SNOWMAN NETWORK

Knowledge for sustainable soils

Agricultural soils : practices and transition pathways to improve ecosystem service provision

Introduction

More than 95% of our food is directly or indirectly derived from soils. What is less known is that soils also contribute to a range of key cultural, regulation and maintenance ecosystem services. Responsible for a doubling of grain production over a mere four decades, the agricultural practices inherited from the Green revolution have tremendously enhanced food production[1]. However, they have traded short-term increases in provisioning services for long-term losses in other ecosystem functions and services, possibly undermining the very capacity of ecosystems to sustain agriculture itself[2]. The challenge for agriculture is thus to match the rapidly changing demand for food, fuel and fiber from a larger and wealthier population in ways that are both environmentally and socially sustainable.

The management of agricultural soils exerts a strong influence on ecosystem services in the European Union where it affects nearly 40 percent of the land area. Hence a necessary step towards better land management is to quantify and understand how, under various environmental conditions, different agricultural practices alter bundle of ecosystem services. Ecosystem services indeed often covary in complex, non-linear ways and trade-offs are commonplace[3] (Figure 1). Synthesizing the most salient results of four research projects funded by the SNOWMAN network, this *Policy brief* assesses the consequences of several fertilization and tillage practices on multiple provisioning, regulation and maintenance ecosystem services. It further discusses possible tools and pathways likely to foster transition towards the sustainable management of agricultural soils.

Main findings

- Regular application of organic waste products improves soil biodiversity, fertility, climate change mitigation and water regulation relative to mineral fertilization while maintaining or even increasing crop yield and quality.
- Reduced tillage improves regulation and maintenance ecosystem services. Its effects on crop production are more variable, in the -10% – +7% range, strongly depending on crop and other agricultural practices. Some crops show exclusively neutral to positive effects on yield.
- Composting organic waste products drastically reduces the sanitary risks related to their application.
- Scientists, technical experts and decision-support tools are instrumental in facilitating dialogue and cooperation between stakeholders around a shared reality.
- Policies with sufficient flexibility that empower farmers and local actors may foster swifter change in soil management.
- Soil stakes still require strong awareness raising and may need to be integrated in broader environmental issues to foster stakeholder buy-in.

Key policy recommendations

- ► Encourage (partial) **substitution of mineral fertilizers by organic waste products**.
- ► Encourage **composting of** the subset of **organic waste products that causes sanitary risks of bacterial origin**.
- ► Encourage **reduction in tillage depth and frequency**.
- ► Engage in **sustained awareness raising and main-streaming of soil stakes across policies**.
- ► Reinforce **knowledge brokering and technical assistance** to catalyse transition towards sustainable soil management.

1. Quantification of ecosystem services and trade-offs

Content and methodology

Two SNOWMAN projects investigated the effects of various modalities of fertilisation and tillage intensity (Box 1) on ecosystem services. The ECOSOM project compared six organic waste products (OWP) in long-term experimental plots in France (Paris and Alsace regions). Persistent organic pollutants were also analysed in Swedish field samples. The SUSTAIN project aggregated data collected over 15 years in France (Brittany) and over 5 years in the Netherlands (Flevoland, Hoeksche Waard) to compare six tillage practices ranging from conventional ploughing to direct seeding. Thanks to an extensive network of experimental plots and farmer's parcels, the comparison was carried out under organic and conventional farming as well as under organic and mineral fertilization.

The effects on soil biodiversity and nutrient cycling, water regulation, climate regulation, soil contamination and crop production were studied both separately and in an aggregated manner to compare the quantitative impacts of farming practices on trade-offs between ecosystem services (Figure 1).

