ENHANCING SOIL FERTILITY AS AN ECOSYSTEM SERVICE

Evidence for the effects of actions

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NERC Knowledge Exchange Programme on

Sustainable Food Production

NATURAL ENVIRONMENT RESEARCH COUNCIL

UNIVERSITY OF CAMBRIDGE

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About this synopsis

What are synopses of evidence?

Synopses of evidence synthesize and disseminate scientific research findings for practical use, focusing on the effectiveness of actions that practitioners may take. Synopses have been widely applied in medical disciplines and, more recently, to support biodiversity conservation through the Conservation Evidence[1] project, which has already summarized evidence for amphibian, bee, bird and northern and western European farmland conservation. In 2012-2013 the NERC Knowledge Exchange Programme on Sustainable Food Production[2] developed three synopses to assess the effectiveness of actions for: improving the sustainability of Atlantic salmon and warm water prawn aquaculture; enhancing the ecosystem service of natural pest control; and improving the condition of farmed soils (the focus of this document).

The purpose of Conservation Evidence/NERC Knowledge Exchange synopses:

Synopses of evidence do:	Synopses of evidence **do not**:
• Bring together scientific evidence captured by rigorous trawls of scientific journals and wider literature searches on the effects of actions to produce food sustainably, improve ecosystem services and conserve biodiversity	• Include evidence on the basic science (e.g. crop biology, species ecology) of food production, farmed/wild species and habitats, and associated ecosystem services, or the threats to them.
• List all realistic actions for the subject in question (ecosystem services, food production systems, habitats or species groups), regardless of how much evidence for their effects is available	• Make any attempt to weigh or prioritize actions according to their importance or the size of their effects
• Describe each piece of evidence, including methods, as clearly as possible, allowing readers to assess the quality of evidence	• Weigh or numerically evaluate the evidence according to its quality
• Work in partnership with agricultural scientists, policymakers, farm advisors and other practitioners to develop the list of actions and ensure we have covered the most important literature	• Provide recommendations for farming methods and regimes, but instead provide scientific information to help with decision-making

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[1] www.conservationevidence.com

[2] www.nercsustainablefood.com

Who is this synopsis for?

We hope you are someone who has to make decisions about how best to farm sustainably, support ecosystem services and/or conserve biodiversity. You might be a farmer, a land manager in the public or private sector, a farming advisor, a consultant, a conservationist, a policy maker, a campaigner or a researcher. The Conservation Evidence and NERC Knowledge Exchange synopses summarize scientific evidence relevant to your farming, conservation or broader land management objectives and the actions you could take to achieve them.

We do not aim to make your decisions for you, but to support your decision-making by telling you what evidence there is (or isn't) about the effects that your planned actions could have.

When decisions have to be made with particularly important consequences, we recommend carrying out a systematic review, as this is likely to be more comprehensive than the summary of evidence presented here. Guidance on how to carry out systematic reviews can be found from the Centre for Evidence-Based Conservation[3] at the University of Bangor.

The NERC Knowledge Exchange Project on Sustainable Food Production

The Programme aimed to enhance the use of science in efforts to make UK food production systems more environmentally sustainable. It ran from June 2012 to September 2013, and its main outputs are openly accessible.

The outputs from the Programme include:

- Synopses of evidence on aquaculture, maintaining soil, enhancing natural pest control and farming for wildlife, freely available and searchable on a web-based information hub[4] and in downloadable documents
- Papers presenting priority knowledge needs for sustainable agriculture[5] and aquaculture in the UK, as well as priority research questions for the UK food system[6] as a whole[7]
- Working partnerships built between research scientists and food businesses to address issues of sustainable production
- A published meta-analysis of trade-offs and synergies between different aspects of agricultural sustainability across land-management practices and environmental contexts (for further details contact Richard German[8])
- An online catalogue[9] of NERC research related to the UK food system

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[3] www.cebc.bangor.ac.uk

[4] www.nercsustainablefood.com

[5] Dicks L., Bardgett R., Bell J., Benton T., Booth A., Bouwman J., *et al.* (2013) What do we need to know to enhance the environmental sustainability of agricultural production? A prioritisation of knowledge needs for the UK food system. *Sustainability*, 5, 3095-3115.

[6] www.foodsecurity.ac.uk/assets/pdfs/priority-research-questions-uk-food-system.pdf

[7] Ingram J.S.I., Wright H.L., Foster L., Aldred T., Barling D., Benton T.G., *et al.* (in press) Priority research questions for the UK food system. *Food Security*, 5, 617-636.

[8] richard_german11@hotmail.com

[9] http://nercsustainablefood.com/site/page?view=contribution

The programme adopted the Conservation Evidence methods of summarizing and disseminating evidence and the natural pest control synopsis was developed at the Conservation Evidence project's home in the Department of Zoology, University of Cambridge. The programme worked with Lancaster University, Plymouth Marine Laboratory, University of Bangor, University of Leeds, University of Manchester and the Global Food Security programme[10] to deliver the soils and aquaculture synopses and other outputs.

Scope of the soil fertility synopsis

The synopsis considers scientific evidence from across the world and for all conventional forms of terrestrial farming: arable, perennial and livestock or pasture systems. We defined our range of crop types and livestock animals using the Food and Agricultural Organisation's (FAO) list of production commodities[11], supplemented by forage crops and pastures included in the United States Department of Agriculture (USDA) crop nutrient tool[12]. For the purpose of this synopsis, 'farming' includes horticultural production of fruit and vegetables but flower, timber and garden plant cultivation are excluded.

Evidence is included irrespective of the date of study but, given the relatively contemporary subject area and our reliance on electronic library sources, the overwhelming majority of our evidence (99%) originates from after 1975.

Identifying actions for enhancing soil fertility

The list of 27 actions to enhance soil fertility was developed from a list suggested by academics. These actions were refined and added to as we reviewed the literature on enhancing soil fertility. An international advisory board of six experts (from academia, private-sector research and agri-business) also commented on and added to the list.

Actions were included if they were interventions that farmers or land-managers would realistically be prepared to or could do. We included actions regardless of whether they had already been adopted or whether or not evidence for their effectiveness already existed.

Nearly 40% of the actions we have identified relate to tillage practices. In some cases, and particularly for actions affecting soil microorganisms, the mechanisms of increasing soil resilience may still be poorly known.

Where several actions are frequently combined together in practice (making it difficult to determine their separate effects) we have created broad actions such as 'convert to organic farming' and 'reduce pesticide, herbicide or fertilizer use generally (including integrated management methods)', in addition to the more specific actions that comprise them. However, where evidence is provided for individual actions we present this under the most specific action tested. Therefore a study on the effect of reducing herbicide use (as opposed to chemical use in general) would be included

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[10] www.foodsecurity.ac.uk

[11] FAO. *FAOSTAT production domain commodities*. 2012 [cited 18/10/2012]; Available from: http://faostat.fao.org/site/384/default.aspx

[12] USDA. *Crop nutrient tool*. 2012 [cited 18/10/2012]; Available from: http://plants.usda.gov/npk/main

under ‘reduce herbicide use’, but would not appear under ‘reduce pesticide, herbicide or fertilizer use generally (including integrated management methods)’.

How we reviewed the literature

We identified the major threats to soil fertility, such as erosion, nutrient loss, and biodiversity loss, using lists compiled by the Soil Association[13] and Scottish Environment Protection Agency[14]. Then, to identify the scientific literature relevant to enhancing or maintaining soil fertility, we used two approaches: a literature search (querying databases with search terms) and a journal trawl (looking at every published article and manually selecting relevant papers, based on title or abstract). The literature search was undertaken by research associates at Lancaster University, using the database Web of Science[15]. The search terms were chosen by an iterative process of searching and refining; see Annex 1 for the complete list of terms. The action terms used in this search focused on actions to maintain or restore natural (or semi-natural) habitat. These searches returned 37,748 studies once duplicates were removed.

All study titles were examined (by Lancaster University and University of Manchester) and irrelevant references were excluded. Study abstracts for the remaining 543 references were then scanned to identify studies meeting two major criteria:

- there was an action that farmers or land-managers could do to enhance soil fertility on their land
- the effects of the action were monitored quantitatively.

These criteria excluded studies examining the effects of specific actions without actually doing them. For example, predictive modelling studies and those looking at species distributions in areas with supposed (but not precisely documented) longstanding management histories (correlative studies) were excluded. Such studies can suggest that an action is effective, but do not provide direct evidence of a causal relationship between the action and the observed biodiversity pattern.

For the journal trawl, seven journals were selected based on the wide scope of their research and on the recommendation of experts in the field of soil science. They were trawled for studies testing relevant actions: *European Journal of Soil Science, Geoderma, Global Change Biology, Land Use Policy, Soil Biology Biochemistry, Soil Use Management, Journal of Applied Ecology*. Study titles and abstracts were scanned from volume one of each journal to mid-2012 volumes. The trawl identified 175 studies relevant to all soil fertility actions.

These literature review methods taken together returned a total of 718 studies monitoring the effects of interventions in the list. Our search methods mostly picked out English language papers or studies with abstracts written in English. Our database of references is therefore only a sample of the global literature, but is nonetheless a significant body of evidence.

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[13] http://www.soilassociation.org/
[14] http://www.sepa.org.uk/land/soil/threats_to_soil_quality.aspx
[15] http://apps.webofknowledge.com/

How the evidence is summarized

Actions to enhance soil fertility are primarily presented by farming system. 'All farming' includes actions relevant to a range of land-based farming systems. Actions in more specific farming systems, such as arable, perennial and livestock/pasture farming, may have relevance to other farming systems, but have not been tested in those other systems to date. We also include a section on the theme 'reducing agricultural pollution' which applies to all farming systems.

Each action section begins with a series of key messages and these group studies according to their results to provide a succinct summary of the overall evidence. Key messages compile the results in the following consistent order: biodiversity loss, compaction, drought, erosion, nutrient loss, soil organic carbon, soil organic matter and soil types covered.

Studies are then individually summarized in alphabetical order. The key results from each study are included with a brief explanation of methods (where space permits). For detailed information on methods we encourage you to access the original paper. Background paragraphs provide further information on the aims of the action, the likely mechanisms that deliver enhanced natural pest control or the methods used in the studies.

Studies that were published in more than one place are summarized only once, choosing the publication with the most stringent peer-review process (e.g. choosing academic journals over bulletins) or the most recent publication date. Studies using the same experimental set-up to test the same action are all summarized individually if there are (at least partially) different results elements presented. We indicate where studies overlap in the summary paragraphs.

Many studies investigated several actions at once. When the effects of different interventions can be separated the results are summarized separately under the relevant actions. However, often the effects of multiple actions cannot be separated and, when this is the case, the study is included for each relevant action and we highlight in the text that several actions were used.

Some of the literature was inaccessible to us, either because a full text version of the paper could not be obtained, or because we lacked the translation services to handle papers other than those in English. For actions that do not contain all of the identified literature we include a statement in the background section (e.g. 'Here we present five of eight studies…') to inform you of how many papers we summarized versus how many were identified as relevant.

All the evidence in this synopsis can be searched and accessed freely at www.nercsustainablefood.com and www.conservationevidence.com, where links to related conservation actions and hyperlinks to full-text sources are provided.

Terminology used to describe evidence

Unlike systematic reviews of particular questions or actions, we do not quantitatively assess the evidence, or weight it according to quality. However, to allow you to interpret evidence, we clearly report the size and design of each trial. The table below defines the terms that we use.

The strongest evidence comes from randomized, replicated, controlled trials with paired-sites and before and after monitoring.

Terms for describing types of trial

Term	Meaning
Site comparison	A study that considers the effects of actions by comparing sites that have historically had different actions or levels of intervention.
Replicated	The action was repeated on more than one individual or site. In conservation and ecology, the number of replicates is much smaller than it would be for medical trials (where thousands of individuals are often tested). Ideally, for studies on soil fertility, sites should be replicated four or more times to see how variable effects of an intervention are across sites. We provide the number of replicates wherever possible.
Controlled	Individuals or sites treated with the action are compared with control individuals or sites not treated with the action.
Paired sites	Sites are considered in pairs, within which one was treated with the action and the other was not. Pairs of sites are selected with similar environmental conditions, such as soil type, aspect or topography. This approach aims to reduce variation in soil conditions that are due to the environment and make it easier to detect a true effect of the action on soil fertility.
Randomized	The action was allocated randomly to individuals or sites. This means that the initial condition of those given the action is less likely to bias the outcome.
Before-and-after trial	Monitoring of effects was carried out before and after the action was imposed.
Review	A conventional review of literature. Generally, these have not used an agreed search protocol or quantitative assessments of the evidence.
Systematic review	A systematic review follows an agreed set of methods for identifying studies and usually for carrying out formal 'meta-analysis'. It will weight or evaluate studies according to the strength of evidence they offer, based on the size of each study and the rigour of its design. All environmental systematic reviews are available at: www.environmentalevidence.org/index.htm

Pesticides and herbicides

We use ‘pesticides’ to refer to insecticides, fungicides, molluscicides, rodenticides and nematicides but not herbicides, which are treated separately. The majority of pesticide-related studies focus on insecticides. This synopsis contains literature on all pesticides (including old studies on chemicals now banned in some countries) so we strongly recommend that you refer to the latest health and environmental requirements applicable to your area before undertaking the actions described. Readers should also be aware that chemicals may have beneficial or detrimental effects to crops and other organisms and we do not attempt to assess all of these impacts here.

Taxonomy

In general we employ the species names (common or binomial) used in the original paper and do not update taxonomy (or attempt to employ a universal common name). In a few cases we have updated taxonomy where the older binomial latin name is now clearly obsolete (e.g. corn earworm as *Helicoverpa zea* not *Heliothis zea*). Common and binomial names are both given the first time a species is mentioned in each summary paragraph.

Significant results

Throughout the synopsis we have quoted results from studies. These results reflect statistical tests presented in the paper, unless we state that studies ‘report’ a finding or that the effect was only slight. If statistical tests were not performed we typically report the results (e.g. ‘There were 10 earthworms in treatment A compared to 6 earthworms in treatment B”) without describing the difference between treatments (i.e. avoiding the terms ‘higher’, ‘lower’, ‘greater’, ‘smaller’ etc.).

2. Reducing agricultural pollution

2.1. Reduce fertilizer, pesticide or herbicide use generally

- **Biodiversity:** Two site comparison studies from Italy[1] and Pakistan[3] (one also replicated[1]) found a higher diversity of soil invertebrates and microorganisms in low chemical-input systems.
- **Nutrient loss:** One study from Canada[2] found lower nutrient levels and yields in low-input systems.
- **Soil types covered:** course sandy[1], loam[1, 2], sandy-loam [1], and silt[3].

Background

Soil microbial biomass is the amount of tiny living microorganisms within a given area or amount of soil. Functional diversity is the value and range of functional roles (or 'traits') that organisms play in a given ecosystem (Tilman 2001), in this case the agro-ecosystem. An abundant, diverse, and active soil microbial and animal community is generally indicative of good soil fertility (Bardgett 2005)

Tilman D. 2001. Functional diversity. Pages 109-120 in: S.A. Levin (ed.) Encyclopedia of Biodiversity. Academic Press, Waltham, USA.
Bardgett. R.D. 2005. The Biology of Soil. Oxford University Press.

A replicated, site comparison study, in spring 2008 across loam, sandy-loam and coarse sandy soils in Salerno district, Italy (1) found that the functional diversity of soil microorganisms was 18% and bacterial species richness 14% lower under high chemical-input systems, as well as 24% lower organic carbon, compared to the low-input systems. Broad differences in soil microbial community properties were found between farms classified as high-input, intensive, and low-input systems. The high-input systems were described as intensive farming systems under plastic cover, while low-input systems were orchards. Soil samples were taken from three plastic tunnels in each high-input system and from one area of orchard in each low-input system, then analysed for biochemical and biological properties in the laboratory.

A replicated experiment in 2001-2006 on loamy soil in Saskatchewan, Canada (2) found less nitrate (74 kg N/ha) and phosphorus (19 kg P/ha) in soil under organic inputs than under high or reduced inputs (85 kg N/ha, 24 kg P/ha respectively). Nitrate was usually higher in treatments with fewer crop types. Lower yields were recorded in organic compared to high or reduced input treatments (amounts not specified). Three input (tillage/management) levels (organic, reduced, high) were replicated four times. Within these input levels were three crop diversities: low (fallow/wheat *Triticum aestivum*/oilseed *Brassica juncea*); cereal (wheat / mustard *Brassica juncea* or canola *Brassica napus*/ lentil *Len culinaris*) rotations; or grain (perennial forage crop (sweet clover *Melilotus officinalis*, pea *Pisum sativum*, flax *Linum usitatissimum* or alfalfa *Medicago sativa*/ barley *Hordeum vulgare*) rotations. Within these were six crop phases, rotating the above species with green manure and fallow phases, which were tested in 40 x 12.8 m plots. Fertilizers and pesticides were not applied to the organic treatment. Crop rotations were six years long. Each year, two soil samples were taken from each crop phase (with a third also taken in 2006) to measure nitrate-N, carbon, nitrogen, and phosphorus.

A site comparison study in 2007-2009 on silt soils in Faisalabad, Pakistan (3) found a higher number of species of large soil invertebrates in low input fields (79 species) compared to high input fields (61 species). Ten acres of sugarcane *Saccharum* sp. crop were selected in areas using either high chemical input cultivation (nitrogen (70 kg/acre), phosphorus (50 kg/acre), potassium (70-80 kg/acre), calcium (7 kg/acre), sulphur (12 kg/acre), magnesium (12 kg/acre) and organic fertilizers (2400-3200 kg/acre)), or low chemical input cultivation (using anything less than the high chemical input treatment). Soil samples were taken from three randomly selected areas within 1 acre fields in each system: one on the edge of the field, one under the shade of scrub or trees and one within the field. Soil invertebrates were identified to species.

(1) Bonanomi, G., D'Ascoli, R., Antignani, V., Capodilupo, M., Cozzolino, L., Marzaioli, R., Puopolo, G., Rutigliano, F. a., Scelza, R., Scotti, R., Rao, M. a. & Zoina, A. (2011) Assessing soil quality under intensive cultivation and tree orchards in Southern Italy. *Applied Soil Ecology*, 47, 184–194.

(2) Malhi, S. S., Brandt, S. A., Lemke, R., Moulin, A. P. & Zentner, R. P. (2009) Effects of input level and crop diversity on soil nitrate-N, extractable P, aggregation, organic C and N, and nutrient balance in the Canadian Prairie. *Nutrient Cycling in Agroecosystems,* 84, 1-22.

(3) Rana, N., Rana, S. A., Khan, H. A. & Sohail, A. 2010. Assessment of handicaps owing to high input (HIP) farming on the soil macro-invertebrates diversity in sugarcane field. *Pakistan Journal of Agricultural Sciences,* 47, 271-278.

2.2. Change the timing of manure application

- One controlled, randomized, replicated, site comparison study from the UK[1] found less nitrate was lost from the soil when manure application was delayed from autumn until December or January.
- **Soil types covered:** sandy-loam[1].

A controlled, randomized, replicated, site comparison study in 1990-1994 on sandy-loam in the UK (1) found greater nitrate losses following manure application in September-November (23.3 and 12.4 mg N/l lost at the two study sites, respectively), but applications in December or January were no different to the untreated control (< 0.5 mg N/l lost). Two manure treatments were tested at each site. Pig/cattle slurry and farmyard cattle manure were tested at a Shropshire site and poultry litter and farmyard manure were tested at a Nottinghamshire site. Manures were applied at 200 kg N/ha monthly between September and January to overwinter fallow or onto winter rye *Secale cereale*. Both sites also had an untreated control. An extra treatment was included to test the nitrification inhibitor dicyandiamide, which was applied at 20 l/ha. All treatments were replicated three times at both sites. Plots were 12 x 4 m and 15 x 4 m at the Shropshire and Nottinghamshire sites respectively.

(1) Beckwith C.P., Cooper J., Smith K.A. & Shepherd M.A. (1998) Nitrate leaching loss following application of organic manures to sandy soils in arable cropping. I. Effects of application time, manure type, overwinter crop cover and nitrification inhibition. Soil Use and Management, 14, 123-130

3. All farming systems

3.1. Change the timing of ploughing

- **Nutrient loss:** Two replicated site comparison studies from Denmark[1] and Norway[2] (one also randomised[1]) found reduced erosion soil loss and nitrate leaching when ploughing was delayed until spring.
- **Soil types covered:** sandy[1], sandy-loam [1], silty-clay loam[2].

Background

Nitrate leaching is when nitrate, a highly mobile chemical form of nitrogen that is readily taken up by plants, is lost from the soil.

A randomised, replicated site comparison study in 1989-1995 on coarse sand and sandy-loam soils in Denmark (1) found that nitrate loss from soil (leaching) was lower when ploughed in spring (81.5 kg N/ha) compared to winter (106.4 kg N/ha). Nitrate leaching was higher on coarse sand (160-254 kg N/ha) compared to sandy loam (129-233 kg N/ha) soils. Wheat *Triticum aestivum*, barley *Hordeum vulgare* and rye *Secale cereal* were grown at two locations. A ryegrass *Lolium perenne*/clover *Trifolium repens* ley mix was used, undersown with spring barley on areas 126 m^2. Within these were two sampling plots 11 m^2 (at Jyndevad) and 15 m^2 (Foulum). There were five treatments: autumn ploughing with wheat followed by rye; autumn ploughing – wheat/barley; autumn ploughing – barley/rye; autumn ploughing – barley both years, spring ploughing – barley/rye. Soil samples were taken at the start and end of each treatment. Soil water, organic carbon and total nitrogen were measured.

A replicated, site comparison study, from 1984 to 1996 on silty clay loam soils in southern Norway (2) found that spring tillage reduced annual soil loss by 90% compared with autumn tillage. Variations in winter climate (e.g. rainfall) also influenced soil loss. There were six sites, with varying plot size: Bjørnebekk (144m^2, 11 replicates), Syverud (210m^2, 12), Askim (147 and 267 m^2, 6), Øsaker (176 m^2, 8), Hellerud (180, 720, 816 m^2, 8), Holt (2.7 ha catchment, not replicated). The tillage treatments were autumn ploughing, spring ploughing, autumn harrowing, spring harrowing, and direct drilling. Runoff and amount of eroded soil was measured.

(1) Djurhuus, J. & Olsen, P. (1997). Nitrate leaching after cut grass/clover leys as affected by time of ploughing. *Soil Use and Management,* 13, 61-67.

(2) Lundekvam H. & Skøien S. (1998) Soil erosion in Norway: An overview of measurements from soil loss plots. *Soil Use and Management,* 14, 84-89.

