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How can pedology and soil classification contribute towards sustainable development as a data source and information carrier?[☆]

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ABSTRACT

Soil classification is based on both the properties of the soil material and the pedogenetic pathways responsible for those properties. Because soil properties are linked to soil function and potential, information on soil classification has formed the basis for empirical interpretations of mapping units in terms of limitations or suitabilities for a wide range of land uses. In this way, a soil type acts as an accessible *"carrier of information"* presenting *"the story of..".* Though valuable for broad land-use assessments, these empirical interpretations of soil functionality are inadequate to answer modern interdisciplinary questions focused on sustainable development. Four case studies are presented showing various quantitative approaches focusing on soil functions contributing to ecosystem services in line with the United Nations Sustainable Development Goals (SDGs) and the European Green Deal, demonstrating that: (i) the use of soil surveys and associated databases feeding soil–water-atmosphere-plant simulation models can contribute to defining soil functions and ecosystem services; (ii) hydropedological characterization of soil types can allow a strong reduction in the number of landscape units to be considered, improving practical applicability; (iii) pedotransfer functions can successfully link soil data to modeling parameters; (iv) functionality requires expression of soil management effects on properties of a given soil type, to be expressed by phenoforms; (v) only models can be applied to explore important future effects of climate change by running IPCC scenarios; and (vi) the most effective level of soil classification—acting as carriers of information when defining soil functionality—will differ depending on the spatial scale being considered, whether local, regional or higher.

1. Introduction

Soils are receiving increasing emphasis in the international science and policy arena, as evidenced by, for example, the European Union's Mission on: "A Soil Deal for Europe" (EC, 2021) and extensive soil health programs in the United States (Moebius-Clune et al., 2016; NCRS-USDA, 2019; Norris et al., 2020). This is part of a general trend in society to emphasize the urgent need to realize sustainable development as shown by the acceptance of the seventeen United Nations Sustainable Development Goals (SDGs) by 193 governments in 2015 (https://sdgs.un.org), and the Green Deal in the European Union (EU) in 2019 (https://ec.europa.eu/greendeal), the latter broadly following the scope of the SDGs. The formulated goals have to be reached by 2030, presenting a major challenge not only to society at large but to the research community as well.

Clearly, soils play an important role when reaching at least seven of the SDGs (e.g., Lal et al., 2021). They contribute significantly to the production of healthy food (SDGs 2&3: *zero hunger and good health and wellbeing); clean water and sanitation* (SDG 6), *affordable and clean energy* (SDG 7), *responsible consumption and production* (SDG 12), *climate action*

[☆] **Footnote:** This paper is based on contributions to a symposium at the 2021 Soil Science Society of America Meetings in Salt lake City, UT, entitled, "Can Soil Taxonomy Contribute to a Sustainable Economy as a Carrier of Soil Information?" convened by Johannes Bouma and Daniel Hirmas.

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by limiting greenhouse gas emissions and enhancing carbon capture (SDG 13), and *life on land*, with a focus on combatting soil degradation and biodiversity loss (SDG 15). Most important for agriculture are, arguably: SDGs 2&3, 6, 13 and 15. In particular, SDG 2 "Zero Hunger" aims to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture. Soils are explicitly mentioned in action point 2.4: "…*implement resilient agricultural practices that increase productivity and production, and that progressively improve land and soil quality."* Sustainable development goal 15 "Life on Land" has as its goals to *"protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation*…;" clearly soils are a key resource in reaching this goal.

How do we frame soil contributions in this context in the most effective manner, realizing that SDGs can only be reached by an interdisciplinary research effort, involving agronomists, hydrologists, meteorologists, economists, sociologists and others? The key question here is: how can soil functions contribute to land-related ecosystem services in line with the various SDGs (e.g., Bouma, 2014; Keesstra et al., 2016) where ecosystem services are services provided by the ecosystem to mankind (https://www.millenniumassessment.org). Linking soil functions directly with the SDGs is unrealistic—soils cannot do it alone! Sustainability conditions are reached, in principle, when indicators for the various ecosystem services associated with the SDGs, have values above critical thresholds for each service. Many of these thresholds still have yet to be defined. Soil functions make important contributions to these ecosystem services as expressed by the soil health definition: "*the continued capacity of soils to contribute to ecosystem services in line with the SDGs"* (Veerman et al., 2020). To quantify these contributions and thereby reveal the vital role of soils to policy makers again require a set of objectively defined and defensible soil indicators and associated thresholds for soil health (e.g., Veerman et al., 2020, Bouma, 2021). The soil health concept is suitable to express such soil contributions as it focuses on a small set of indicators that are essential for root growth and, as a result, crop and vegetation development that affects all SDGs—the healthier the soil, the higher the contributions.

Contributions of soil science to assessing soil use suitabilities or limitations have traditionally been expressed in terms of soil survey interpretations for "representative" soil profiles within each mapping unit (Soil Science Division Staff, 2017) or land evaluations (FAO, 2007). In this way, soil types function as: "*carriers of information"* presenting *"the story of…,"* following empirical, qualitative procedures that were and are valuable for regional land use assessments and town-and-country planning but do not, however, provide adequate information for modern interpretations in an SDG context. Moreover, soil classification and its application to soil mapping are based on pedogenic-landform relationships and defined by relatively permanent soil properties formed by long-term soil genesis. Soil survey interpretations, in contrast, focus on short-term functionality in relation to land use.

In contrast to empirical relationships, widely-used dynamic models of the soil–water-atmosphere-plant system offer an integrated interdisciplinary approach to characterize soil functionality (e.g., White et al., 2013; Kroes et al., 2017; Holzworth et al., 2018; Bieger et al., 2017). Such models are ideal vehicles for interdisciplinarity as they require input not only by soil scientists but also by agronomists, hydrologists, climatologists and ecologists. Models can be used to quantify ecosystem services related to biomass production that are important for several SDGs (2, 12, 13 and 15).

Soil research during the last few decades has made much progress developing, among many other activities, innovative spatial analyses and digital mapping techniques, but modernization of soil survey interpretations, including the most effective application of soil databases, has received less attention. However, more attention is needed now that sustainable development is receiving priority in the policy arena.

