Helping stakeholders select and apply appraisal tools to mitigate soil threats: Researchers' experiences from across Europe

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Abstract
Soil improvement measures need to be ecologically credible, socially acceptable and economically affordable if they are to enter widespread use. However, in real world decision contexts not all measures can sufficiently meet these criteria. As such, developing, selecting and using appropriate tools to support more systematic appraisal of soil improvement measures in different decision-making contexts represents an important challenge. Tools differ in their aims, ranging from those focused on appraising issues of cost-effectiveness, wider ecosystem services impacts and adoption barriers/opportunities, to those seeking to foster participatory engagement and social learning. Despite the growing complexity of the decision-support tool landscape, comprehensive guidance for selecting tools that are best suited to appraise soil improvement measures, as well as those well-adapted to enable participatory deployment, has generally been lacking. We address this gap using the experience and survey data from an EU-funded project (RECARE: Preventing and REmediating degradation of soils in Europe through land CARE). RECARE applied different socio-cultural, biophysical and monetary appraisal tools to assess the costs, benefits and adoption of soil improvement measures across Europe. We focused on these appraisal tools and evaluated their performance against three broad attributes that gauge their differences and suitability for widespread deployment to aid stakeholder decision making in soil management. Data were collected using an online questionnaire administered to RECARE researchers. Although some tools worked better than others across case studies, the information collated was used to provide guiding strategies for choosing appropriate tools, considering resources and data availability, characterisation of uncertainty, and the purpose for which a specific soil improvement measure is being developed or promoted. This paper provides insights to others working in practical soil improvement contexts as to why getting the tools right matters. It demonstrates how use of the right tools can add value to decision-making in ameliorating soil threats, supporting the sustainable management of the services that our soil ecosystems provide.

Keywords: soil degradation, soil improvement, stakeholder engagement, impact assessment, decision-support tools, Europe

1. Introduction

The soils that underpin the Earth's food and agricultural systems face numerous degradation threats (Dominati *et al*., 2010; McBratney *et al*., 2014). Soil threats generally occur at different spatiotemporal scales and are caused by the interplay of biophysical, socio-economic and political factors (Admunson *et al*., 2015). Threats such as erosion, compaction, salinisation, contamination, acidification and sealing have long been recognised in the Soil Thematic Strategy of the European Commission (CEC, 2006). These threats are also reported in the State of the World's Soil Resources Report as contributors to soil carbon decline, nutrient imbalance and loss of biodiversity (ITPS, 2015). Around the world, soil threats limit the capacity of the soil to act both as a renewable energy source and a sink in the carbon cycle (Koch *et al*., 2013), and ultimately affect the continued delivery of benefits to humans from the soil, *in situ* and across landscapes.

The societal responses required to address soil threats are complex and multi-faceted (Montanarella *et al*., 2016). Depending on the natural attributes of a particular soil, the type and extent of soil threats, and the ecological goal to be met, several measures are being used across the world to mitigate soil threats and achieve soil improvement objectives. Examples of measures include agricultural practices that use cover crops and nutrient management (Doberl *et al*., 2013) as well as ecological restoration measures that target reforestation (Harper et al., 2012) and conservation (Diaz *et al*., 2008; Tibbett *et al*., 2019), or in the case of polluted lands, phytoremediation (Mahar *et al*., 2015). Although soil improvement measures differ in their effectiveness in meeting specific targets and end user requirements (Keizer and Hessel, 2019), their implementation is typically location-specific, occurring within widely differing environmental, technology-related and socio-economic contexts (Harrison *et al*., 2018). With growing interest in soil improvement research, a variety of appraisal tools have emerged to support more systematic appraisal of remediation and restoration options and to better inform the selection of measures that are ecologically credible, socially acceptable and economically affordable (Kiker *et al*., 2009; Gonzalez-Redin *et al*., 2016). Tools in use range from those focusing on soil functioning (Volchko *et al*., 2014) and wider ecosystem services delivery (e.g. biophysical tools using expert-based and stakeholder qualitative processes (Harrison *et al*., 2018) and multicriteria analysis approaches (Saarikoski, *et al*., 2016); to those elaborating on cost-effectiveness issues (e.g. monetary tools (Boerema *et al*., 2018) and barriers or opportunities related to public acceptance and uptake of remediation and restoration measures (Pannel *et al*., 2006; Ndah *et al*., 2012)). The choice of a particular tool to apply in appraising a specific soil remediation and restoration measure can depend on many factors, including the aim of the appraisal, the policy and decision-making contexts, the strengths and limitations of different tools, the ecosystem services at stake and pragmatic reasons such as availability of data, expertise and resources (Dunford *et al*., 2018).

Although several tools are being applied in multi-level, interdisciplinary and participatory ways involving stakeholders (Harrison *et al*., 2018), what is really lacking are comprehensive guidelines for identifying and choosing tools that can be used both singly and in combination (and that are best suited) to appraise remediation and restoration measures, as well as those well-adapted to enable participatory deployment. Participatory deployment here implies stakeholder engagement in ways that enable legitimacy, validation, knowledge integration and democratisation/uptake of innovations (Puente-Rodríguez, 2014). Guidance is essential to help researchers and those working in practical soil improvement contexts to better assess where, and in what contexts, different tools can be applied, and the values specific tools can add in fostering widespread deployment of measures that offer maximum ecological outcomes at acceptable costs. In addition, guidance is needed to enhance the capacity of soil managers to be able to select, combine and test the most beneficial improvement measures that account for their needs and constraints and are sustainable in terms of enhancing the environmental status of a site on a long-term basis. This demand for guidance has been recognised in the wider sustainability assessment domain (Gasparatos and Scolobig, 2012) and specifically in the soil ecosystem services (Bagstad *et al*., 2013; Korbeľová and Kohnová, 2017) and soil improvement assessment (Helming *et al*., 2018) literature.

In this paper, we aim to provide case study examples and insights from the 7th framework programme EU-funded (EU FP7) RECARE project (Preventing and REmediating the Degradation of Soils in Europe through Land CARE) to assist researchers and practitioners embarking on soil improvement trials and programmes where priorities are driven by practical end-user needs. The RECARE project (see Stolte *et al*., 2015; Schwilch *et al*., 2018) focused on different soil threats and decision-making contexts across Europe. It applied different socio-cultural, biophysical and monetary valuation tools, combining scientific and local knowledge, to assess soil functions and ecosystem services, as well as the costs, benefits and adoption of soil remediation and restoration measures. In particular, RECARE was framed as a context-specific and problem-focused assessment of soil threats and their mitigation options, driven by scientists and local, regional and national stakeholders, and requiring the flexibility and adaptability of research teams across 15 case studies. As such, the project offers a useful empirical context through which to understand how researchers can use different tools to appraise soil threats and facilitate stakeholder acceptance of soil improvement measures.

We first provide an overview of our methodological approach, showing the tools and case studies used in the RECARE project. We then present our results highlighting the tools case study teams prioritised, the reasons they prioritised those tools and the key activities carried out in preparation before using specific tools. We also describe which attributes of the tools help to characterise their strengths and limitations, how tools differ from each other, the tools that are best suited to participatory deployment, and those that work best to appraise soil remediation options (i.e. tools that added the most value for stakeholders to aid decision-making). Further, we highlight some important questions to consider when selecting appraisal tools, illustrating how different tools might work together to better capture different user demands and decision-making contexts, including why it matters to get the tools right.

