterized by the fact that the bulk density was not assessed even if it is an essential information to be able to compute soil carbon stocks (Martin et al., 2009). So, again, we encourage a strong partnership between MRV providers and scientists for developing accurate soil health MRV procedures. This type of co-creation of MRV procedures for soil health is currently on going (Imbert et al., 2024).

5. Conclusions

This study sheds light upon an overview of MRV procedures for soils. It bridges the scientific gap, previously completed by studies focused on the most common applications, i.e. carbon markets in the agricultural context (Batjes et al., 2024). In the soil science community, MRV is an emergent framework, and we strongly encourage soil scientists to employ the term MRV more stringently in their publications to engage in communication with the private sector. Aligning the scientific language to common market terminology will also help to improve the robustness of proprietary MRV procedures, as developers and users can more easily refer to scientific research that critically reflects such developments. We also encourage the providers of MRV procedures to clearly communicate to avoid suspicion of green washing. Indeed, major information as sampling design or costs were often inaccessible or scarce. Therefore, more visibility of these components of MRV procedures is required. In the present study, we succeeded in building a typology of MRV procedures and to develop a decision tool to make our work more easily accessible to as many people as possible. The next step is to understand how to pass from a (mainly) carbon-focused MRV procedure to a broader one, assessing soil health. With a maximum of nine parameters assessed, existing MRV procedures do not currently cover soil health. They could be completed with new soil parameters, but the major problem stays the cost.