There is another important dimension to the current use of soil survey interpretations as soil units can be used as carriers of information for communication purposes. Attaching local names to soil series in the USA has, for example, been quite effective to connect soils and society. To enhance adoption of research results by land users, the EC (2021), following suggestions by the Board for Soil Health and Food (Veerman et al., 2020), proposes establishment of 100 "Living Labs" in Europe where scientists and land users (mostly farmers) will work together in a co-learning mode to develop management systems that satisfy thresholds of the various ecosystem services in line with corresponding SDGs. Once achieved, such living labs qualify as "Lighthouses" functioning as inspiring examples for other farmers. As management systems will be different on different types of soil, it would be attractive to attach a successful management practice to that particular type of soil, with the soil type acting as a *carrier of information* presenting a convincing *"story of the particular soil type being considered",* and allowing extrapolation of results to unmeasured locations where the same soil occurs. This is, of course, the standard procedure for classical soil survey interpretation, whereby soil types function as a "class-pedotransfer function"(Bouma, (1989). But what is the most effective level of the soil classification system to be considered? Traditionally, the soil series level has been used but is this the most effective and does the choice depend on the spatial scale being considered, be it local, regional, or broader?

In summary, the objective of this paper is to: (i) explore the potential contributions of data derived from soil classification and associated databases to feed interdisciplinary models for ecosystem services, aimed at developing new expressions of soil functionality contributing to realizing the SDGs;(ii) discuss the most effective way to apply soil information to act as inspiring *carriers of soil information* relevant for communicating the role of soil science in realizing sustainable development; and (iii) present and discuss case studies where innovative approaches to both objectives are being explored.

2. From pedogenesis to functionality

Linking soil science with functional interpretations has traditionally followed the sequence: pedology - soil classification - soil survey - interpretations/land evaluation. Many countries have completed soil surveys at different spatial scales with soil map legends based on many different soil classification systems. The most prominent and internationally applied systems are the US Soil Taxonomy (Soil Survey Staff, 2014) and the World Reference Base (IUSS, 2014). Many countries have their own well-developed soil classification systems used for mapping. These systems are all hierarchical monothetic and share a similar underlying philosophy by emphasizing: observable diagnostic properties and horizons, with a presumed link to pedogenesis and a link with soil functions and soil survey interpretations.

Soil classes, as opposed to lists of soil properties (e.g, profile records with field and laboratory measurements) are holistic expressions of the soil's "personality"—that is, its overall functioning and geographical setting. The concept behind classes is that soils of the same class should behave similarly under natural and managed conditions, including climate shocks. In hierarchical systems, such as those cited above, more specific statements—that is, a more detailed "personality"—can be made as the hierarchical level becomes lower (e.g., subclasses). Functioning of soils for various forms of land use depend strongly on management practices. At least four aspects are important for soil functionality:

(i) A given soil type—the genoform—can function quite differently as a result of past and present management and this can be expressed by showing effects of soil management on soil functioning for every soil type in terms of a series of phenoforms. In this context the soil type is considered to represent the genoform (Droogers and Bouma, 1997; Rossiter and Bouma, 2018; Rossiter, 2021)

(ii) Even though different soil drainage classes and general moisture regimes are distinguished in soil classifications, dynamic soil moisture regimes are so essential for soil functionality that a combined consideration of soil and water would appear to be advisable when considering soil functionality, as has already been advocated in hydropedology (e.g., Lin et al., 2006).

(iii) As discussed, soil functions contribute to ecosystem services and that requires an interdisciplinary research approach. Process modeling is common in agronomy, hydrology, climatology, and other sciences and soil contributions should, therefore, preferably be framed in terms of data contributions that fit into soil–water-atmosphere-plant simulation models, mentioned above, that are already widely used as are pedotransfer functions, that statistically relate soil parameters to parameters needed for dynamic modeling of the soil–water-atmosphere-plant system (Bouma, 1989; Van Looy et al., 2017). Using these functions, hydraulic parameters including moisture retention and hydraulic conductivity can be predicted from texture, organic matter content, and bulk density data.

When applying pedotransfer functions fo define basic soil data for modeling, unrealistic results can be obtained in crop growth or hydrology models when: (i) the functions were derived from other soils than the ones being characterized, (ii) non soil scientists are not aware of specific soil features, such as different clay mineralogies that strongly affect soil behavior, (iii) combining separately calculated flow patterns for one-dimensional soil profiles to characterize often complex three-dimensional flow patterns in a landscape, and (iv) validation of models is lacking, which, however, applies to all modeling studies also the ones where reliable measurements of basic data and input of pedological expertise was provided. Models are, after all, highly simplified representations of complex field conditions. Validation can, for example, include measured time series of crop development or soil water contents (see case no.2) to be improved by applying modern remote- and proximal-sensing methods. Validation is often not part of standard procedures and this is undesirable.

Overall, there is a risk that non-soil scientists feel that all they need are a few parameters from widely available soil databases (textures, bulk densites and organic matter contents) to take care of the soil in their interdisciplinary crop growth or hydrology models. To avoid this, soil scientists are uniquely qualified and needed to contribute their knowledge and expertise on “living soils in living landscapes” to the interdisciplinary research arena which turns out to be in line with the current emphasis on:”Living Labs” in the Missions of the new Horizon Europe research and innovation program (EC, 2021).

3. The communication challenge

There appears to be a gap between science and society. Veerman et al. (2020) report that 60–70% of soils in the EU are degraded and unhealthy even though, after many years of research, the remedies are well-known. However, they are not widely applied and, thus, modern forms of communication should be explored to improve the record by attempting to reduce this apparent gap between science and society.

Communication applies at least in two ways:

(i) Results obtained at Lighthouses, when all ecosystem services pass their particular thresholds, have to be broadly communicated to land users elsewhere, the policy arena, and to citizens at large. Decision Support Systems can be helpful (, e.g. Terribile et al., 2017; Bampa et al., 2019; Manna et al., 2020) but producing accessible storylines may be more in line with the way farmers interact (e.g., Bouma, 2020). In any case, linking each storyline to a particular type of soil, acting as a *carrier of information,* would seem to be logical, as soil input has a major effect on simulations or measurements of ecosystem services. But the most suitable level of detail by which the soil type is described, needs particular attention. Often, the soil series will be used but sometimes different soil series act the same. For example, Baker (1978) measured hydraulic conductivities in six soil series in loess soils in Wisconsin, studying soil disposal of septic tank effluent, and concluded that they could be represented by one single curve, also expressing variability. In their soil health program, Moebius-Clune et al. (2016) concluded that only three soil texture classes would be adequate for communication purposes—coarse, medium, and fine—representing a barebone representation of soil classification. Various communication methods will be discussed in the case studies.

(ii) Pro-active engagement with land users, governmental agencies, and land-use planners by generating jointly developed demonstrations of successful application of modern methods of land evaluation, resulting in continued cooperation and interaction is necessary to achieve communication goals. If not embraced and internalized by third parties, our land evaluation procedures may remain a sterile academic, soil-focused exercise.