A Effects of different agricultural practices on ecosystem services

B Trade-offs between ecosystem services

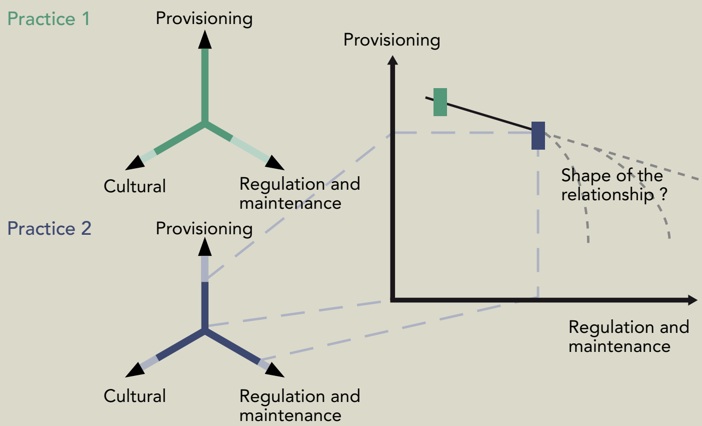

Figure 1. Ecosystem services and agricultural pratices.

The delivery of multiple ecosystem services under different practices can be represented with flower diagrams[2] (**A**). For illustration purposes, two hypothetical practices are compared and ecosystem services have been aggregated in their three main categories. Rather commonplace, trade-offs occur, as shown in **B**, when a change in agricultural practices increases one ecosystem service but entails a decrease in another one. How disproportionate the trade-offs are, that is the exact shape of the relationship between ecosystem services (**B**), remains largely unknown in practice.

Box 1: Practices studied in the ECOSOM and SUSTAIN projects

Fertilisation (ECOSOM)	Tillage treatments (SUSTAIN)
Mineral fertilisation **6 organic waste products (OWP):** **BIO :** Biowaste compost **SS :** Sewage sludge **GWS :** Sludge co-composted with green wastes **FYM :** Farmyard manure **FYMC :** Composted farmyard manure **MSW :** Municipal solid waste compost	**Conventional**, deep mouldboard **ploughing** (25 cm) **5 forms of reduced tillage:** Shallow mouldboard plough (15 cm) Non inversion tillage (deep 15-20 cm; shallow 8 cm) Minimum tillage (8 cm) Direct seeding **(No till)**

Soil biodiversity and nutrient cycling

Consistent with the scientific literature[4,5], **repeated application of OWP stimulates soil bacterial biomass** (40% increase after 7 applications of OWP). This positive effect is stronger on nitrifying bacteria, which transform organic nitrogen in nitrates usable by plants, than on denitrifying populations, which produce N_2O out of nitrates. Regular application of **OWP** thus **improves soil fertility** without increasing significantly greenhouse gas emissions (*see Climate regulation*). Compared to conventional ploughing, **reduced tillage does not alter total microbial biomass** but its distribution by concentrating micro-organisms at the soil surface (+19% in the 0-15 cm soil horizon after 10 years of minimum tillage).

OWP and reduced tillage have positive effects on earthworms communities. The density of individuals is multiplied by 3 to 6 depending on the type of OWP and, in most cases, biomass increases by +40 to +60% g/m^2 under reduced tillage. Reduced tillage increases species richness and evenness by favouring anecic and epigeic earthworms. Feeding on surface residues, these **specific types of earthworms accelerate organic matter decomposition**. Anecic species, which forms deep vertical galleries in the soil, **also improve soil water infiltration capacity**.

Water regulation

As soil organic matter is positively associated with available water capacity[6], **OWP** addition slightly **augments plant water availability** (as far as 4 mm for GWS – see Box 1 – over a total of 59 mm in one of ECOSOM's trials). By extending soil plastic limit, OWP also **reduce** the **risk of soil compaction** due to agricultural field traffic (see Box 2). SUSTAIN confirmed that **reduced tillage systems decrease** both **erosion and element transfer** (pesticides and particulate phosphorous) thanks to enhanced soil cover by vegetation and residues. Experiments showed reduction of 70-90%. **For water run-off** and thus **soluble pesticide and nutrient transfer**, they revealed a **strong variation between crops**. Run-off was strongly lower under spring crops (e.g., maize) with reduced tillage but not under winter crops (e.g., wheat), because of season-specific conditions (high soil moisture, stronger rainfall events) and also because tillage increases soil porosity.