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Appendix A

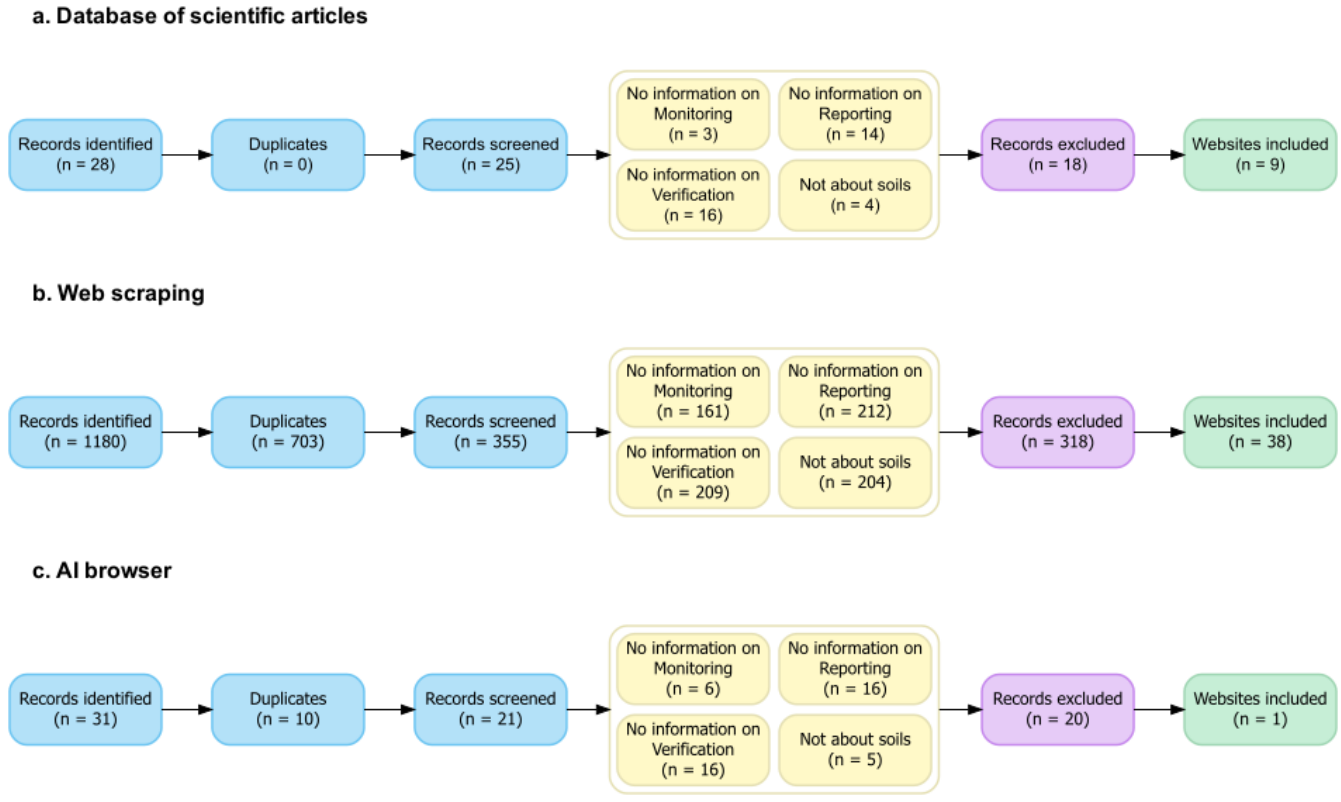
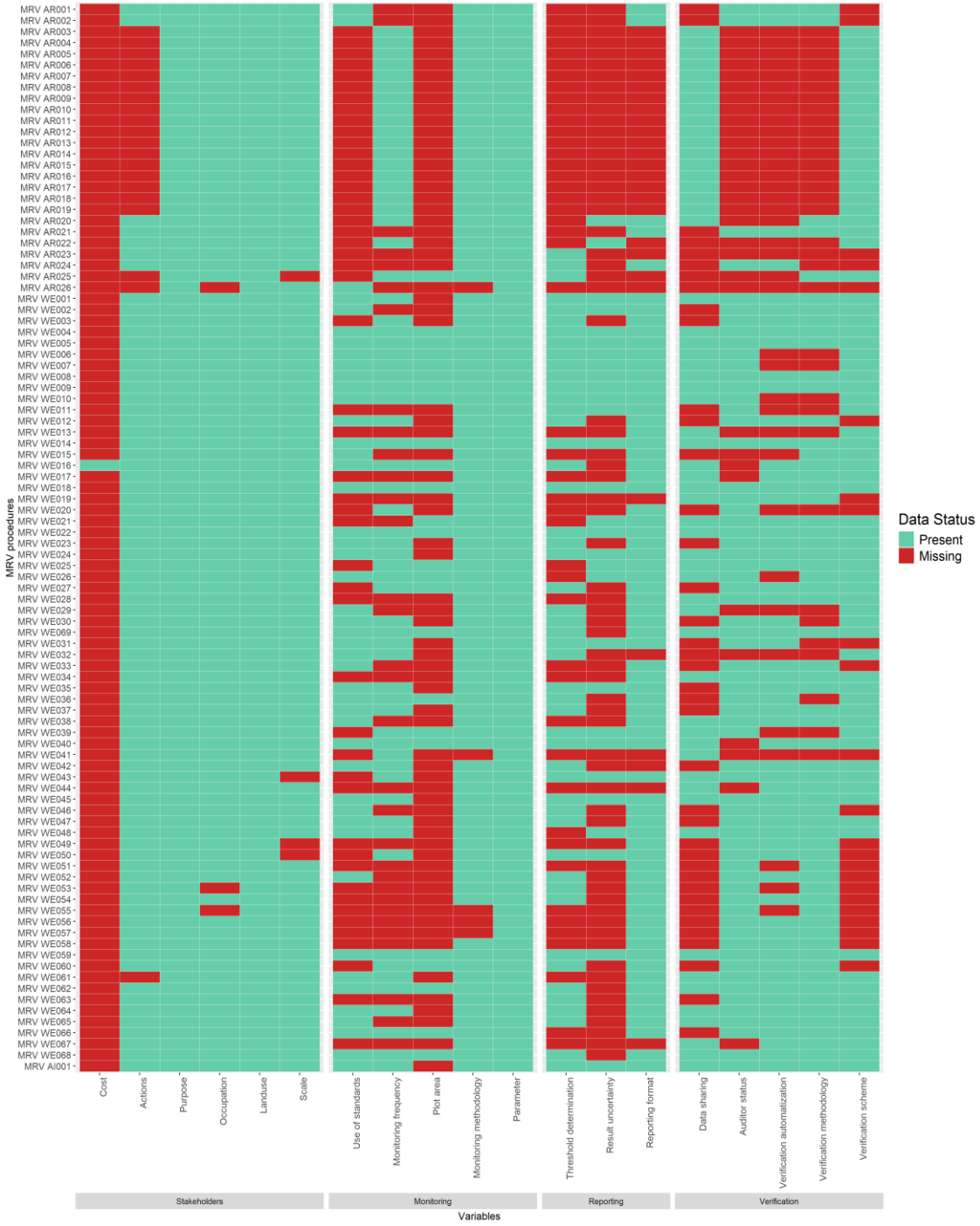