4. Case studies

Four case studies will be presented and analysed covering the various aspects discussed above at three spatial levels: local, regional, and world. Attention will be paid to: (i) how soil research was initiated, possibly by initiatives beyond the soil science community, illustrating the position of soil research in a broader societal context; (ii) the selection procedure of soil data and its application in interdisciplinary ecosystem analysis, and (iii) the most effective communication practices.

4.1. Soil functionality for agriculture and viticulture in Italy

The Campania Region, through its Rural Development Programme (RDP), provided funding for applied research on land use and soil management (Focus Area 4C: Preventing soil erosion and improving soil management) in order to better frame and design their activities and regulations. Similarly, the EU, funded the SoilConsWeb project through its LIFE + program in the same area on soil conservation and land management.

A group of farmers, suffering from yield decline due to extended dry periods, welcomed research that allowed them to choose between either irrigation or growing drought resistant varieties of maize as they lacked independent advice. Options varied significantly among soil types (Bonfante and Bouma, 2015). This past work qualifies as Living Lab activities that are now promoted by the EU, 2021.

Answering questions about the performance of particular types of soils, Bonfante et al. (2020) applied the SWAP model to calculate maize yields for soil series including measurement of water retention and hydraulic conductivity functions. Following the international yield-gap program, Yw is the model-calculated yield for an undisturbed soil based on calculated water availability and assuming adequate nutrients for plant growth and absence of pests and diseases (Van Ittersum et al., 2013). Yw-phenoforms are calculated yield taking into account effects of soil management in terms of, in this case, three phenoforms resulting from: compaction, soil surface erosion, and an increase of topsoil organic matter. Yields define an important ecosystem service in line with SDG 2. In addition, these Yw values are determined for four climate periods as defined by the RCP 8.5 climate-scenario of the IPCC. Results for the *Masseria Battaglia* loamy sand soil series, shown as an example in Fig. 1, indicate strong effects of the phenoforms. Moreover, the effects of climate change on yield production are significant beyond 2040 to the extent that economically viable forms of agriculture may not be practical by the end of the 21st century unless irrigation is feasible. As fresh water will be increasingly in short supply this presents a bleak picture of the future. Differences among different soil series, not shown here, were significant, indicating that soil series are effective *carriers of information* presenting *the story of particular soil series.* Bonfante et al. (2020) also defined yields in relation to potential production where water

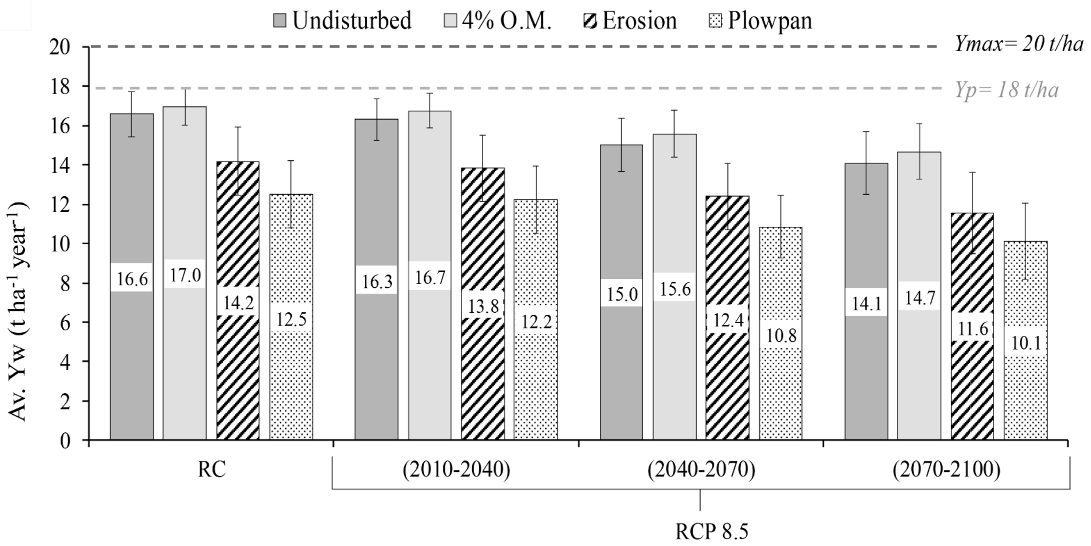

Fig. 1. Calculated yields (Yw) for maize considering three phenoforms next to an undisturbed soil profile for the Italian *Masseria Battaglia* loamy sand soil series. The plot also illustrates the impact of future climate change scenarios.

availability is not limiting (Yp) and Ymax (as shown in Fig. 1)—that is, the highest yield that is theoretically proposed on earth—allows a comparison among different soils. They also presented a quantitative expression for soil health and soil quality, but a discussion of these issues is beyond the scope of this paper.

Of particular interest is the engagement of grape growers who are quite interested, for commercial purposes, in better defining and quantifying the central but still rather mysterious concept of "terroir"—a real as yet hardly explored niche for soil studies as soil conditions play a key role in determining the concept. The various results will be described broadly with reference to several detailed publications. Water stress experienced by plants during the growing season has a direct effect on grape quality (Acevedo-Opazo et al., 2010; Intrigliolo and Castel, 2011) because water is the main regulator of the hormonal balance of grapevines (Champagnol, 1997).

Bonfante et al (2015, 2017) studied terroir in two large vineyards in Southern Italy (Valle Telesina and Mirabella Eclano, growing the Aglianico grape vine) by preparing detailed soil surveys, including application of geophysical methods (electromagnetic induction, EMI) and by applying simulation models of the soil–water-atmosphere-plant system. This way they could refine the existing empirical "homogeneous zone" by defining "functional homogeneous zones" for a better identification of the terroir. They also could relate soil characteristics to quality parameters for wine, such as: color hue and intensity and contents of anthocyanins, polyphenols and tannins, demonstrating the prominent effect of soils on the character of the wine.

In Italy, most high-quality wine production originates from rainfed vineyards where climate change will have a strong effect on the soil water balance due to more irregular rainfall and an increase of evapotranspiration during the growing season. Also, higher temperatures will strongly affect grape quality. Consequently, the typicality of grapes associated with particular terroirs may no longer be maintained and this is a major concern among growers that need reliable information on future developments to allow timely changes in their highly capital-intensive operations.

Bonfante et al., (2018) used modeling to evaluate the effects of climate change (applying the RCP 4.5 scenario of the IPCC) on the resilience of terroirs for the Aglianico grapevine in the study area Guardia Sanframondi. They showed that the suitable area was reduced from 38% (2010–2040) to 19% (2040–2070) and < 5% beyond 2070.