Climate regulation

OWP addition increases soil carbon storage. Depending on the type of OWP, soil carbon stocks within the first 30 cm increased from 40 tC/ha to 50 (MSW) and 60 tC/ha (FYM, BIO & GWS) over 15 years of OWP addition. For an annual application of 1 tC/ha, this amounts to a yearly increase of 0.2 (MSW) and 0.5 (BIO & GWS) tC/ha[7]. Over 5 and 10 years depending on SUSTAIN's sites, **reduced tillage had no effect on soil carbon stocks** except for a tendency of soil organic matter to accumulate at the soil surface.

Fertilization practices have bigger impact on N_2O emissions than tillage treatments. It is indeed established that **lower N_2O emissions under reduced tillage are detected only after 10 years** of sustained soil disturbance limitation (-26%)[8]. **OWP release very little N_2O into the atmosphere** (potential Emission Factor $EF<0.3\%$ of N-input; measured in lab conditions) **compared to mineral fertiliser** ($EF=1\%$)[9], except for SS ($EF >1.5\%$).

Disservices due to OWP: soil contamination

ECOSOM detected strains of bacteria (*E. coli*) indicative of faecal contamination and antibiotic resistance genes in some OWP. **Composting OWP drastically reduces the concentration of *E. coli* and genes of resistance** (by a factor of 5 to 400). In the short-term, composting may reduce the fertilisation potential of OWP but in the long-term their positive effect on soil fertility is maintained.

The concentration of persistent organic pollutant (POP) and trace elements remains under legal thresholds in all amended soils but their potential accumulation in the long term remains to be investigated. By increasing soil pH, OWP nonetheless reduce the mobility, and thus the availability for plants, of trace elements.

Crop production

Various publications already showed that for most crops, **yields are not statistically different between organic and mineral fertilization**[10,11]. ECOSOM further demonstrated that **sufficient OWP addition produces higher yields than mineral fertilisation** (Figure 2A).

Global analyses lumping together various crops, climates, soils and practices show that the **impacts of reduced tillage systems on production are generally negative** in the order of - 5% [8,12,13]. SUSTAIN highlighted that **they are nonetheless highly variable, from negative to positive**, and that they strongly **depend on crop, year and other practices** (Figure 2B). Averaging over time, reduced tillage had no consequence on the yield of crops such as rapeseed and grass-clover, which confirms that even no-till yields match conventional tillage yields for oilseeds and legumes[14]. For wheat, yields were on average 10% lower in direct seeding but similar with minimum till compared to conventional ploughing (French experimental site, Figure 2B). Under organic farming, non inversion tillage and minimum tillage increased spring wheat yields by 7% on average (Dutch experimental site). Consistent with the scientific literature[12,15], negative effects of reduced tillage on yields were smaller and less frequent with increasing tillage depth.