Figure A1. PRISMA diagrams according to the data source: article database (a.), webscraping (b.) and AI browser (c.)

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365 **Figure A2. Missing information for each MRV procedure**

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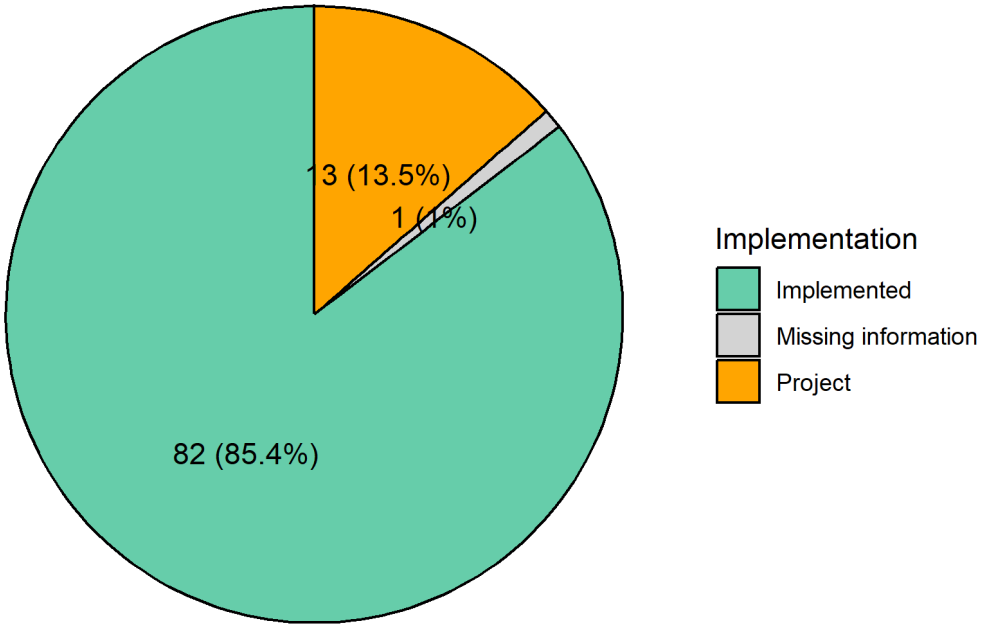


Figure A3. Number (percentage) of MRV procedures according the implementation level