Returning to the issue of information being "carried" by soil types, the Italian studies show that soil series with local names can function well on the local and regional level, when combined with a modern modeling approach. Applications for viticulture, defining terroir in terms of functional homogeneous zones, are particularly intriguing and promising for future research. Also, application of modeling of the soil–water-atmosphere-plant system allows incorporation of important new features, such as climate change and phenoforms, that make results attractive in the future for not only local stakeholders but for governmental planning agencies as well. Finally, working on farms and in vineyards is in line with the emphasis in EC (2021) on working in Living Labs where scientists and land users join forces.

4.2. *Environmental impact assessment in South Africa*

In South Africa, hydropedological research was readily adopted by the government through the Department of Water and Sanitation (DWS). A hydropedological survey now forms part of the Environmental Impact Assessment (EIA) procedure for application for a water-use license in new developments (e.g., mining, residential, industrial) (Van Tol, 2020). Since hydropedology forms part of environmental policy in South Africa, training of soil science consultants to conduct hydropedological surveys and knowledge transfer (from theory to practice) of hydropedological research has become essential.

The relationship between soil morphology and soil water regimes is embedded in the South African Soil Classification System (Soil Classification Working Group, 2018) and is used to distinguish between different soils at various hierarchical levels (e.g., diagnostic horizons, soil forms and families). Soil taxonomic maps are generally created for agricultural production purposes but can also be a carrier of valuable information serving the hydrological community. Here we present a South African case study (described in detail by Van Tol et al., 2021) demonstrating how traditional soil maps can be used to improve the efficiency of hydrological modelling at watershed levels to support water resource management and ultimately address targets associated with SDG 6.

The soil map of the 157 ha Weatherley research catchment in the Eastern Cape Province of South Africa contains 18 soil forms that were converted to a hydropedological map with six groups (Van Tol and Le Roux, 2019). Hydraulic parameters were measured for representative diagnostic horizons of the six groups (Lorentz et al., 2008; Van Huyssteen et al., 2005). Three major flow patterns were distinguished as visualized for a representative hillslope in Weatherley in Fig. 2: *Recharge soils* are soils without any indication of periodic saturation. Vertical

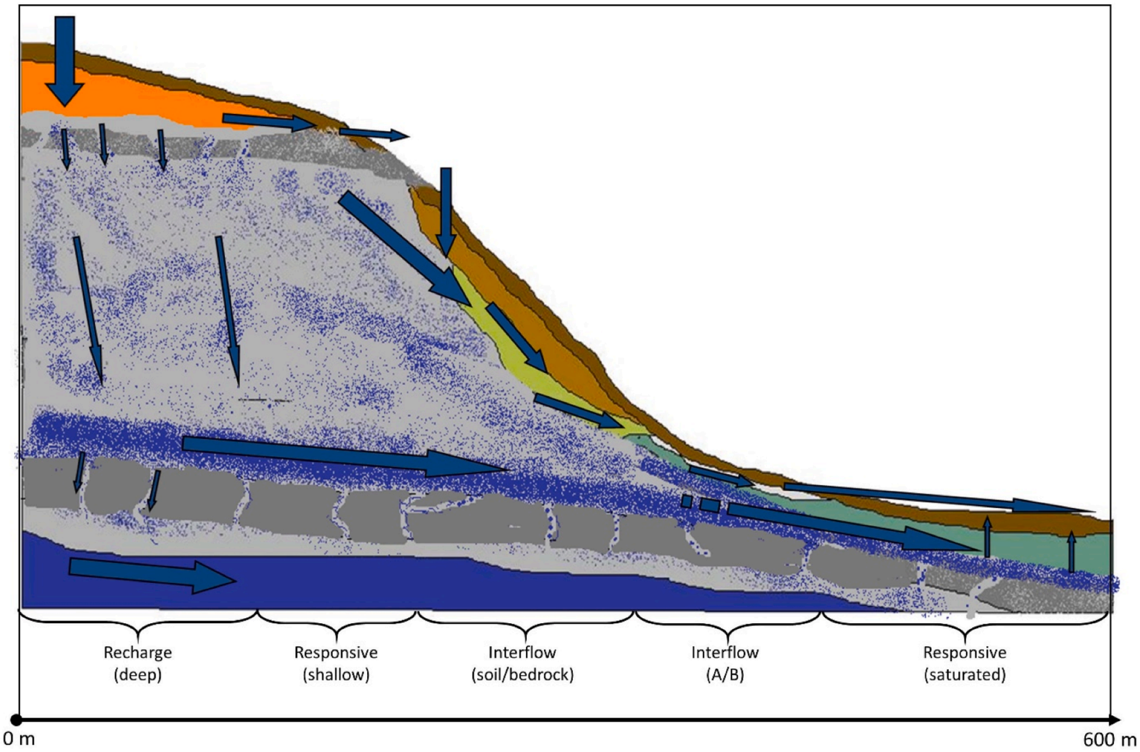

Fig. 2. Hillslope hydrological response inferred from the soil distribution pattern ().
adapted from van Tol et al., 2010

drainage in and out of the profile into the underlying bedrock is the dominant process with a distinction between *recharge (shallow)* and *recharge (deep)* soils, where the former consists of a topsoil horizon overlying fractured rock (not present in the hillslope in Fig. 2) and the latter marked by one or more subsoil horizons. In *interflow soils* subsurface lateral flow is dominant, either at the *soil/bedrock* interface or at the *A/B horizon* interface due to differences in conductivities. In *responsive soils*, overland flow is the dominant hydrological process which can be generated on soils which are saturated for long periods (*responsive wet*) or very shallow soils with limited storage capacity (*responsive shallow*). Excess overland flow due to low infiltration rates is also included in the last soil class. These flow patterns introduce a new three-dimensional approach to soil functionality that is crucial for sloping areas all over the world. The classic and common one-dimensional functional characterization of soils, as reported in the other case studies, does not allow lateral flow in interflow soils.

The behaviour of the hillslopes was imbedded in the setup of the hydrological model SWAT+ (Bieger et al., 2017). SWAT + is a restructured version of the widely used Soil and Water Assessment Tool (SWAT), a process based, semi-distributed catchment scale model (Arnold et al., 1998). The model divides a catchment into Hydrological Response Units (HRUs), which are homogenous areas in terms of soils, land use, and slope. Water balance components including overland flow, infiltration, lateral flow, percolation, and evapotranspiration, are calculated for each HRU using soil and plant parameters specific to that HRU. In SWAT+, the modeler then has the option to route outflow types to another downslope HRU or landscape element (e.g., stream or aquifer).