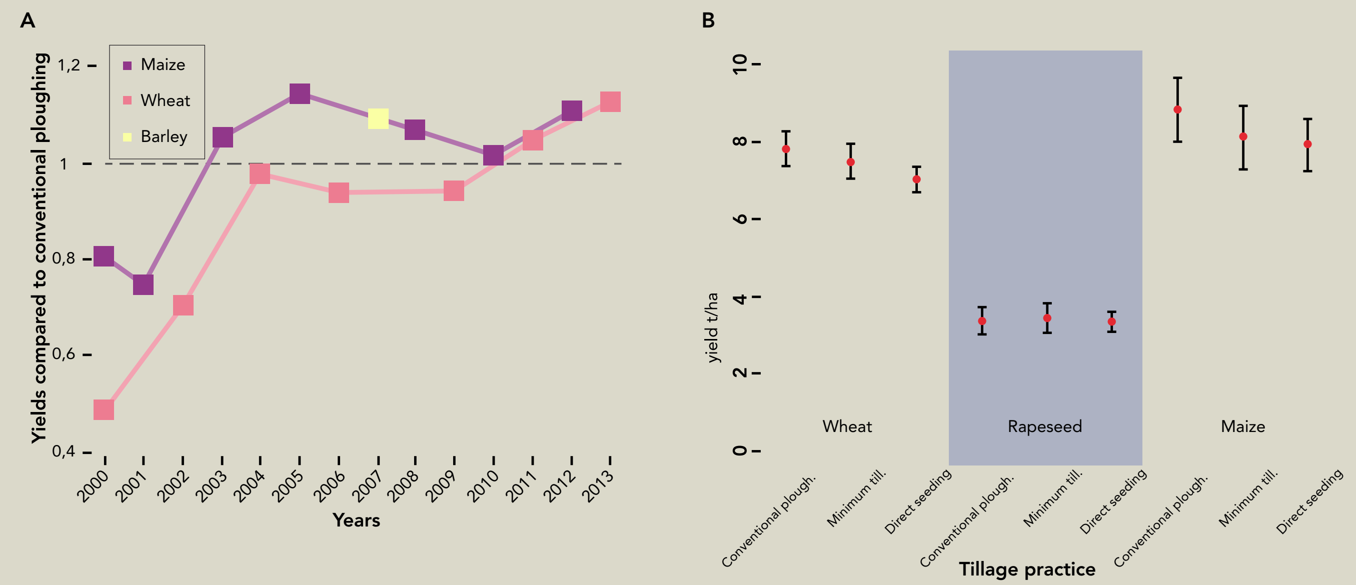

Figure 2. Effects of fertilisation and tillage practices on yields

A : Temporal evolution of the ratio of yields under exclusive organic fertilization (GWS) relative to that under mineral fertilisation (ECOSOM project). Ratios for wheat, maize and barley are shown in different colours. Values above one indicate better yields with organic fertilization.

B : Comparison of average yields measured under conventional ploughing, minimum tillage and direct seeding for wheat, rapeseed and maize (SUSTAIN project, French experimental site). Error bars show 95% confidence intervals for the estimates of the tillage practice effect. The only statistically significant difference (α=5%) is for wheat between conventional ploughing and direct seeding (p<0.01).

Synthesis

Aggregative approaches allow for the comparison of the effects of agricultural practices on multiple ecosystem services (Figure 3). Appropriate repeated organic fertilization improves nutrient cycling, climate change mitigation, water regulation and maintains crop production relative to mineral fertilization (Figure 3A). Hence, **substitution of mineral nitrogen by OWP is beneficial. The choice of a specific OWP will be the result of a trade-off within regulation and maintenance ecosystem services**. For instance, biowaste composts (BIO) are less efficient at improving soil biodiversity but they should be favoured whenever stronger importance is given to short-term soil sanitary status.

Reducing tillage enhances the regulation and maintenance services studied by SUSTAIN but has more variable results, including negative, neutral and positive effects, on crop production (Figure 3B). Such results can help to **better calibrate incentives** whenever strong positive effects on a range of ecosystem services are insufficient **to compensate for yield reductions of 5 to 10% for farmers to reduce tillage**.