Group	Variable modality	Percentage of individuals belonging to the group within the modality	Percentage of individuals with the modality within the cluster	Percentage of individuals with the modality within all MRV procedures	p-value of the v-test	Value of the v-test
1	Occupation_Software_developers=Occupation_Software_developers_Missing_information	100.00000	100.00000	2.083333	0.00021929824561403492917 85	3.695681
1	Occupation_Other_companies=Occupation_Other_companies_Missing_information	100.00000	100.00000	2.083333	0.00021929824561403492917 85	3.695681
1	Occupation_Project_developer=Occupation_Project_developer_Missing_information	100.00000	100.00000	2.083333	0.00021929824561403492917 85	3.695681
1	Occupation_Consultancy=Occupation_Consultancy_Missing_information	100.00000	100.00000	2.083333	0.00021929824561403492917 85	3.695681
1	Occupation_NGOs=Occupation_NGOs_Missing_information	100.00000	100.00000	2.083333	0.00021929824561403492917 85	3.695681
1	Occupation_Educational_Institutions_Research=Occupation_Educational_Institutions_Research_Missing_information	100.00000	100.00000	2.083333	0.00021929824561403492917 85	3.695681
1	Occupation_Public_Administrators=Occupation_Public_Administrators_Missing_information	100.00000	100.00000	2.083333	0.00021929824561403492917 85	3.695681
1	Occupation_Agroindustry=Occupation_Agroindustry_Missing_information	66.66667	100.00000	3.125000	0.00065789473684210524832 14	3.406550
1	Occupation_Farmers=Occupation_Farmers_Missing_information	66.66667	100.00000	3.125000	0.00065789473684210524832 14	3.406550
2	Parameter_Soil_pH=Parameter_Soil_pH_Yes	100.00000	80.00000	8.333333	0.00000000339369147125115	6.279637
2	Parameter_Nutrient_availability=Parameter_Nutrient_availability_Yes	87.50000	70.00000	8.333333	0.00000007850618560349415 11	5.370529
2	Parameter_Soil_moisture=Parameter_Soil_moisture_Yes	66.66667	60.00000	9.375000	0.00001725847528776464697 31	4.297693
2	Occupation_Educational_Institutions_Research=Occupation_Educational_Institutions_Research_Yes	46.66667	70.00000	15.625000	0.00005244270149039324975 79	4.044465
2	Occupation_NGOs=Occupation_NGOs_Yes	43.75000	70.00000	16.666667	0.00009070052184571622522 73	3.914210
2	Scale_National=Scale_National_Yes	38.88889	70.00000	18.750000	0.00023861196421292275794 86	3.674183
2	Occupation_Agroindustry=Occupation_Agroindustry_Yes	36.84211	70.00000	19.791667	0.00036725408165720439942 69	3.562561
2	Occupation_Public_Administrators=Occupation_Public_Administrators_Yes	28.00000	70.00000	26.041667	0.00293853655406069906932 95	2.974095
2	Parameter_CEC=Parameter_CEC_Yes	75.00000	30.00000	4.166667	0.00323303110210430960722 4	2.944666
2	Parameter_Particle_size_distribution_Texture=Parameter_Particle_size_distribution_Texture_Yes	60.00000	30.00000	5.208333	0.00777474482063234776513 25	2.661699
2	Scale_Local=Scale_Local_Yes	16.12903	100.00000	64.583333	0.00953188251219100855793 35	2.592364
2	Parameter_Water_holding_capacity=Parameter_Water_holding_capacity_Yes	100.00000	20.00000	2.083333	0.00986842105263157146066 71	2.580406
2	Parameter_Soil_type=Parameter_Soil_type_Yes	100.00000	20.00000	2.083333	0.00986842105263157146066 71	2.580406
2	Parameter_Soil_porosity=Parameter_Soil_porosity_Yes	100.00000	20.00000	2.083333	0.00986842105263157146066 71	2.580406
2	Parameter_Soil_temperature=Parameter_Soil_temperature_Yes	100.00000	20.00000	2.083333	0.00986842105263157146066 71	2.580406
2	Purpose=Decision_making	100.00000	20.00000	2.083333	0.00986842105263157146066 71	2.580406
2	Scale_Global=Scale_Global_Yes	100.00000	20.00000	2.083333	0.00986842105263157146066 71	2.580406
2	Scale_Continental=Scale_Continental_Yes	100.00000	20.00000	2.083333	0.00986842105263157146066 71	2.580406
2	Occupation_Consultancy=Occupation_Consultancy_Yes	20.00000	80.00000	41.666667	0.01336477601119854044520 17	2.473898