Two model runs were conducted: one without routing and a second run where the routing of fluxes was included. The hydropedological soil map and associated properties were used as soil input data for both runs. The focus was therefore not on soil input details, but rather on representing hydropedological process understanding through the modelling setup. Simulations of streamflow and soil water contents were then compared with measured data at two weirs (draining 25 ha and 157 ha, respectively) and 13 soil profiles with long-term soil water content measurements (van Huyssteen et al., 2005). Results show that both model runs performed very well (Nash-Sutcliff Efficiencies greater than 0.8) but that including the routing in the model did not significantly improve simulation accuracy of streamflow. However, the *hydropedological* approach yielded better predictions of soil water contents, especially of wetland soils (Fig. 3). This was because sub-surface lateral flow from the midslope soils were routed to the wetland soils in the valley bottom, thereby correcting underestimation of soil water contents on average by 56% in these soils (based on PBIAS calculations). The routing is especially effective following wet seasons and during periods without distinct dry-spells (e.g. 2000/03 season in Fig. 3). Without routing, water contents are not replenished resulting in a considerable underestimation of water contents, leading to underestimation of evapotranspiration and percolation.

Relating the soil forms in the traditional soil map to their dominant hydropedological behavior served as basis for routing fluxes of water through the landscape, thereby reflecting the internal catchment structure better. Although it did not improve the simulations of streamflow directly, it did provide a more realistic representation of the streamflow generation processes—that is, *how* water will reach the catchment outlet. This could strongly affect water quality, relevant for SDG 6, which was not yet studied. Failing to capture these internal processes in the modelling effort could result in erroneous conclusions and possible mismanagement of water resources, especially when scenarios of change are simulated (Arnold et al., 2015; Kirchner, 2006; Yen et al., 2014).

In terms of communication, emphasis is not anymore only on the soil forms as such, as in classical soil survey interpretation, but on the hydropedological groups and their effect on the spatial distribution of hydrological processes, as reflected by modelling. This allows communication about the entire watershed.

4.3. The WaterVision Agriculture system

More than 50% of the land area of the Netherlands is below sea level

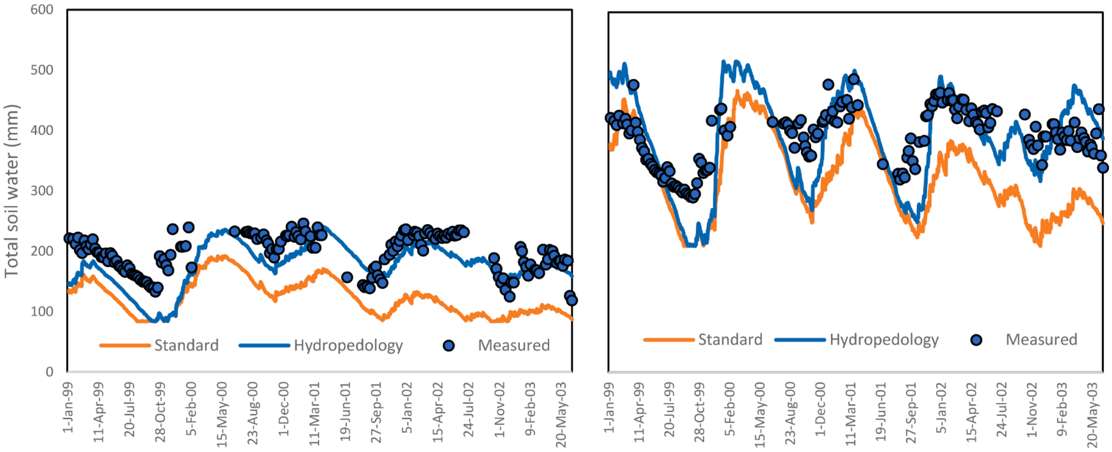

Fig. 3. Examples of simulated vs. measured soil water contents of two wetland soils when including the hydropedological routing and without routing (). adapted from van Tol et al., 2021

and water management has therefore always received major emphasis in both research and environmental policy. For regional water management, information is required on the effect of policy decisions on the environment and on agricultural production. Such information cannot be delivered by traditional empirical land evaluation systems but requires quantitative approaches through the application of simulation models. Quantitative land evaluation can thus be used for water management to gain insight in different realistic options for current and future conditions. To serve the needs of different types of users, like water authorities, provinces, drinking water companies, and the National Department of Infrastructure and Water Management, the WaterVision Agriculture system was developed in close interaction with the various agencies. It allows addressing questions as to how crop development is affected by the soil moisture regime as determined by water management including an assessment of the associated farm incomes. The system will be widely applied in the Netherlands and results are likely to also affect future environmental and land-use legislation (Hack-ten Broeke et al., 2016; 2019).

WaterVision Agriculture is based on the 1:50000 soil map of the Netherlands (De Vries, 1999) containing 368 representative soil profiles for the various mapping units. These profiles were analyzed with a hydropedological procedure, starting with the distinction of 18 textural classes for top soils and 18 textural classes for subsoils. For each of these classes, average water retention and hydraulic conductivity characteristics were calculated based on measurements (the so-called Dutch Staring series; Heinen et al., 2020). Some of these soil profiles, though different pedologically, behave similarly in terms of water retention and conductivity, offering the possibility to derive a limited number of functional soil clusters. Thus, 79 unique soil physical units were obtained (the so-called BOFEK map, Heinen et al., 2021) for the entire country reducing the total number of required simulations by 79%.

Modeling involved the combined application of the hydrological simulation model SWAP[1] (Soil-Water-Atmosphere-Plant; van Dam et al., 2008; Kroes et al., 2017) and the crop growth model WOFOST[2] (WOrld FOod STudies; Boogaard et al., 2014; de Wit et al., 2019). SWAP simulates water transport in the unsaturated zone using soil parameters, meteorological data, and boundary conditions (like groundwater levels). WOFOST simulates crop growth as a function of meteorological conditions and crop parameters. Shortage of water when soils are dry or oxygen depletion when soils are wet results in reduced transpiration and crop growth. A million model runs were made, reflecting representative variations in land use and meteorological and groundwater conditions. From that a *meta*-model was derived describing the relationship between the crop yield and its growth conditions.

As an example, an application of WaterVision Agriculture is presented for the catchment of the small river ‘De Raam’, requested by the regional water authority ‘Aa and Maas.’ The authority was interested to know how crop yield would respond to either excessive dryness or wetness as a basis for improved land management practices. Actual conditions in terms of groundwater dynamics, land use, and locations where irrigation was applied were derived from a regional groundwater model (GRAM) and used as input.