3.2. Change tillage practices

- **Biodiversity loss:** Nine studies from Canada[7], Europe[1, 2, 4, 5, 6, 8], Mexico[3], or the USA[9] measured effects of reduced tillage on soil animals or microbes. Of these, six (including three replicated trials[3, 7, 8] (two also randomized[7, 8] and one also controlled[3])) found more microbes[1, 7, 8], more species of earthworm[5], or higher microbe activity[2, 3] under reduced tillage. One replicated trial[9] found increased numbers of soil animals and earthworms under reduced tillage. Two, (including one controlled, replicated trial[4]) found no effect of reduced tillage on earthworm activity[6] or microbe activity[4].
- **Compaction:** Five studies from Australia[12], Canada[13], and Europe[10, 11, 14] measured the effect of controlled traffic and reduced tillage on compacted soils. Of these, two (including one before-and-after trial[10] and one replicated trial[12]) found reduced compaction and subsequent effects (reduced water runoff, for example) under controlled traffic, and one[12] also found that crop yields increased under no-tillage. Three replicated trials[11, 14], including one site comparison study[13], found higher compaction under reduced tillage.

- **Drought:** Three replicated trials from Europe[15, 16] and India[17] (one also randomized[17]) found the size of soil cracks decreased, and ability of soil to absorb water and soil water content increased with conventional tillage and sub-soiling.
- **Erosion:** Ten replicated trials from Brazil[19], Europe[22, 25, 27, 28], India[21], Nigeria[23, 24] and the USA[18], and one review[29] showed mixed results of tillage on soil erosion. Seven trials[19, 23, 24, 25, 28, 29] (one also controlled and randomized[21]) showed reduced soil loss and runoff under reduced tillage compared to conventional ploughing. One trial[27] showed no differences between tillage systems, but demonstrated that across-slope cultivation reduced soil loss compared to up-and-downslope cultivation. Two trials[18, 22], showed that no-tillage increased soil loss in the absence of crop cover.
- **Soil organic carbon:** Twelve studies from Australia[38], Canada[44], China[12], Europe[35, 36, 37, 42, 43, 45, 47], Japan[40] and the USA[39] compared the effect of no-tillage and conventionally tilled systems on soil organic carbon. All (including two randomized[42, 43], five replicated[36, 37, 39, 45, 47], two randomized, replicated[38, 44], and one controlled, randomized, replicated[12]) found higher soil organic carbon in soils under a no-tillage or reduced tillage system compared to conventionally tilled soil. One review[40] showed that no-tillage with cover cropping plus manure application increased soil organic carbon. One randomized, replicated trial from Spain[8] found greater soil organic carbon in conventionally tilled soil.
- **Soil organic matter:** Twelve studies from Canada[33, 49], China[48], Europe[20, 26, 30, 34, 50], Morocco[46], and the USA[31, 32, 39] measured effects of reduced tillage on soil organic matter content and nutrient retention. Of these, six studies (including three replicated[46, 48, 49], two site comparisons[26] (one also replicated[50]) and one controlled[20]) found maintained or increased soil organic matter and improved soil structure under reduced tillage. Four trials (including two replicated[30, 33] and two site comparison studies[31, 34]) found higher nutrient retention under reduced tillage. One controlled, replicated trial from the USA[32] found less carbon and nitrate in no-till compared to conventionally tilled soil, but conventionally tilled soil lost more carbon and nitrate.
- **Soil types covered**: anthrosol[48], calcareous silt loam[28], chalky[16], clay[12, 17, 19, 30, 34, 38, 46], clay loam[12, 26, 31, 44], fine sandy loam[8, 9], loam[5, 13, 37, 42, 49], loamy-clay[45], loam - sandy loam[10, 27], loam – silt-loam[7], loamy silt[6], non-chalky clay[15], sandy[17], sandy clay loam[39], sandy loam[3, 14, 20, 31, 33, 43], sandy silt-loam[21], silt loam[18, 31, 32], silty[17, 36, 50], silty-clay[2, 4, 11, 22], silty clay loam[25, 35], silty loam[47].

Background

There are several ways of tilling the soil in preparation for crop planting. Harrowing and ploughing are also known as conventional tillage. Harrowing is the disturbing or breaking up of soil using an agricultural implement with spike-like teeth (tines) or upright discs. Mouldboard ploughing involves using a plough that turns the soil. Both methods plough to 20 cm depth or more. Shallow tillage uses the same techniques as conventional tillage, but involves only tilling to 15 cm or less in depth. Conservation tillage comprises several methods of soil tillage which leave a minimum of 30% of crop residue on the soil surface. No-tillage involves direct drilling of crops straight into the soil, or leaving fields fallow without disturbing the soil.

Many different measures can be used to determine the fertility of the soil. Soil porosity is a measure of the volume of air in soil and is an indicator of good soil structure, which is a hallmark of a fertile soil. Bulk density is a measure of the density of the soil, and fertile soils tend to be less compacted, and hence of lower density than infertile soils. Unsaturated hydraulic conductivity is the ability of the soil to transmit water when a hydraulic (water) gradient is applied. The soil microbial biomass is the amount of tiny living microorganisms in a given amount of soil, whereas along side microves live many microscopic animals, such as nematodes. Having high numbers of microbes or nematodes in the soil is generally an indicator of good soil fertility. Arbuscular mycorrhizal fungi are a group of fungi that live around the roots of plants. By living together, the fungi and host plant benefit each other: the fungi can live in a habitat without having to compete for resources and have a supply of carbon from the plant, while they provide an enhanced supply of nutrients to the plant, improving plant growth, the ability to reproduce and tolerance to drought. Arbuscular mycorrhizal fungi colonise a wide variety of host plants, including grasses, herbs, agricultural crops and legumes, and are known to reap benefits for soil fertility (Bardgett 2005).

Bardgett (2005) *The Biology of Soil: A community and ecosystem approach*. Oxford University Press, Oxford.

A replicated study in 2005, carried out in greenhouses and field conditions (soil type not specified) at the University of Évora, Portugal (1) found that no-till cultivation techniques were effective in maintaining the abundance (proportion of colonization: 0.14 and 0.03 for no-till and conventional tillage respectively) and diversity of arbuscular mycorrhizal fungi in the soil of a wheat crop *Triticum aestivum* during Mediterranean summer conditions. Experimental treatments were established in 42 pots, corresponding to seven replicates of two treatments, under greenhouse conditions. Pots were then buried in the field and subjected to typical Mediterranean temperature and rainfall regimes.

A replicated study in 1990 on silty-clay soil near Stuttgart, Germany (2) found that organic carbon, nitrogen and soil microbial activities in the topsoil were higher in rotary cultivated plots (1.6% C, 1.7 mg N/g, 6.8 µmol ATP/kg respectively) than under ploughing (1.3% C, 1.45 mg N/g, 4.5 µmol ATP/kg respectively). Below the topsoil, there was either no difference between tillage systems, or there was a marginal increase in the ploughed plots. There was an overlapping effect of cultivation and crop rotation on soil organic matter and microbial biomass. There were four replicates of two tillage treatments (ploughing to 25 cm; rotary cultivation 10-12 cm depth), and two crop rotations: legume/cereals (alfalfa *Medicago sativa*/wheat *Triticum aestivum*/oats *Avena sativa*/clover grass *Trifolium spp.*); rape *Brassica napus*/cereals (rape/wheat/oats/barley *Hordeum vulgare*). Plots were 15 x 6 m. Soil organic matter was added to the plots. Soil samples were collected to 25 cm depth. Enzyme activities, organic carbon, the potential for carbon and nitrogen mineralization and water-soluble carbon were measured.

A replicated experiment in 2005 on sandy loam in El Batán, Mexico (3) found that the rate at which microbes used carbon (metabolic activity) was higher when under conventional tillage with residue retention compared to zero tillage with residue removal, in maize. Soil microbial biomass was higher in wheat *Triticum aestivum* (369 mg C/kg) compared to maize *Zea mays* (319 mg C/kg). There were two tillage treatments: zero and conventional tillage. Within these were two residue treatments; removed or retained. Within these were maize and wheat crops, which were fertilized at 120 kgN/ha. Crop rotation plots (continuous wheat/maize, wheat and maize) were

7.5 x 22 m. There were two replications. Soil samples were collected to 15 cm depth from all plots. Total nitrogen and organic carbon were measured.

A controlled, replicated experiment in 2007-2008 on silty-clay soil in Saxony, Germany (4) found that reducing tillage intensity reduced the amount of carbon broken down in the soil by microbes (1.6 and 0.95 mg muramic acid/g total C for maize *Zea mays* and wheat *Triticum aestivum* straw respectively) and breakdown activity, compared to ploughing (1.9. and 1.5 mg muramic acid/g total C for maize and wheat straw respectively). The tillage treatments were ploughing (mouldboard plough to 30 cm depth) and reduced tillage (harrowing to 8cm depth). There were three replicate plots (12.8 x 36 m). The cereal-crop rotation included: wheat, barley *Hordeum vulgare*, oats *Avena sativa*, maize, peas *Pisum sativum*, and broad beans *Vicia faba*. Six 5 x 20 cm bags of wheat straw and maize leaves were buried to 20 cm depth for 6 or 12 months in the soil in each tillage treatment. Biochemical and microbial breakdown indicators (muramic acid, for example) were measured.

A replicated study over a 22 year period on loamy soil in western France (5) showed that conventional tillage reduces both earthworm abundance (22 individuals/m^2) and functional diversity (four species), whereas occasional tillage (4-yr rotation) only reduces earthworm abundance (60 individuals/m^2, six species). The study comprised 3 treatments, established in plots 9 × 16 m in size: continuous maize treated with pig slurry for 22 years; the pasture phase of a rye-grass / maize rotation, also treated with pig slurry for 22 years; pasture sown with white clover and rye-grass, maintained for 9 years. Three replicate samples of the earthworm community were sampled from each treatment.

A site comparison study in 1995-1997 of compaction on a loamy silt soil in Lower Saxony, Germany (6), found that neither of the two earthworm species studied were affected by changes in tillage. *Lumbricus terrestris* was not affected by compaction. Compared to uncompacted soil, burrows made by earthworm species *Aporrectodea caliginosa* were still lower in length (9 mm/g/day), volume (68 mm^3/g/day), and windiness (17%) two years later due to the compaction event. One part of the field was compacted six times in spring 1995 by repeated wheeling by heavy four-wheel-drive machinery with a 5 Mg wheel load, the other part was uncompacted. Undisturbed soil monoliths were taken from fields in 1997 under conventional tillage or conservation tillage. X-ray computed 2D images were used to analyse soil structure.

This replicated, randomized field trial, established in 1992 on loam – silt-loam soil in Alberta, Canada (7) found that management with zero tillage encouraged greater soil microbial biomass (516.36 mg/kg soil), compared with conventional tillage (382.30 mg/kg soil). Rotation with legume crops also enhanced soil microbial biomass (593.99 mg/kg soil (red clover *Trifolium pratense*), 448.40 mg/kg soil (field pea *Pisum sativum*)), relative to those left to fallow (322.68 mg/kg soil) or cropped continuously (432.25 mg/kg soil). The trial treatments were zero tillage and conventional tillage (3-4 mechanical cultivations per year), combined with four different crop rotations preceding the wheat *Triticum aestivum* crop planted prior to sampling between 1995 and 1997: field peas, red clover, summer fallow, or continuous wheat. The trial included three replicate plots of each treatment combination, and 10 soil samples were taken from each plot and mixed before analysis.

A randomized, replicated experiment in 2008 on fine sandy loam soil in Spain (8) found greater soil organic carbon levels in tilled soil (9.94 g C/kg) and soil with a mown cover crop (9.91 g C/kg) than soil with no cover crop (5.36 g C/kg). Bacteria counts under tillage were lower (233 million/g soil) than under mown cover crops (952 million/g soil) or cover crops plus herbicide (1.4 billion/g soil), but were higher than in the no cover crop (32 million/g soil). There were four long-term treatments in an olive *Olea europaea* orchard: tillage (3-4 passes with disk harrow to 30 cm depth, tine harrow in summer); no-till and no cover (treated with glyphosate herbicide); cover crop plus herbicide (treated in March); cover crops plus mower (herbicide-free). Each plot was 11 x 11 m and consisted of 16 trees. Each treatment was replicated four times. Two soil samples were taken from the centre of each plot. Soil bacterial numbers and community structure were measured.

A randomized, replicated experiment in 2004 on a fine sandy-loam soil in North Carolina, USA (9) found nematode numbers were 48% higher and earthworm numbers were 31 times higher under strip tillage compared to conventional tillage. Nematode numbers were more than four times higher in organic strip tillage plots compared to conventional tillage plots receiving synthetic chemicals. Nematode and earthworm numbers were up to four times and 30 times higher respectively in plots where strip tillage and organic inputs were combined. There were four treatments: strip tillage with organic inputs (soybean *Glycine max* meal fertilizer and pesticide), strip tillage with synthetic inputs (ammonium nitrate at 200 kg/ha), conventional tillage with organic inputs and conventional tillage with synthetic inputs. There were four replications. The study took nematode samples and earthworm extractions (species not specified for either group).

A before-and-after trial in 2003-2005 on a loam - sandy loam soil in Scotland, UK (10) found that mechanical weeding caused structural deterioration and subsoil compaction under broad bean *Vicia faba* crops (17.5 kPa – 39 kPa with increasing depth) due to tractor wheeling. In the carrot *Daucus carota* crop, soil was >50 kPa for each soil type when wheeled, and <22 kPa for each soil type in unwheeled areas. Compaction control measures (controlled traffic and precision driving) are therefore important when using mechanical weeding. The broad bean crop was part of an eight year rotation of vegetables, potatoes, wheat *Triticum aestivum,* beans, barley *Hordeum vulgare,* peas *Pisum sativum* and red clover *Trifolium pratense*. The carrot crop was part of a cereal/potato/carrot/spring cereal rotation undersown with grass and clover and peas. Carrot beds were roughly 2 m wide. Soil strength and the soil density were measured. Weeds were controlled by several passes of a light spring-tine harrow in the broad bean crop, and by a steerage hoe between the rows of carrot.

A replicated study in 2001-2006 on a silty-clay soil in Lower Saxony, Germany (11) found that adopting mouldboard ploughing reduced soil penetration resistance (0.5-1.0 MPa) compared to shallow tillage (1.5 MPa). Soil porosity under shallow tillage changed depending on the soil depth, but was uniform at all depths when under mouldboard ploughing. Shallow tillage reduced sugar beet yield (15 Mg/dm/ha) compared to mouldboard ploughing (19 Mg/dm/ha). Sugar beet *Beta vulgaris* was planted at a density of about 90,000 plants/ha in three adjacent fields. Cultivation of crops under shallow tillage or mouldboard ploughing followed regional standards of good professional practice. Soil penetration resistance was measured to 0.65 m depth in spring. After sugar beet sowing, undisturbed and disturbed soil core samples were taken in spring 2004-2006, from 0.05m to 0.6 m depth.

A replicated experiment in 1994-1999, on clay soil in Queensland, Australia (12) found that water infiltration and yield were higher in plots using conservation tillage. Controlled traffic combined with zero tillage reduced runoff by 47.2 % and increased yield by 14.5 %. The 90 m^2 tillage plots were arranged in pairs: one plot had zero tillage and the other stubble mulch tillage, within which were two traffic treatments: non-wheeled and wheeled. This was replicated four times. Compacted areas were wheeled annually using a 100 kW tractor. Crops included: wheat *Triticum aestivum*, sorghum *Sorghum bicolor*, maize *Zea mays*, sunflower *Helianthus annus* and sweet corn (different cultivar of maize). Yield was determined from harvested transects in the plots. Runoff and soil moisture content was measured by taking soil cores between 0-50 mm depth and measuring moisture content gravimetrically. Controlled traffic and zero tillage combined were not separated in results.

A replicated, site comparison in 1984-1989 on loam soils in Alberta Canada (13) found that regardless of residue management, soil density between 0-15 cm depth was higher under no-tillage (1.35 Mg/m^3 av.) compared to rototilled (1.19 Mg/m^3 av.) plots. Soil resistance was higher under no-tillage (1195 kPa av.) than rototilled plots (703 kPa av.); however residue retention decreased resistance in no-tillage plots (942 kPa av.). The wind-erodible fraction of soil aggregates (<1 mm) was lowest under no-tillage (18%) and largest under rototilling (39%). Water infiltration was 33% lower under no-tillage than rototilled plots. In four replicates were two tillage systems: no-tillage (direct drilling), tillage with rototilling (10 cm depth); and two residue levels: straw removed and straw retained. Plots were 6 x 2.7 m. The crop rotation was barley *Hordeum vulgare*/rape *Brassica napus*. Soil samples were taken from each plot. Soil density, penetration resistance, particle aggregation and water infiltration were measured.

A randomized, replicated experiment in 2005-2006 on calcareous sandy-loam soil in Lyon, France (14) found that mouldboard tillage reduced compacted zones (23% of ground surface) compared to shallow mouldboard (34%), reduced (34%) and shallow tillage systems (38%). The compacted areas in the mouldboard tillage were restricted mainly to wheeled areas. Mouldboard ploughing also created better conditions for microbial growth. There were three replicates of four tillage systems: mouldboard ploughing (35 cm depth), shallow mouldboard ploughing (15-18 cm), reduced tillage (chisel plough, 15 cm), shallow tillage (rotary cultivator, 5-7 cm). Sample plots measured 12 x 80 m. A regional traditional alfalfa *Medicago sativa*/maize *Zea mays*/soya *Glycine max*/wheat *Triticum aestivum* rotation was used. For each treatment 10 compacted and 10 non-compacted soil clods were sampled. Soil structure, total organic carbon and nitrogen, and microbial biomass (volume of organisms per unit area) were measured.

A replicated, controlled experiment in 2000 on a non-chalky clay soil in Bhopal, India (15) found that sub-soiling in a soybean *Glycine max* - linseed *Linum usitatissimum* system reduced the size of soil cracks (12.5% in width, 10% depth, 5% length and 12% surface area) compared to conventional tillage. In a soybean-wheat *Triticum aestivum* rotation the smallest cracks were in mouldboard (0.014 m) compared with reduced (0.025 m) and no tillage plots (0.022 m). There were two experiments: (1) soybean /wheat rotation, with no-, reduced, mouldboard (wheat residue incorporated), and conventional tillage (wheat residue removed). There were three replications on 45 x 16 m plots, inorganic fertilizers were applied; (2) soybean/linseed rotation. This was under conventional tillage or sub-soiling (deep tillage). There were three replications 8 x 5 m, and three fertilizer treatments: no fertilizer, inorganic fertilizer, inorganic fertilizer plus farm yard manure. Crack length, depth and width, and the soil water content and density were measured.

A replicated experiment in 2009 on chalky soils in Valencia, Spain (16) found that slight water repellency (a characteristic that influences the movement of water into the soil) was found in no-till soils with added manure and plant residues (0-65 s wettable soil, >60 is strongly water repellent), compared to conventional tillage where the soils remained wettable (0 s wettable soil). This was due to the higher levels of soil organic carbon in the no-till (2.3-8.3% organic matter) compared to conventionally tilled plots (1.2-2.4% organic matter). There were four replications of citrus-cropped soil plots (species and plot size not specified). Within the crop, the treatments were: no-tillage with plant residues, organic manure and no chemical fertilizer; no-tillage and conventional herbicides; conventional tillage. Water repellency and soil organic carbon were measured.

A randomized, replicated experiment in 1996-1998 on a sandy, silty and clay soil in Ludhiana, India (17) found that tillage and straw mulching had no effect on soil water storage in the coarsest soil. Soil water content was higher in tilled soil (0.131 m^3 water/m^3) and soil with straw mulch (0.132 m^3 water/m^3 soil) relative to untreated and mulched soils (0.106 and 0.118 m^3 water/m^3) across all three soil types. Tillage did not increase soil water content to the same extent as straw mulch in coarse- to medium-textured soils. The study tested four treatments: untreated, tilled to 8 cm-depth, straw mulch (rice *Oryza sativa* in September and wheat *Triticum aestivum* in April) 6 t/ha, and straw incorporation. The treatments were replicated three times on each of three soil types in 2.5 x 3.5 m, 5 x 3 m, and 6 x 4 m plots. Mechanical weeding or herbicides (glyphosate) kept plots weed free. Soil water content was measured every 15-20 days below the tillage and straw incorporation layer.

A replicated experiment in 1992 on silt loam in Illinois, USA (18) found decreased infiltration rates and increased soil loss under both no-till (from >70 to 47.1 mm/h and 0.01-0.15 kg/m^2/h) and till (from 64.1 to 37.2 mm/h and 0.1-0.6 kg/m^2/h respectively), when crop residue was removed. Removing residue from a no-till system increased soil loss at Site 2 from 0.01-0.13 kg/m^2/h and Site 3 from 0.01-0.16 kg/m^2/h. There were three sites under corn *Zea mays*-soybean *Glycine max* rotations. Site 1 was under conventional tillage and treatments were: tilled and tilled residue removed. Sites 2 and 3 had been no-till for more than 15 years. Site 2 treatments were: no-till, no-till residue removed, tillage residue replaced on surface, and tillage residue removed. Site 3 treatments were: no-till, no-till residue removed, tillage residue removed, and tillage residue removed again after three soil-drying days. Plots were 1 x 2 m and respective treatments were replicated six times at each site. Rainfall was simulated at an intensity of 70 mm/h on each plot for 90 minutes.

A controlled, replicated experiment in 1994-1996 on clay in Brazil (19) found the lowest soil loss under crops with no-till (1 t/ha), followed by crops under reduced tillage (4 t/ha) compared to conventional ploughing with crops (13 t/ha) and conventional ploughing on bare soil (80 Mg/ha in one crop cycle). Water losses were very low with no difference between treatments. On slopes 0.035, 0.065 and 0.095 m/m^{-1} gradient, the following treatments were applied after harvest of soybean *Glycine max* and black oat *Avena strigosa* crops: conventional tillage (20 cm depth), reduced tillage (8 cm depth), and no-till. There was an additional bare soil treatment under conventional tillage. Plots were 24 x 50 m and replicated three times. Tillage and planting operations were performed along contour lines in all plots except one where ploughing/disking operations were performed up-and-down-slope. Rain gauges were installed to measure runoff.

A controlled experiment in 2003-2006 on sandy loam soil near Copenhagen, Denmark (20) found that reducing tillage improved soil structure by increasing soil organic matter and reducing soil density. Soil stability was higher under reduced tillage in wet conditions (74.3% on average) compared to conventional ploughing (66.8% on average), but higher under conventional ploughing in dry conditions. This is due to higher soil organic matter content in the reduced tillage (3.06 mg/m^3) compared to the conventional ploughing (2.6 mg/m^3). The optimal time for tillage appears to be determined by the water content of the soil. There were two tillage treatments in an experimental field (size not specified); reduced tillage with harrowing, and convention mouldboard ploughing with harrowing. Soil samples were taken 6 times during the tillage year. Soil texture, organic matter, stability and density were measured.

A controlled, randomized, replicated experiment in 2007-2010 on sandy silt-loam in India (21) found that soil loss and runoff were lower under minimal tillage with palmarosa *Cymbopogon martini* (3.4 t/ha and 234 mm, respectively), than with no vegetation barrier (7.1 t/ha, 428 mm). Conventional tillage with panicum was less effective (5.2 t/ha, 356 mm) than conventional tillage with palmarosa. Maize *Zea mays* yield was 43% higher under minimal tillage with palmarosa compared to no vegetation barrier with conventional tillage. The succeeding wheat *Triticum aestivum* yield was on average 73% higher in the palmarosa relative to panicum treatment, and 99% higher than with no vegetation barrier. It was not clear whether these results were due to organic amendments, mulching or reduced tillage. There were three replications of three treatments in a maize-wheat crop rotation: conventional tillage with no vegetation barrier but applying fertilizers and herbicides; conventional tillage with a panicum *Panicum maximum* vegetation barrier, fertilizers and herbicides; minimal tillage (30% crop cover retained) with a palmarosa vegetation barrier plus mulching and farmyard manure, vermicompost (produced by worms) and poultry manure applications. Plots were 100 x 20 m.