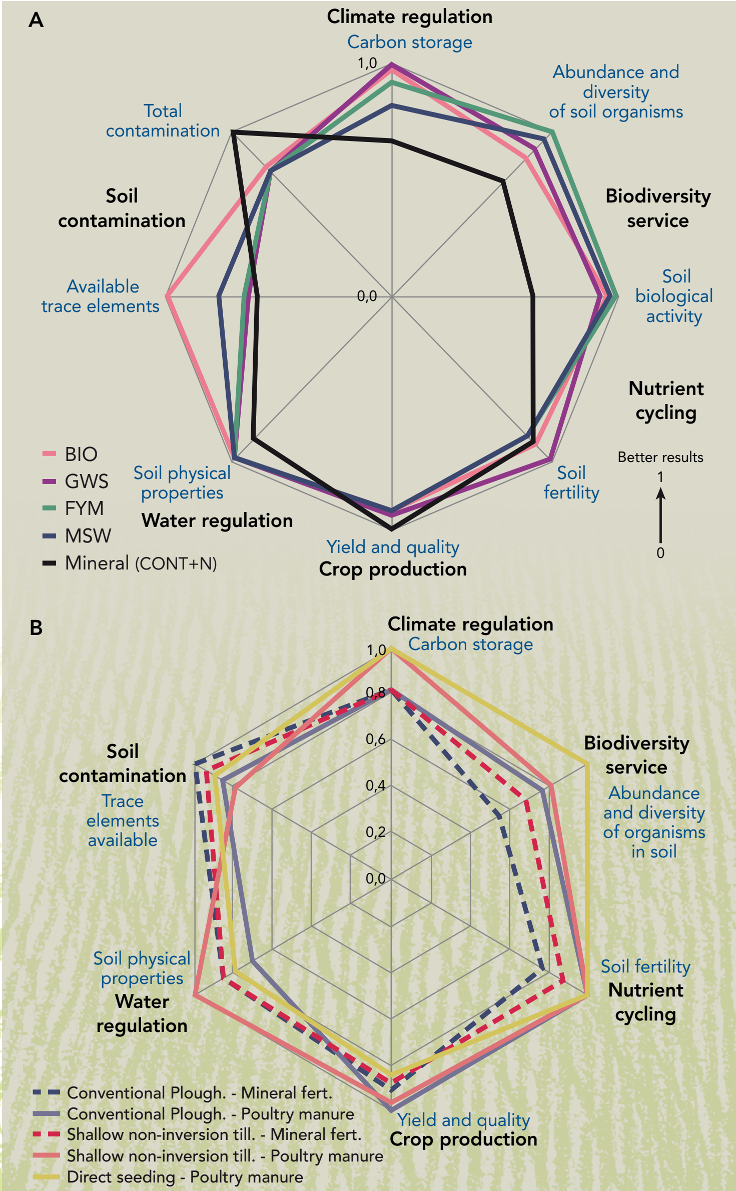

Figure 3. Multi-criteria comparison of farming practices

A : mineral vs 4 organic fertilisations (ECOSOM project);
B : Three tillage practices (SUSTAIN project). Based on experimental data, each practice is scored along six dimensions corresponding to crop production and multiple regulation and maintenance ecosystem services. Higher scores correspond to higher ecosystem service provision. Along each dimension, scores are normalized so that the best practice among the ones studied in the project receives the maximum value of 1. Note that the underlying scoring methods (**A** and **B**) are different so that the graphs cannot be directly compared. Here climate regulation only accounts for changes in soil C stocks.

2. Fostering the transition to sustainable cropland management

Content and methodology

Some SNOWMAN projects identified soil sustainable management options. But what public policies and private actions can catalyse the transition towards such practices? The RAISOILCOMP project focused on awareness raising and developed a decision-support tool to reduce sub-soil compaction (see Box 2). The SUSTAIN project carried out sociological surveys in France (Brittany) to identify farmers' motivations for and obstacles to reducing tillage. Finally, the SAS-STRAT project analysed sustainable soil quality management as an issue of transition in socio-technical systems through the comparison of three European case studies (Box 3).

Box 2: Avoiding soil compaction

Soil compaction is acknowledged by the European Commission[16] as one of the main threats to soils in the EU. As conventional ploughing techniques cannot reach the depth at which soil horizons are affected by compaction, it is almost irreversible. **Compaction reduces the quality and the quantity of crop yield** by lowering soil aeration, limiting the development of the root system and its ability to uptake nutrients. Today, about **32% of the subsoils in Europe are highly vulnerable** to subsoil compaction, mainly due to heavier machines and traffic on wet field. The RAISOILCOMP project showed that farmers in Sweden, Denmark and Belgium are aware of the issue and that some already modified their practices. However, the financial losses due to soil **compaction are under-documented and the cost of mitigation measures is important**. This could explain why most of the farmers are reluctant to take action. **Mitigation measures include reduced tillage, use of caterpillar tracks and use of organic waste products** (OWP). Indeed, even if the weight of OWP spreaders tends to compact the plough-pan, the application of organic fertilizers increases both soil aggregate stability and the porosity of the surface horizon (ECOSOM project). **To help farmers in their decision making** and to raise awareness, the project extended and disseminated a **tool** called **TERRANIMO ®**. Terranimo **models and predicts the risks of soil compaction** (Figure 4) as a function of farmers' machinery and soil parameters. It is **available in six languages**, including English, German and Dutch at www.terranimo.dk.