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Group	Variable modality	Percentage of individuals belonging to the group within the modality	Percentage of individuals with the modality within the cluster	Percentage of individuals with the modality within all MRV procedures	p-value of the v-test	Value of the v-test
2	Parameter_Soil_depth=Parameter_Soil_depth_Yes	36.36364	40.00000	11.458333	0.01565369722918796835386 96	2.416891
2	Driver_Agricultural_practices=Driver_Agricultural_practices_Yes	16.07143	90.00000	58.333333	0.03317865948843688735255 95	2.129915
3	Scale_Global=Scale_Global_Missing_information	100.00000	100.00000	3.125000	0.00000699888017917133720 48	4.493723
3	Scale_National=Scale_National_Missing_information	100.00000	100.00000	3.125000	0.00000699888017917133720 48	4.493723
3	Scale_Regional=Scale_Regional_Missing_information	100.00000	100.00000	3.125000	0.00000699888017917133720 48	4.493723
3	Scale_Continental=Scale_Continental_Missing_information	75.00000	100.00000	4.166667	0.00002799552071668529461 01	4.189187
3	Scale_Local=Scale_Local_Missing_information	75.00000	100.00000	4.166667	0.00002799552071668529461 01	4.189187
3	Driver_Grazing=Driver_Grazing_Yes	100.00000	33.33333	1.041667	0.03124999999999999653055 30	2.153875
4	Driver_Fire_management=Driver_Fire_management_No	74.66667	100.00000	78.125000	0.00000000016779983168153 00	6.388245
4	Driver_Grazing=Driver_Grazing_No	74.66667	100.00000	78.125000	0.00000000016779983168153 00	6.388245
4	Driver_Restoration=Driver_Restoration_No	76.38889	98.21429	75.000000	0.00000000019518705041477 13	6.365081
4	Driver_Deforestation=Driver_Deforestation_No	75.00000	96.42857	75.000000	0.00000000707498760436662 34	5.789135
4	Driver_Land_conversion=Driver_Land_conversion_No	73.33333	98.21429	78.125000	0.00000001020222976623694 55	5.727332
4	Driver_Irrigation=Driver_Irrigation_No	73.33333	98.21429	78.125000	0.00000001020222976623694 55	5.727332
4	Driver_Weathering=Driver_Weathering_No	73.33333	98.21429	78.125000	0.00000001020222976623694 55	5.727332
4	Driver_Conservation=Driver_Conservation_No	73.33333	98.21429	78.125000	0.00000001020222976623694 55	5.727332
4	Driver_Forest_management=Driver_Forest_management_No	72.97297	96.42857	77.083333	0.00000008518861854807838 60	5.355779
4	Data_Land_Management=Data_Land_Management_Yes	80.76923	75.00000	54.166667	0.00000130714771056761647 79	4.838664
4	Driver_Afforestation_Reforestation=Driver_Afforestation_Reforestation_No	72.22222	92.85714	75.000000	0.00000223231369064371338 29	4.731168
4	Driver_Agricultural_practices=Driver_Agricultural_practices_Yes	78.57143	78.57143	58.333333	0.00000226552540262547134 46	4.728170
4	Occupation_Farmers=Occupation_Farmers_Yes	76.27119	80.35714	61.458333	0.00000847715052274581992 55	4.452765
4	Occupation_Consultancy=Occupation_Consultancy_No	77.77778	75.00000	56.250000	0.00001380260386698524589 66	4.346978
4	Parameter_Soil_pH=Parameter_Soil_pH_No	63.63636	100.00000	91.666667	0.00057997055469627726512 90	3.440812
4	Result_based=Result_based_Yes	70.49180	76.78571	63.541667	0.00177360084889447615699 72	3.125737
4	Scale_National=Scale_National_No	66.66667	89.28571	78.125000	0.00237495783829707370754 52	3.038834
4	Land_use_Peatland_Wetland=Land_use_Peatland_Wetland_No	63.21839	98.21429	90.625000	0.00374344630758506342199 65	2.899009
4	Scale_Continental=Scale_Continental_No	62.22222	100.00000	93.750000	0.00414043150010444654246 51	2.867260
4	Format_Document=Format_Document_No	88.23529	26.78571	17.708333	0.00519991906209535392768 83	2.794381
4	Parameter_Nutrient_availability=Parameter_Nutrient_availability_No	62.50000	98.21429	91.666667	0.00903348076102687691513 18	2.610784
4	Scale_Global=Scale_Global_No	61.53846	100.00000	94.791667	0.01076512190027153689777 30	2.550232
4	Data_Soil_samples=Data_Soil_samples_Yes	68.33333	73.21429	62.500000	0.01207786811692482253910 44	2.509861
4	Action_based=Action_based_No	69.81132	66.07143	55.208333	0.01290073317286838036621 61	2.486498
4	Scale_Local=Scale_Local_Yes	67.74194	75.00000	64.583333	0.01362794614918763462518 84	2.466924
4	Parameter_Soil_depth=Parameter_Soil_depth_No	63.09524	94.64286	87.500000	0.01674586290219055167982 63	2.392241