A replicated, randomized experiment in 2000-2004 on silty-clay soil in Cordoba, Spain (22) found that no-tilled plots lost the most soil (8.5 t ha/yr), compared to those under conventional tillage (4.0 t h/yr) and grass cover (1.2 t ha/yr). There were three soil management systems: no-tillage (soil kept weed-free with herbicides), conventional tillage (3-4 passes with rotary tiller 15cm deep), grass cover (rotary tilled to 10 cm, then barley *Hordeum vulgare* until April, residue retained once cut). Each experimental plot was 6 x 12 m and enclosed two olive *Olea europaea* trees. Water runoff and sediment were measured. Soil samples up to 5 cm depth were taken from each plot. Soil organic matter, density and moisture were measured.

A replicated experiment in 1970-1974 on sandy-clay to clay soil in Nigeria (23) found lower runoff under no-till maize *Zea mays*-cowpea *Vigna unguiculata* treatments (2% of total annual rainfall) compared to conventionally ploughed bare fallow (36%). Soil loss was lower under no-till (0.1 t/ha) compared to conventionally ploughed continuous maize (41 t/ha), cowpea-maize (43 t/ha) and bare fallow (230 t/ha) treatments. Slopes of 1, 5, 10 and 15% received the following treatments: bare fallow (conventionally ploughed); continuous maize (conventionally ploughed, mulched); continuous maize (conventionally ploughed, no mulch); maize-cowpea rotation (zero-tillage); and cowpeas-maize rotation (conventionally ploughed). Plots were 25 x 4 m and were replicated five times on each slope. Soil and runoff water was collected from each plot after every rainstorm using a water collection system below ground level downslope of the plots.

A replicated experiment in 1970-1974 on sandy-clay to clay soil in Nigeria (24) found lower nutrient loss in maize *Zea mays*-cowpea *Vigna unguiculata* under no-till (4.3 kg/ha) compared to conventionally ploughed cowpeas- maize (12 kg/ha), continuous maize (17 kg/ha) and bare fallow (55 kg/ha). Slopes of 1, 5, 10 and 15% received the following treatments: bare fallow (conventionally ploughed); continuous maize (conventionally ploughed, mulched); continuous maize (conventionally ploughed, no mulch); maize-cowpea rotation (zero-tillage); and cowpea-maize rotation (conventionally ploughed). Maize received 120, 26 and 60 kg/ha nitrogen, phosphorus and potassium respectively. Plots were 25 x 4 m and were replicated five times on each slope. Soil and runoff water was collected from each plot after every rainstorm using a water collection system below ground level downslope of the plots.

A replicated, site comparison study, from 1984 to 1996 on silty clay loam soils in southern Norway (25) found that autumn harrowing reduced soil loss by 20-60% compared to autumn ploughing. Variations in winter climate (e.g. rainfall) also influenced soil loss. There were six sites, with varying plot size: Bjørnebekk (144m^2, 11 replicates), Syverud (210m^2, 12), Askim (147 and 267 m^2, 6), Øsaker (176 m^2, 8), Hellerud (180, 720, 816 m^2, 8), Holt (2.7 ha catchment, not replicated). The tillage treatments were autumn ploughing, spring ploughing, autumn harrowing, spring harrowing, and direct drilling. Runoff and amount of eroded soil was measured.

A site comparison study in 1989 on clay loam soils in north-central Italy (26) found that conventional tillage decreased soil stability and organic matter content by 81.4 mg/kg compared to untilled plots. Soil density was slightly higher (by 0.018 g cm^3) and the soil less porous (by 0.52%) under conventional tillage compared to not tilled or minimum tilled land. The experiment was carried out at three locations: Vicarello (soil not tilled and conventionally tilled), Fagna (soil minimal till, conventionally tilled), Gambassi (not tilled (alfalfa *Medicago sativa* pasture) and conventionally tilled). Plot size was not specified. Soil samples were collected at each location. The density of soil and the number of pores, as well as soil stability were measured.

A replicated experiment from 1988 to 1998 on a loamy-sandy loam soil in Woburn, England (27) found that there were no major differences in soil loss between minimal and standard tillage treatments. Soil loss was lower on across-slope plots (148 kg/ha) compared to up-and-downslope plots (262 kg/ha). Runoff was also lower in across- (0.82 mm) than up-and-downslope plots (1.32 mm). Crop yields were higher on across-slop plots than on the up-and-downslope plots, in 10 of 11 years tested. The experimental crop was a potato *Solanum tuberosum*/barley *Hordeum vulgare*/wheat *Triticum aestivum*/sugar beet *Beta vulgaris*/fallow (not specified) rotation. The main treatments were cultivation direction (up-and-downslope, across-slope) and tillage (minimal with some residue retention, conventional mouldboard ploughing with all residue removed). There were two replicates of four 25 x 35 m plots. Soil loss, runoff and yield were measured.

A randomized replicated experiment in 1990-1991 on a calcareous silt loam soil in Shoreham, England, UK (28) found that shallow cultivation reduces the amount of soil lost (4.53 g/h on average) and the amount of runoff (0.82 l/h on average) during heavier rainfall events compared to conventionally cultivated and rolled (with a heavy roller) land (25.54 g/h, 5.87 l/h on average, respectively). There were two sites with cultivated plots (number not specified), which were 100 x 18 m. Plots had three different cultivation practices (shallow cultivation, conventional deep cultivation, and deep cultivation followed by heavy rolling). A rainfall simulator was used, with each treatment subjected to three simulated rainfall events, lasting one hour at 42.5 mm/h. Runoff and eroded soil was caught in a trap in the slope immediately below the rainfall simulator. The volume of runoff and weight of eroded soil were measured.

A review of 76 papers in 1991 (29) reported lower runoff under no-till (9 mm), soil rotivated to 15 cm depth (24 mm), cultivated with no-till (57 mm), and ploughed then disk-harrowed (55 mm), compared to soil ploughed to 15 cm depth (171 mm) (Burwell *et al.*1966). Corn *Zea mays* yield increased with tillage depth, the effect greatest in soil with low water holding capacity (8 mm/m soil depth, Arora *et al.* 1991). The studies showed that contouring (cultivation across-slope rather than down-slope), furrow diking (small earthen dikes built at intervals between tillage ridges in semi-arid areas), strip-cropping (narrow strips of plants or plant residues), terraces (level terraces are built across a slope), and graded furrows (miniature graded terraces) can be used together with tillage to increase soil and water conservation benefits.

A controlled, replicated experiment in 1998-2001 on a clay soil in Sweden (30) found that higher average phosphorus levels were found in soil under the no-tillage treatment (1.86 kg/ha) compared to conventional tillage (1.59 kg/ha) and conventional tillage plus incorporation of phosphorus fertilizer (1.25 kg/ha). There was no major effect of tillage compared with no-tillage treatments on phosphorus filtration through the soil. Large columns of soil (monoliths) were collected and exposed to three treatments: conventional tillage (five replicates), no-tillage (five replicates), and phosphorus fertilizer incorporation (three replicates). All liquid draining from the monoliths was collected, and the concentrations of soil phosphorus and dissolved phosphorus were measured.

A site comparison study in 1981-1982 on clay-, silt- and sandy-loam and loam soils in Oklahoma and Texas, USA (31) found that total phosphorus loss was 93% lower from no-till soil than conventionally tilled soil. In no-till soil, 73% of the phosphorus was bioavailable (the point at which it becomes available for use after application) compared with 28% in conventionally tilled soil. At Bushland, the wheat *Tiricum aestivum* – sorghum *Sorghum bicolor* fallow rotation was under reduced tillage (stubble mulch tillage). At El Reno and Woodward, wheat was under conventional tillage/ploughing (chisel, mouldboard and discing). At Fort Cobb, the peanut *Arachis hypogaea* – sorghum rotation was under conventional tillage/ploughing (chisel, mouldboard, harrowing and discing). At each unfertilized and fertilized watershed, four soil samples were collected at monthly intervals. Runoff, total, organic and inorganic phosphorus were measured.

A controlled, replicated experiment in 2000-2002 on a silt loam soil in California, USA (32) found that tillage decreased soil quality, increasing greenhouse gas emissions and potential nitrate loss. Carbon dioxide lost from soil was highest in disked soil (39 mgCO_2 m^2/h) immediately after tillage. When irrigated, highest carbon dioxide loss was from no-till soil (161 mgCO_2 m^2/h). Nitrate levels were consistently higher in tilled than no-till soil. Two weeks after tillage, tilled soils held twice as much nitrate as no-till (12 µg NO_3-N/g and 6 µg NO_3-N/g respectively). Nitrogen loss from tilled soil was consistently higher in tilled than no-till soil. Tillage caused immediate changes in soil microbial community structure. There were three treatments (rototilled, disk, and no-till control), replicated three times (field scale, but area not specified). Soil cores from each replication were taken over eight sampling times. Soil carbon and nitrogen were measured. Microbial community structure was described.

A randomized, replicated experiment in 2003 on a sandy-loam soil in Quebec, Canada (33) found that adopting no-tillage increased soil aggregation (accumulation of soil particles) and nutrient retention under maize *Zea mays* production. The proportion of larger aggregates (soil particles larger than 2 mm) was greater under no-tillage (37.2%) compared to conventional tillage (31%). C, N and P concentrations were three, five and eight times higher (respectively) in smaller aggregates (0.25-0.053 mm) than larger aggregates (>2 mm). There were four replicates of two tillage systems: conventional (tandem disk 10 cm deep, mouldboard plough 20 cm) and no-tillage. Within these were maize *Zea mays,* soybean *Glycine max*/maize, maize/soybean rotations (20x 24 m). Within these were four fertilizer treatments: inorganic fertilizers, composted cattle manure, and the two mixed together (20 x 6 m plots). Soil samples (10 cm) were taken after crop harvest. Soil carbon, nitrogen, phosphorus and size of aggregates were measured.

A site comparison study in 1984-1987 on peat overlaying clay soil in Plynlimon, UK (34) found that disc harrowing can cause large quantities of nitrate to be released (18.2 mg N/l) compared to reduced tillage (less than 1 mg N/l). There were two sites: (1) 1.5 ha of soft rush *Juncus effusus* and purple moor grass *Molinia caerulaea*. The area was disc harrowed, and lime, basic slag, fertilizer and a nitrogenous fertilizer were applied; (2) 19.5 ha area with purple moor grass and small areas of blanket mire *Calluna vulgaris-Eriophorum vaginatum.* Lime and phosphate fertilizer were applied, then grass seed was sown using the spike seeding method (a reduced tillage method - ground is spiked with a spike-aerator, then seed is broadcast over the soil). Soil and water samples were collected. Water flow, nitrate, phosphorus and potassium levels were measured.

A controlled experiment in 2003-2004 on silty clay loam soil in Peñaflor, Spain (35) found that soil organic carbon was more than 30% higher in topsoil under no-tillage (853 g/m^2 continuous barley, 671 g/m^2 barley-fallow) compared to conventional tillage (547 g/m^2 continuous barley, 490 g/m^2 barley-fallow). Organic carbon levels in large aggregated soil particles was greater under no-tillage (4.1 g C/kg) than conventional tillage (1.2 g C/kg) in continuous barley, indicating improved soil structure, but did not differ in the barley/fallow rotation. Three tillage systems (no-tillage with a direct driller and herbicide treatment, reduced tillage with a chisel plough to 30 cm, conventional tillage with a mouldboard plough to 35 cm and a pass with a tractor-mounted scrubber), contained two cropping systems: barley *Hordeum vulgare*/fallow rotation, continuous barley. In each plot, 12 soil cores were taken to 20 cm depth (size/number of plots not specified). Total soil organic carbon was measured.

A replicated experiment in 2004-2006 on silty soils in Germany (36) found that soil organic carbon was higher in no-tillage (11.6 g/kg soil) and mulch tillage (12.3 g/kg soil) than conventional tillage (10.1 g/kg soil). Results were similar across all sites. Yields of sugar beet *Beta vulgaris* and winter wheat *Triticum aestivum* were higher under conventional (72.7 t/ha, 8 t/ha) and mulch tillage (69.7 t/ha, 8 t/ha) than no-tillage (62.8 t/ha, 7.5 t/ha respectively). There were four replicates (sites). Sugar beet was followed by two years of winter wheat as crop rotations. At each site, one field was chosen and divided into three plots (size not specified). Each plot had a different tillage treatment: conventional tillage (25-30 cm deep), mulch tillage (10-15 cm), no-tillage. In 2010, 15 soil samples were taken from each treatment. Soil organic carbon and nitrogen were measured. Yields were measured annually from 2004 to 2010.

A replicated experiment in 1985-1987 on loamy soil in Essonne, France (37) found that, soil organic carbon in wheat *Triticum aestivum* was higher under no-tillage (11.14 mg C/g) compared to conventional tillage (10.1 mg C/g). Superficial tillage was similar to conventional in the ploughed layer. In maize *Zea mays,* superficial tillage had higher soil organic carbon (9.88 mg C/g) compared to no-tillage (6.73 mg C/g) and conventional tillage (9.3 mg C/g). Average annual maize yields were 6.5 t/ha under conventional, 6.2 t/ha under superficial and 5.7 t/ha under no-tillage (wheat not reported). Crops were continuous wheat and maize. Three tillage treatments were applied to each crop in four replicates: conventional (ploughing to 30 cm, field cultivator), superficial (rotivator to 12 cm, field cultivator) and no-tillage (direct sowing). Plot size not specified. Soil samples were taken from 10 x 20 cm areas in each treatment, and carbon levels were measured using ^{13}carbon.

A randomized, replicated experiment from 1968 to 2008 on clay soil in Queensland, Australia (38) found higher soil organic carbon under no-tillage (20.21 Mg/ha) compared with conventional tillage (19.83 Mg/ha). Total soil nitrogen was not affected by tillage treatment. Average grain yield was highest under no-tillage when crop residue was retained (2.86 Mg/ha) with high fertilizer application, and lowest under conventional tillage when crop residue was retained (2.28 Mg/ha) with no fertilizer. This 40- year experiment was cropped with wheat *Triticum aestivum* except for three years which were cropped with barley *Hordeum vulgare* and had the following treatments: tillage (conventional tillage (3-4 times to 10 cm depth), no-tillage); crop residue management (residue burned, residue retained); and nitrogen fertilizer application (none applied, 30 kg N/ha/year (low), and 90 kg N/ha/year (high), applied at sowing). Plots were 61.9 x 6.4 m and were replicated four times. Five soil samples were taken from each plot at the end of the experiment (May 2008) to 1.5 m depth.

A randomized, replicated experiment in 2004-2007 on sandy-clay loam in Georgia, USA (39) found higher soil carbon under strip tillage with alley cropping (13.4 Mg C/ha) compared to strip tillage with organic management (7.7 Mg C/ha) and conventional tillage (10.7 Mg C/ha). Soil microbial biomass was not affected. Crop yields were highest under strip tillage with alley cropping except the corn *Zea mays*/squash *Curcurbita moschata* intercrop, which was highest under strip tillage with organic management. It was not clear whether these effects were due to tillage or other management practices. Four treatments included: alley cropping with strip tillage, organic management with strip tillage, conventional tillage and fertilizer, mowed fallow (four, four, eight and six replicates respectively). Vegetable crops (okra *Abelmoschus esculentus*, hot pepper *Capsicum annum*, corn, squash) were grown in rotation with winter cover crops: crimson clover *Trifolium incarnatum*, pea *Pisum sativum* and rye *Secale cereale.* Soils were sampled each year to 15 cm depth, and measured soil carbon, nitrogen and microbial biomass.

A review of 120 papers testing interventions on a range of soils largely in Japan (40) found that no-tillage practices, cover crop management and manure (and organic by-product) application enhance soil organic carbon storage. Balanced and integrated increases in the soil organic carbon pool, lessening of non-carbon dioxide emissions, and control of soil nutrients based on location-specific recommendations are also needed. No review methods were specified. Tillage systems reviewed included: no-tillage, conservation tillage (surface residues retained), conventional tillage (mouldboard plough, rotary tillage, disked). Cover crops reviewed included a mix of leguminous and grass covers: rye *Secale cereale*, hairy vetch *Vicia villosa*, and crimson clover *Trifolium incarnatum*.

A replicated, randomized, controlled trial between 2006 and 2009 in a clay loam soil in Hubei Province, China (41) found that soil organic carbon in the top 5 cm of the soil was increased under: no tillage for rape *Brassica napus* but tillage for rice *Oryza sativa* (by 6 %), continuous no tillage (by 9%), and continuous no tillage with a mulch of crop residues (by 17%), relative to full tillage. The trial used four crop rotation and tillage treatments: rape and rice with full tillage, rape and rice with continuous no tillage, rape without but rice with tillage, and rape and rice without tillage but with mulches. Tillage plots were tilled by hand to 10 cm depth then mouldboard ploughed to 30 cm depth. Rape and rice were harvested in May and October each year, and residues were air dried before being left on the soil surface in the mulching treatment.

A randomized, paired experiment in 2004 on loamy soil in Essonne, France (42) found that soil organic carbon levels were 11.4% higher in soil under no-tillage than under conventional tillage management. No-tilled soils also contained more potassium (3.5-11% compared to 3-4.5%). No effects on yield were found between conventional and no-tillage management. No-tillage management showed strong pH gradients depending on soil depth, but ploughed soil had an even pH. The experimental field was divided into two 50 x 16 m plots, which were subjected to either conventional or no-tillage treatment. The crops grown were maize *Zea mays* followed by wheat *Triticum aestivum.* Maize/wheat plantings received similar fertilizers. Soil samples were taken from three random locations within each tillage treatment. Organic carbon, potassium and soil pH were measured. To measure the density of the soil, five soil samples were taken from five random locations in each tillage treatment.

A randomized experiment in 2010 on sandy loam soil in north-east Spain (43) found that soil organic carbon levels were highest in soils which had been managed under no-till for 11 years (ranging from 7.1 to 24 g C/kg dry soil) compared to no-till for one year (8.9-10.5 g C/kg dry soil) and four years (8.5-20 g C/kg dry soil) respectively. The experimental field was 7500 m^2, and had previously been intensively tilled. Two crops (either wheat *Triticum aestivum* or barley *Hordeum vulgare*) were exposed to one of five treatments: conventional tillage (mouldboard plough, 1500 m^2), no-till for one year, no-till for four years, no-till for 11 years, no-till for 20 years (the remaining 6000 m^2). Pig slurry was applied across the whole experiment as fertilizer. From each treatment, three soil samples were taken in 2010 after crop harvest. Soil organic carbon levels were measured.

A randomized, replicated experiment in 1979-1988 on clay loam in Alberta, Canada (44) found higher organic carbon content under no-till plus straw (5.81%) compared to tillage plus straw incorporation (5.79%) and tillage no straw treatments (5.5%). Differences between treatments decreased with increased depth. Soil aggregates were 38% larger in no-till plus straw than tillage plus straw, and 175% larger than tillage no straw. The wind-erodible fraction of soil aggregates (smaller than 1 mm diameter) was smallest (16%) in no-till plus straw (i.e. soil structural stability was higher), followed by tillage plus straw (29%) compared to tillage no straw (49%). Three tillage and residue treatments were applied to a spring barley *Hordeum vulgare* crop: no tillage (direct seeding), straw retained on surface, tillage (rotivation to 10 cm depth in autumn and spring), straw incorporated into topsoil, and tillage, straw removed. Individual plots measured 6.8 x 2.7 m and were replicated four times. Nitrogen was applied at 56 kg N/ha in all treatments. Soils were sampled to 5 cm depth.

A controlled, replicated experiment from 1995 to 2004 on a loamy-clay soil in Burgos, Spain (45) found that after 10 years, soil organic carbon was 25% greater under no-tillage than conventional tillage, 16% greater than under minimal tillage, and 17% higher in minimal tillage compared to conventional tillage. Tillage treatment affected soil organic carbon levels more than crop rotation. There were 15 plots (450 m^2) replicated four times. There were three tillage treatments: conventional (mouldboard plough 25-30 cm deep, cultivator, harrow, roller, residue removed), minimum (chisel plough 10 cm, harrow, roller, residue retained), no-till (herbicides, residue retained). Within these were cereal (wheat *Triticum aestivum*, barley *Hordeum vulgare*)/legume (vetch *Vicia sativa*) and cereal/cereal rotations. Samples of cereal grain and straw were taken. Soil samples were taken from each plot (0-30 cm) before and after cropping. Soil density and organic matter were measured.

Two replicated, randomized, controlled experiments from 1987 to 1998 on a clay soil in Settat, Morocco (46) found that there was an increase in soil organic carbon in no tillage systems (by 3.5 t/ha after 4 years, and by 3.4 t/ha after 11 years) compared to conventional tillage. Nitrogen slightly decreased under both tillage practices, however the no-tillage soils contained more nitrogen than the conventionally tilled soils in both experiments. Two long-term experiments were started in 1987 and 1994. Wheat *Triticum aestivum*, wheat-fallow, wheat-corn *Zea mays*-fallow, wheat-lentils *Lens culinaris*-fallow and wheat-forage fallow rotations were investigated in both experiments. There were three replicates in each experiment and experimental plots were 6 x 30 m. Tillage treatments included no-tillage and conventional tillage using disc harrows. Soil samples were collected from unwheeled areas after harvest in 1998. Soil organic carbon and total nitrogen were measured.

A controlled, replicated experiment in 2005-2009 on silty loam soil in eastern Spain (47) found that after five years, conventional ploughing gave the lowest levels of soil organic matter (2%), arbuscular mycorrhizal proteins (400 mg/g soil), aggregate stability (57%), and higher soil erosion rates (0.01 Mg/ha/h) compared to soil under native vegetation. Ploughing plus sown oats had similar values to conventional ploughing. All treatments without ploughing had similar values to the control (2.7% organic matter, 696 mg/g soil, 57.4% aggregate stability and 0.01 Mg/ha/hour respectively). There were three replicates of five management treatments including: ploughing (four times/year to 20 cm depth), ploughing (as before) then sowing oats, herbicide application (three times/year) and no ploughing, addition of oat straw mulch and no ploughing, and land abandonment (control). Plots were 6 x 10 m. Soil under native vegetation was used as a reference. Six soil samples from each plot were taken annually to 5 cm depth. Five rainfall simulations were also conducted during the summer drought period on 1 m^2 plots to test for soil erosion. Simulations lasted one hour at 55 mm/h.