While past studies such as Dunford *et al* (2018) and Harrison *et al* (2018) cover monetary, socio-cultural, biophysical and integrative tools beyond those captured in RECARE, they show limited evidence of combination, testing and application of multiple tools within the same project-specific sites as is the case in RECARE. They also did not consider a series of concrete case studies covering different soil conditions throughout Europe. Conducting surveys that cover 15 European countries and including researchers applying a variety of soil management appraisal tools (in order to provide guidelines for identifying and choosing tools that are best suited to appraise different aspects of remediation and restoration measures) make this study novel.

2. Methodological approach

Using a structured process that involved a series of stakeholder workshops and other transdisciplinary approaches (see Hessel *et al*., 2014; Leventon *et al*., 2016), RECARE designed and deployed a DPSIR (Driving Forces-Pressures-State-Impacts-Responses) inspired framing of land management (see Schwilch *et al*., 2016) in which five tools (Table 1) were used by RECARE researchers to appraise measures that mitigate soil threats in different case study locations in Europe, often in collaboration with stakeholders (see Table 2). The study locations cover varying (past and present) soil degradation threats, occurring at different spatial scales. The soil threats considered are soil erosion, salinisation, compaction, sealing, desertification and floods, as well as soil contamination, loss of organic matter in peat and mineral soils, and loss of biodiversity.

RECARE focused on studying various causes, impacts, problems and possible solutions to soil threats, identifying and testing sustainable soil management practices with land users (Prosdocimi *et al*., 2016; Zoumides *et al*., 2017). The five appraisal tools used in RECARE cover issues relating to cost-effectiveness (monetary), wider ecosystem service impact (biophysical) and adoption barriers and opportunities (socio-cultural) of soil remediation and restoration measures. The tools are an indicative rather than an exhaustive selection of potential tools that could be applied to appraise options for mitigating soil threats.

To comprehensively evaluate the tools used, we surveyed RECARE researchers across 15 case study sites using an online questionnaire (see Supplementary Material). Researchers (who played a key role in at least one of the tools being evaluated) were requested to: (i) provide information on the specific tools they applied, their previous experience of using different types of tools, the reasons they selected particular tools, and the key activities performed in preparation to using the tools; (ii) give a general assessment of the tools in free text, describing those that worked best to appraise options and which they felt were best suited to participatory deployment; and (iii) comment on the 'ensemble of the tools' – i.e. whether tools used were sufficiently integrated and complementary, and whether they addressed all relevant aspects of stakeholder decision-making.

Responses from the researchers were analysed using a thematic analysis approach. This involved checking, interpreting and coding of responses into themes in Excel to unpack the key issues researchers considered during and after tool selection. Themes here covered: researchers' considerations in the selection of particular tools; activities performed in preparation for applying tools; and efficacy of tools in appraising options. Where necessary, insights from ad-hoc review of published work from the RECARE project were used to provide additional details and clarify uncertainties. Thirty-four researchers completed the online questionnaire (19 males and 15 females from 15 case studies spread across 15 European countries). Their disciplinary backgrounds intersect soil, agriculture, ecosystems and environmental social sciences, and their career positions range from senior researcher and professor to post-doctoral researcher.

Table 1
Overview of the five tools applied in RECARE case studies that we evaluated in this paper

Tool (**T**) applied in RECARE	Overview
Biophysical-oriented tool: impact assessment on ecosystem services and valuation by (i) experts (**T1**) and (ii) stakeholders (**T2**) Two biophysical tools encompassing an expert-based qualitative valuation (T1) of changes in ecosystem services (resulting from applied mitigation measures), both for the plot and a wider area as well as for short- and long-term, and a stakeholder valuation of ecosystem serviceimpacts (T2) were used in RECARE. Both involved a qualitative process through which the impact of soil improvement options on a broad range of 15 ecosystem services were assessed (see Schwilch et al., 2018)	One of the primary advantages of this appraisal tool is its holistic approach to consider wider soil-related provisioning, regulating and cultural ecosystem services. Tools that raise awareness about different soil threats and provide insights across a broad range of ecosystem services are relevant to practitioners (Schwilch *et al*., 2016). RECARE sought substantive expert and stakeholder engagement and brought together different types of knowledge to evaluate soil ecosystem services impacts.
Integrative tool: participatory development and use of innovative probabilistic Bayesian Belief Network (BBN) framework (**T3**)	RECARE used BBNs developed both by experts and in collaboration with stakeholders, with system diagrams as outputs, operationalised by populating conditional probability tables (see details in Dal Ferro *et al*. (2018). BBNs often integrate different data types and values to more comprehensively assess soil remediation options (Kelly *et al*., 2013; Gonzalez-Redin *et al*., 2016).
Monetary-oriented tool: process-based cost-effectiveness analysis at local and regional scales (**T4**) This tool involves the elaboration of cost-effectiveness analysis (CEA) and/or cost-benefit analysis (CBA) for the trialled remediation options (see Fleskens et al., 2016)	Cost is one of the major issues to consider in selecting soil threat mitigation options, especially where such costs are not covered by public resources. Both CEA and CBA are decision-support tools. While the former is used for ranking alternative measures of mitigating the same soil threats by their ratio of effectiveness to cost, the latter is used for screening alternative measures by their internal rate of return or ranking alternatives by their net present value or discounted cost and benefit ratio (Boardman *et al*., 2006; Saarikoski *et al*., 2016).
Sociocultural-oriented tool: examining barriers to adoption and uptake of measures for addressing soil threats (**T5**)	In RECARE, T5 involved a short questionnaire and the construction of problem and solution trees of barriers affecting adoption, with input from stakeholders. Stakeholder engagement explored how the historical, policy, institutional and individual socio-economic contexts across case study locations create barriers for adoption and uptake of remediation and restoration measures, as well as opportunities for new activities with subsequent soil impacts. T5 is useful in understanding: barriers ranging from purely cultural and economic to purely institutional; those affected by soil threats; who should take action; why soil threats persist; and why actions to address them often fail (see Chinseu *et al*., 2018).

Note: The different tools used in RECARE served different purposes, examined different aspects of soil improvement measures, and therefore are not simply interchangeable. For example, T1 cannot replace T5 and T4 cannot replace T2 because they focus on different aspects. T1 and T2 were designed to be used in sequence (T2 draws on the results of T1; although T1 could be used as stand-alone tool). See Table S2 for tool-specific reflections from RECARE researchers who developed each tool highlighted in Table 1.

Table 2.
Overview of the soil threat amelioration measures trialled, and the tools used to appraise them across 15 case study locations (see Keizer and Hessel, 2019) .

Primary soil threat	Location and country	Main measures trialled	Tool(s) used to appraise measures
Soil erosion by water	Frienisberg, Switzerland;	Damming potato furrows with the 'dyker' technology	T1, T2, T4 and T5
	Caramulo, Portugal	Post-fire mulching with eucalyptus logging residue	T1, T2, T3, T4 and T5
	Peristerona Watershed, Cyprus	Maintenance and rehabilitation of dry-stone terraces	T1, T2, T4 and T5
Salinisation	Timbaki, Crete, Greece	Use of biological agents to increase crop resistance to salinity	T1, T2, T3, T4 and T5
Soil sealing	Wroclaw & Poznan, Poland	Effects of spatial planning for improved soil protection based on soil quality information	T2, T4 and T5
Desertification	Gunnarsholt, Iceland	Use of seeding, fertilizer and tree establishment to reclaim land	T1 and T2
Floods and landslides	Vansjø-Hobøl Catchment, Norway	Flood retention measures and the impact of vegetation on river bank stability	T1, T2, T3, T4 and T5
	Myjava Catchment, Slovakia	Use of small wooden check dams for the stabilisation of gullies; application of sustainable land and crop management practices to reduce soil water erosion	T1, T2, T3, T4 and T5
Loss of organic matter - peat soils	Veenweidegebied, The Netherlands	Use of submerged drains to reduce peat oxidation (so loss of OM)	T2, T4 and T5
	Broddbo, Sweden	Alternative grass species, such as Reed canary grass and Tall fescue to improve carbon capture efficiency	T1, T2, T3, T4 and T5
Loss of organic matter - mineral soils	Olden Eibergen, The Netherlands	Grass undersowing in maize	T1, T2, T4 and T5
	Veneto region, Italy	Continuous soil cover and conservation agriculture practice	T1, T2, T3 and T5
Soil contamination	Guadiamar, Spain	Soil amendment using as sugar lime, biosolid compost and leonardite	T1, T2, T4 and T5
	Copsa Micã, Romania	Amendments to reduce heavy metals mobility in soil and uptake by plants (using bentonite, dolomite, natural zeolite and manure)	T1 and T2
Loss of soil biodiversity	Isle of Purbeck, United Kingdom	Soil acidification using sulphur to restore heathlands and acid grasslands	T1, T2, T4 and T5