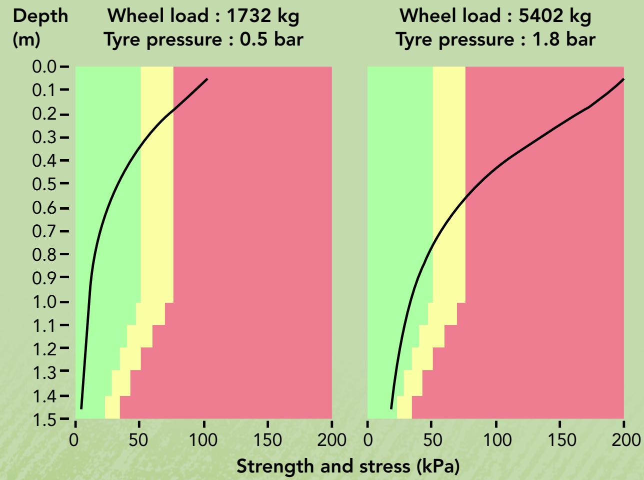

Figure 4: Outputs from Terranimo for two different machineries.

Black lines show vertical soil stress as a function of depth.
The line should be in the green area to avoid compaction, and in the yellow one to avoid serious compaction.

Box 3 : Strategies for agricultural soil quality management: case studies (SAS-STRAT project)

Country	The Netherlands	France	Belgium
Region	Northern Holland	Normandy	Wallonia
Main actors	The CONO Cheese dairy cooperative that partnered with an ice-cream company (Ben & Jerry's) and its "Caring Dairy" sustainability program	Two inter-communal watershed committees (Austreberthe and Staffimbec rivers) and a regional association for soil studies and improvement in Northern-Normandy (AREAS) concerned with flooding, erosion and run-off	A farmer association (Greenotech) promoting the transition toward conservation agriculture, which is characterized by minimum soil disturbance, permanent organic soil cover and crop rotation.
Approach	Market based	Territorial	Collective learning – farmers' network
Principle	The cooperative gives premiums to the members who adopt sustainable practices, e.g. farmers are paid an additional 0.0025€/kg of milk (~1500€/year for an average farm) to halve their use of phosphorous fertilizers.	Prospective co-diagnostic aiming to involve stakeholders in the resolution of a complex, strategic issue (patrimonial audit[17])	By sharing their practices, farmers stop considering ploughing as mandatory. Conservation agriculture is spread as a niche emerging within the frame of conventional agriculture
Transition process	*Fit and Conform*: the niche innovation develops in such a way that it fits into and conforms to a relatively unchanged selection environment (milk market)	*Stretch and Transform*: processes that re-structure mainstream selection environments in ways favourable to the niche	
		Attempted co-construction of a multi-stakeholder transition pathway toward integrated soil, flooding and erosion management	Normative and cognitive break in farmers' perceptions, from "a substrate" soil becomes considered as "a living ecosystem"
Tools	Visual Soil Assessment[18]. Easy to use in the field by farmers, it allows for a rapid and cost-effective assessment of soil quality and the farm's sustainability.	Semi-directive interviews with the main stakeholders and a feedback meeting	Network of more than 200 people: field visits, advice, research results, newsletter and personal feedback from farmers. Contracts with municipalities confronted to mudslides.
Indicators of change	Use of phosphorus fertilizers dropped from 8 kgP_2O_5/ha in 2013 to 5,3 on average in 2014 with an objective of 4 in 2015.	Establishment of a collective process, a collective language and a forum. Remained latent in the case study.	From just a handful of farmers in the 1980, conservation agriculture has been adopted by 10% of the total, and up to 20% for winter wheat producers.