A randomized, replicated experiment in 2007 on an Anthrosol (soil greatly modified by human activity) in the Sichuan Basin, China (48) found that tillage affected soil fertility mainly by changing soil structure. Soil organic carbon, nitrogen, and phosphorus were roughly 23% higher under ridge no-tillage than conventional tillage. Calcium levels were also higher under ridge no-tillage (13.92 cmol Ca^{2+}/kg average) than conventional tillage (13.25 cmol Ca^{2+}/kg average). Conventional tillage reduced soil stability by 35% compared with ridge no-tillage. The crop was rice *Oryza sativa* followed by winter rape *Brassica napus*. There were four replications of two tillage regimes started in 1990: ridges with no-tillage (ridges from prior ploughing/harrowing kept intact), conventional tillage (ploughing/harrowing to 20-30 cm depth). Plots were 4 x 5 m. Soil samples were collected and soil organic carbon, nitrogen, phosphorus, calcium and magnesium were measured.

A replicated experiment in 2001-2006 on loam soil in Saskatchewan, Canada (49) found that reducing tillage intensity increased soil stability, due to increased crop residue cover (50% cover in the reduced input treatment, compared to 24% in organic and 30% in high input treatments). Excess soil nitrogen was stored as soil organic matter in dry weather, largely due to reduced tillage. Three input levels were replicated four times: organic (organic management under conventional tillage), reduced (combined pest and nutrient management under no tillage) and high (recommended fertilizer and pesticide application under conventional tillage) inputs (treatment size not specified). At the end of each growing season 36 soil samples were taken from each input treatment, with an additional 18 taken in 2006. Soil stability, organic carbon and crop residue cover were measured.

A replicated, site comparison study in 1993-1995 on a silty soil in Kedainiai, Lithuania (50) found that soil organic matter content in the topsoil was higher in minimally-tilled soils (1.46 g/kg) compared to shallow (1.04 g/kg) and conventionally tilled soils (0.97g/kg). There were two long-term tillage experiments, one with high application rates of mineral fertilizers (experiment one: $N_{30-45}P_{45}K_{60}$), and the other with low application rates (experiment two: $N_{60}P9_{0}K_{90-120}$). Both experiments received mineral fertilizers and farmyard manure. There were four replicates and each area was 36 m^2. The crops included vetch *Vicia sativa*-oat *Avena sativa* rotation and sugar beet *Beta vulgaris*. Soil sampling was done annually up to 30 cm in depth in 1993-1995. Soil nitrogen and phosphorus were measured.

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3.3. Control traffic and traffic timing

- **Biodiversity:** One randomised, replicated study from Poland[8] found higher numbers and bacterial activity under controlled traffic. One replicated site comparison study from Denmark[8] found higher microbial biomass when farm traffic was not controlled
- **Erosion:** Five trials from Europe[2, 3, 4, 6] and Australia[5] (including three replicated trials[3, 5, 6], one controlled before-and after-trial[4], and one review[2]) found a higher number of pores in the soil[3, 4], less compaction[2], reduced runoff[6] and increased water filtration[5] into the soil under controlled traffic. One controlled, replicated trial from India[1] found increased soil crack width when traffic was not controlled.
- **Yield:** One replicated trial from Australia[4] found increased yield under controlled traffic.
- **Soil types covered:** clay[5, 1], loamy-silt[4], sandy loam[7], silty[8], silty-clay[3], silt loam[6].

Background

Soil microbial biomass is the amount of tiny living organisms within a given area or amount of soil. A higher number of soil pores (or soil porosity) is an indicator of good soil structure.

A controlled, replicated experiment in 2000 on a non-chalky clay soil in Bhopal, India (1) found that increased compaction increased soil crack width. The smallest cracks were found in uncompacted plots (0.027 m) compared to low (0.037 m) or high compaction plots (0.040 m). Within a rotation of rice *Oryza sativa* and wheat *Triticum aestivum* there were three compaction or puddling treatments: low (four passes by power tiller), high (eight passes by power tiller) and no compaction. There were three replicates in plots of 5 x 8 m. Crack length, depth and width, and soil water content and soil density were measured.

A review of 37 studies covering countries in the European Union (2) found that controlled traffic with precision guidance can avoid compacting soil in a cropped area. Changing tyre load and tyre inflation achieved reduced risk of compaction. Studies showed that compaction was reduced on-farm by avoiding working the soil in wet conditions, adjusting to out-of-furrow ploughing (i.e. not ploughing repeatedly along the same lines), confining the compaction to particular areas (such as tracks outside the cropping area), reduced loosening of topsoil and subsoil, and the use of equipment with low ground pressure.

A replicated study in 2001-2006 on a silty-clay soil in Lower Saxony, Germany (3) found that subsoil structure was improved with no traffic/wheeling compared to repeated wheeling with present-day heavy agricultural machinery. The number of soil pores decreased under wheeling. Three adjacent fields were used, with sugar beet *Beta vulgaris* planted at a density of about 90,000 plants/ha. Cultivation of crops followed regional standards of good professional practice. Wheeling was carried out with a six-row self-propelled sugar beet tanker harvester and compared with an unwheeled control treatment. Soil penetration resistance was measured to 0.65 m in depth. After sugar beet sowing, undisturbed and disturbed soil core samples were taken in spring 2004-2006, from 0.05m to 0.6 m in depth. Water infiltration rate in the field was measured in May 2005 and 2006.

A controlled, before-and-after trial in 1995-1997 on a loamy silt soil in Lower Saxony, Germany (4) found 70-85% more soil pores in unwheeled compared to soil compacted by heavy machinery. Earthworms *Lumbricus terrestris* were not affected by compaction. Burrows made by earthworms *Aporrectodea caliginosa* were still lower in length (9 mm/g/day), volume (68 mm^3/g/day), and windiness (17%) compared to uncompacted soil two years after the compaction event. One part of the field was compacted six times in spring 1995 by repeated wheeling by heavy four-wheel-drive machinery with a 5 Mg wheel load, the other, uncompacted. Undisturbed soil monoliths (a vertical sample showing several soil horizons) were taken from fields in 1997 under conventional tillage or conservation tillage. X-ray computed 2D images were used to analyse soil structure.

A replicated experiment in 1994-1999, on a clay soil in Queensland, Australia (5) found that runoff decreased by 36% and yield increased by 9% in controlled traffic plots compared to compacted plots. Soil water content was higher in compacted plots at 0-500 mm depth. Controlled traffic and zero tillage combined decreased runoff by 47% and increased yield by 14.5 %. Reduced tillage also reduced runoff regardless of traffic. Tillage plots of 90 m^2 were arranged in pairs (one plot had zero tillage and the other plot had stubble mulch tillage), within which were two traffic treatments: non-wheeled and wheeled. This was replicated in four blocks. Compacted areas were wheeled annually using a 100 kW tractor. Crops included: wheat *Triticum aestivum*, sorghum *Sorghum bicolor*, maize/sweet corn *Zea mays* and sunflower *Helianthus annus*. Yield was determined from harvested transects in the plots. Runoff was recorded and soil moisture content was measured by taking soil cores to 5 cm depth.

A randomised, replicated experiment in 1990-1991 on silt loam soil in Shoreham, UK (6) found lower runoff in uncompacted ground (3 l/h) compared to compacted ground in tractor wheelings (8 l/h). There were two sites with 100 x 18 m cultivated plots (number not specified). Plots had three different cultivation practices (shallow cultivation, conventional deep cultivation, and deep cultivation followed by heavy rolling). A rainfall simulator was used to test runoff, with each treatment subjected to three simulated rainfall events, lasting one hour at 42.5 mm/h. Runoff and eroded soil was caught in a trap immediately downslope of the rainfall simulator. The volume of runoff and weight of eroded soil were measured.

A replicated, site comparison study in 2001-2003 on sandy loam soil in Denmark (7) found 25% lower microbial biomass at Flakkebjerg in uncompacted compared to compacted soil across all three cropping systems. No difference was found at Foulum. There were three 4-year crop rotations at two sites: cereal (oats *Avena sativa*, barley *Hordeum vulgare*, lupin *Lupinus angustifolius* and wheat *Triticum aestivum*) without manure; cereal plus manure; and cereal-grass *Lolium perenne*-clover *Trifolium repens* and *Trifolium pratense* rotation without manure. Part of each plot was compacted by a medium-sized tractor. There were two replicates of 216 m^2 plots at Foulum and 169 m^2 plots at Flakkebjerg. Soils were sampled to 13 cm depth at Foulum and 10 cm depth at Flakkebjerg in spring in the wheat plots, from compacted and uncompacted plots.

A randomised, replicated experiment in 2008 on silty soils in Lublin, Poland (8) found fewer bacteria (1,700 million colonies/kg) and lower bacterial activity in strongly compacted soil, but higher numbers and activity in moderately compacted soil (4,650 million colonies/kg) compared to an uncompacted treatment (2,600 million colonies/kg). Bulk density was 22.5% and 15.5% higher in the strongly and moderately compacted soil respectively, compared to uncompacted soil (1.3 Mg/m^3). There were three compaction treatments in a soybean Glycine max crop obtained using a wheel tractor: strongly (5 passes), moderately (3 passes) and uncompacted (0 passes) soil. There were six replicates; total area for each compaction was not specified. Within each treatment were 1.8 x 2.1 m plots with no mulch, or mulched with straw. Fertilizer was applied uniformly to all plots at 54-70-80 kg/ha NPK. Soil was sampled three times during crop development from the centre of the soybean rows. Microbial parameters including bacterial number and enzyme activities were measured.

(1) Bandyopadhyay, K. K., Mohanty, M., Painuli, D. K., Misra, A. K., Hati, K. M., Mandal, K. G., Ghosh, P. K., Chaudhary, R. S. & Acharya, C. L. (2003). Influence of tillage practices and nutrient management on crack parameters in a Vertisol of central India. *Soil Tillage & Research,* 71, 133-142.

(2) Chamen, T., Alakukku, L., Pires, S., Sommer, C., Spoor, G., Tijink, F. & Weisskopf. (2003) Prevention strategies for field traffic-induced subsoil compaction: a review Part 2. Equipment and field practices. *Soil & Tillage Research,* 73, 161-174.

(3) Koch. H. J., Heuer, H., Tomanova, O. & Marlander, B. (2008) Cumulative effect of annually repeated passes of heavy agricultural machinery on soil structural properties and sugar beet yield under two tillage systems. *Soil & Tillage research*, 101, 69-77.

(4) Langmaack, M., Schrader, S., Rapp-Bernhardt, U. & Kotzke K. (2002) Soil structure rehabilitation of arable soil degraded by compaction. *Geoderma*, 105, 141-152.

(5) Li, Y. X., Tullberg, J. N. & Freebairn, D. M. (2007) Wheel traffic and tillage effects on runoff and crop yield. *Soil & Tillage Research,* 97, 282-292.

(6) Robinson, D. A. & Naghizadeh R. (1992) The impact of cultivation practice and wheelings on runoff generation and soil erosion on the South Downs: some experimental results using simulated rainfall. *Soil Use and Management,* 8, 151- 156.

(7) Schjønning, P., Munkholm, L. J., Elmholt, S. & Olesen, J. E. 2007. Organic matter and soil tilth in arable farming: Management makes a difference within 5-6 years. *Agriculture, Ecosystems and Environment,* 122, 157-172.

(8) Siczek, A. & Frąc, M. 2012. Soil microbial activity as influenced by compaction and straw mulching. *International Agrophysics*, 26, 65-69.

3.4. Convert to organic farming

- **Biodiversity:** Four studies in Asia, Europe, and the USA (including two site comparison studies[1, 2] and three replicated trials[3, 4, 6]) found higher numbers, diversity, functional diversity (see background) or activity of soil organisms under organic management.
- **Soil organic carbon:** Two replicated trials in Italy and the USA showed that organically managed orchards had higher soil carbon levels compared to conventionally managed orchards[3, 6]. One randomised, replicated trial in the USA[5] found soil carbon was lower under organic management compared to alley cropping.
- **Soil organic matter:** One replicated trial in Canada[7] found that soil nutrients were lower in organically managed soils.
- **Yield:** One replicated trial in Canada[7] found lower yields in organically managed soils. Two replicated trials in the USA[3] (one also randomised[5]) found that fruit was of a higher quality and more resistant to disease, though smaller[3] or that organic management had mixed effects on yield[5].
- **Soils types covered:** clay[2], clay loam[2], fine sandy-loam[4], loam[7], sandy loam[1, 2, 3], sandy-clay loam[5, 6], silt, silty-clay[3], silt-loam[2, 6].

Background

Soil microbial biomass is the amount of tiny living microorganisms within a given area or amount of soil. Arbuscular mycorrhizal fungi are a group of fungi that live around the roots of plants. By living together, the fungi and host plant benefit each other: the fungi can live in a habitat without having to compete for resources and have a supply of carbon from the plant, while they benefit the plant with an enhanced supply of nutrients, improved growth and ability to reproduce, and tolerance to drought. Arbuscular mycorrhizal fungi colonise a wide variety of host plants, including grasses, herbs, agricultural crops and legumes (Bardgett 2005), and are especially abundant in extensively managed and undisturbed soils. Functional diversity is the value and range of functional roles (or 'traits') that organisms play in a given ecosystem (Tilman 2001), in this case the agro-ecosystem. A highly abundant, diverse and active soil community is generally considered a good indicator of soil health. Functional diversity tends to be measured using indexes based on the number of species, or the number of different groups that perform different functions within the ecosystem, for example (there are more). Nematodes play important roles in soil nutrient cycling by feeding on microorganisms and excreting nutrients that were contained in the microbes into soil, where they can be accessed by plants. They can be good indicators of soil fertility as they feed on a wide range of organisms and their community structure reflects the health of their environment.

Bardgett R. (2005) *The Biology of Soil: A community and ecosystem approach*. Oxford University Press, Oxford.
Neher, D.A., 2001. Role of nematodes in soil health and their use as indicators. *Journal of Nematology,* 33 (4), 161–168.
Tilman D. 2001. Functional diversity. Pages 109-120 in: S.A. Levin (ed.) Encyclopedia of Biodiversity. Academic Press, Waltham, USA.

A replicated, randomised site comparison study in 2010 on sandy loam soils in Maharashtra, India (1) found greater functional diversity of soil microorganism communities in organically managed land (Simpson diversity index of 0.0022) compared to chemically managed land (index of 0.0018) and fallow grassland (index of 0.0015). Organically managed land was fertilised with composted cow manure while fallow grassland was left uncultivated and chemically managed land was fertilised with a mix of nitrogen, phosphorus and potassium in a ratio of 60:30:30 kg/ha. All fertilizers were applied annually for 16 years before 2010. Within each management type, soil samples were taken from four 10 × 10 m plots, at a depth of 15 cm. Soil samples from three of the plots were then randomly selected and mixed together, providing the final sample for analysis.

A replicated, site comparison study in 2001-2003 on a range of soil types in North Carolina, USA (2) found higher functional diversity in soil bacterial communities on organic farms(average Shannon diversity index of 2.63) compared to sustainable (index of 2.44) and conventional (index of 2.39) farms. Of the 10 arable farms sampled, three were organic (no synthetic pesticides or fertilizers), three were sustainable (synthetic fertilizers but no pesticides) and four were conventional (synthetic fertilizers and pesticides). Three locations on each farm were sampled taking multiple soil cores. Each of the farm types encompassed a range of soils but all included farms with loamy sand soils. Additional soil types were clay loam with sand (on one organic farm), silt loam (one conventional and one sustainable farm) and clay with rock (one sustainable farm).

A replicated, paired experiment in 2004-2005 on sandy-loam and silty-clay loam soils in California, USA (3) found 159.4% more microorganisms, 33.3% more microorganism activity and a higher genetic diversity of soil organisms (656 genes/group of organisms) on organic farms compared to conventional farms (504 genes/group of organisms). There was 22% more carbon and 30% more nitrogen in organically managed soils. Higher quality strawberry *Fragaria ananassa* fruit was produced on the organic farms (8.5% more antioxidants (substance which prevents a chemical reaction causing food to deteriorate)) and strawberries were more resistant to disease (strawberries survived 4.54 days on average when mould present) than on conventional farms (strawberries survived 4.15 days). Fruit from organic farms was 13.4% smaller than from conventional farms. The experimental areas included 13 replications of paired commercial organic and conventional strawberry farms. The study took repeated samples of strawberries and soils (to 30 cm depth) to measure strawberry quality, soil biological and chemical properties, and numbers of soil microorganisms.

A randomised, replicated experiment in 2004 on a fine sandy-loam soil in North Carolina, USA (4) found more than four times more nematodes in organic strip tillage plots than in conventional tillage plots with synthetic chemical inputs. Nematode numbers were 41% higher under organic inputs, and 48% higher under organic with strip tillage, compared to plots with synthetic inputs and conventional tillage. Earthworm numbers were 31 times higher under strip compared to conventional tillage, and higher under organic rather than conventional inputs in spring only. Combining strip tillage and organic inputs resulted in the highest numbers of nematodes and earthworms. There were four treatments: strip tillage with organic inputs, strip tillage with synthetic inputs (pesticides and fertilizers), conventional tillage with organic inputs and conventional tillage with synthetic inputs. Within each treatment were 12.2 x 24.4 m plots which had vegetable rotations including: wheat *Triticum aestivum,* crimson clover *Trifolium incarnatum,* sweet corn *Zea mays,* cabbage and broccoli *Brassica oleracea,* tomato *Solanum lycopersicum*, squash *Curcurbita pepo*, cucumbers *Cucumis sativus* and peppers *Capsicum annuum.* There were four replications of the tillage and input combinations. The study took nematode samples and earthworm extractions (species not specified for either group).

A randomised, replicated experiment in 2004-2007 on sandy-clay loam in Georgia, USA (5) found soil carbon was lower under organic management with strip tillage (8.0 MgC/ha) than under alley crop management (13.4 MgC/ha). Soil nitrogen followed a similar pattern. Alley cropping stored more soil carbon than conventional tillage (10.7 MgC/ha). Soil microbial biomass was not affected. Crop yields were highest under alley cropping (3932 and 5060 kg/ha okra *Abelmoschus esculentus* and hot pepper *Capsicum annum* respectively) except the corn *Zea mays*/squash *Curcurbita moschata* intercrop, which was highest under organic management with strip tillage (4087 kg/ha). Four treatments included: alley cropping with strip tillage, organic management with conservation tillage, conventional tillage and fertilizer, and mowed fallow (4, 4, 8 and 6 replicates respectively). Mimosa *Albizia julibrissin* hedges were 5 m apart with crops grown in between in 15 cm wide by 15 cm deep furrows. Compost and straw mulch were added to each treatment. Vegetable crops were grown in rotation with winter cover crops: okra, hot pepper, corn, squash, crimson clover *Trifolium incarnatum*, pea *Pisum sativum* and rye *Secale cereale.* Soils were sampled each year to 15 cm depth, and measured soil carbon, nitrogen and microbial biomass.

A replicated experiment in 2009 on gravelly silt loam and sandy-clay soils in Sicily, Italy (6) found higher carbon levels in the soil (11,000 mg C/kg soil) in organic compared to conventionally managed orchards (8,750 mg C/kg soil). Greater numbers and activity of soil microorganisms occurred in organic (110 mg/kg and 8 mg/kg respectively) than conventional orchards (60 mg/kg and 8 mg/kg respectively). Maximum yield was lower in organic orchards (20 t/ha) compared to conventional orchards (35 t/ha). There were 13 replications of paired organically and conventionally managed citrus orchards (crop species not specified). The study measured soil organic carbon and microbial biomass and activity.

A replicated experiment in 2001-2006 on loamy soil in Saskatchewan, Canada (7) found less nitrate (74 kg N/ha) and phosphorus (19 kg P/ha) in soil under organic inputs than under high or reduced inputs (85 kg N/ha, 24 kg P/ha respectively). Nitrate was usually higher in treatments with fewer crop types. Lower yields were recorded in organic compared to high or reduced input treatments (amounts not specified). Three input (tillage/management) levels (organic, reduced, high) were replicated four times. Within these input levels were three crop diversities: low (fallow/wheat *Triticum aestivum*/oilseed *Brassica juncea*); cereal (wheat / mustard *Brassica juncea* or canola *Brassica napus*/ lentil *Len culinaris* rotations; or grain (perennial forage crop (sweet clover *Melilotus officinalis*, pea *Pisum sativum*, flax *Linum usitatissimum* or alfalfa *Medicago sativa*)/ barley *Hordeum vulgare*) rotations. Within these were six crop phases, rotating the above species with green manure and fallow phases, which were tested in 40 x 12.8 m plots. Fertilizers and pesticides were not applied to the organic treatment. Crop rotations were six years long. Each year, two soil samples were taken from each crop phase (with a third also taken in 2006) to measure nitrate-N, carbon, nitrogen, and phosphorus.

(1) Chaudhry, V., Rehman, A., Mishra, A., Chauhan, P.S. & Nautiyal, C.S. (2012) Changes in bacterial community structure of agricultural land due to long-term organic and chemical amendments. *Microbial Ecology*, 64, 450–60.

(2) Liu, B., Tu, C., Hu, S., Gumpertz, M. & Ristaino, J.B. (2007) Effect of organic, sustainable, and conventional management strategies in grower fields on soil physical, chemical, and biological factors and the incidence of Southern blight. *Applied Soil Ecology*, 37, 202–214.

(3) Reganold, J. P., Andrews, P. K., Reeve, J. R., Carpenter-Boggs, L., Schadt, C. W., Alldredge, J. R., Ross, C. F., Davies, N. M. & Zhou, J. 2010. Fruit and soil quality of organic and conventional strawberry agroecosystems. *PLoS ONE,* 5, 1-14.

(4) Overstreet, L. F., Hoyt, G. D. & Imbriani, J. 2010. Comparing nematode and earthworm communities under combinations of conventional and conservation vegetable production practices. *Soil &Tillage Research,* 110, 42-50.

(5) Jacobsen, K. L. & Jordan, C. F. 2009. Effects of restorative agroecosystems on soil characteristics and plant production on a degraded soil in the Georgia Piedmont, USA. *Renewable Agriculture and Food Systems*, 24, 186-196.

(6) Canali, S., Bartolomeo, E. Di, Trinchera, A., Nisini, L., Tittarelli, F., Intrigliolo, F., Roccuzzo, G. & Calabretta, M. L. 2009. Effect of different management strategies on soil quality of citru orchards in Southern Italy. *Soil Use and Management,* 25, 34-42.

(7) Malhi, S. S., Brandt, S. A., Lemke, R., Moulin, A. P. & Zentner, R. P. (2009) Effects of input level and crop diversity on soil nitrate-N, extractable P, aggregation, organic C and N, and nutrient balance in the Canadian Prairie. *Nutrient Cycling in Agroecosystems,* 84, 1-22.

3.5. Plant new hedges

- Five studies in Slovakia[4], Kenya[1] and Thailand[2] measured the effects of planting grass or shrub hedgerows on soil animals and soil fertility. All five found hedgerows to maintain or improve soil fertility and soil animal activity. Of these, three replicated studies[1, 2, 5] found reduced soil erosion and higher soil organic matter levels. Another replicated trial[4] found a higher diversity of soil animals near to the hedgerows. One of the replicated studies[5] and one review[3] found that adding woody species to the hedgerows improved many factors contributing to soil fertility.
- **Soil types covered:** Alluvial[4], clay[1, 5], sandy-loam[2].

Background

Alluvial soil is a fine-grained fertile soil deposited by water flowing over flood plains or in river beds.