Note: Both qualitative and quantitative approaches were used across case studies to identify various soil threat amelioration measures; also measures were selected using participatory approaches (see Schwilch et al., 2012; Leventon et al., 2016; Panagea et al., 2016). For further details about the selected measures see Schwilch et al. (2018).

3. Results

3.1 Participant considerations in the selection of tools

Survey findings showed a range of factors were considered across case studies in selecting specific tools for appraising soil improvement measures. Here, we group the factors using three specific features of trialled measures: i) cost-effectiveness; ii) ecosystem services and functions; and iii) scale, timing and stakeholder adoption and uptake.

Cost-effectiveness indicates the tools' ability to ascertain whether trialled remediation and restoration options 'have value for money', and whether internal rate of return or net present value is reasonably high based on a monetary comparison of costs and benefits of applying alternative options. Ecosystem services and functions reasons are underpinned by the understanding that different prevention, remediation and restoration measures are likely to have various effects on soil functioning and wider ecosystem services provisioning. These effects were captured by key soil properties and by impact indicators, ranging from biophysical indicators such as reduced soil loss and increased soil organic matter, to socio-economic indicators such as increased production or reduced workload (see Panagea *et al*., 2016). Considerations based on scale, timing and stakeholder adoption and uptake included whether application of the remediation/restoration option was limited to a specific geographical area and/or season(s) of the year, including short-to-long-term intervals before soil improvement outcomes became evident; and whether both the appraisal tools and mitigation options can easily be adopted and used by stakeholders.

Researchers focused on one or more of these considerations, exploring local preferences for soil remediation and restoration options, and accounting for tools that: i) integrate ecological, cultural and economic aspects to raise awareness of the importance of ecosystem services and functions threatened by soil degradation; ii) accurately evaluate existing remediation options, policies or projects in ways that add credibility and trust to the decision-making process and increase stakeholder confidence (buy-in) in the use of threat amelioration options; iii) are flexible enough for use in diverse soil improvement decision contexts and that can be affordably applied; and iv) can reasonably be incorporated into public and private-sector ecological decision making on a routine basis. Note that all the 15 case studies had one overarching purpose, which was to understand the soil-related ecosystem services and functions that were impacted (covering groups of services such as cultural, regulating and provisioning services), as well as the cost, benefits and adoption of prevention, remediation and restoration measures. As such, the results from the surveys only covered the tools prioritised in the case studies.

3.2 Activities performed in preparation for applying tools

The surveys revealed that a wide variety of activities were performed in preparation for using the different tools. The activities, grouped into seven categories, include: following a training session; reading tool guidelines; adopting the tool (e.g. learning by doing through tool application); reading literature on the tool; deliberation with the work package leader; seeking advice from colleagues; and conducting pilot trials.

Figure 1 reveals the number of times (expressed as a percentage) the different activities performed by RECARE researchers were cited across all the tools used. The majority of individual respondents (> 65%) applied more than one tool and tended to maximise their use of each tool by 'reading tool-related guidelines'. Asking colleagues for advice (> 50%) and following the training provided (> 55% for T3-5) are also frequently cited, but these are highly variable across the tools. One tool in particular (i.e. T3: *participatory model development for evaluation of remediation options – Bayesian Belief Networks*) required several activities in preparation for its use. The majority of RECARE researchers (83%) who used this tool indicated they had no previous experience of applying the tool, and as such, read literature on the tool; asked colleagues for advice; asked work package leaders for guidance; and followed the training provided. Previous experience of tool application, expertise within the case study teams, as well as the ease of tool application and operationalisation, underpin why case study teams performed the various activities highlighted.

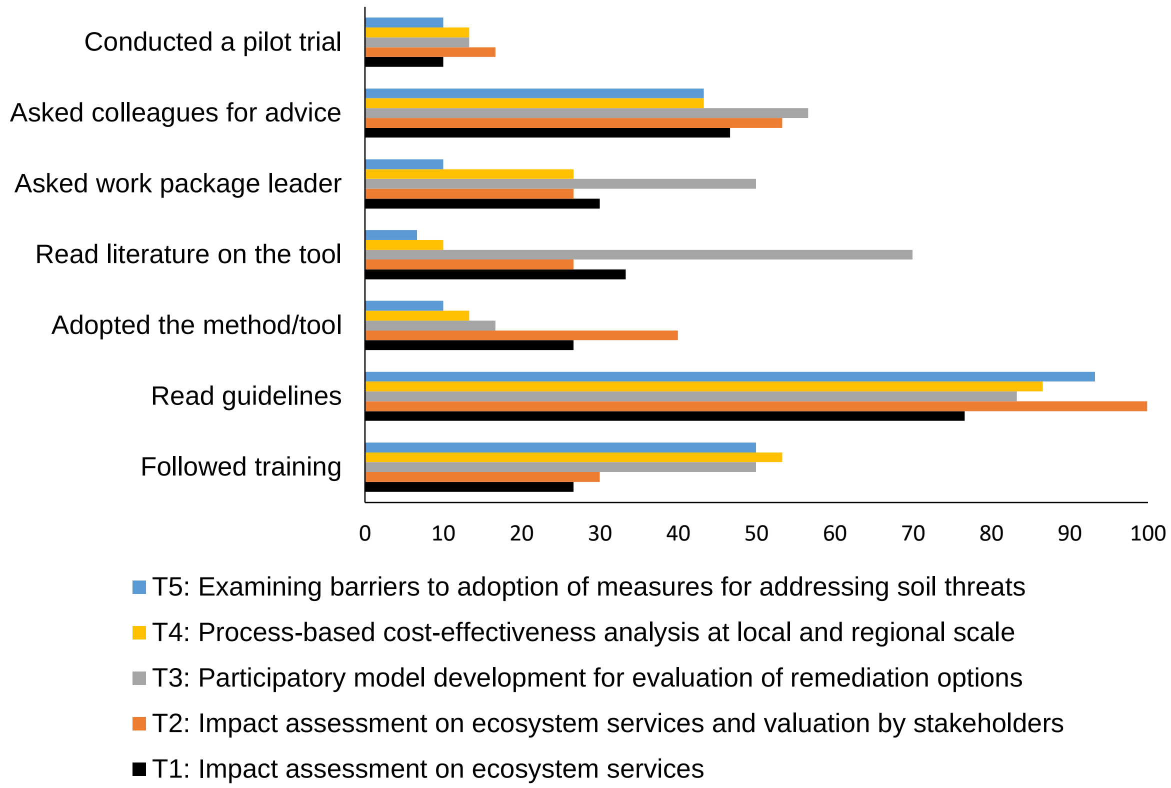

Figure 1. Frequency of use (expressed as a percentage) of different preparatory actions for tool deployment (n = 34).