Photo by Ron Nichols/USDA NRCS North Carolina/CC BY 2.0

Synthesis

Case studies (Box 3) **revealed a strong socio-technical lock in the regime of conventional agriculture** that can be overcome through adaptive (The Netherlands) or transformative (Belgium) strategies depending on the context, the model of collective action and its legitimacy. Change can indeed be facilitated by influencing the broader political, social and economic context of farming activities but also by supporting niches of innovation, such as conservation agriculture. In both cases, **public policies that empower farmers and local actors and incorporate sufficient flexibility appear more likely to catalyse change**.

In the specific **case of tillage reduction**, SUSTAIN showed that **saving labour time and fuel costs** were **the main motivations for change**. Agronomic and environmental benefits are not the trigger but are increasingly recognized and contribute to the maintenance of the practice.

Farmers also expressed a **need for stronger networking and technical advice**, which plays a crucial role. Scientists and experts raise awareness, support collective learning and provide instrumental technical tools. Beyond supporting farmers' **decisions**, **tools** such as *Terranimo* (see Box 2) or *Visual soil assessment* act as "intermediary objects"[19]. These tools **help to structure the dialogue and facilitate multi-stakeholder discussions around a shared reality**.

SAS-STRAT pointed that **soil issues may have to be integrated in the management of a broader object** to be fully taken into account by all the stakeholders that affect soil quality. Any broader object can be relevant, insofar as it can mobilize stakeholders and capture all dimensions of soil quality.

Conclusions

Adapted farming practices can enhance overall ecosystem service provision but technical advice and incentives may be required for farmers to manage trade-offs between ecosystem services. **Substitution of mineral fertilisers by organic waste products** improves or maintains all ecosystem services studied by SNOWMAN's projects except, in some cases, soil sanitary status. For sanitary risks of bacterial origin, this trade-off can be reduced through **composting**. Reducing tillage enhances regulation and maintenance ecosystem services while its effects on crop production are more variable, from negative to positive. Overall, **reduction in tillage depth and frequency is nonetheless both beneficial and realistic** if accompanied with proper organic matter management (cover crops, crop residues, crop rotation, organic waste, etc.) and contextualized according to crop, soil type and local climate.

Strong awareness raising on the extent and impact of soil degradation is still necessary, notably on soil compaction. In parallel, **main-streaming soil stakes across policies, including the Common Agricultural Policy**, is recommended. Already instrumental, **knowledge brokering and technical advice should be reinforced** to favour a swifter transition towards sustainable soil management. Solutions include adequate training of scientists and experts, facilitating the engagement of academia in knowledge exchange activities, supporting collective learning fora and integrating the mediation role of decision-support tools in their inception and development.

About the SNOWMAN network

The SNOWMAN Network is a transnational group of research funding organizations and administrations in the field of sustainable management of soil in Europe. Acting as a Science-Policy-Practice interface, it aims to bridge the gap between knowledge demand and supply.

This policy brief is part of a series presenting the main results of the 17 European research project funded from 2006 to 2015 by the network.

More information on www.snowmannetwork.com.

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SNOWMAN Projects

ECOSOM: Houot, S. et al. (2015) Soil organic matter as a key factor in the provision of soil ecosystem services.

SUSTAIN: Pérès, G., Pulleman, M. et al. (2015) Soil functional biodiversity and ecosystem Services, a transdisciplinary approach.

RAISOILCOMP: Hack-ten Broeke, M. et al. (2014) Raising awareness on the impact of subsoil compaction.

SAS-STRAT : Baudé, S. et al. (2014) Sustainable agriculture and soil: comparative study of strategies for managing the integrated quality of agricultural soils in different regions of Europe.

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