4	Format_Online=Format_Online_Yes	75.86207	39.28571	30.208333	0.02313737342014987943827 90	2.271159
4	Data_Spatial_images=Data_Spatial_images_Yes	68.51852	66.07143	56.250000	0.02441626756251515442674 99	2.250515
4	Parameter_Soil_moisture=Parameter_Soil_moisture_No	62.06897	96.42857	90.625000	0.02920942611833979990487 72	2.180648
5	Land_use_Peatland_Wetland=Land_use_Peatland_Wetland_Yes	55.55556	83.33333	9.375000	0.00001200584689274185575 87	4.377482
5	Data_Modelling=Data_Modelling_Missing_information	80.00000	66.66667	5.208333	0.00002228254979904476952 31	4.240698
5	Data_Spatial_images=Data_Spatial_images_Missing_information	80.00000	66.66667	5.208333	0.00002228254979904476952 31	4.240698
5	Data_Land_Management=Data_Land_Management_Missing_information	80.00000	66.66667	5.208333	0.00002228254979904476952 31	4.240698
5	Data_Soil_samples=Data_Soil_samples_Missing_information	66.66667	66.66667	6.250000	0.00006596959374837496949 93	3.990373
5	Result_based=Result_based_Missing_information	26.08696	100.00000	23.958333	0.00010889076606030764005 02	3.869876
5	Action_based=Action_based_Missing_information	26.08696	100.00000	23.958333	0.00010889076606030764005 02	3.869876
5	Driver_Restoration=Driver_Restoration_Yes	75.00000	50.00000	4.166667	0.00055087960119929173415 10	3.454713
5	Data_on_site_images=Data_on_site_images_Missing_information	36.36364	66.66667	11.458333	0.00135652478363198743596 67	3.203745
5	Parameter_Soil_depth=Parameter_Soil_depth_Yes	36.36364	66.66667	11.458333	0.00135652478363198743596 67	3.203745
5	Occupation_Project_developer=Occupation_Project_developer_Yes	33.33333	66.66667	12.500000	0.00200687924455768013781 71	3.089212
5	Parameter_Subsidence=Parameter_Subsidence_Yes	100.00000	33.33333	2.083333	0.00328947368421052743422 96	2.939307
5	Land_use_Agriculture=Land_use_Agriculture_No	23.52941	66.66667	17.708333	0.00899115608543306181477 12	2.612390
5	Driver_Agricultural_practices=Driver_Agricultural_practices_No	20.00000	66.66667	20.833333	0.01752053040808971423603 07	2.375598
6	Driver_Fire_management=Driver_Fire_management_Missing_information	95.00000	100.00000	20.833333	0.00000000000000000035618 04	8.949783
6	Driver_Deforestation=Driver_Deforestation_Missing_information	95.00000	100.00000	20.833333	0.00000000000000000035618 04	8.949783
6	Driver_Forest_management=Driver_Forest_management_Missing_information	95.00000	100.00000	20.833333	0.00000000000000000035618 04	8.949783
6	Driver_Afforestation_Reforestation=Driver_Afforestation_Reforestation_Missing_information	95.00000	100.00000	20.833333	0.00000000000000000035618 04	8.949783
6	Driver_Land_conversion=Driver_Land_conversion_Missing_information	95.00000	100.00000	20.833333	0.00000000000000000035618 04	8.949783
6	Driver_Irrigation=Driver_Irrigation_Missing_information	95.00000	100.00000	20.833333	0.00000000000000000035618 04	8.949783
6	Driver_Grazing=Driver_Grazing_Missing_information	95.00000	100.00000	20.833333	0.00000000000000000035618 04	8.949783
6	Driver_Weathering=Driver_Weathering_Missing_information	95.00000	100.00000	20.833333	0.00000000000000000035618 04	8.949783
6	Driver_Restoration=Driver_Restoration_Missing_information	95.00000	100.00000	20.833333	0.00000000000000000035618 04	8.949783
6	Driver_Conservation=Driver_Conservation_Missing_information	95.00000	100.00000	20.833333	0.00000000000000000035618 04	8.949783
6	Driver_Agricultural_practices=Driver_Agricultural_practices_Missing_information	95.00000	100.00000	20.833333	0.00000000000000000035618 04	8.949783
6	Format_Online=Format_Online_Missing_information	66.66667	94.73684	28.125000	0.00000000000583835004956 63	6.883539
6	Format_Document=Format_Document_Missing_information	66.66667	94.73684	28.125000	0.00000000000583835004956 63	6.883539
6	Occupation_Farmers=Occupation_Farmers_No	50.00000	89.47368	35.416667	0.00000008352167548420710 96	5.359351
6	Data_Land_Management=Data_Land_Management_No	43.58974	89.47368	40.625000	0.00000157924140387744588 26	4.800938
6	Occupation_Consultancy=Occupation_Consultancy_Yes	42.50000	89.47368	41.666667	0.00000266438992911406320 83	4.695129
6	Result_based=Result_based_No	75.00000	47.36842	12.500000	0.00001170186323096772366 30	4.383070