3.3 Attributes that define applicability of tools in evaluating amelioration options to soil threats

The appraisal tools used in RECARE have specific features which underpin their differences and appropriateness for use in assessing soil remediation and restoration options. Table 3 classifies the tools according to the key attributes that define their relevance/applicability. Evidence on each attribute was provided by RECARE researchers according to their expert judgement of the tools they used across case study locations. The attributes encompass three broad dimensions: stakeholder-orientation, methodological-orientation and research-orientation (Table 3).

Table 3 depicts a useful empirical basis for the selection of tools. Given the variety of measures in use for tackling soil degradation, RECARE researchers were more interested in tools that can both enable stakeholder dialogue and inform collaborative decision-making (this interest informed our discussion on the stakeholder orientation aspect of Table 3 than other aspects in this section). Many appraisal tools designed with stakeholder needs in mind are well-recognised in the sustainability research community as capable of fostering social learning and local buy-in (Schwilch *et al.*, 2012; Doberl *et al*., 2013). Participatory appraisal tools that are stakeholder-oriented (e.g. T2 in RECARE) are relatively easy/straightforward to apply without specific need for disciplinary expertise, heavy datasets and/or resources. Monetary valuation (T4) and integrative (T3) tools were observed to be highly data intensive, requiring large amounts of qualitative and quantitative data, including advanced expertise in the use of specific software. A significant time investment in their application can mean that outputs from the tools are unlikely to emerge quickly. T4 is generally useful in terms of informing cost accounting, pricing and decisions requiring information on investments that offer good value for money. Similarly, tools that are integrative in nature (such as the BBNs - T3 in RECARE) tend to take advantage of mixed data, including significant expertise and resources available in case study locations. Although BBNs can accommodate stakeholder engagement, they were not used in that way by most case studies because of the level of time investment and expertise required.

Table 3.
Comparing tools' attributes based on evidence from the RECARE project [Note: (+++): very positive; (++): moderately positive; (+): slightly positive; (-): not applicable/relevant]. T1: Impact assessment on ecosystem services by experts; T2: Impact assessment on ecosystem services by stakeholders; T3: Participatory model development for evaluation of remediation options; T4: Process-based cost-effectiveness analysis at local and regional scale; T5: Examining barriers to adoption of measures for addressing soil threats.

Attribute	T1	T2	T3	T4	T5
Stakeholder orientation					
- Stakeholder participation	-	+++	-	-	+++
- Incorporates local knowledge	-	+++	-	-	+++
- Fosters social learning	-	++	-	-	++
- Easy communication/raising awareness	+	++	+	+	++
- Transparent (outcome easy to understand)	+	+++	+	+	++
- Informs decision making	++	+++	+	++	+++
Methodological orientation					
- Requires large data which may be unavailable	++	++	+++	+++	-
- Use of qualitative data	+	++	++	+	+++
- Use of quantitative data	+	+	++	+++	-
- High level expertise needed	+	-	+++	+++	-
- High amount of resources needed	+	-	+	++	-
- Ease of use/application	+	++	-	+	++
Research orientation					
- Advances knowledge of soil threats/solutions	+	+++	+	+	+++
- Integration across disciplines	++	+++	++	+	++
- Addresses soil-related knowledge gaps	++	+++	+	-	+
- Recognised in research community as novel	++	+++	++	+++	-
- Flexibility across sites to compare results	+++	+++	+	++	+
- Enables integrated treatment of soil threats	+	+	+++	-	++
- Explores uncertainty	+	+	++	-	+
- Confidence in tool results	++	++	+	++	+++
- Integration of socio-ecological processes	+++	+++	+	-	+

A number of tools (i.e. T1 and T2) focus on specific ecosystem services, such as variations in soil organic matter, which require different expert-based and stakeholder-oriented qualitative processes and valuation activities. Beside ecosystem services, T1 and T2 also enabled understanding between stakeholder groups in ways that created awareness, facilitating the use of stakeholder knowledge and helping to both resolve conflicts and spur uptake of soil restoration measures. The combination of T1 and T2, and specifically the use of T2, unveiled the different perceptions/valuation of different stakeholders as they valued the changes in ecosystem services differently.T1 and T2 were designed and applied to characterise the effects of soil improvement measures on soil functions and the wider ecosystem services provision. By using T1, experts qualitatively assessed the impacts of soil threat mitigation measures on ecosystem services. On the basis of the results from the expert assessment, different stakeholders valued the identified changes/impacts from their specific stakeholder perspective. The valuation was done in a participatory stakeholder workshop for which a step-by-step methodological guideline (T2) was developed within RECARE..

In addition, the ability of specific tools (e.g. T5) to identify opportunities and address barriers to adoption of soil improvement measures may constitute the key attribute that defines their relevance in a case study. Application of T5 enabled engagement of stakeholders to explore how historical, policy, institutional and individual socio-economic contexts create barriers/opportunities for uptake of new soil improvement measures (see Chinseu *et al*., 2018). Researchers noted that adoption of measures is often quicker when spaces for social learning, cooperative dialogue and reflection, and co-creation of knowledge are created in a deliberative stakeholder-oriented context. Adoption is also facilitated when tools' outcomes are easy to understand and communicate, particularly in contexts where the objective is to raise awareness about soil threats and measures to address them.

There are specific attributes of soil improvement measures for which RECARE researchers felt sufficient evidence is required to better inform decision making. According to the researchers' responses, there is a need for detailed economic and socio-ecological balancing of evidence on soil improvement measures. The surveys reveal that using tools that account for multiple soil ecosystem issues, and that integrate socio-cultural and ecological processes, including stakeholder views and/ or research disciplines, can enhance the utility of the assessment process. In order words, stand-alone tools that lack research orientation in terms of integration of socio-ecological processes across disciplines or knowledge domains are irrelevant for decision making/planning, and by extension often lack stakeholder buy-in and relevance in the broader soil management research community. In RECARE, integration is accounted for to different degrees by different tools (e.g. sequencing of tools such as applying T1 first in order to be able to use the outcome in T2), and this is based on the primary focus across case study locations. T3 adopts multi-criteria decision analysis to evaluate remediation options and their performance (in terms of soil management and policy options), accounting for varying decision-making problems defined by experts (cross-cutting soil-related social, economic and ecological sustainability concerns), and involving human judgment and preferences.

3.4 Efficacy of tools in appraising options

The surveys carried out in this study reveal that tools that worked best to appraise options across all case studies are generally those that can: (i) readily identify soil threats and generate promising solutions/options to deal with them; (ii) generate useful results and additional insights where necessary; and (iii) elicit stakeholder buy-in based on the confidence in the results generated. Using these three criteria to assess T1-5, we found that tools vary in their ability to appraise different aspects of value across cost, benefit, ecosystem gains/losses and adoption constraints. While all the tools provided insights on soil improvement measures to varying extents, T2's insights were deepest (although T2 depended on the outcomes from T1). Researchers indicated that T5 produced results that target audiences/stakeholders considered to be useful; a few researchers appeared to have a relatively high level of confidence in the results generated from T3 (because of the integrative nature of the tool) compared to any other tool used across all case studies.

Our assessment of researchers' overall choice of the tool with the biggest contribution to understanding the threats and appraising remediation options in their case studies reveals a relatively higher response (>35%) pointing to T2 as the tool with the biggest contribution. This is followed by T5 (>18%) and T1 (>15%). T3 had the lowest contribution amongst all of the tools evaluated. Reflections from RECARE researchers who developed T1-5 (see full details in Table S2 in the Supplementary Material) indicate that T3 requires substantial data and time to elicit stakeholder knowledge to be able to operationalise the relationships captured in the model. Stakeholders complained that T3 has several technical/methodological bottlenecks. These reveal why it is the least preferred across case studies.