Results are presented in Fig. 4. The dominant land use is grassland and maize, but also some arable crops are grown in the area. The soil types are mainly sandy soils varying from fine textured Podzols with a shallow rooting depth to Anthrosols with a thick top soil. River clay soils are present in the northeast. A large part of the catchment is irrigated in dry periods during the summer. Although the hydrological conditions seem to be relatively dry, groundwater levels during the winter period can be relatively wet with levels up to 20 cm below the soil surface. The meteorological conditions for the period 1991–2020 were used for the simulations. Yield reduction can be caused by either drought or by oxygen stress due to wetness (in this part of the Netherlands salinity stress can be neglected). Overall, the drought stress is dominant in the catchment but in the central part of the area near the river the yield reduction is largely due to wetness and oxygen stress.

Of course, many other questions about crop productions under various climate or environmental conditions can be raised and answered by the illustrated modeling approach. The focus on yields makes data relevant for SDG 2. Of particular interest is the manner in which results are communicated for the various hydropedological landscape units. Rather than names derived from soil classification, dominant texture and well-known physiographic landscape units are selected (e.g., light marine clay soils), ensuring effective communication with both land users, the public and the policy arena.

4.4. *Soil functionality on world level*

ISRIC-World Soil Information is an independent foundation by Dutch law, based on the campus of Wageningen University and Research (WUR). It was founded in 1966 at the request of the international soil science community (represented by the International Union of Soil Sciences) and of UNESCO, related to the initiative by the FAO to develop the first harmonized soil map of the world and its accompanying legend (FAO, 1974). It is a service provider to the international science community, policy communities, and the private sector dealing with issues

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[1] https://swap.wur.nl/.

[2] https://www.wur.nl/en/Research-Results/Research-Institutes/Environmental-Research/Facilities-Tools/Software-models-and-databases/WOFOST.htm.

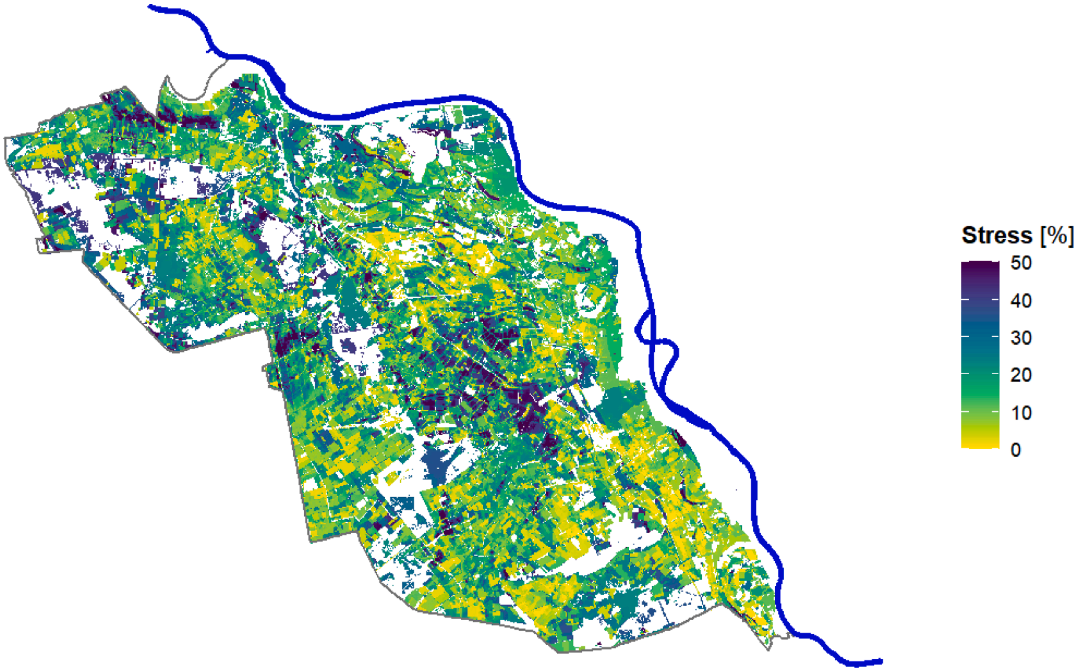

Fig. 4. Map of the "De Raam" catchment indicating the average yield reductions, expressed as % stress, calculated for the period 1991 – 2020.

aligned with the SDGs.

This service-provision role is achieved by providing harmonized and quality-assessed soil data for the world, most notably via the WoSIS database of soil profile observations and accompanying laboratory-measured soil properties (Batjes et al. 2020). Since its founding ISRIC has been a leader in mapping the world's soil resources, first with the FAO Map of the World—a 1:5M polygon map of general soil classes (FAO 1974, 1990)—and later (along with IIASA) the Harmonized World Soil Database (HWSD) 30 arc-second raster (IIASA et al., 2012) and various regional maps at 1:1M or somewhat larger scales following the SOTER protocol (van Engelen and Dijkshoorn, 2013). These maps all showed the principal soil classes in each polygon or grid cell, along with estimated soil properties from generalized profiles. This information was used as the basis for several global assessments, including the GLASOD map of soil degradation (Oldeman et al. 1991) and the ongoing Global Agro-Ecological Zones project (FAO, 1978; 2018).

ISRIC was a founding member of the GlobalSoilMap.net initiative from 2008 (Arrouays et al., 2014). This ambitious project was a response by the digital soil mapping (DSM) community to a challenge by Pedro Sánchez to provide consistent soil property (not class) information at a sufficiently detailed resolution to be used directly in land surface modellng. This distributed project has had some local success, but for various reasons was not able to create a global map. As this became apparent, ISRIC initiated the SoilGrids project to provide a consistent global product, first at 1 km nominal grid resolution (Hengl et al. 2014), then at 250 m resolution (Hengl et al. 2017) and now with version 2 still at 250 m resolution (Poggio et al. 2021), and soon as generalized products (1 km, 5 km resolutions) as input to coarser-scale models.