A controlled, randomised, replicated experiment in 1997-1999 on clay soil in Kenya (1) found that contour hedges conserved more soil on a 20% slope (168 Mg/ha) and 40% slope (146 Mg/ha) compared to plots with no hedges. Runoff was lower from 20% and 40% slopes (298 mm, 186 mm) compared to control plots (356 mm, 222 mm respectively). Less nitrogen and phosphorus was lost from the 20% slope than 40% slope with hedges, than without them. Calliandra *Calliandra calthyrsus*-Napier grass *Pennisetum pupureum* yield was 12 Mg/ha (20% slope) and 9 Mg/ha (40% slope), and used as animal fodder. Contour hedgerows containing calliandra and Napier grass were planted in 12 plots split between a 20% and 40% slope, and also control plots without hedges. There were three replicates. Maize *Zea mays* was grown on all plots. The study took soil samples from each plot and measured runoff, soil loss, nitrogen, phosphorus and yield.

A controlled, replicated experiment in 2011 on a sandy loam in Thailand (2) found that vetiver *Vetiver nemoralis* hedgesreduce runoff volume by 31-69% and soil loss by 62-86% compared to the control without hedges. Vetiver hedges (vetiver grass barrier planted along contours) were planted on three slope gradients (30, 40 and 50%). There were four plots on each slope, 2 x 6.71 m in size. One plot on each slope was a control without hedges. An artificial rainfall system was used to test rainfall erosion, applying rainfall intensities of: 35, 60, 85, 110, 135, and 160 mm/h. There were three replicates. Runoff and soil loss were measured.

A 1997 review of case studies in sub-Saharan Africa, gathered from published literature (3) reported that woody species in alley cropping systems can improve nutrient recycling, reduce soil nutrient loss, encourage soil animal activity, control erosion, improve soil fertility and sustain levels of crop production. Legume species suitable for alley cropping include: gliricidia *Gliricidia sepium,* Leucaena *Leucaena leucocephala,* pigeon pea *Cajanus cajan,* calliandra *Calliandra calothyrsus,* mountain immortelle *Erythrina poeppigiana,* apa apa *Flemingia macrophylla,* and Christ thorn *Dactyladenia barteri.* In alley cropping multipurpose trees and shrubs and food crops are intercropped (two or more crops grown between the rows of another).

A replicated study in 1996 on alluvial soils near to the Ondava River, Slovakia (4) showed that soil conditions close to or beneath uncultivated field margins (willow *Salix alba* hedgerows) can be beneficial for oribatid mite (mites which live in the topsoil) diversity. Sampling was carried out along a transect incorporating a range of habitats (see below) over 212 m, in a corn *Zea mays* field. The willow hedgerow was found to have greater diversity than the other four sampled transect sites. At each site, eight soil samples were collected from random locations within a 9 m^2 plot, at 12 weekly intervals. The sampling sites along the transect were: willow hedgerow, corn field, depression in field, followed by two more sites located further into the corn field.

A randomised, controlled, replicated experiment in 2001-2003 on clay soil in Kenya (5) found less soil was lost from slopes with Napier grass *Pennisetum purpureum* barriers (14.9 t/ha) than with combination tree/Napier hedges (calliandra 19.2 and leucaena 16.2 t/ha), tree hedges alone (calliandra 25.3, leucaena 27.8 t/ha), or control plots (61.9 t/ha). Inorganic nitrogen was higher in tree hedge plots (33.1 and 30.8 (NH_4 + NO_3) kg/ha) compared to Napier barrier or control plots. Tree and combination hedges had higher maize *Zea mays* yield (2.6-2.9 t/ha) than Napier (1.5 t/ha) and control plots (2.2 t/ha). On 33 farms, hedges/barriers of calliandra *Calliandra calothyrsus* (tree), leucaena *Leucaene trichandra* (tree) or Napier grass, and combinations of the tree species with Napier grass were established, on slopes exceeding 5%. Control plots had no hedges. Plots were 10 m long stretches of hedge. Soils were sampled 20 months into the experiment; soil fertility and loss, and maize *Zea mays* crop yield were measured.

(1) Anigma, S. D., Stott, D. E., O'Neill, M. K., Ong, C. K., Weesies, G. A. (2002) Use of calliandra-Napier grass contour hedges to control erosion in central Kenya. *Agriculture, Ecosystems and Environment*, 91, 15-23.

(2) Donjadee, S. & Tingsanchali, T. (2013) Reduction of runoff and soil loss over steep slopes by using vetiver hedgerow systems. *Paddy Water Environment*, 11, 573-581.

(3) Kang, B. T. (1997) Alley cropping – soil productivity and nutrient recycling. *Forest Ecology and Management,* 91, 75-82.

(4) Ľuptáčik, P., Miklisová, D. & Kováč, Ľ. (2012) Diversity and community structure of soil Oribatida (Acari) in an arable field with alluvial soils. *European Journal of Soil Biology*, 50, 97–105.

(5) Mutegi, J. K., Mugendi, D. N., Verchot, L.V., Kung'u, J. B. (2008) Combining napier grass with leguminous shrubs in contour hedgerows controls soil erosion without competing with crops. *Agroforestry Systems,* 74, 1-13.

4. Arable farming

4.1. Add mulch to crops

- **Biodiversity:** Three replicated trials from Canada[1], Poland[9] and Spain[2] (including one also controlled, one also randomised and one also controlled and randomised) showed that adding mulch to crops (whether shredded paper, municipal compost or straw) increased soil animal and fungal numbers, diversity and activity. Of these, one trial[2] also showed that mulch improved soil structure and increased soil organic matter.
- **Nutrient loss:** One replicated study from Nigeria[11] found higher nutrient levels in continually cropped soil.
- **Erosion:** Five studies from India[3], France[4], Nigeria[6, 7] and the UK (including one controlled, randomised, replicated trial[3], one randomised, replicated trial[5], two replicated[6, 7] (one also controlled), and one controlled trial[4]) found that mulches increased soil stability, and reduced soil erosion and runoff. One trial[3] found that some mulches are more effective than others.
- **Drought:** Two replicated trials from India found that adding mulch to crops increased soil moisture[8, 10].
- **Yield:** Two replicated trials from India[3, 8] found that yields increased when either a live mulch or vegetation barrier combined with mulch was used.
- **Soil types covered:** clay[6, 10], fine loam[8], gravelly sandy loam[1], sandy[10], sandy-clay[7, 11], sandy loam[4, 5], sandy silt-loam[3], silty[9, 10], silty loam[2].

BACKGROUND

For this synopsis we consider higher numbers and a higher diversity of microorganisms as indicators of fertile soil. Protozoa are single-celled organisms which can move around, feed on organic matter (carbon and nitrogen compounds) and often also photosynthesise, which means they can fix carbon into organic compounds, providing food sources for other organisms. Nematodes are tiny microscopic worms. Arbuscular mycorrhizal fungi are a group of fungi that live around the roots of plants. By living together, the fungi and host plant benefit each other: the fungi can live in a habitat without having to compete for resources and have a supply of carbon from the plant, while they provide an enhanced supply of nutrients to the plant, improving plant growth, the ability to reproduce and tolerance to drought. Arbuscular mycorrhizal fungi colonise a wide variety of host plants including grasses, herbs, agricultural crops and legumes (Bardgett 2005).

Soil aggregates are groups of soil particles that bind to each other more strongly than to adjacent particles. Aggregate stability is the ability of soil aggregates to resist disintegration when disruptive forces associated with tillage and water or wind erosion are applied. Soil stability can is the ability of a soil to resist damage and chemical and physical change.

Bardgett R. (2005) *The Biology of Soil: A community and ecosystem approach*. Oxford University Press, Oxford.

A controlled, randomised, replicated experiment in 1994-2000 on gravelly-sandy loam in British Columbia, Canada (1) found that soil nematode and protozoan diversity was higher under mulches of shredded paper (56 Shannon diversity index) and shredded paper combined with municipal compost (54 Shannon diversity index), relative to the unmulched control (45 Shannon diversity index). Soil nematode diversity was reduced under mulches of municipal biosolids (solid processed sewage sludge) and alfalfa *Medicago sativa* hay compared to the control. Spartan apple *Malus domestica* trees were established in rows in 1994, and seven treatments were applied between rows: control (conventional management), municipal biosolids, shredded office paper, shredded office paper over municipal biosolids, shredded office paper over a composted mixture of biosolids and garden waste, alfalfa hay and black polypropylene mulch. Soil samples for nematode and protozoan community analyses were taken from each plot in October 1998, June 1999 and October 2000.

A controlled, replicated experiment in 2005-2009 on silty loam soil in eastern Spain (2) found that after five years, oat *Avena sativa* straw mulching had the highest levels of soil organic matter (4.5% of the soil), arbuscular mycorrhizal proteins (1,350 mg proteins/g soil) and aggregate stability (80%) compared to herbicide or ploughed plots (2% organic matter, 700 and 400 mg/g proteins, 41% and 57% aggregate stability, respectively). Plots with oat mulching also had lower soil erosion rates (0 Mg/ha/h soil loss) than herbicide or ploughed plots (0.97 Mg/ha/h and 0.01 Mg/ha/h, respectively). The other treatments had similar values to an abandoned land control. There were three replicates of five management treatments including: herbicide application; ploughing; ploughing then sowing oats; addition of oat straw mulch (0.25 kg/m^2/year); and land abandonment (control). Plots were 6 x 10 m. Soil under native vegetation was used as a reference. Six soil samples from each plot were taken annually to 5 cm depth. Five rainfall simulations were also conducted during the summer drought period to test erosion on 1 m^2 plots. Simulations lasted one hour at 55 mm/h.

A controlled, randomised, replicated experiment in 2007-2010 on sandy silt-loam in India (3) found lower soil loss and runoff from the palmarosa *Cymbopogon martinii* treatment with mulching, organic manures and minimal tillage (3.4 t/ha, 234 mm), than with no vegetation barrier (7.1 t/ha, 428 mm). The panicum without mulch treatment was less effective (5.2 t/ha, 356 mm) than mulched palmarosa. Maize *Zea mays* yield was 43% higher under minimal tillage with mulched palmarosa compared to no vegetation barrier with conventional tillage. The succeeding wheat *Triticum aestivum* yield was on average 73% higher in the palmarosa relative to panicum treatment, and 99% higher than with no vegetation barrier. It is not clear whether these results were due to organic amendments, mulching or reduced tillage. There were three replications of three treatments in a maize-wheat crop rotation: conventional tillage with no vegetation barrier but applying fertilizers and herbicides; conventional tillage with a panicum *Panicum maximum* vegetation barrier, fertilizers and herbicides; minimal tillage (30% crop cover retained) with a palmarosa vegetation barrier plus mulching and farmyard manure, vermicompost (produced by worms) and poultry manure applications. Plots were 100 x 20 m.

A controlled experiment in 1991-2000 on a sandy loam in vineyards in Champagne, France (4) found higher soil particle stability in the topsoil under coniferous bark mulch (soil stability index of 15.2) and poplar bark mulch (soil stability index of 13.6) compared to an unmulched control (soil stability index of 10.5). The highest stability was found under a grass cover (soil stability index of 21.7). The conifer bark layer also increased stability in soils. Four treatments were tested, of which three were in 35 x 8 m plots: a bluegrass *Poa pratensis* cover between vine rows only, organic mixed mulch of coniferous *Abies alba, Picea excelsa, Pinus sylvestri* bark between and in vine rows (61 t/ha applied every three years), organic mulch of poplar *Populus* spp. bark (67 t/ha applied every three years), or bare soil between rows (15 x 8 m control plot). Soil under the grass cover was sampled in and between vine rows; the mulch and control treatments were sampled only between vine rows. All soils were sampled to 20 cm depth.

A randomised, replicated experiment in 1986 on sandy loam in East Malling, UK (5) found that straw mulch reduced soil erosion by 85% in the alleys between trees, compared to the bare ground treatment (average of 0.45 t/ha lost). Erosion was highest between trees where soil had been compacted by traffic. There were two treatments in a 144 x 18 m mature apple *Malus domestica* orchard: bare soil mulched with 6 t/ha of straw and bare soil treated with 2.4 kg/ha simazine herbicide applied in spring. Each of the eight treatment plots was 36 x 9 m, replicated four times. Two troughs set into the soil downslope of all the plots measured soil loss.

A replicated experiment in 1970-1974 on sandy-clay to clay soil in Nigeria (6) found that mulched continuous maize *Zea mays* after ploughing had the lowest soil loss (0 t/ha) compared to continuous maize without mulch (41 t/ha) and bare fallow plots (230 t/ha). Runoff was also lower in the mulched treatment (2% of total annual rainfall) compared to bare fallow (36%). Slopes of 1, 5, 10 and 15% received the following treatments: bare fallow (conventionally ploughed); continuous maize (conventionally ploughed, mulched); continuous maize (conventionally ploughed, no mulch); maize-cowpea *Vigna unguiculata* rotation (zero-tillage); and cowpeas-maize rotation (conventionally ploughed). Plots were 25 x 4 m and were replicated five times on each slope. Soil and runoff water was collected from each plot after every rainstorm using a water collection system below ground level downslope of the plots.

A controlled, replicated experiment in 1970-1974 on sandy-clay to clay soil in Nigeria (7), found runoff was lowest under 6 t/ha straw mulch (2% of total annual rainfall), then 4 t/ha (4%) and 2 t/ha (10), compared to no mulch (50%). Soil loss from rainstorms where more than 25 mm fell was lowest under 6 t/ha mulch (0.4 kg/ha), then 4 t/ha (2 kg/ha) and 2 t/ha (16 kg/ha), compared to no mulch (143 kg/ha). Slopes of 1, 5, 10 and 15% received the following treatments: no mulch, 2, 4, and 6 t/ha straw mulch. Plots were 25 x 4 m and were replicated five times on each slope. Plots were ploughed, harrowed and mulched at the beginning of each growing season. Soil and runoff water was collected from each plot after every rainstorm using a water collection system below ground level downslope of the plots.

A replicated experiment in 2000-2004 on fine loamy soil in Dehradun, India (8) found that live mulching with sunnhemp *Crotalaria juncea* or leucaena *Leucaena leucocephala* increased soil moisture content by 6.8-8.8% compared to no mulching. Combining both sunnhemp and leucaena increased soil moisture by a further 2.1-2.3% and increased overall grain yield by 15% of both maize *Zea mays* and wheat *Triticum aestivum*. A maize crop was grown followed by a wheat crop. In each main crop were four treatments in 130 m^2 plots: no mulching (control), sunnhemp grown in situ (live mulching), leucaena prunings/twigs, and sunnhemp and leucaena combined. Each treatment had 29 m^2 subplots with fertiliser applied at a rate of 0, 30, 60 or 90 kg N/ha for maize, and 0, 40 or 80 kg/ha for wheat. There were four replications.

A randomised, replicated experiment in 2008 on silty soils in Lublin, Poland (9) found that adding a straw mulch increased bacteria counts (3.5 billion colonies/kg) and activity compared to soil with no mulch (2.4 billion colonies/kg). There were three compaction treatments in a soybean *Glycine max* crop obtained using a wheel tractor: strongly compacted (5 passes); moderately compacted (3 passes); and uncompacted (0 passes) soil. There were six replicates. Within each treatment were 1.8 x 2.1 m plots with either no mulch or straw mulch. Fertiliser was applied uniformly to all plots at 54-70-80 kg/ha NPK. Bacterial numbers and enzyme activities were measured in soil samples taken three times during crop development from the centre of the soybean rows.

A randomised, replicated experiment, in 1996-1998 on sandy, silty and clay soil in Ludhiana, India (10) found higher soil moisture storage during dry conditions by applying straw mulch, (30.3 mm water/20 cm soil) compared to untreated coarse- and medium-textured soils (28.8 cm). Straw incorporation was better in rain-free conditions (26.7 cm) and rainy conditions (22.2 cm) in medium coarse-textured soils compared to untreated soil (24.2 and 21.1 cm). In the coarsest soil, tillage and straw mulching did not increase soil water storage any more than untreated soil. Below the tillage and straw incorporation treatments, soil water content was higher (0.1318 and 0.1314 m^3 water/m^{-3} soil, respectively) relative to the untreated and mulched soils (0.1059 and 0.1180 m^3/m^3). There were four treatments on three soil types: untreated, tilled to 8 cm depth, straw mulch (rice *Oryza sativa* in September and wheat *Triticum aestivum* in April) at 6 t/ha, and straw incorporation. The treatments were replicated three times in 2.5 x 3.5 m, 5 x 3 m and 6 x 4 m plots, for fine, medium coarse, and coarse soil respectively. Mechanical weeding or herbicides (glyphosate) kept plots weed free. Soil water content was measured every 15-20 days.

A replicated experiment in 1970-1974 on sandy-clay to clay soil in Nigeria (11), found lower nutrient loss in continuous maize *Zea mays* with mulch (2.3 kg/ha) continuous maize no mulch (17 kg/ha) and bare fallow (55 kg/ha). Slopes of 1, 5, 10 and 15% received the following treatments: bare fallow (conventionally ploughed); continuous maize (conventionally ploughed, mulched); continuous maize (conventionally ploughed, no mulch); maize-cowpea rotation (zero-tillage); and cowpea *Vigna unguiculata*-maize rotation (conventionally ploughed). Maize received 120, 26 and 60 kg/ha nitrogen, phosphorus and potassium respectively. Plots were 25 x 4 m and were replicated five times on each slope. Soil and runoff water was collected from each plot after every rainstorm using a water collection system below ground level downslope of the plots.

(1) Forge, T.A., Hogue, E., Neilsen, G. & Neilsen, D. (2003) Effects of organic mulches on soil microfauna in the root zone of apple: implications for nutrient fluxes and functional diversity of the soil food web. *Applied Soil Ecology*, 22, 39–54.

(2) García-Orenes, F., Roldán, A., Mataix-Solera, J., Cerdà, A., Campoy, M., Arcenegui, V. & Caravaca, F. 2012. Soil structural stability and erosion rates influenced by agricultural management practices in a semi-arid Mediterranean agro-ecosystem. *Soil Use and Management*, 28, 571-579.

(3) Ghosh, B. N., Dogra, P., Bhattacharyya, R., Sharma, N. K. & Dadhwal, K. S. 2012. Effects of grass vegetation strips on soil conservation and crop yields under rainfed conditions in the Indian sub-Himalayas. *Soil Use and Management,* 28, 635-646.

(4) Goulet, E., Dousset, S., Chaussod, R., Bartoli, F., Doledec, A. F & Andreux, F. 2004. Water-stable aggregates and organic matter pools in a calcareous vineyard soil under four soil-surface management systems. *Soil Use and Management*, 20, 318-324.

(5) Hipps, N. A., Hazelden, J. & Fairall, G. B. N. 1990. Control of erosion in a mature orchard. *Soil Use and Management*, 6, 32-35.

(6) Lal, R. 1976. Soil erosion on Alfisols in Western Nigeria, I. Effects of slope, crop rotation and residue management. *Geoderma*, 16, 363-375.

(7) Lal, R. 1976. Soil erosion on Alfisols in Western Nigeria, II. Effects of mulch rates. *Geoderma*, 16, 377-387.

(8) Sharma, A. R., Singh, R., Dhyani, S. K. & Dube, R. K. 2010. Moisture conservation and nitrogen recycling through legume mulching in rainfed maize (*Zea mays*)-wheat (*Triticum aestivum*) cropping system. *Nutrient Cycling in Agroecosystems*, 87, 187-197.

(9) Siczek, A. & Frąc, M. 2012. Soil microbial activity as influenced by compaction and straw mulching. *International Agrophysics*, 26, 65-69.
(10) Jalota, S. K., Khera, R. & Chahal, S. S. 2001. Straw management and tillage effects on soil water storage under field conditions. *Soil Use and Management*, 17, 282-287.
(11) Lal, R. 1976. Soil erosion on Alfisols in Western Nigeria, IV. Nutrient element losses in runoff and eroded sediments. *Geoderma,* 16, 403-417.

4.2. Amend the soil with bacteria or fungi

- **Biodiversity:** One randomised, replicated trial from India[2] showed that adding soil bacteria and arbuscular mycorrhizal fungi resulted in higher microbial diversity.
- **Soil organic matter:** One controlled, randomised, replicated trial from Turkey[1] found increased soil organic matter content in soil under mycorrhizal-inoculated compost applications
- **Yield:** Two randomised, replicated trials (including one also controlled[1]) from India[2] and Turkey[1] found higher crop yields.
- **Soil types covered:** clay-loam[1], sandy-loam[2].

BACKGROUND

Soil microbial biomass is the amount of tiny living microorganisms within a given area or amount of soil. Arbuscular mycorrhizal fungi are a group of fungi that live around the roots of plants. By living together, the fungi and host plant benefit each other: the fungi can live in a habitat without having to compete for resources and gain a supply of carbon from the plant, while they provide an enhanced supply of nutrients to the plant which improves plant growth, the ability to reproduce and tolerance to drought. Arbuscular mycorrhizal fungi colonise a wide variety of host plants, including grasses, herbs, agricultural crops and legumes (Bardgett 2005).

Bardgett R. (2005) *The Biology of Soil: A community and ecosystem approach*. Oxford University Press, Oxford.

A controlled, randomised, replicated experiment from 1996 to 2008 on clay-loam soil in southern Turkey (1) found 24% higher organic matter content in soil under mycorrhizal-inoculated compost applications compared to the control. The largest soil aggregations were found under mycorrhizal-inoculated compost (0.11 mm), manure (0.05 mm) and compost (0.07) applications. Crop yield was highest under mineral fertilizer (13720 kg/ha) followed by manure (10500 kg/ha), compost (8780 kg/ha) and mycorrhizal-inoculated compost (7630 kg/ha), compared to the control (5900 kg/ha). Within a wheat *Triticum aestivum*-maize *Zea mays* rotation were three replicates five 10 x 20 m treatments: control, mineral fertilizer (300-60-150 kg N-P-K/ha), manure (25 t/ha), compost (equal mixture of grass, wheat stubble and plant leaves, 25 t/ha), mycorrhizal *Glomus caledonium*-inoculated compost (10 t/ha). Soil samples were taken to 30 cm depth 2008.

A controlled, randomised, replicated experiment in 2002-2004 on sandy-loam soil in Udham Singh Nagar, India (2) found that adding soil bacteria and arbuscular mycorrhizal fungi (see background section) increased soil microbial diversity (2.5 x 10^3 colonies/g soil), compared to the control (1.9 x 10^3 colonies/g soil). Crop yields in okra *Hibiscus esculentus*, pea *Pisum sativa* and cowpea *Vigna unguiculata* increased when bacteria (33, 25 and 8 kg/ha, respectively) and arbuscular mycorrhizal fungi (40, 28 and

11 kg/ha) were added, compared to the control (22, 21, and 4 kg/ha). Three crops were grown in rotation: okra, pea and cowpea. Each plot was 16 m^2. AMF *Glomus intraradices* and a bacterium species *Pseudomonas fluorescens* were added to the soil as treatments. Only crop residues were added during the experiment. There were three replicates. Soil samples were taken and soil microbe numbers were measured. The effect of rotation was not reported.