Combining the above three criteria, survey results show that the tool that added the most value for stakeholders to aid decision-making across case study locations is T2. T2 (a stakeholder valuation of soil ecosystem service impacts) drew out differences between stakeholder categories in terms of valuation of ecosystem services. Researchers indicated they had to use T1 before using T2, implying that T2 is not a stand-alone tool. Integration of T1 and T2 works best to appraise soil threat options across the case studies; T2 in particular relates to a range of simple ecosystem impact valuation approaches with stakeholder input. It is also the 'most preferred' in terms of its usefulness in identifying what the preferred options are to deal with soil threat(s).

4. Discussion

We have drawn on RECARE's case study examples across 15 locations and countries to: illustrate the tools used to meet case study/stakeholders' priorities; assess soil improvement measures and the reasons different tools were selected; highlight the activities performed in preparation to using specific tools; understand key attributes that define the relevance of each tool; and identify the tools that are best suited to appraise options. In this discussion, we begin by identifying and discussing tools that are best suited to participatory deployment. Thereafter, we offer guidelines for choosing tools that are best suited to appraise soil improvement measures. We provide an overview of the (possible) considerations required for tool selection; how different tools can be combined to meet user demands; and why it matters to get (appraisal) tools right.

4.1 *What tools are best suited to participatory deployment?*

Various forms of participatory deployment, e.g. social learning, information exchange and awareness raising, involving scientists, practitioners and local stakeholders, are highlighted in the literature (e.g. Reed, 2008; Pretty, 1995; Martin and Sherington, 1997). Participation in the context of soil improvement measures is a socio-cultural and ecological imperative in the sense that stakeholders/citizens have to perceive themselves as part of the efforts to better manage soils. Stakeholders engaged across case study locations include soil /land management practitioners, farm managers, advisory service, non-governmental organisations, government organisation/policy makers, private sector, researchers and farming community leaders. In RECARE, tools that endorse or promote peoples' rights and support stakeholders' ability to influence decisions are readily more suited to participatory deployment, supporting findings from elsewhere in the literature (e.g. de Vente *et al*., 2016; Stringer *et al*., 2014; Stringer *et al*., 2017).

We determined which tools were best suited for participatory deployment by examining the responses RECARE researchers gave on the contributions T1-5 made in terms of facilitating engagement with stakeholders. Although the majority of the researchers (>71%) indicated that the ensemble of tools aided stakeholder decision-making, our assessment of researchers' choice of tools for stakeholder collaboration reveals T2 as the most appealing. T2 (linked to outcomes from T1) readily allows assessments to be conducted with end users; it relies heavily on the interactions between individuals and groups; as well as on the plausibility of social interactions to foster stakeholder buy-in. The surveys show that T2 (as well as T5 to a limited extent) generally supports the capacity of stakeholders to: receive the results generated by the RECARE trials; enter into dialogue over different perceptions; contribute information during the appraisal process; analyse information; and generate recommendations where required.

Our results suggest that tools that are best suited to participatory deployment have the capacity to foster: social relations; account for diversity of interests and perceptions; communicate complex technical aspects (e.g. ecosystem service impacts); and individual or group collaborative learning and experimentation in ways that facilitate understandings of how soil threat mitigation options work best and how different tools may interact (i.e. ensemble of tools) to achieve soil management outcomes. Mostert (2006) and Dale *et al*. (2019) argued that targeting participatory deployment as an objective can enhance the possibility for: informed and creative decision-making; stakeholder acceptance and ownership of the decision-making process; social learning that is adapted to manage disagreements; and shared governance and enhanced democratisation of power.

4.2 What considerations are required for tool selection?

Many of the RECARE researchers stressed a number of specific considerations required for tool selection which can be summarised into three main questions: What are the prevailing soil threats and mitigation measures? What types of resources (data, knowledge and expertise) are available to develop and successfully deploy the tools? What promising insights can be gained from tool outputs and results - on what scale and with what (anticipated) level of confidence?

Evidence from RECARE reveals that soil threats and specific mitigation options vary from place to place; and that tool selection is site-specific (Bagstad *et al.,* 2013)). Understanding what the prevailing soil threats are for a particular location and identifying appropriate mitigation measures (e.g. through stakeholder consultation) can inform the selection of appropriate appraisal tools (see Gasparatos and Scolobig, 2012).

The RECARE project shows, (as have other projects e.g. the OpenNESS project – Harrison *et al*., 2018) that tool selection (including tool construction and implementation) needs to consider availability of good quality local data(i.e. qualitative and quantitative data). Qualitative data incorporate stakeholder perceptions, expert views or some types of data derived from interviews and focus groups (e.g. descriptive and categorical data). Quantitative data capture the measurable characteristics of a soil improvement measure that a tool seeks to appraise, and may include survey, spatial or time series data. Some tools, such as Bayesian belief networks and multi-criteria decision analysis, are highly data intensive, combining different (good quality) data types to enable a more comprehensive appraisal. As such, it is important to settle the issue of data requirement/availability (as well as the intended purpose for using a tool) before/during tool selection processes (Gasparatos and Scolobig, 2012).

Further, having a valuable knowledge base that integrates local and expert knowledge (and/or that advances expertise in specific disciplines or software) is necessary (Pretty, 1995; Leventon *et al*., 2016) Also necessary are the time/human and financial resources required to apply a specific tool or a combination of tools (Dunford *et al*., 2018).

In terms of promising insights and level of confidence, tools should be able to appraise soil improvement options by providing insights into different components of a particular option (e.g. the amount of resources and partnership required) and support decision making across various ecological, social and economic contexts (Kelly *et al*., 2013). Confidence is gained as outcomes from tool application (increasingly) reveal the utility of soil threat mitigation options and/or facilitate needs-based, context-specific decisions that better support soil management and desired outcomes.

4.3 How can different tools be combined to meet user demands?

RECARE researchers recognised that the tools they applied were not completely independent of each other. They selected and applied a combination of tools in different ways across the case studies. In most cases tools were applied consecutively and complementarily in ways that enabled one tool to build on the outcome of another – they were not applied all at once.

For example, in the Myjava Catchment (Slovakia) case study, T1 and T2 were applied in sequence to enable identification of complementary measures (e.g. use of small wooden check dams, contour ploughing and green buffer strips) for tackling mud floods and soil erosion. Similarly, in Frienisberg (Switzerland), tools were combined by 'direct transfers' of data, results and concepts/learning. In Veneto region (Italy), data, results and concepts from T2 were directly integrated into T5. T4 and T5 complemented each other in the Wroclaw and Poznan (Poland) case study. Here, building problem trees in T5 revealed financial limitations for improved spatial planning based on soil data. The raised limitations were, for example, cost of data, software and new staff needed for mapping and spatial GIS analysis. T4 helped to express the cost in numbers and to verify whether the cost barrier is real or perceived (see Table S1 in the Supplementary Material on how the combination of tools worked across case study countries).

Benefits exist in combining tools that build upon and complement each other and in applying similar tools within a single case study to better capture uncertainties associated with particular soil remediation options. Such benefits include the provision of insights across a range of soil threat mitigation options, which often is of a high priority to stakeholders and practitioners. That RECARE's T1-5 can all assess a range of remediation and restoration options demonstrate that there are a range of different ways in which the suite of options can be investigated and understood, e.g. from in-depth interviews and workshops with stakeholders to monetary valuations and scenarios of ecosystem impacts.