SoilGrids uses the WoSIS harmonized soil database to train a machine-learning model to generate a set of soil properties at six standard depth intervals, as specified by GlobalSoilMap.net (Science Committee, 2015). This is a standard approach used in so-called digital soil mapping (DSM); see the review of Wadoux et al. (2020). The method as described in detail by Poggio et al. (2021) is as follows. First, the soil properties to be mapped are known for each entry in the WoSIS soil profile data base. Also, the geographic coordinates of each point are known. The idea is to build an empirical model which relates the known properties to values of a set of so-called environmental covariates, which are selected to represent soil-forming factors. These covariates cover the entire world—that is, the area where the map is to be made. Typical examples are terrain features extracted from digital elevation models, representing the 'r' (relief) soil forming factor, and vegetation indices, representing the 'o' (organisms) soil forming factor, derived from multispectral satellite sensors such as Landsat. Through map overlay, the values of these covariates are extracted at each known point. This is possible because the covariate is known everywhere. With this information an empirical-statistical model is built that relates the soil property to the covariates. For example, a high concentration of topsoil soil organic matter might be related to concave landscape positions and abundant vegetation. These models are built by machine learning, trained on many soil property observations and their associated values of the covariates. A common model type, used in SoilGrids and many other DSM projects, is random forest regression (Breiman, 2001), which is a large set of decision trees having as its predictors (at the branch points of the decision tree) values of the covariates and as the predictand (at the leaves of the tree), the target soil property. The "forest" is built by several randomization procedures, so that the trees are not identical. The final prediction is a summary of the predictions from each tree in the forest. Once the model is built, then at every prediction point (i.e., the center of each 250 × 250 m grid cell covering the world), and at six standard depth intervals, the covariate values at that point are used as inputs to the calibrated random forest model, which results in a predicted value of the target soil property. In this way the entire world is mapped.

SoilGrids makes maps of nine primary soil properties: three soil particle size classes, coarse fragments, bulk density, pH, CEC, organic C, and total N. From these, SoilGrids has two properties that are derived: organic C density and stock. Importantly, the quantile random forest regression method used by SoilGrids not only predicts the most likely values (mean and median), but it also computes the 5% and 95% quantiles and an uncertainty index. This allows modelers to decide on the fitness for use of the products in their application.

SoilGrids soil property maps are directly useable in models of the soil–water-atmosphere-plant system focused on soil functions and ecosystem services, as data can be used to develop pedotransfer functions, as discussed in case studies 1, 2 and 3. An initial result is shown in Fig. 5, indicating the potential for C sequestration, important for SDG 13 "Climate Action". This is evaluated by a pedotransfer function from

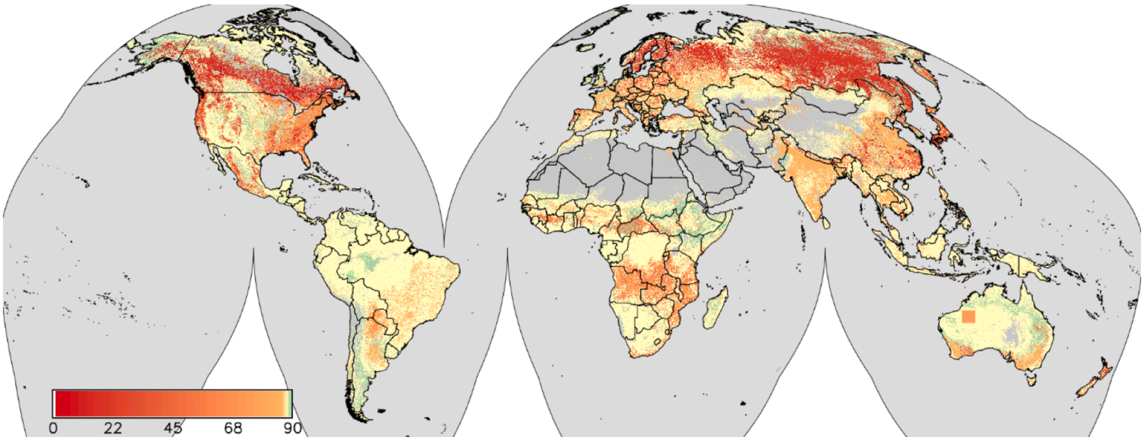

Fig. 5. A preliminary map of the soil function “C sequestration potential” (Relative scale: 0 = least, 1 = most.).

Chen et al. (2018), using as inputs SoilGrids properties SOC concentration, bulk density, coarse fragments, and clay, as well as expert opinion to reclass land cover. This shows which soils could potentially sequester more C than their current levels, not the C stocks potential.

Because of the large uncertainty involved and because we do not yet have a satisfactory way to match local functions to soil geographic regions, we only report the functions as ranks, and even for these, the distance in the ranking should not be taken as a true ratio scale. The next step is to map quantified soil functions, not just ranks. Most promising are the hydrological functions. Derived hydrologic properties, such as available water capacity (AWC), have been mapped by Dai et al. (2019) using pedotransfer functions from basic soil properties as recorded in the USDA soil database (NASIS).

Soil classes are effective holistic information carriers. The first two versions of SoilGrids included, therefore, maps showing the probability of occurrence of soil classes derived from both the World Reference Base (WRB) in terms of soil reference groups (IUSS Working Group WRB, 2015) and US Soil Taxonomy (Soil Survey Staff, 2014) at the great group level. These maps were, however, not satisfactory, mainly because of the dearth of classified profiles especially in some soil-geographic settings and the failure of attempts to automatically convert between systems. In the current version, SoilGrids shows only the WRB reference groups. Some of these are narrowly defined and are directly useful to zone soil management (e.g., Vertisols, Solonchaks, Solonetz). Others are defined by distinctive sets of soil properties (e.g., Chernozems and Andosols). But many groups are too broad to be useful for SDG-oriented actions. Maps based on aggregation of calculations for separate pixels, as shown in Fig. 5, are therefore the main output of the SoilGrids procedure.

The results of these global models are not meant to be used as-is for local studies, but rather to focus on areas where more detailed local studies are potentially most productive. This provides crucial information for agencies that have a world-wide mandate, such as the FAO.

Finally, communication with users in the policy arena who could benefit from SoilGrids is crucial. To that end ISRIC is an active participant in important user groups, including the World Overview of Conservation Approaches and Technologies (WOCAT), the Global Soil Partnership (GCP) of the FAO, OCP Africa, and The Nature Conservancy (ISRIC, 2022a). The maps themselves may be freely accessed via several protocols (ISRIC, 2022b). SoilGrids and WoSIS are widely-consulted and referenced showing the demand for globally-consistent and reliably-sourced soil information.

5. Discussion

Procedures followed in the various case studies are summarized in Fig. 6.