(1) Celik, I., Gunal, H., Budak, M. & Akpinar, C. 2010. Effects of long-term organic and mineral fertilizers on bulk density and penetration resistance in semi-arid Mediterranean soil conditions. *Geoderma*, 160, 236-243.

(2) Srivastava, R., Roseti, D. & Sharma, A. K.2007. The evaluation of microbial diversity in a vegetable based cropping system under organic farming practices. *Applied Soil Ecology,* 36, 116-123.

4.3. Amend the soil with composts not otherwise specified

- **Soil organic matter:** One controlled, randomised, replicated trial in Italy[1] found that applying a high rate of compost increased soil organic matter levels, microbial biomass and fruit yield.
- **Soil types covered:** Silty-clay[1].

Background

Soil microbial biomass is the amount of tiny living microorganisms within a given area or amount of soil.

A controlled, randomised, replicated experiment in 2001-2009 on silty-clay soil in Italy (1) found 169% more soil organic matter in soil receiving 10 t/ha/year of compost compared to an unfertilised control, after 8 years. Soil receiving 5 t/ha/year of compost applied had 75% more organic matter compared to the control. Mineral fertilizers had no effect on organic matter levels. Soils receiving compost at 10 t/ha/year had higher microbial biomass (12 mg/g soil) and fruit yield (51 kg/tree) compared to the control (6.6 mg/g soil and 43 kg/tree, respectively). Six treatments replicated four times were applied to nectarine *Prunus persica* trees: (1) unfertilized control, (2) mineral fertilizer including phosphorus (100 kg/ha), potassium (200 kg/ha) and nitrogen (70 kg/ha), (3) cow manure (10 decreasing to 5 t/ha), (4) compost at planting then 5 t/ha/year, (5) compost at 5 t/ha/year, (6) compost at 10 t/ha/year. Soil samples were collected annually in September to 40 cm depth. Nectarine trees were spaced at 5 m between rows and 3.8 m between trees. Compost and manure were measured in tonnes of dry weight.

(1) Baldi, E., Toseli, M., Marcolini, G., Quartieri, M., Cirillo, E., Innocenti, A. & Marangoni, B. 2010. Compost can successfully replace mineral fertilizers in the nutrient management of commercial peach orchard. *Soil Use and Management*, 26, 346-353.

4.4. Amend the soil with crops grown as green manures

- **Soil organic matter:** Two controlled, randomized, replicated studies from India[2] and Pakistan[1] found higher soil organic carbon, and one[1] found increased grain yields when green manures were grown.
- **Soil types covered**: Clay loam[1, 2].

A controlled, randomized, replicated experiment in 2007-2008 on clay loam in Pakistan (1) found the highest rice yield after a sesbania Sesbania rostrata green manure (3.73 t/ha), then mungbean Vigna radiata (3.57 t/ha) and berseem Trifolium alexandrinum (3.53 t/ha) green manures, compared to the rice Oryza sativa-wheat Triticum aestivum only rotation (2.59 t/ha). Wheat yield was also higher under sesbania (2.81 t/ha), mungbean (2.69 t/ha) and cowpeas Vigna unguiulata (2.63 t/ha) compared to rice-wheat only (2.59 t/ha). Soil organic carbon increased from 0.67% to 0.72% (of total soil collected) during the experiment. Four green manures were grown and harvested prior to the planting of a rice-wheat rotation, which included: mungbean, cowpeas, sunflower *Helianthus annuus*, sesbania. Three more green manures were sown after harvesting the rice crop including: berseem, lentil Lens culinaris, canola Brassica napus. These were compared to a rice-wheat crop only rotation. All green manures were incorporated into the soil before rice or wheat was transplanted or sown. Plots were 10 x 14 m. There were three replicates. Soils were sampled before sowing and after harvest of the rice-wheat crops to 20 cm depth.

A controlled, randomized, replicated experiment in 2000-2002 on clay loam in India (2) found 10.6% higher soil organic carbon when sesbania Sesbania rostrata was included in cropping, compared to continuous rice Oryza sativa. There were five combinations of rice and sesbania consisting of: fallow-rice-rice, sesbania-rice-rice, sesbania-rice-sesbania-rice, sesbania-rice-rice-sesbania, and sesbania-rice-sesbania-rice-sesbania. Each combination was divided into four manure treatments: control (none applied), farm yard manure (12.5 t/ha), poultry manure (5 t/ha), and dual cropping with fern Azolla hybrid. There were three replication of each crop combination. Plot size was not specified. Soils were sampled after each rice harvest (depth not specified).

(1) Ali, R. I., Awan, T. H., Ahmad, M., Saleem, M. U. & Akhtar, M. 2012. Diversification of Rice-Based Cropping Systems to Improve Soil Fertility, Sustainable Productivity and Economics. *The Journal and Animal & Plant Sciences,* 22, 108-112

(2) Ramesh, K. & Chandrasekaran, B. 2004. Soil Organic Carbon Build-up and Dynamics in Rice-Rice Cropping Systems. *Journal Agronomy & Crop Science,* 190, 21-27.

4.5. Amend the soil with formulated chemical compounds

- **Nutrient loss:** Three[3, 4, 12] of five replicated trials from New Zealand[3, 4, 5] and the UK[1, 2] measured the effect of applying nitrification inhibitors to the soil and three found reduced nitrate losses[3, 4, 12] and nitrous oxide emissions[4], although one of these found that the method of application influenced its effect[12]. One trial[1] found no effect on nitrate loss. One trial[5] found reduced nutrient and soil loss when aluminium sulphate was applied to the soil.
- **Soil organic matter:** Four [6, 9, 11] of five studies (including two controlled, randomised and replicated[6, 11] and one randomised and replicated[2]) in Australia[2], China[11], India[6], Syria[9] and the UK[8] testing the effects of adding chemical compounds to the soil showed an increase in soil organic matter or carbon when nitrogen or phosphorus fertilizer was applied. One site comparison study[8] showed that a slow-release fertilizer resulted in higher nutrient retention. One study[11] found higher carbon levels when NPK fertilizers were applied with straw, than when applied alone, and one replicated study from France[7] found higher soil carbon when manure rather than chemical compounds were applied.

- **Yield:** One replicated experiment from India[10] showed that maize and wheat yield increased with increased fertilizer application.
- **Soil types covered:** clay[2, 7, 8, 9, 11], fine loamy[10], gravelly-sandy loam[6], loam[3, 12], sandy loam[1, 3, 4], silty[11], silty-clay[11], silt-loam[3, 5].

Background

Water potential measures the tendency of water to move from one area to another due to osmosis, gravity, mechanical pressure, or other effects. Water potential is useful in understanding water movement within plants, animals, and soil. If possible, water will move from an area of higher water potential (lots of water molecules per given volume) to an area that has a lower water potential (fewer water molecules per given volume).
Most slow-release fertilizers release nutrients gradually over time and at specific soil temperatures. Quick-release fertilizers are useful for plants which require higher amounts of nutrients, or a quick supply due to a nutrient deficiency. They tend to break down in the soil much more quickly than slow-release fertilizers. Ammonium-N is often added to soils as a fertilizer for crops. When added to the soil, soil bacteria convert it to nitrate (nitrification). If plants do not take up the ammonium-N immediately it gets converted to nitrate and can be lost from the soil (leaching). A nitrification inhibitor stops or slows down this conversion, and can reduce the loss of nitrate from the soil.

A controlled, randomised, replicated site comparison study in 1990-1994 on a sandy loam in the UK (1) found that applying the nitrification inhibitor dicyandiamide with manure had little to no effect on reducing nitrate leaching (50 kg N/ha lost manure only, 42.5 kg N/ha lost manure with inhibitor). There were two manure treatments at each site: pig/cattle slurry and farmyard cattle manure in Shropshire and poultry litter and farmyard cattle manure in Nottinghamshire. Manures were applied monthly at 200 kg N/ha between September and January to overwinter fallow or directly onto winter rye *Secale cereale*. An extra treatment was included to test dicyandiamide, which was applied at 20 l/ha. All treatments were replicated three times at both sites. Plots were 12 x 4 m and 15 x 4 m in the Shropshire and Nottinghamshire sites, respectively. Total soil mineral nitrogen was measured.

A randomised, replicated experiment from 1968 to 2008 on clay soil in Australia (2) found soil organic carbon was highest under high (20.40 Mg/ha), then medium (20.13 Mg/ha), compared to no nitrogen application (19.53 Mg/ha), in the topsoil. Fertilizer application only affected carbon levels when crop residue was retained, (1.8 Mg C/ha more carbon under high fertilizer with residues retained, compared to no fertilizer no residue). Nitrogen was 125 kg N/ha higher under high fertilizer application compared to no fertilizer. Total soil nitrogen increased with nitrogen fertilizer application only when crop residues were retained. Average grain yield was highest under no-tillage plus crop residue and high fertilizer (2.86 Mg/ha) and lowest under conventional tillage plus crop residue, no fertilizer (2.28 Mg/ha). Wheat *Triticum aestivum* was the principle crop bar three years which were cropped with barley *Hordeum vulgare.* Treatments included: tillage (conventional tillage 10 cm depth, no-tillage); crop residue management (burned or retained); and nitrogen fertilizer application (none applied, low or high application (30 and 90 kg N/ha/year respectively). Plots were 61.9 x 6.4 m and replicated four times. Soil was sampled in each plot at the end of the experiment to 1.5 m depth.

A replicated study in 2009 on loam, silt-loam and sandy loam soils in South Island, New Zealand (3) found that adding the nitrification inhibitor dicyandiamide reduced nitrate loss by an average of 59% across different soil types and contrasting rainfall conditions. Soils in Canterbury, West Coast and Southland regions were fertilized with cow urine at a rate of 1,000 kg N/ha. Dicyandiamide was applied to half the soils at 10 kg/ha following urine application, and under two rainfall conditions (1,100 and 2,200 mm/year). There were four replicates of each treatment and soils were sampled in large (0.5 x 0.7 m), undisturbed sections.

A replicated, controlled study in 2008 on sandy loam in New Zealand (4) found that two nitrification inhibitors, dicyandiamide and 3,4-dimethylpyrazole phosphate (DMPP), were both effective at reducing nitrogen loss through nitrous oxide emissions and nitrate leaching. Adding dicyandiamide to pasture reduced nitrous oxide emissions by 62% and nitrate loss by 36%, while adding DMPP to pasture reduced nitrous oxide emissions by 66% and nitrate loss by 28%, compared to the control. The study used three treatments, replicated four times on pasture plots planted with a mixture of ryegrass *Lolium perenne* and white clover *Trifolium repens*. Treatments were control (cow urine, 1000 kg/ha), dicyandiamide (cow urine and dicyandiamide at 10 kg/ha) and DMPP (cow urine and DMPP at 1 kg/ha or 5 kg/ha). Treatments were applied in mid-winter and re-applied in early spring. Dicyandiamide and DMPP were both applied as liquid formulations.

This controlled, replicated experiment in 2004-2008 on silt loam soil in New Zealand (5) found that applying alum (aluminium sulphate) after grazing of forage crops by cattle or sheep reduced phosphorus loss by 29% and 26%, and fine sediment loss by 16% and 43%, respectively, compared to normal forage crop grazing. Grazing cattle or sheep on forage crops increased phosphorus loss from fields by approximately 100% (1.3 kg/ha) and 33% (0.9 kg/ha) respectively, compared to normal sheep grazing on pasture (0.6 kg/ha). Forage grazing by cattle or sheep increased fine sediment loss by 1,000% (0.7 mg/ha) and 500% (0.4 mg/ha), relative to grazing pasture with sheep (0.06 mg/ha). Twenty-eight 10 × 25 m plots included four replicates of combinations of the following treatments: cattle or sheep grazing on winter forage crops (triticale *Triticosecale Wittmack*, then kale *Brassica oleracea*), sheep pasture, restricted grazing, or alum addition on the forage crops (20 kg/ha following grazing).

A controlled, randomised, replicated experiment in 2009 on gravelly sandy loams in the South Andaman Islands, India (6) found that adding phosphorus to a cover crop increased nitrogen levels by 16%. Nitrogen mineralisation (the breakdown of organic matter, e.g. leaves, into mineral nitrogen) was greater in cover-cropped soils with added phosphorus than in cover-cropped soils without added fertilizer (73% and 39% greater than control, respectively). Nitrogen levels were 8% higher in soil with no cover crop plus phosphorus, compared to the control. There were six replicates of four treatments in a coconut palm *Cocos nucifera* plantation: no cover crop (control), no cover crop plus phosphorus (16% P (P_2O_5) at 24 kg/ha), cover crop (Kudzu *Pueraria phaseoloides*) and cover crop plus phosphorus (24 kg/ha). Each plot was 40 x 40 m and contained 28 coconut palms 7.5 m apart. Each month 10 soil samples were taken to 15 cm depth from each plot. Soil carbon, nitrogen and nitrogen mineralisation were measured.

A replicated experiment from 1929 to 1999 on clay soil in France (7) found the highest soil organic carbon levels under manure application (37.2 g/kg soil) compared to the control (7.1 g/kg). The remaining treatments had carbon levels similar to or less than the control. Water retention was highest under manure application under low and higher water potential (0.32 g/cm^3 and 0.009 g/cm^3 respectively), compared to nitrogen and potassium treatments (0.17 g/cm^3) (control figures not presented). Manure also had higher soil stability (81.9 % large soil aggregates) compared to phosphorus (22.2%) and nitrogen and potassium treatments (33.8%). Treatments included: no application (control, 10 plots); nitrogen (150 kg/ha/year); potassium (150 kg/ha/year); phosphorus (1t/ha/year); calcium (1 t/ha/year), horse manure (100 t/ha/year). Each treatment was replicated twice in 5 x 5 m plots. Soils were sampled at the end of the experiment.

A site comparison study in 1984-1987 on a peat overlaying clay soil in Plynlimon, UK (8) found that about 10% of phosphorus from quick-release fertilizers (superphosphate) was lost through leaching, compared to slow-release fertilizers (basic slag) for which phosphorus levels in the soil were not affected. There were two sites, the first comprising 1.5 ha of soft rush *Juncus effusus* and purple moor grass *Molinia caerulaea*. This site was disc harrowed, and lime, basic slag, fertilizer and a nitrogenous fertilizer were applied. The second site (19.5 ha) contained purple moor grass and small areas of blanket mire *Calluna vulgaris-Eriophorum vaginatum.* Lime and phosphate fertilizer were applied at this site and grass seed was sown using the spike seeding method (a reduced tillage method whereby ground is spiked with a spike-aerator, then seed is broadcast over the soil). Soil and water samples were collected. Water flow and phosphorus levels were measured.

A replicated experiment from 1989 to 1997 on a clay soil in northern Syria (9), found that increasing nitrogen fertilizer addition (0, 30, 60 and 90 kg N/ha) increased soil organic matter (246, 249, 262, 264 t/ha, respectively). Three replications of 36 x 120 m plots included the following crop rotations: continuous fallow, continuous wheat *Triticum aestivum*, and wheat grown in rotation with lentil *Lens culinaris*, chickpea *Cicer arietinum*, vetch *Vicia sativa,* pasture medic *Medicago* spp., or watermelon *Citrullus vulgaris*. Within each rotation were four smaller 36 x 30 m sub-plots with 0, 30, 60 or 90 kg N/ha applied. Within these were 12 x 30 m grazing treatments: no grazing/stubble retention, medium and heavy grazing. Soil organic matter, nitrogen/nitrates, and phosphorus were measured at the beginning of each cropping season.

A replicated experiment in 2000-2004 on fine loamy soil in Dehradun, India (10) found that maize *Zea mays* yield increased from 1.2 to 2.1, 2.6 and 3.0 t/ha as nitrogen fertilizer rates increased from 0 to 30, 60, and 90 kg N/ha respectively. Wheat *Triticum aestivum* yields also increased with increased nitrogen fertilizer application (1.3, 2.1 and 2.8 t/ha for 0, 40 and 80 kg N/ha). Maize was grown followed by wheat and each crop had four mulching treatments in 130 m^2 plots: no mulching (control), sunnhemp *Crotalaria juncea*, leucaena *Leucaena leucocephala* prunings/twigs, and sunnhemp and leucaena combined. Each treatment had 29 m^2 subplots with fertilizer applied at a rate of 0, 30, 60 or 90 kg N/ha for maize, and 0, 40 or 80 kg/ha for wheat. There were four replications.

A controlled, randomised, replicated experiment from 1990 to 2005 on silty, silty-clay and clay soil at four sites in China (11) found higher soil organic carbon levels under nitrogen/phosphorus/potassium (NPK) plus straw (9.1 g C/kg soil) compared to NPK alone ()8.4 g C/kg) or the control (7.7 g C/kg). Three treatments were applied to long-term wheat *Triticum aestivum*-maize *Zea mays* rotations at four sites: control (no fertilizer), NPK (at 165-362 kg N/ha, 25-41 kg P/ha, and 68-146 kg K/ha), and NPK plus straw (at 2.2-6 Mg/ha)). Weeds were removed manually and crops were irrigated when necessary. Soils were sampled to 20 cm depth at each site in autumn after maize harvest, and before the next fertilizer application.

A replicated, controlled study in 1984-1985 on a loam soil in Berkshire, the UK (12) found that adding a nitrification inhibitor to cattle slurry injected into pasture reduced nitrogen losses from 58 kg N/ha (slurry with no inhibitor) to 28 kg N/ha, and to 34 kg N/ha by spreading slurry on the surface. The effect was less pronounced in spring. The slurry treatments – surface application, injection into pasture, and injection with the nitrification inhibitor nitrapyrin – were applied to ryegrass *Lolium perenne* in December and April at a rate of 80 t/ha. Slurry was poured into ploughed slots in the injection treatments. Each treatment was replicated four times.

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4.6. Amend the soil with fresh plant material or crop remains

- **Biodiversity:** One randomized, replicated experiment from Belgium[7] found increased microbial biomass when crop remains and straw were added.
- **Compaction:** One before-and-after trial from the UK[1] found that incorporating straw residues by discing (reduced tillage) did not improve anaerobic soils (low oxygen levels) in compacted soils.
- **Erosion:** Two randomized, replicated studies from Canada[3] and India[2] measured the effect of incorporating straw on erosion. One found straw addition reduced soil loss[3], and one[2] found mixed effects depending on soil type.
- **Nutrient loss:** Two replicated studies from Belgium[7] and the UK[8] (one also controlled[8] and one also randomized[7]) reported higher soil nitrogen levels when

compost or straw was applied, but mixed results when processed wastes were added[8].
- **Soil organic carbon:** Three randomized, replicated studies[3, 4, 6] (two also controlled[4, 6]) from China and India, and one controlled before-and-after site comparison study from Denmark[5] found higher carbon levels when plant material was added. One[6] found higher carbon levels when straw was applied along with NPK fertilizers. One[3] also found larger soil aggregates.
- **Soil types covered:** clay[2, 6], clay loam[3], loam/sandy loam[1], loamy sand[7], sandy[2], sandy clay loam[4], sandy loam[5, 7, 8], silt loam[7], silty[2, 6], silty-clay[6].

Background

This intervention refers to plant material and crop remains which have been brought in from elsewhere, rather than being left as 'residues' in the soil or on the soil surface after harvest of the valuable crop part (see also 'Retain crop remains'). Soil microbial biomass is the amount of tiny living microrganisms in a given amount of soil and is measured by the amount of carbon or nitrogen they release into the soil. Soil aggregates are groups of soil particles held together by moist clay, organic matter (such as roots), organic compounds (from bacteria and fungi) or fungal hyphae (long, branching structures of a fungus). Some soil particles fit closely together, some do not, creating different-sized spaces. These spaces (or pores) within and between soil aggregates can store air and water, microbes, nutrients and organic matter. Large aggregations of particles retain the most nutrients. Nitrogen mineralization is the process by which soil microbes break down soluble and insoluble organic matter and convert it into inorganic forms which can be used by plants; in contrast, immobilization is when microbes absorb inorganic nutrients from soil solution, thereby reducing their availability for plant uptake. In this intervention, immobilization is being encouraged after cropping to reduce nitrogen leaching. Macroorganic matter is defined as the fraction of soil organic matter with particles larger than 150 μm, made up of fragmented plant residues and microbial debris. Although a small component of soils (macroorganic matter makes up 3-6% of total soil organic matter), it is often called the 'active' fraction as it is linked to water availability and nutrient supply for both plants and microorganisms.

A before-and-after trial in 2003-2005 on loam/sandy loam soils in the UK (1) found that incorporating straw using reduced tillage (without ploughing) did not improve topsoil quality in compacted soils. Anaerobic growing conditions were found, shown by the high nitrous oxide flow to the air from below the straw layer (720 g N/ha/day) compared to above it (50 g N/ha/day). The carrot *Daucus carota* crop was part of a cereal/potato *Solanum tuberosum*/carrot/spring cereal rotation undersown with grass, clover *Trifolium pratense* and peas *Pisum sativum*. Carrot beds were roughly 2 m wide. Straw was incorporated into the soil before the carrot crop. Straw was incorporated using reduced tillage by discing to about 10 cm depth, without ploughing. Nitrous oxide and carbon dioxide fluxes were measured to determine whether soil conditions were anaerobic.

A randomized, replicated experiment in 1996-1998 on a sandy, silty and clay soil in Ludhiana, India (2) found that straw incorporation was better in rain-free conditions (26.7 cm) and rainy conditions (22.2 cm) in medium coarse-textured soils compared to untreated soil (24.2 and 21.1 cm). In the coarsest soil, tillage and straw mulching did not increase soil water storage any more than untreated soil. Below the tillage and straw incorporation treatments, soil water content was higher (0.1318 and 0.1314 m^3 water/m^{-3} soil, respectively) relative to the untreated and mulched soils (0.1059 and 0.1180 m^3/m^3). There were four treatments on three soil types: untreated, tilled to 8 cm depth, straw mulch (rice *Oryza sativa* in September and wheat *Triticum aestivum* in April) at 6 t/ha, and straw incorporation. The treatments were replicated three times in 2.5 x 3.5 m, 5 x 3 m and 6 x 4 m plots, for fine, medium coarse, and coarse soil respectively. Mechanical weeding or herbicides (glyphosate) kept plots weed free. Soil water content was measured every 15-20 days.

A randomized, replicated experiment in 1979-1988 on clay loam in Alberta, Canada (3) found higher soil organic carbon (5.81%) under no tillage plus straw mulch and with tillage plus straw incorporation (5.79%) compared to tillage with no straw treatment (5.5%). Differences between treatments became less pronounced with increased soil depth. Soil aggregates were 38% larger in no tillage plus straw than tillage plus straw treatments, and 175% larger than tillage with no straw. The wind-erodible fraction of soil aggregates (aggregates smaller than 1 mm diameter) was smallest (16%) in no tillage plus straw (meaning soil structural stability was higher), followed by tillage plus straw (29%) compared to tillage with no straw (49%). The effects of tillage and straw remains were not separated. Three tillage and straw treatments were applied to a spring barley *Hordeum vulgare* crop. Treatments included: no tillage (direct seeding) and straw retained on the soil surface; tillage (rotavation to 10 cm depth in autumn and spring) and straw incorporated into topsoil; and tillage with straw removed. Individual plots measured 6.8 x 2.7 m and were replicated four times. Nitrogen was applied at 56 kg N/ha in all treatments. Soils were sampled to 5 cm depth.