Table 4 highlights some of the reasons (benefits) that may inform tool combination, as well as how tools can be combined to meet user demands.

Table 4.
Unpacking insights on tool combination (based on evidence in RECARE with additional insight from Dunford *et al*., 2018)

Reasons to pursue tool combination	Overview of how tools can be combined
i) Researching or engaging different stakeholder groups; ii) Addressing methodological weaknesses relating to a single tool, e.g. to complement weaknesses in other tools, increase robustness and validation; iii) Meeting decision-making context needs, e.g. across different ecosystem services and functions; iv) Assessing different values of soil improvement measures beyond those possible with a single tool (e.g. socio-cultural, biophysical, monetary and ecosystem impacts); v) Informing different stages of developing soil threat amelioration options across case studies.	i) Direct transfers e.g. of: - concepts, ideas, innovations and learning between tools; - data and results between tools; - tools between different remediation and restoration issues. ii) Customisation and hybridisation of tools based on contexts iii) Cross-comparison of tools' outputs (e.g. to enable cross-checking, collaborative learning, tool development, triangulation of results, etc.)

In case studies where soil improvement measures are to be designed and implemented, there will be a range of stakeholders holding a variety of interests in and commitments to the specific measures of concern. Stakeholders will draw from a range of different knowledge bases (e.g. their knowledge of soil threats and lived experiences). For soil improvement measures to contribute to addressing the problems they face, there is a need for tool combination to facilitate discussion and trust building, allowing stakeholders with local and scientific knowledge to engage with the appraisal of options (Harrison *et al*., 2018).

Whilst improved rigour in tool selection/combination is required, it is clear from across the RECARE case studies that there are specific tools available (e.g. T1, T2 and T5) that can add credibility to and build trust in the soil improvement decision process so as to meet practical user needs and increase stakeholder confidence. The RECARE case study teams who used more than one tool, in conditions where stakeholder engagement was a priority, identified different aspects of stakeholder integration that can inform tool combination and trust building, including that: the tool should facilitate dialogue among stakeholders; foster participation in decision-making; enable the combination of different knowledge areas; spur easy communication; and make results easily accessible. T1 and T2 which focused on ecosystem service impacts were most commonly combined for expert and stakeholder engagement. T2 was ranked highly with respect to researching and engaging different stakeholder groups and stimulating dialogue on the soil ecosystem aspects of remediation/restoration options.

On the basis of methodological weaknesses relating to a single tool, tool combination could achieve the following five goals: enhance the sharing of inputs and data between tools (e.g. to improve accuracy of results); foster triangulation of findings (e.g. to increase stakeholder confidence); spur follow on assessment of issues highlighted by the findings of another tool; facilitate response to stakeholder priorities or changes in a variety of decision contexts; and strengthen the level of robustness (e.g. in the way certain realities are communicated). In terms of meeting different decision-making context needs within practical case studies, tool combination at different 'decision stages' – e.g. awareness raising about soil threats, formulation of amelioration options, target setting for different options and decision-making – is needed (McIntosh *et al*., 2011). Accounting for these various stages can determine the extent to which tool combination is seen as successful by researchers and stakeholders.

Although benefits and opportunities exist when tools are combined, there are a range of challenges that may arise. These include: (i) practical constraints relating to availability of data, expertise, time and resources (Saarikoski *et al*., 2016); (ii) stakeholder-related constraints in terms of logistics required for finding, engaging and negotiating with stakeholders, and managing stakeholder rivalry and conflicts (Leventon *et al*., 2016); (iii) methodological constraint (e.g. differing units of measurement of values, spatiotemporal scales and units, etc.) where it is required to overcome differences in approaches embedded within different tools (Volchko *et al*., 2014); and (iv) contradictions in findings through the use of each tool creating a need for additional processes for their resolution. Practical evidence on how a combination of tools have helped to facilitate assessment of soil improvement measures draws on strengthening stakeholders' connection to different amelioration options, and making outputs from interlinked tools relevant for policy and extension strategies. The RECARE case studies highlight the importance of creativity when practically combining soil improvement measures - research teams in particular emphasised the significance of incorporating stakeholder engagement within all aspects of the research process (cf. Reed et al., 2014).

4.4 Why does it matter that we get the tools right?

Some of the issues discussed above reflect certain aspects/features of the RECARE project focusing on appraisal of soil improvement measures, but the key messages are beneficial to any soil improvement assessment. In this section, we highlight key take-home messages for practitioners concerning why getting the tools right matters. In doing so we reflect on the outcome of the RECARE project, and in particular the benefits of participatory deployment of soil improvement measures that address soil threats.

A wide variety of tools that is suited to appraise soil remediation or restoration options, and a growing number of methods to help users identify and decide which tool to use are emerging (Gasparatos and Scolobig, 2012; Volchko *et al*., 2014; Harrison *et al*., 2018). However, the survey of RECARE researchers reveals that efforts to address soil threats can be strengthened if practitioners/stakeholders can properly choose the tools that are well-adapted to assess remediation and restoration options. Getting the tools right can yield the following benefits:

- The right tools (or a combination of the right tools) can increase analytical capability and help appraise all the important soil improvement measures in a given context, facilitating the assessment processes of different types of soil functions and values (socio-cultural, monetary and biophysical);
- Exchange of ideas, knowledge, innovations and skills amongst stakeholders, local experts and researchers can be enhanced when the right tools are in use – this can foster valuable learning (e.g. local ecological knowledge) and opportunities, spur uptake of soil improvement measures and support long-term sustainability of soil structure and soil functions;
- The right tools can provide insight into how to reduce uncertainty (e.g. in relation to costs), highlighting biases and weakness and allowing new options to be deployed in response to changes in soil threats;
- Meeting the needs of the case study context(s) can sometimes mean that the right tools must reflect the range of different values that local stakeholders hold, including the time, budget and expertise available at any particular location;
- Building confidence in tools' outputs and results; identifying ways in which to improve soil remediation and restoration measures; enabling interdisciplinary working and stakeholder engagement; and maintaining flexible and dynamic procedures in anticipation of opportunities or constraints, all constitute additional benefits that can be derived when practitioners use the right tools.

5. Conclusions

This paper explored researchers' understandings of the 5 tools applied to appraise measures to prevent and remediate degradation of soils in 15 case studies across a wide range of soil threats and socio-cultural contexts (in the context of the RECARE project). It revealed the ways in which different factors, such as cost-effectiveness, ecosystem services and functions, and availability of data, expertise and knowledge, can inform tool selection. Also important are the groups of (external and internal) stakeholders, including their positions and ability to understand different soil improvement measures. Important attributes of tools that define their relevance in appraising soil threat amelioration options were identified, encompassing methodological, stakeholder and research related issues. Results presented show that tools that work best to appraise options and enable participatory deployment are those that: readily identify soil problems and generate promising solutions and options to deal with soil threats; generate useful results and additional insights (e.g. on soil improvement measures) where necessary; and elicit stakeholder buy-in by increasing the level of confidence in the results generated. Tools that endorse and promote people's rights and support stakeholders' abilities to influence decisions are readily more suited to participatory deployment. Answering a variety of important questions can provide practitioners with the necessary guidance they need for tool selection – this includes questions concerning the nature and types of the prevailing soil threats and mitigation measures; types of resources (data, knowledge/expertise, time) available to develop and successfully deploy the selected tools; and the anticipated insights and level of confidence to be gained from tool outputs/results. As with all environmental sustainability problems, application of specific tools requires that users first have a good understanding of the purpose of the tool and of the timing and types of data available to parameterise it before embarking on the tool selection process.