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Group	Variable modality	Percentage of individuals belonging to the group within the modality	Percentage of individuals with the modality within the cluster	Percentage of individuals with the modality within all MRV procedures	p-value of the v-test	Value of the v-test
6	Data_Soil_samples=Data_Soil_samples_No	46.66667	73.68421	31.250000	0.00002737351307161013078 17	4.194284
6	Scale_Local=Scale_Local_No	43.33333	68.42105	31.250000	0.00024430276631727347851 77	3.668160
6	Parameter_Soil_compaction_Bulk_density=Parameter_Soil_compaction_Bulk_density_No	28.78788	100.00000	68.750000	0.00030814280397702733258 27	3.608357
6	Action_based=Action_based_Yes	45.00000	47.36842	20.833333	0.00391594839042495694581 00	2.884854
6	Data_Modelling=Data_Modelling_Yes	25.33333	100.00000	78.125000	0.00510844094653876718697 96	2.800115
6	Occupation_NGOs=Occupation_NGOs_No	24.35897	100.00000	81.250000	0.01195452808295803699689 67	2.513484
6	Occupation_Educational_Institutions_Research=Occupation_Educational_Institutions_Research_No	24.05063	100.00000	82.291667	0.01574012864256139204721 66	2.414886
6	Occupation_Agroindustry=Occupation_Agroindustry_No	24.32432	94.73684	77.083333	0.03609964935554058756972 40	2.095803

Table A1. Contribution of variable modalities computed with MCA and HCPC

Code and data availability

The scripts used for data analysis, web scraping and the decision tool are available here : https://github.com/LucileRb/MRV-procedures . Data are in open-access here : https://doi.org/10.5281/zenodo.23397302 .

Author contributions

CI: Conception, Data collection, Data analysis, Tool conception, Paper writing, Paper revision

AB: Paper revision

SG: Data collection, Paper revision

PH: Data collection, Paper revision

TS: Data collection, Paper revision

SS: Data collection, Paper revision

LR: Tool conception, Paper revision

KW: Data collection, Paper revision

Competing interests

The authors declare that they have no conflict of interest.

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