A controlled, randomized, replicated experiment in 2001-2011 on sandy clay loam in India (4) found 43.5% higher soil carbon under rice straw plus green manure (using *Sesbania aculeata*) compared to the control (5.16 g/kg). Microbial biomass (measured by quantities of carbon) was highest under farmyard manure plus green manure (250 mg/kg), followed by farmyard manure alone (233 mg/kg), compared to the control (153 mg/kg). Rice yield was highest under farmyard manure plus green manure (3.51 t/ha), followed by rice straw plus green manure (3.35 t/ha), farmyard manure alone (3.25 t/ha), and green manure alone (3.09 t/ha), compared to the control (1.93 t/ha). Treatments were applied to plots of paddy 20 days before plots were planted with transplanted rice *Oryza sativa* (*Geetanjali* variety) seedlings. Treatments included: no amendment (control), farmyard manure, green manure, farmyard manure plus green manure, and rice straw plus green manure (both incorporated into the soil 20 days before seedling transplantation). There were three replications. Soils were sampled at the beginning and end of the experiment to 60 cm depth.

A controlled before-and-after, site comparison study from 1988 to 2002 on four sandy loam soils in Denmark (5) found annual increases in soil carbon of 53-94 g/C/m^2/year when maize *Zea mays* crop remains were incorporated into the soil, compared to 36-47 g/C/m^2/year increases in three of four soil types receiving no amendment. Soil was collected from four arable fields (each with a different soil type) and placed outside in large, open-ended cylinders (0.7 m diameter x 0.5 m depth; number of cylinders not specified). After maize harvest, one cylinder for each soil type had chopped maize incorporated into the top 25 cm of soil. Remaining cylinders received no maize residue. Soil samples were taken every two-to-three years in spring to determine the amount of soil organic carbon.

A controlled, randomized, replicated experiment from 1990 to 2005 on silty, silty-clay and clay soil at four sites in China (6) found higher soil organic carbon levels under nitrogen/phosphorus/potassium (NPK) plus straw (9.1 g C/kg soil) compared to NPK alone ()8.4 g C/kg) or the control (7.7 g C/kg). Three treatments were applied to long-term wheat *Triticum aestivum*-maize *Zea mays* rotations at four sites: control (no fertilizer), NPK (at 165-362 kg N/ha, 25-41 kg P/ha, and 68-146 kg K/ha), and NPK plus straw (at 2.2-6 Mg/ha)). Weeds were removed manually and crops were irrigated when necessary. Soils were sampled to 20 cm depth at each site in autumn after maize harvest, and before the next fertilizer application.

A randomized, replicated experiment in 2003-2005 on silt loam, sandy loam and loamy sand in Flanders, Belgium (7) found greater microbial biomass (measured by nitrogen quantities) under treatment with crop remains plus straw incorporation, with the largest increase in sandy loam (123 kg N/ha) then loamy sand (86 kg N/ha) and silt loam (98 kg N/ha), compared to a treatment using crop remains only (37, 34, 63 kg N/ha, respectively). Straw immobilized 96% of nitrogen released from crop remains in loamy sand, 76% in sandy loam, and 65-80% in silt loam. Crop remains plus green waste compost and sawdust did not affect microbial biomass or nitrogen immobilization. There were three replicates of 5.5 x 1.5 m treatment plots. Crop remains of cauliflower *Brassica oleracea* or leek *Allium porrum* were initially incorporated into plots along with a green waste compost on the loamy sand and silt loam. Sawdust was applied to the silt loam. After one year, crop remains plus cereal straw were incorporated into the soil instead, followed by barley malting sludge on the loamy sand and vinasses (residue from distillation of sugar) on the sandy loam. Soils were sampled regularly throughout the experiment to 90 cm depth.

A replicated, controlled study in 2000 on sandy loam soil in Wellesbourne, United Kingdom (8) found that adding sugar beet *Beta vulgaris* tops with compost to a barley *Hordeum vulgare* crop increased soil mineral nitrogen by 11 kg/ha and yield by 11% , compared to no addition. Adding paper waste with sugar beet tops did not affect soil mineral nitrogen but improved yield by 23%. Adding sugar beet tops with straw, compactor waste or double rates of compactor waste reduced soil mineral nitrogen by 25, 15 and 36 kg/ha, and reduced yield by 47%, 21% and 63%, respectively. Amendments were applied at 3.2-3.8 t/ha, including compactor (machine which compresses waste material to reduce the space it takes up) and paper waste from the recycling industry, recently-harvested wheat *Triticum aestivum* straw, compost from municipal green waste, and liquid molasses (thick brown, uncrystallized juice from raw sugar) from the sugar refining industry. Amendments were applied with 42 t/ha sugar beet tops.

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4.7. Amend the soil with manures and agricultural composts

- **Biodiversity loss:** Three controlled, replicated studies from the UK[8] and USA[1, 2] found higher microbial biomass when manure[1] or compost[2] was applied, and higher microbial respiration when poultry manure[8] was applied.
- **Erosion:** One controlled, randomized, replicated study from India[3] found lower soil loss and water runoff with manure application in combination with other treatments.
- **Nutrient management:** Two randomized, replicated studies from Canada[7] and the UK[4] (one also controlled[4]) found lower nitrate loss[4] or larger soil aggregates (which hold more nutrients) when manure was applied[7], compared to broiler (poultry) litter, slurry[4] or synthetic fertilizers[7]. One study[4] found that treatment in winter was more effective than in autumn and that farmyard manure was more effective than broiler (poultry) litter or slurry in reducing nutrient loss. One controlled, replicated study from Spain[5] found higher nitrate leaching.
- **Soil organic carbon:** Three studies (including two controlled[6, 8], replicated studies and a review[9]) from India[6], Japan[9] and the UK[8] found higher carbon levels when manures were applied.
- **Soil organic matter:** One controlled, randomized, replicated study from Turkey[10] found higher organic matter, larger soil aggregations and a positive effect on soil physical properties when manure and compost were applied. One study from Germany[11] found no effect of manure on organic matter levels.
- **Yield:** Four controlled, replicated studies[5] (including four also randomized[3, 6, 10]) from India[3, 6], Spain[5] and Turkey[10] found higher crop yields when manures or compost were applied. One study[2] found higher yields when manure were applied in combination with cover crops.
- **Soil types covered:** Clay loam[10], loam[2], loamy[1], sandy loam[4, 5, 7, 8], sandy clay loam[6], silty loam[11], and sandy silt loam[3].

Background

Soil microbial biomass is the amount of tiny living microorganisms in a given amount of soil. Soil microbial respiration is the production of carbon dioxide (CO^2) when soil organisms respire (breaking down molecules to produce energy). Arbuscular mycorrhizal fungi are a group of fungi that live around the roots of plants. By living together, the fungi and host plant benefit each other: the fungi can live in a habitat without having to compete for resources and have a supply of carbon from the plant, while benefit the plant with an enhanced supply of nutrients, improved growth and ability to reproduce, and tolerance to drought. Arbuscular mycorrhizal fungi colonize a wide variety of host plants, including grasses, herbs, agricultural crops and legumes (Bardgett 2005). They are associated with less intensively cultivated and undisturbed soils.

Soil aggregates are groups of soil particles held together by moist clay, organic matter (such as roots), organic compounds (from bacteria and fungi) or fungal hyphae (long, branching structures of a fungus). Some soil particles fit closely together (high soil density), some do not (low density), creating different-sized spaces. These spaces (or pores) within and between soil aggregates can store air and water, microbes, nutrients and organic matter. Large aggregations of particles retain the most nutrients. Since organic amendments act as strong binding agents between particles, mean weight diameter (MWD) of the aggregates (in mm) soils are likely to increase with applications of organic material such as manures and composts. Soil penetration resistance MPa is the soil's ability to withstand penetration by water or roots. Often with low penetration resistance comes higher hydraulic conductivity, which is the ease with which a fluid (usually water) can move through pore spaces in the soil. Higher hydraulic conductivity is an indicator of a healthy soil.

Excess levels of soluble salts in the soil can adversely affect plant life by changing a plant's water balance and basic function, resulting in wilting or scorching. Electrical conductivity is a general measure of the soluble salt content or nutrient level of a soil (high conductivity values typically indicate high salt levels). Good quality topsoil should have an electrical conductivity value within the range of 100-1500 microSiemens/cm (μS/cm). Ceramic cup sampling measures the electrical conductivity of a soil, using a vacuum is connected to tubes in the soil. On the end of the tubes are small ceramic cups which filter moisture from the soil when suction is applied.

Ammonium-nitrate is often added to soils as a fertilizer and if plants do not take it up immediately, the ammonium-nitrate gets converted to nitrate by soil bacteria (nitrification) and can be lost from the soil (leaching). A nitrification inhibitor stops or slows down this conversion, and can reduce the loss of nitrate from the soil.

Bardgett R. (2005) *The Biology of Soil: A community and ecosystem approach*. Oxford University Press, Oxford.

A controlled, replicated experiment in 2009 on loamy soil in Colorado, USA (1), found higher soil microbial biomass under high levels of composted dairy manure (239 μg C/g soil, 80.8 μg N/g soil) or an alfalfa *Medicago sativa* crop (277 μg C/g soil, 90.9 μg N/g soil) when added to grass pasture, compared to medium (158 μg C/g soil, 38 μg N/g soil), low (144 μg C/g soil, 38 μg N/g soil) or no additions (157 μg C/g soil, 29.3 μg N/g soil). There were three replicates (in 3 x 12 m plots) of four treatments: composted dairy manure applied at low (22.4 Mg/ha), medium (33.6 Mg/ha) and high rates (44.8 Mg/ha), and alfalfa interseeded into the grass mixture (including orchardgrass *Dactylis glomerata,* meadow brome *Bromus biebersteinii*, and smooth brome *B. inermis*). Soil samples were taken up to 15 cm depth after roughly 1.5 years, and measured soil microbial biomass (levels of carbon and nitrogen) and the size of accumulated soil particles.

A controlled, replicated experiment in 2005-2009 on loam in Michigan, USA (2) found higher microbial biomass under perennial ryegrass *Lolium perenne* and compost (195-210 μg/g dry soil) than under ryegrass without compost, or ryegrass/vetch *Vicia sativa* with and without compost (145-160 μg/g dry soil). Microbial respiration was highest in soil under the ryegrass-compost combination (282 μg carbon dioxide/g dry soil), compared to ryegrass/vetch with no compost (126 μg carbon dioxide). Tomato *Lycopersicon esculentum* yield was higher in soils after the ryegrass-compost treatment (44 kg/ha) than in ryegrass/vetch with no compost (22 kg/ha). It was not clear whether these effects were due to the cover crop or compost treatments. Two cover crop treatments were sown into soil between crops: ryegrass and ryegrass with vetch. Within these were two compost treatments: compost (25 t/ha dairy compost, but reduced to 12.5 t/ha in 2009) and no compost. There were four replications. Cover crops were mowed and incorporated into the soil before tomato seedlings were transplanted into 7.6 x 0.6 m beds. Four soil samples were taken to 15 cm depth from each treatment during the growing season.

A controlled, randomized, replicated experiment in 2007-2010 on sandy silt-loam in India (3) found lower soil loss (3.4 t/ha) and runoff (234 mm of water) when organic manures, mulching and minimal tillage were applied to plots with a palmarosa *Cymbopogon martini* vegetation barrier than when conventional inputs were applied to plots with no vegetation barrier (7.1 t/ha and 428 mm respectively). The palmarosa barrier treatment was also more effective than a panicum *Panicum maximum* barrier treatment with conventional inputs (5.2 t/ha, 356 mm). Maize *Zea mays* yield was 13% lower in the palmarosa compared to panicum treatment, but 43% higher than having no vegetation barrier. Wheat *Triticum aestivum* yield was on average 73% higher in the palmarosa relative to panicum treatment, and 99% higher than with no vegetation barrier. It is not clear whether these results were due to organic amendments, mulching or reduced tillage. There were three replications (using 100 x 20 m plots) of three treatments in a maize-wheat crop rotation: no vegetation barrier with conventional tillage, fertilizers and chemical weed control; panicum barrier with conventional inputs; and a palmarosa barrier (with farmyard manure, vermicompost (produced by worms), poultry manure, minimal tillage, or weed mulching.

A controlled, randomized, replicated study in 1990-1994 on sandy loam in the UK (4) found lower nitrate losses for farmyard manure (10 and 19 kg N/ha from sites A and B respectively) than for broiler litter (24 kg N/ha) or slurry (56 kg N/ha) treatments. Nitrate losses were greatest following manure application in September-November (23 and 12 mg N/l for sites A and B), but were tiny when applications were made in December or January (less than 0.5 mg N/l for both sites). There were two manure treatments at each site: site A (Shropshire) received pig/cattle slurry and cattle farmyard manure, and site B (Nottinghamshire) received broiler (poultry) litter and farmyard manure. Manures were applied at 200 kg N/ha monthly between September and January to overwinter fallow or onto winter rye *Secale cereale*. All treatments were replicated three times at both sites. Plots were 12 x 4 m and 15 x 4 m at sites A and B respectively.

A controlled, replicated experiment in 1998-2001 on sandy loam in Madrid, Spain (5) found the highest nitrate leaching from soil under excessive pig slurry (329 kg N/ha), followed by medium (215 kg N/ha) and low application (173 kg N/ha), compared to the control (78 kg/ha). Dissolved salts in the soil were higher under high (6,058 kg salts/ha) compared to medium application (2,019 kg salts/ha). Maize *Zea mays* grain yield was higher under high (11,961 kg/ha), medium (10, 984 kg/ha) and low application (10,797 kg/ha) compared to the control (9,363 kg/ha). Four slurry treatments were applied to a maize crop: control (no fertilizer), suboptimal/low (as urea), optimal/medium (170, 162 and 176 kg N/ha for 1998, 1999 and 2001), and excessive/high application (not specified). Slurry was applied to soil through a band spreader connected to a tanker and then incorporated into the soil by rotivatimion. There were three replicates of 9.9 x 11.1 m plots. Barley *Hordeum vulgare* was grown in 2000 to avoid excessive repeat-cropping with wheat, but results of that year were not reported in the study. Soils were sampled 33 times throughout the experiment using ceramic cups.

A controlled, randomized, replicated experiment in 2001-2011 on sandy clay loam in India (6) found 34% higher soil organic carbon and 53% more total carbon (including inorganic carbon) under rice straw plus green manure (using *Sesbania aculeata*) compared to the control (5.2 g/kg). Microbial biomass (measured by quantities of carbon) was highest under farmyard manure plus green manure (250 mg/kg), followed by farmyard manure (233 mg/kg) compared to the control (153 mg/kg). Rice yield was highest under farmyard manure plus green manure (3.51 t/ha), followed by rice straw plus green manure (3.35 t/ha), farmyard manure alone (3.25 t/ha), and green manure alone (3.09 t/ha), compared to the control (1.93 t/ha). Treatments were applied to plots of paddy 20 days before plots were planted with transplanted rice *Oryza sativa* var. *Geetanjali* seedlings. Treatments included: control (no amendment), farmyard manure, green manure, farmyard manure plus green manure, and rice straw plus green manure (both incorporated into the soil 20 days before seedling transplantation). There were three replications. Soils were sampled at the beginning and end of the experiment to 60 cm depth.

A randomized, replicated experiment in 2003 on sandy-loam soil in Quebec, Canada (7) found that the application of 30 and 45 Mg/ha/y of composted manure produced a higher proportion of large soil aggregates (35% and 41% respectively) than inorganic fertilizer application. There were four replicates of two tillage systems: conventional (tandem disk to 10 cm soil depth, mouldboard plough 20 cm) and no-tillage. Within these were maize *Zea mays,* soybean *Glycine max*/maize and maize/soybean rotations (in 20 x 24 m plots) and then within these were four fertilizer treatments: inorganic fertilizers, composted cattle manure at 30 or 45 Mg/ha/y, and the two mixed together (in 20 x 6 m areas of plots). Soil samples (to 10 cm depth) were taken after crop harvest. Soil carbon, nitrogen, phosphorus and the size of aggregates were measured.

A controlled, replicated experiment in 2002-2004 on sandy clay loam in Edinburgh, the UK (8) found higher total soil carbon under cattle slurry (32.3 kg C/m^3), sewage (36.5 kg C/m^3) and poultry manure (44.5 kg C/m^3) compared to the control (26.8 kg C/m^3). Soil carbon under mineral fertilizers was no higher than under the control. Soil microbial respiration was highest under poultry manure (10,748 kg CO_2/ha), followed by cattle slurry (9,835 kg CO_2/ha) and sewage sludge (9,284 kg CO_2/ha) treatments, compared to the control (5,636 kg CO_2/ha). Respiration was lower in both mineral fertilizer treatments compared to poultry manure. Six fertilizer treatments were applied to 12 x 6 m plots of perennial ryegrass *Lolium perenne* grassland over two years. Treatments were sewage sludge, cattle slurry, poultry manure, urea, ammonium nitrate (all applied at 300 kg/ha/y) and a control receiving no fertilizer. Treatments were replicated three times. Soil microbial respiration was determined by measuring carbon dioxide levels in closed cylindrical chambers placed on the soil surface clear of vegetation. Soil samples were collected to 10 and 20 cm depths in April each year.

A review of 120 papers testing interventions on a range of soils largely in Japan (9), found enhanced soil organic carbon storage under manure (and other organic by-products) application, cover crop management, and no-tillage practices. Balanced and integrated increases in the soil organic carbon pool, lessening of non-carbon dioxide emissions, and control of soil nutrients based on location-specific recommendations are also needed. No review methods were specified. Tillage systems reviewed included: no-tillage, conservation tillage (surface residues retained), conventional tillage (mouldboard plough, rotary tillage, disced). Cover crops reviewed included a mix of leguminous and grass covers: rye *Secale cereale*, hairy vetch *Vicia villosa*, and crimson clover *Trifolium incarnatum*.

A controlled, randomized, replicated experiment from 1996 to 2008 on clay-loam soil in Turkey (10) (found 69%, 32% and 24% higher soil organic matter content in soil under manure, compost and mycorrhizal-inoculated compost applications respectively, compared to the control. Mineral fertilizer had no effect on organic matter accumulation. The largest soil aggregations were found under manure (0.05 mm), mycorrhizal-inoculated compost (0.11 mm) and compost (0.07 mm) applications. The lowest soil density was under compost (1.1 Mg/cm^3) compared to the control (1.4 Mg/cm^3). Lower penetration resistance was found under compost (1.06 MPa) and manure (1.17 MPa) application, with the highest under mineral fertilizer application (1.29 MPa) and in the control (1.51 MPa) plots. Combined wheat *Triticum aestivum* and maize *Zea mays* yield was highest under mineral fertilizer (13,720 kg/ha) followed by manure (10,500 kg/ha), compost (8,780 kg/ha) and mycorrhizal-inoculated compost (7,630 kg/ha), compared to the control (5,900 kg/ha). Within a wheat-maize rotation were three replicates of five 10 x 20 m treatments: control, mineral fertilizer (300-60-150 kg N-P-K/ha), manure (25 t/ha), compost (equal mixture of grass, wheat stubble and plant leaves, 25 t/ha), mycorrhizal *Glomus caledonium*-inoculated compost (10 t/ha). Soil samples were taken to 30 cm depth 2008.

An experiment in 2001-2005 on silty loam soil in Villmar-Aumenau, Germany (11) found no obvious changes in soil carbon or nitrogen under different manure and cover crop management. Available nitrogen increased when manures were digested before application (70 kg N/ha), compared to undigested manures (61 kg N/ha). There were two trials. Trial 1 had eight treatments: 1-2) clover/grass ley; 3) wheat *Triticum aestivum* plus cover crops receiving farmyard manure (FYM) as slurry or effluents; 4) potatoes *Solanum tuberosum* receiving FYM and solid effluents, or maize *Zea mays* receiving FYM; 5) rye *Secale cereale* plus cover crops plus FYM; 6) peas *Pisum sativum* plus cover crops; 7) spelt *T. aestivum* spp*. spelta* plus cover crops plus FYM, and 8) wheat undersown with clover/grass ley plus FYM and solid manures. Trial 2 included: 1) clover/grass ley; 2) potatoes plus solid effluents; 3) winter wheat plus liquid effluents; 4) peas; 5) winter wheat plus liquid effluents; 6) spring wheat plus solid effluents. All manuring treatments were applied before ploughing. Five soil samples were taken from each plot to 30 cm depth and measured soil nitrogen and carbon.

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(2) Nair, A. & Ngouajio, M. 2012. Soil microbial biomass, functional microbial diversity, and nematode community structure as affected by cover crops and compost in an organic vegetable production system. *Applied Soil Ecology*, 58, 45-55.

(3) Ghosh, B. N., Dogra, P., Bhattacharyya, R., Sharma, N. K. & Dadhwal, K. S. 2012. Effects of grass vegetation strips on soil conservation and crop yields under rainfed conditions in the Indian sub-Himalayas. *Soil Use and Management,* 28, 635-646.

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(5) Díez, J. A., Hernaiz, P., Muñoz, M. J., de la Torre, A. & Vallejo, A. 2004. Impact of pig slurry on soil properties, water salinization, nitrate leaching and crop yield in a four-year experiment in Central Spain. *Soil Use and Management,* 20, 444-450.

(6) Bhattacharyya, P., Roy, K. S., Neogi, S., Chakravorti, S. P., Behera, K. S., Das, K. M., Bardhan, S. and Rao, K. S. 2012. Effect of long-term application of organic amendment in relation to global warming potential and biological activities in tropical flooded soil planted to rice. *Nutrient Cycling in Agroecosystems*, 94, 273-285.

(7) Jiao, Y., Whalen, J. K. & Hendershot. (2006) No-tillage and manure applications increase aggregation and improve nutrient retention in a sandy-loam soil. *Geoderma,* 134, 24-33.
(8) Jones, S. K., Rees, R.M., Kosmas, D., Ball, B. C. and Skiba, U. M. 2006. Carbon sequestration in a temperate grassland; management and climatic controls. *Soil Use and Management,* 22, 132-142.
(9) Komatsuzaki, M. & Ohta, H. (2007) Soil management practices for sustainable agro-ecosystems. *Sustainability Science*, 2, 103-120.
(10) Celik, I., Gunal, H., Budak, M. & Akpinar, C. 2010. Effects of long-term organic and mineral fertilizers on bulk density and penetration resistance in semi-arid Mediterranean soil conditions. *Geoderma*, 16, 236-243.
(11) Möller, K. 2009. Influence of different manuring systems with and without biogas digestion on soil organic matter and nitrogen inputs, flows and budgets in organic cropping systems. *Nutrient Cycling in Agroecosystems*, 84, 179-202.

4.8. Amend the soil with municipal wastes or their composts

- **Erosion:** Two controlled, replicated trials in Spain[2] and the UK[1] measured the effect of adding wastes to the soil. One trial[2] found that adding municipal compost to semi-arid soils greatly reduced soil loss and water runoff. One[1] found mixed results of adding composts and wastes.
- **Soil types covered:** coarse loamy[2], sandy loam[1].