It is beyond the scope of this paper to provide definitive guidance on the methods to apply to accurately decide on the right appraisal tools or on how to integrate different tools as this will depend on the case study context. As there is no one-size-fits-all tool for appraising all soil improvement options, guidance based on applying a single tool in isolation should recognise that tools are not completely independent of each other, and that there may be benefits in combining different tools to address specific case study issues (see Table S1 for insights on benefits across case study countries). This is especially so if practitioners are keen to assess a full range of plural (soil) values attributed to all soil threat amelioration options. Most stand-alone tools are incapable of grasping multiple soil value types without combining them with others.

In sum, selecting the right tools to foster transfer of ideas, knowledge, innovations and skills amongst stakeholders, local experts and researchers from different disciplines can ensure that the right soil improvement measures are diffused quickly. The right tools can facilitate valuable learning and opportunities for sustainable management of the services and functions that our soil ecosystems provide.

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The coordinating institution requires all projects to undergo ethical checks to signal instances where research subjects need additional protections beyond those in the project consortium agreement. As the consortium agreement of the RECARE project already had clauses on data collection (including ethical considerations around participant anonymity, confidentiality, and informed consent), data access and sharing, and arbitration options which applied to the subjects of the study (the subjects in this paper were researchers affiliated with the participating institutions that signed the consortium agreement), it was deemed unnecessary to obtain further, additional clearances beyond the good ethical research practices that had already been signed up to in the consortium agreement.

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Supplementary Material

1. The Online Questionnaire used in surveying RECARE researchers across 15 case study sites can be found in the link here:

https://docs.google.com/forms/d/1mNIqmu7pW7TxGNR35p6t5iVJiJGmIVy3aa293asTDho/prefill

2. Table S1.
Tool combination – how it worked and the benefits across different sites

Some practice-based examples on: (i) how the combinations of tools worked in different sites; and (ii) the benefits tool combination had across different sites
In Crete [Greece] T1 provided an efficient way to collate and group information and test scenarios regarding the impact of each property group on ecosystem services (ES), taking into account the feasible ranges of each property. T3 and T4 (co-developed with stakeholders through interviews) revealed the financial feasibility of measures to tackle salinisation - the BBN developed in T3 provided information for a single timestep, while T4 better quantified financial indicators by working in multiple annual timesteps. Although the information provided by T4 was more accurate in terms of financial flows, T3 helped identify systems components and their interconnection better, thus providing a better view of agricultural inputs and yields with respect to changes in system variables (e.g. soil salinity). T5 provided feedback about the barriers and opportunities of adoption, as well as who the bearers of the cost of technology application should be. The experience gained from all previously applied tools was very helpful for the application of T2. The highlight of T2 was that it succeeded in reframing the context of the soil threats both in space and time (wider area vs farm scale; and long-term vs short term). T2 had a high

degree of novelty and complication (for both stakeholders and moderators), also uncovering opportunities for better collaboration between stakeholders. Combinations of tools enabled collaborative working between case study researchers, experts and stakeholders, supporting efficient ecological, economic and social assessment of measures to tackle soil salinization.
In Guadiamar [Spain] the combinations of T1, T2, T4 and T5 worked to improve communication with stakeholders in ways that enabled comprehensive evaluation of soil measures. Tools' outcomes helped in selecting strategies for soil remediation that were more acceptable to stakeholders. Ecosystem services (ES) valuation (using T1 and T2) for soil amendments and phytoremediation measures showed the importance of 'stabilisation of contamination' and 'recreational activities' as the most important ES.
In Myjava Catchment [Slovakia] T1 and T2 were applied in sequence to enable identification of complementary measures (e.g. use of small wooden check dams, contour ploughing and green buffer strips) for tackling mud floods and soil erosion. Although T5 flagged up adoption barriers (e.g. lack of subsidies and agencies to support implementation), application of T3 and T4 faced data constraints due to the peculiarity of the soil improvement measures trialled for the region. T1 and T2 in particular fostered stakeholder cooperation which led to identification of measures to exclude (e.g. production of row crops) in order to maintain soil fertility in the region.
In Peristerona Watershed [Cyprus] the combination of tools worked well - tools were applied consecutively and they complemented each other. For instance, regarding T1 and T2, although 'ecosystem services' was a new term to almost all stakeholders attending the third workshop in Cyprus, the flow of exercises and the necessary simplification helped them to see benefits that were previously not so obvious, e.g. regarding cultural heritage, or soil formation. In addition, the cost-effectiveness tool (T4), provides more objective results; ultimately, land users are interested in becoming more economically efficient, thus any investment in improving soil management should be worth it in monetary terms. The last tool (barriers and opportunities – T5) was also very helpful and with hindsight, could usefully have been undertaken at earlier periods of time, e.g. at the beginning of the project.
In Frienisberg [Switzerland] T1 and T2 were used in combination as T2 builds on the results of T1. This combination worked well and triggered interesting discussions in the stakeholder workshop, where the stakeholder valuation brought to the light the different perceptions/priorities that the different stakeholders have in regard to ecosystem services. In the same workshop T5 was applied, which was also a success. It was very helpful to have the different stakeholders there, because in the discussion, the main barriers could be identified and clarified to an extent that would not have been possible without the face-to-face interaction of the different stakeholders. Overall, a number of possibilities to support the adoption of the tested technology were jointly identified. In addition, it was ideal to include T5 in the stakeholder workshop as it would have been very difficult to organize an additional face-to-face event with the stakeholders. T3 was only used as a stand-alone tool within the research team and only in a basic version. It helped to sharpen understanding of the connections between different elements of the system, and the impact chains. However, the feeling people had was that it is not a very 'stakeholder-friendly' tool and is too complicated to be used with stakeholders. In addition, the timing of T3 was not ideal. Researchers felt T3 was applied somehow 'isolated' – they did not clearly see a link to the other tools. T4 was a bit 'isolated' and not clearly linked with the other tools. Researchers used it within their team, and in consultation with the farmers who tested the measure. However, if it would have been applied earlier in the project period, stakeholders could have been better involved. Only one measure was tested and the outcomes were highly variable because they strongly depended on factors such as topography and timing, and amount of rainfall