5.1. *Contributions of soil data to assess ecosystem services in line with the SDGs*

To obtain quantitative information on soil functionality, three case studies applied simulation models of the soil–water-atmosphere-plant system, defining soil moisture regimes and associated plant development. Cases 1 and 3 focused on individual soils. Case 2 on a watershed. In these three studies, measurements of soil hydraulic characteristics were made first and then used to develop pedotransfer functions allowing predictions of hydraulic characteristics for modelling. Measurements were based on pedological soil characterizations in terms of the occurance and depth of soil horizons, avoiding sampling at fixed depth intervals. Case 2 demonstrated the strong effect of slowly permeable subsurface soil horizons on flow patterns in the landscape. Cases 1 and 3 used the SWAP model that had been validated by other studies. In contrast, case 2 involved field validations of modeling results by the SWAT + model. Case 4 followed a different approach defining a set of soil characteristics (derived by machine learning based on existing soil maps and soil databases) for grids of 250 m square. These data are

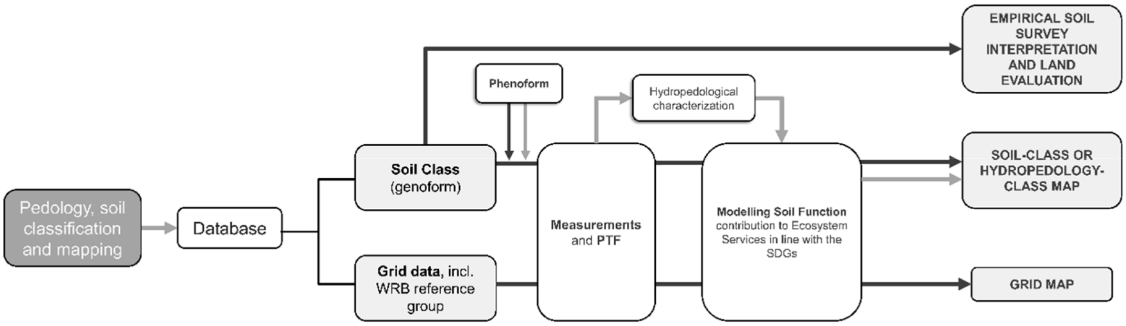

Fig. 6. Schematic representation of various procedures applied in the case studies aimed at characterizing soil functionality.

available to derive maps of either the separate types of data or of soil functions applying appropriate pedotransfer functions. Pixel data in case 4 included WRB soil classifications at the rather generalized reference group level.

5.2. Communication

Case 1 applied the traditional procedure of attaching innovative interpretations to a given soil series, assuming a "representative" profile on which calculations were based. This presents a meaningful example of a soil series acting as a "*carrier of information*" presenting *"the story of…,"* which is attractive for communication purposes. Cases 2 and 3 covered many different soils and were based on the conviction that soil functionality should not be based on soil alone but requires a structural consideration of soil water regimes as well, implying a hydropedological transformation. This resulted in a strong reduction in the number of soil units to be distinguished, which was favorable from an operational point of view. Case 3 introduced new names for these hydropedological units in terms of easily recognizable terms based on texture and physiographic landscape types, thereby abandoning soil classification terminology. Cases 1, 2, and 3 all showed that either soil types or hydropedological transformations of soil types acted not only as "*carriers of information*" but also as *"the story of…"*. Case 4 essentially produced a grid-based map as a final product. Soil classification could only be applied to grids in terms of the WRB generalized reference groups. This level is too general to allow effective communication of results because of the very wide variety of results obtained within each reference group. *"The story of…"* would not be specific enough to be useful for SDG-oriented research. This implies that every new grid map, by itself a *carrier of information,* is unique and that extrapolation of results obtained in one area cannot meaningfully be extrapolated to other areas.

More studies are needed to compare communication approaches based on either soil classification units, possibly transformed hydropedologically, with grid-based assessment. But in any case, different approaches may be needed at different spatial scales, be it local, regional, or broader if only because the stakeholders and the audience are different at different levels.

Models applied in case studies 1, 2, and 3 can be used to quantify ecosystem services in line with biomass production (SDGs 2, 12, 13, 15). This allows a direct assessment of contributions to SDG 2 related to crop growth, while SDG 3 is satisfied when no soil pollution occurs. Also, modeling of nutrient regimes can define precision application of fertilizers and biocides, protecting water quality (SDG6) (e.g., Stoorvogel et al., 2015). Overall, quantitative expressions of soil moisture regimes by modeling are important to evaluate and support biological soil processes that are crucial for soil functionality relating to SDGs 12, 13, and 15 that are not further discussed in this paper.

Wadoux et al. (2020) have defined ten challenges for future soil research, reflecting important discussions within the IUSS-PEDOMETRICS working group. Their Challenge 7 focuses on recognizing, quantifying, and mapping soil functionality and challenge 10 on how to generate quantitative soil contributions to realizing ecosystem services. Discussions in this paper can, therefore, be seen as a contribution to this important PEDOMETRICS discussion. Clearly, more research is needed to develop protocols of general validity.

Finally, cases presented show that soil science research has either been initiated by third parties, often governmental agencies, or these agencies have embraced and implemented research results, demonstrating that soil science provides a significant contribution to linking science with society.

6. Conclusions

1. Soils play an important role when contributing to sustainable development but classical soil survey interpretations don't provide adequate soil-functional information for interdisciplinary efforts to characterize soil functions and the associated ecosystem services in line with the United Nations SDGs and the European Green Deal.
2. Three local, regional, and national case studies used soil survey information, associated databases and pedotransferfunctions to successfully apply simulation models of the soil–water-atmosphere-plant system to define soil functions and ecosystem services in line with SDGs. Hydropedological characterization of soil types, defining soil moisture regimes, could strongly reduce the number of land units to be considered in a spatial analysis and is proposed as a procedure when assessing soil functionality in the future.
3. Soil types (soil series in case 1) and hydropedological soil types (cases 2 and 3) were used as "*"carriers of information"* presenting *"the story of..,"* and allowed extrapolation of data obtained to identical soil types elsewhere, facilitating communication with stakeholders, the policy arena, and society at large.
4. Case study 4 at the world level was based on basic soil data, derived from soil surveys and associated databases, assembled in 250 m square gridpoints that could be used to develop soil functions by applying appropriate pedotransfer functions. Maps showing aggregated values for all gridpoints are successful *carriers of information* but don't allow extrapolation, since the very large number of gridpoints does not allow a link with soil classification. The stakeholders and audiences are different at different spatial scales and communication has to vary accordingly.
5. A given soil type (the genoform), formed by usually long-term soil forming factors, can function quite differently following different forms of management. Distinction of phenoforms is therefore suggested when assessing soil functionality in the future.
6. Modelling, as demonstrated in case studies 1,2 and 3 is the only way to explore possible future effects of climate change, an ever more relevant aspect of soil functionality. Case study 1 presented examples.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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