events. Therefore, it was quite easy to assess the costs, but very difficult to assess the monetary benefits of the measure. In general, researchers felt that the combination of the different tools during the entire project period (both time and content wise) was not always clear.
In Wroclaw & Poznan [Poland] T2, T4 and T5 were applied in the context of soil sealing case studies. T4 and T5 in particular appeared to be complementary. Building problem trees in T5 revealed financial limitations for improved spatial planning based on soil data. The raised limitations were, for example, cost of data, software and new staff needed for mapping and spatial GIS analysis. T4 helped to express the cost in numbers and to verify whether the cost barrier is real or perceived.
In Veneto region [Italy] the T5 problem-solution tree was performed at the same workshop as the valuation of ecosystem services (T2). T5 was performed for conservation agriculture (CA) only, however it was an interesting way to combine different approaches to evaluate sustainable land management (SLM) practices that aim at mitigating SOM decline in mineral soils. Results from T2 and T5 showed they were complementary: T2 focused mainly on biophysical aspects of selected and tested measures (environmental impacts); T5 mainly handled socio-cultural and technological aspects (e.g. reasons on why measures were not adopted in the past). Combining T2 and T5 addressed methodological weaknesses relating to each single tool. In fact, different tools had assessed different dimensions and values, and therefore their implementation directed stakeholders towards different issues. Interestingly also with T2, stakeholders highlighted some technological issues, even if the tool was mainly related to biophysical aspects. In particular, stakeholders identified low expertise and lack of field training (technical aspects) as bottlenecks for the correct implementation of trialled measures and the occurrence of biophysical drawbacks (e.g. potential increase in pesticide use with conservation agriculture; worsening of water cycle management in practicing cover crops). As a result, “cause-and-effect” relationships were suggested that linked biophysical aspects to barriers hindering adoption of SLM practices. Discussions among stakeholders did not raise any historical, socio-cultural, political, administrative/bureaucratic, or individual reasons related to incorrect implementation of the measure and, consequently, to biophysical drawbacks. However, T2 did not provide evidence of being able (as a single tool) to overcome identified barriers towards possible (implementing) solutions. On the contrary, problem-solution trees in T5 highlighted institutional barriers (poor knowledge transfer to users, limited education, and bureaucratic bottlenecks) as well as solutions that could be likely connected by stakeholders to impact assessment on ecosystem services and valuation. Combining different tools was also useful to identify: 1) to what extent biophysical aspects were affected by the correct/incorrect application of selected measures (e.g. incorrect implementation of CA practice causes soil degradation through compaction); 2) which biophysical drawbacks have been likely pivotal and hindered application of specific measures (e.g. in the past, low crop productivity hindered CA application). Effectiveness of using a combination of different tools may increase whether identified benefits – and drawbacks – from impact assessment are used in the process of developing problem – and solution – trees. Therefore, data, results and concepts from T2 may be directly integrated into T5. Even in the case biophysical aspects are not identified as relevant in any problem-solution tree, this can be an way to explore alternative problems and solutions.
In Caramulo [Portugal] the combination of T2 and T5 was extremely insightful in the sense that it allowed us to understand that: (i) private land owners will not readily engage in post-fire land management practices that specifically target erosion control, unless duly compensated; and (ii) they may consider changing existing practices to minimize their impacts on soil erosion, provided possible additional efforts and costs are acceptable.

Including cost considerations in workshops would not have changed the conclusions of the private stakeholders but would have been of considerable importance for informing the organisations directly involved in operational post-fire emergency stabilisation. All the same, the main message from the cost-effectiveness assessment of post-fire mulching – i.e. timing is the key – has been conveyed at several occasions after the last workshop researchers held in the region.
In Broddbo [Sweden] researchers tested all tools T1 - T5 with varying success. There is no "tool fits all". Depending on what you want to achieve you use the tool you want. There was no obvious benefit from combining the different tools except that T1 and T2 had to be combined if you wanted to use T2. Researchers think it should be emphasised that you cannot use T2 unless you have completed T1. The stakeholder valuation of ecosystem services (T2) is not a stand-alone tool, but builds on the outcomes of T1, which is an expert assessment of the impacts of the different remediation options on ecosystem services at the study sites. In general T5 was the tool that researchers at this study site appreciated the most. The construction of problem and solution trees was quite appreciated by both researchers and stakeholders as it created interesting discussions and new insights.
In Vansjø-Hobøl Catchment [Norway] researchers had positive experiences with all the tools. The combination of tools brought the benefit of placing single measures (retention pond and vegetative buffer zones) in the wider perspective (social, economic, etc.). Moreover, it allowed for better visual presentation of the complex issues and gave room for translation from the experiments of the study sites into useful information understandable by all stakeholders.

Table S2
Reflections from those who developed each tool (i.e. tool developers)

T1: The tool generally worked well for most of the case study sites. Although methodological challenges remain, the ES assessment was shown to be a comprehensive evaluation of the impacts of the trialled measures, and also served as an input to a stakeholder valuation of ecosystem services at local and sub-national levels (T2). The ES assessment provided the opportunity to compare monitoring results across the case study sites. Through the assignment of magnitudes of change, the monitoring data became directly comparable and independent of the parameter used or the unit of measurement applied. Additionally, the request to estimate changes, even if no measured data were available, enhanced the comprehensiveness of the assessment, taking into account drawbacks relating to its accuracy and reliability. However, some researchers were more hesitant in estimating impacts than others.
T2: We noticed that many stakeholders found the concept of ES difficult to understand or work with. While the provisioning services are easy to understand due to their immediate use value or benefit to people, the regulating services are more difficult to perceive, as they frequently involve processes that show their positive or negative effects only in the long term and/or in a bigger context, meaning they are therefore often overlooked. The same holds true for the cultural services, which are less tangible and often go unnoticed. Nevertheless, in a number of case studies, the ES valuation workshops specifically uncovered some of these previously overlooked (by the researchers) cultural services. In most cases, T2 drew out differences between stakeholder categories in terms of valuation of ES. The valuation process also helped to evaluate whether the trialled measure(s) contributed to the benefits that different stakeholders desired. It was found difficult to discuss trade-offs between ecosystem services, which we presume is due to the fact that many of the trialled measures are new to the specific case study contexts, and therefore

long-term results are not available. In many cases, stakeholders found it too difficult to imagine / estimate the potential long-term effects on specific ES. The combination with T5 was demanding for the workshop organisers, but rewarding in most cases.
T3: While Bayesian Belief Networks (BBNs) have been designed to enable participatory model building with stakeholders, the reality was that to do that effectively required development of significant expertise on the part of researchers. Time demands were also substantial - on the part of researchers and stakeholders for all the steps in the model building process and to enable stakeholders to engage effectively. This is not an insignificant undertaking, particularly in combination with other tools. BBNs also require substantial data, or time to elicit stakeholder knowledge, to be able to operationalise the relationships captured in the models. Where BBNs were used they tended to be constructed using knowledge from within research teams rather than through a process with stakeholders, and fully functioning models were only constructed where data were already available. However, where the tool was used it did enable evaluation and recommendation of management strategies to reduce soil degradation (Dal Ferro *et al*., 2018).
T4: The tool (both CEA and CBA) is in principle easy to understand and apply. One of the key challenges encountered was that most soil improvement measures trialled in RECARE are new and only applied in experimental settings, so there is not yet a wider uptake of the measures. This poses two difficulties: a) a translation of costs of the measure from an experimental to real-life situation, and b) the need for a projection of effects, benefits and costs beyond the lifetime of the experiment. Costs were relatively easy to come up with, and many case studies had meaningful interactions with stakeholders to estimate these, as return on investment and cost-effectiveness are important indicators for potential adopters of the measures. The long-term benefits were however highly uncertain and their quantification was hampered by a lack of data on monetization of many benefits (cf. T1 and T2). Despite this, in several cases the tool helped to reach conclusions on the feasibility and cost-effectiveness of measures, and was considered objective; other tools produced 'softer' and more contested outcomes. An easy lesson learnt was that due to the many assumptions that need to be made, it is not necessary to wait for experimental data to start developing the CEA/CBA of measures, and earlier deployment of the tool may enable more stakeholder engagement.
T5: The tool included several components which incorporated both structured and more participatory, free-flowing interactions that enabled stakeholders to put forward their perspectives, learn from one another, while allowing researchers to get a more in-depth understanding of local perceptions and understandings of barriers and opportunities. It also provided a space for stakeholders to air wider concerns about responsibilities (e.g. who pays for soil conservation measures?) and tackle questions about scale (e.g. at what scales do we need to be working?). In RECARE, the tool was applied in the latter part of the project, by which time stakeholders had already been engaged through the use of several of the other appraisal tools. Stakeholder fatigue was therefore a challenge in some case studies. Most case study sites relied on the guidelines provided by the tool developers, adapting them to their contexts as needed. This resulted in the problem and solution trees taking quite different forms across the case studies and the tool yielded different levels of detail from different places and in relation to the different soil threats. Despite the tailoring of the approach, it was easy to compare across the different cases and draw out commonalities and differences in the kinds of barriers faced.