A replicated, controlled study in 2000 on sandy loam soil in Wellesbourne, United Kingdom (1) found that adding sugar beet *Beta vulgaris* tops with compost to a barley *Hordeum vulgare* crop increased soil mineral nitrogen by 11 kg/ha and yield by 11% , compared to no addition. Adding paper waste with sugar beet tops did not affect soil mineral nitrogen but improved yield by 23%. Adding sugar beet tops with straw, compactor waste or double rates of compactor waste reduced soil mineral nitrogen by 25, 15 and 36 kg/ha, and reduced yield by 47%, 21% and 63%, respectively. Amendments were applied at 3.2-3.8 t/ha, including compactor (machine which compresses waste material to reduce the space it takes up) and paper waste from the recycling industry, recently-harvested wheat *Triticum aestivum* straw, compost from municipal green waste, and liquid molasses (thick brown, uncrystallized juice from raw sugar) from the sugar refining industry. Amendments were applied with 42 t/ha sugar beet tops.

A controlled, replicated experiment in 2000 on a semi-arid, coarse loamy soil in Alcantarilla, Spain (2) found that adding composted municipal waste was the most effective of three soil amendments, reducing soil loss by 94% and water runoff by 54% compared to an untreated control. Unstabilized municipal waste and sewage sludge reduced soil loss by 78% and 80% (respectively) and increased the soil's ability to hold water by 43% and 24%. There were four treatments: an untreated control, municipal waste compost, an unstabilized municipal waste and sewage sludge. Treatments were tested in plots of 10 x 3 m and replicated three times. Stability of aggregated soil particles was measured and a runoff collector was installed downslope of each plot.

(1) Rahn, C.R., Bending, G.D., Lillywhite, R.D. & Turner, M.K. (2009) Co-incorporation of biodegradable wastes with crop residues to reduce nitrate pollution of groundwater and decrease waste disposal to landfill. *Soil Use and Management*, 25, 113–123.
(2) Ros, M., Garcia, C. & Hernandez, T. 2001. The use of urban organic wastes in the control of erosion in a semiarid Mediterranean soil. *Soil Use and Management*, 17, 292-293.

4.9. Amend the soil with non-formulated chemicals and mineral wastes

- **Nutrient loss:** Two replicated studies from Australia[1] and New Zealand[2] measured the effects of adding minerals and mineral wastes to the soil. Both found reduced nutrient loss and one study[2] found reduced erosion.
- **Soil types covered:** Sandy clay[1], silt loam[2].

BACKGROUND

Biochar is the remains of organic matter, such as plant material or animal faeces, which has been burned under a limited oxygen supply, at temperatures less than 700 °C.

A controlled, replicated experiment in 2011 using sandy clay in Meckering, Western Australia (1) found that adding clay or biochar to soil reduced nitrate and ammonium loss from soil, by 25% and 20% respectively, compared to the control. Adding biochar saved more nitrate (12.9 mg nitrate remaining in pot) than adding clay (12.1 mg nitrate/pot). Soil was collected from a crop-pasture rotation including wheat *Triticum aestivum* or cape weed *Arctotheca calendula* with annual ryegrass *Lolium rigidum* and clover *Trifolium subterraneum*. Biochar and clay were either added at 25 t/ha as a layer at 10 cm depth with soil on top, or evenly incorporated into the top 10 cm of soil. Biochar was produced using jarrah *Eucalyptus marginata* wood and clay was taken from a clay pit close to the soil collection site. Nitrogen fertilizer was added at 40 kg N/ha. Amended soils were watered with the equivalent of 30 mm rainfall daily for 10 days, then on days 13, 15, 17 and 20.

This controlled, replicated experiment in 2004-2008 on silt loam soil in New Zealand (2) found that applying alum (aluminium sulphate) after grazing of forage crops by cattle or sheep reduced phosphorus loss by 29% and 26%, and fine sediment loss by 16% and 43%, respectively, compared to normal forage crop grazing. Grazing cattle or sheep on forage crops increased phosphorus loss from fields by approximately 100% (1.3 kg/ha) and 33% (0.9 kg/ha) respectively, compared to normal sheep grazing on pasture (0.6 kg/ha). Forage grazing by cattle or sheep increased fine sediment loss by 1,000% (0.7 mg/ha) and 500% (0.4 mg/ha), relative to grazing pasture with sheep (0.06 mg/ha). Twenty-eight 10 × 25 m plots included four replicates of combinations of the following treatments: cattle or sheep grazing on winter forage crops (triticale *Triticosecale Wittmack*, then kale *Brassica oleracea*), sheep pasture, restricted grazing, or alum addition on the forage crops (20 kg/ha following grazing).

1. Dempster, D.N., Jones, D.L. & Murphy, D. V. (2012) Clay and biochar amendments decreased inorganic but not dissolved organic nitrogen leaching in soil. *Soil Research*, 50, 216.
2. McDowell, R.W. & Houlbrooke, D.J. (2009) Management options to decrease phosphorus and sediment losses from irrigated cropland grazed by cattle and sheep. *Soil Use and Management*, 25, 224–233.

4.10. Amend the soil with organic processing wastes or their composts

- **Nutrient loss:** Two controlled, replicated trials from Spain[2] and the United Kingdom[1] (one also randomized[2]) measured the effect of adding composts to soil. One trial[2] found applying high rates of cotton gin compost and poultry manure improved soil structure and reduced soil loss, but increased nutrient loss. One trial[1] found improved nutrient retention and increased barley *Hordeum vulgare* yield when molasses were added.

- **Soil types covered:** sandy –clay[2], sandy loam[1], silty-clay[2].

BACKGROUND

Cotton gin compost is compost made from the stalks, leaves and seed pods of cotton plants. These are discarded as 'gin waste,' hence the name. Soil aggregates are groups of soil particles that bind to each other more strongly than to adjacent particles. Aggregate stability is the ability of soil aggregates to resist disintegration when disruptive forces associated with tillage and water or wind erosion are applied.

A controlled, replicated study in 2000 on sandy loam soil in Wellesbourne, United Kingdom (1) found that adding sugar beet *Beta vulgaris* tops with molasses to a barley *Hordeum vulgare* crop increased soil mineral nitrogen by 46% and yield by 32%, compared to no addition. Adding paper waste with sugar beet tops did not affect soil mineral nitrogen but improved yield by 23%. Amendments were applied at 3.2-3.8 t/ha, including compactor (machine which compresses waste material to reduce the space it takes up) and paper waste from the recycling industry, recently-harvested wheat *Triticum aestivum* straw, compost from municipal green waste, and liquid molasses (thick brown, uncrystallized juice from raw sugar) from the sugar refining industry. Amendments were applied with 42 t/ha sugar beet tops.

A controlled, randomized, replicated experiment in 2001-2004 on silty- and sandy-clay soils in Seville, Spain (2) found that high application rates (7,120 kg/ha/year) of both crushed cotton gin compost and poultry manure reduced soil aggregate instability (see background section) (by 21% and 18%, respectively), soil density (20% and 17%) and soil loss (29% and 25%) compared to the control treatment. Nutrient loss was higher in water from amended soils (19 mg organic carbon/l for cotton compost and 22 mg/l for poultry manure) than the control soil (0 mg/l). Lower application rates of cotton compost and poultry manure also reduced soil instability, soil loss and nutrient loss, but to a lesser extent. There were four replicates of five treatments: untreated soil, cotton compost applied at 3,560 kg organic matter/ha/year, cotton compost at 7,120 kg/ha/yr, poultry manure at 3,560 kg/ha/year, and poultry manure at 7,120 kg/ha/year. Soil samples were collected from each plot to 25 cm depth.

(1) Rahn, C.R., Bending, G.D., Lillywhite, R.D. & Turner, M.K. (2009) Co-incorporation of biodegradable wastes with crop residues to reduce nitrate pollution of groundwater and decrease waste disposal to landfill. *Soil Use and Management*, 25, 113–123.

(2) Tejada, M. & Gonzalez, J. L. 2008 Influence of two organic amendments on the soil physical properties, soil losses, sediments and runoff water quality. *Geoderma,* 145, 325-334.

4.11. Amend the soil using a mix of organic and inorganic amendments

- **Biodiversity:** Five controlled trials from China[5, 7, 11] and India[3, 8] (four also randomized and replicated[3, 5, 7, 8]), and one study from Japan[9] found higher microbial biomass and activity in soils with a mix of manure and inorganic fertilizers. Manure alone also increased microbial biomass. One trial found increased microbial diversity.

- **Erosion:** One controlled, replicated trial from India[1] found that mixed amendments were more effective at reducing the size of cracks in dry soil than inorganic fertilizers alone or no fertilizer.
- **SOC loss:** Four controlled, randomized, replicated trials[2, 3, 5, 6, 7] and one controlled trial[10] all from China and India found more organic carbon in soils with mixed fertilizers. Manure alone also increased organic carbon. One trial[6] also found more carbon in soil amended with inorganic fertilizers and lime.
- **SOM loss:** Three randomized, replicated trials from China[4, 11] and India[8], (two also controlled[4, 8]) found more nutrients in soils with manure and inorganic fertilizers. One controlled, randomized, replicated trial from China[2] found inconsistent effects of using mixed manure and inorganic fertilizers.
- **Yield:** Two randomized, replicated trials from China[4, 11] (one also controlled[4]) found increased maize *Zea mays*[11] or rice *Oryza sativa* and wheat *Triticum aestivum*[2] yields in soils with mixed manure and inorganic fertilizer amendments. One study[2] found lower yields of rice *Oryza sativa* and wheat *Triticum aestivum* under mixed fertilizers.
- **Soil types covered:** clay[1, 9], clay loam[3, 4], sandy-loam[2, 5, 6, 7, 11], silt clay loam[10], silty-loam[8].

Background information and definitions

Soil microbial biomass is the amount of tiny living organisms within a given area or amount of soil. Bacteria and fungi are typically measured in colonies (or colony forming units, CFU). ‘Residue’ refers to crop remains after harvest. High decomposition activity indicates healthy soil. The Shannon diversity index or diversity indices generally are a measure of how many different species there are in a given sample, and how many individuals are present in each species. See also ‘Amend the soil with manures and agricultural composts’ and ‘Amend the soil with formulated chemical compounds.’

A controlled, replicated experiment in 2000 on a non-chalky clay soil in Bhopal, India (1) found that application of farmyard manure plus inorganic fertilizers reduced the volume of cracks in a soybean Glycine max-linseed Linum usitatissimum rotation (63 m3 of cracks) compared to inorganic fertilizers alone (113 m3), or no fertilizers (161.8 m3). The crop was managed under conventional tillage or sub-soiling (deep tillage). Within each tillage treatment were plots of 8 x 5 m in which no fertilizer, inorganic fertilizer, or inorganic fertilizer plus farmyard manure was applied. There were three replicates per treatment. Crack length, depth and width, and the soil water content and density were measured.

A controlled, randomized, replicated experiment in 1990-2003 on sandy-loam in Fengqiu, China (2) found that soil organic carbon increased by 12.2 Mg C/ha in the manure treatment, 7.8 Mg C/ha in the mixed, and 3.7 Mg C/ha in the nitrogen/phosphorus/potassium (NPK) treatments compared to the control, which lost 1.4 Mg C/ha. Wheat Triticum aestivum and maize Zea mays yields were 1.9% and 1.5% lower (respectively) in the mixed fertilizer treatment, and 23.7% and 18% lower with manure-only than in the NPK treatment (5,261 and 7 808 kg/ha), in which yields were highest and most stable. A long-term wheat-maize rotation had the following treatments: inorganic fertilizer (NPK, NP, PK or NK), organic manure fertilizer, mixed nitrogen addition comprising half inorganic fertilizer and half compost (wheat straw, soybean Glycine max and cotton Gossypium herbaceum seed cake); and no fertilizer (control). Each treatment was replicated four times in 45.5 m2 plots.

A controlled, randomized, replicated experiment in 2010 on clay loam in Kerala, India (3) found that soil organic carbon was higher under mixed amendments (16.3 g/kg) and organic amendments (17.4 g/kg) compared to chemical amendments (12 g/kg) or an untreated control (11 g/kg). Microbial biomass (indicated by carbon levels) was 28% and 52% higher under mixed and organic amendments respectively compared to chemical inputs. Ginger Zingiber officinale was grown in 3 × 1 × 0.15 m raised beds cleared of weeds. Treatments included organic amendments (farmyard manure, pressed neem Azadirachta indica waste, ash, vermicompost), chemical amendments (NPK – nitrogen/phosphorus/potassium at 75-50-50 kg/ha, urea, rock phosphate and potash), mixed (integrated) amendments (farmyard manure and NPK combined) and no fertilizer (control). There were five replicates. Four soil samples/bed were taken immediately after ginger harvest.

A controlled, randomized, replicated experiment in 1982-2005 on clay loams in China (4) found higher nitrogen levels under nitrogen, phosphorus and manure (141 and 90 kg N/ha, for rice Oryza sativa and wheat Triticum aestivum respectively) and nitrogen/phosphorus/potassium (NPK) and manure (140 and 89 kg N/ha), than nitrogen and manure (119 and 70 kg N/ha) or the control (58 and 41 kg N/ha) at Suining. Levels were similar between treatments at Wuchang (approximately 100 and 75 kg N/ha). Plant nitrogen uptake was 15.5 and 11.4% higher in rice and wheat under nitrogen and phosphorus plus manure, and 12.8 and 10% higher under NPK plus manure compared to nitrogen plus manure. Rice and wheat yields increased by 23-26% and 21-58% respectively under nitrogen and phosphorus plus manure, and NPK plus manure treatments, compared to nitrogen plus manure (8.4 and 9.1 t/ha/y overall for Suining and Wuchang respectively). Four treatments were applied to rice–wheat rotations at two sites in China: no fertilizer, nitrogen plus manure, nitrogen and phosphorus plus manure, and NPK plus manure. Each treatment was replicated four times in 4 x 3 m plots at each site. Soil samples were taken annually (20 cm depth).

A controlled, randomized, replicated experiment between 1989 and 2007 on sandy-loam soil in Henan Province, China (5) found more bacteria and fungi in soil with mixed manure and inorganic fertilizer (5,626 and 21,000 CFU/g) and manure-only (6,725 and 24,000 CFU/g, respectively) treatments compared to the untreated control (2,238 and 7,000 CFU/g respectively). Soil organic carbon was also improved, with 7.2 and 9.4 g C/kg for mixed and manure-only treatments respectively, compared to 3.9 g C/kg in the control. The treatments used were: organic manure, half organic manure with mineral fertilizer, NPK, NP, PK and NK mineral fertilizers, and an unfertilized control treatment. The experiment was performed on wheat Triticum aestivum-maize Zea mays plots measuring 9.5 × 5 m, with four replicates of each treatment. Five soil samples were taken from each plot and mixed prior to analysis.

A controlled, randomized, replicated experiment in 2001 on sandy loam in Ranchi, India (6) found that soil organic carbon decreased in all treatments over the cropping period. The decrease was less under NPK (nitrogen/phosphorus/potassium) plus manure (8.7%) and NPK plus lime (10.9%) compared to the nitrogen fertilizer treatment alone (28.3%). Soil organic carbon levels were much higher in NPK plus manure (7,167 kg/ha), NPK plus lime (6,633 kg/ha) and NPK-only (6,567 kg/ha) treatments compared to nitrogen fertilizer (4,800 kg/ha) and control (5,167 kg/ha) treatments. NPK with manure or lime improved soil structure, and nitrogen fertilizer worsened soil structure compared to the control. A long-term fertilizer experiment established in 1972 used an annual soybean Glycine max-wheat Triticum aestivum rotation. Six treatments were replicated four times on 10 x 10 m plots: control, nitrogen fertilizer, nitrogen and phosphorus, NPK, NPK plus manure and NPK plus lime. Soils were sampled in 2001 to 60 cm depth.

A controlled, randomized, replicated experiment from 1988 to 2008 on sandy loam in northeast China (7) found more soil organic carbon under manure and manure plus nitrogen/phosphorus/potassium (NPK) fertilizer (18. 5 and 19 g C/kg respectively) compared to the control (11.8 g C/kg). Microbial biomass was higher in the manure (846 mg/kg) and manure plus NPK fertilizer treatments (885 mg/kg) than in the remaining treatments (496, 472 and 426 mg/kg for NPK, nitrogen-only and control treatments, respectively). Throughout the experiment celery cabbage Brassica rapa, frijole Phaseolus sp., radish Raphanus sativus, potato Solanum tuberosum, cucumber Cucumis sativus, onion Allium cepa, beet Beta vulgaris, tomato Solanum lycopersicum, mustard Brassica sp., and aubergine Solanum melongena were grown in rotation. Treatments included an unfertilized control, nitrogen fertilizer, NPK fertilizer, organic manure (horse compost) alone, and organic manure combined with NPK fertilizer. Plots were 1.5 m2 and replicated three times.

A controlled, randomized, replicated experiment in 1990-1992 on silty-loam soil in India (8) found highest nitrogen levels in soil under fertilizer addition plus wheat residue(4.6-16.6 µg/g/month) followed by the fertilizer-only (4.2-14.3 µg/g/month) and wheat residue-only treatments (4-11.2 µg/g/month), compared to the untreated control (3.4-9.8 µg/g/month). The highest microbial biomass was 400 µg/g under fertilizer plus wheat residue, compared to 254 µg/g in the control. There were four treatments replicated three times in 5 x 4.2 m plots: control, chemical fertilizer (NPK at 80/40/30 kg/ha), wheat residue (1 kg/m2), wheat residue plus fertilizer (at 50% fertilizer, 50% wheat residue). The crop sequence was a fallow-rice Oryza sativa-lentil Lens culinaris rotation. Wheat residue was lightly incorporated whereas fertilizer was applied to the soil surface. Soils were sampled at the end of the experiment to 10 cm depth.

An experiment in 2004 on light clay in Japan (9) found that decomposition activity was higher under mixed amendment (18-49% of the control treatment activity) than under chemical amendment (1-37% of the control treatment activity). Decomposition activity under mixed amendment application recovered to control levels 2 (3 µg/g soil/h) and 10 weeks (0.9 µg/g soil/h) after disinfection (after metam sodium and chloropicrin application respectively), but under chemical amendment did not. Fungal contribution to decomposition recovered to control levels under mixed amendment application (1:1 with bacteria) compared with chemical amendment when disinfected with metam sodium. There were two 5 x 20 m treatments on soil which had previously grown melon Cucumis melo and cabbage Brassica oleracea: soil amended with chemical fertilizer, and amended with a mix of chemical and organic fertilizer (40 t/ha/y farmyard manure). Melon and cabbage had previously been grown. Soil samples were taken to 10 cm depth. Soils were disinfected with metam sodium or chloropicrin (to remove soil microorganisms) and incubated at 28°C for 12 weeks.

A controlled experiment from 1990 to 2010 on silt clay loam in Shaanxi, China (10) found highest organic carbon levels in cropped plots treated with nitrogen/phosphorus/potassium (NPK) and 20.6 t/ha manure treatment (13.88 g/kg). Levels were similar in the remaining treatments but higher than in the untreated control (by 34-45%). Microbial biomass was higher under mixed amendments (466 mg

C/kg) compared to nitrogen/phosphorus (211 mg C/kg), NPK (247 mg C/kg) and the control (161 mg C/kg). Three management treatments included land abandonment, bare fallow (both in 14 x 7 m plots) and a wheat Triticum aestivum-maize Zea mays system (14 x14 m plots). Within the wheat-maize system were fertilizer treatments: control (no addition), nitrogen only, nitrogen/potassium, phosphorus/potassium, nitrogen/phosphorus, NPK, NPK plus straw, NPK plus 13.7 t/ha manure, NPK plus 20.6 t/ha manure. All fertilizers were incorporated into the soil to 20 cm depth. Soils were sampled to 20 cm depth at the end of the experiment.

A randomized, replicated experiment from 1986 to 2007 on a sandy loam in China (11) found higher organic carbon, nitrogen, phosphorus and potassium under manure (by 11.36, 1.25, 1.08 and 12.88 g/kg, respectively) and mixed applications (12.42, 1.36, 1.14 and 16.16 g/kg respectively), compared to the control. NPK (nitrogen/phosphorus/potassium) application alone increased carbon (by 11.3 g/kg) and nitrogen (by 1.3 g/kg) relative to the control. Microbial biomass was highest in the mixed and manure-only (265 and 252 nmol/g dry weight) applications, compared to nitrogen application (146 nmol/g dry weight) which had less than the control (198 nmol/g dry weight). Microbial diversity was highest under manure and mixed application (both with Shannon index ratings of 3.2) compared to the control (index of 2.8). Crop yield was highest under mixed (5,173 kg/ha) and manure-only (3,686 kg/ha) applications, followed by NPK alone (3,130 kg/ha). The experimental area was a maize Zea mays crop. Nine fertilizer treatments were replicated three times and included: control (no fertilizer), nitrogen fertilizer, phosphorus, potassium, nitrogen/phosphorus, nitrogen/potassium, nitrogen/phosphorus/potassium (NPK), organic manure (urea, calcium phosphate and composted pig manure) and manure plus NPK (mixed). Soils were sampled in each plot to 20 cm depth.

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(4) Duan Y., Xu M., He X., Li S. & Sun X. (2011) Long-term pig manure application reduces the requirement of chemical phosphorus and potassium in two rice-wheat sites in subtropical China. *Soil Use and Management*, 27, 427-436

(5) Gong W., Yan X., Wang J., Hu T. & Gong Y. (2009) Long-term manure and fertilizer effects on soil organic matter fractions and microbes under a wheat–maize cropping system in northern China. *Geoderma*, 149, 318-324

(6) Hati K.M., Swarup A., Mishra B., Manna M.C., Wanjari R.H., Mandal K.G. & Misra A.K. (2008) Impact of long-term application of fertilizer, manure and lime under intensive cropping on physical properties and organic carbon content of an Alfisol. *Geoderma*, 148, 173-179

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(8) Singh H. (1995) Nitrogen mineralization, microbial biomass and crop yield as affected by wheat residue placement and fertilizer in a semi-arid tropical soil with minimum tillage. *Journal of Applied Ecology*, 32, 588-595

(9) Wada S. & Toyota K. (2006) Repeated applications of farmyard manure enhance resistance and resilience of soil biological functions against soil disinfection. *Biology and Fertility of Soils*, 43, 349-356

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4.12. Encourage foraging waterfowl

- **Soil organic matter:** One controlled, replicated experiment from the USA[1] found increased straw decomposition when ducks were allowed to forage.
- **Soil types covered:** Silty clay[1].

BACKGROUND

The primary goal of rice producers after the rice has been harvested is to remove rice straw (crop remains) over the winter fallow period, before preparations for the next growing season begin. In a bid to reduce air pollution, farmers are now required to adopt alternative methods of reducing rice crop remains other than burning the rice straw. Many farmers now flood their land, providing winter habitat for waterfowl (in this case ducks). The ducks crush and tear at the rice crop remains while searching for insects and bits of grain.

A controlled, replicated experiment in 1995-1996 on a silty clay soil in California, USA (1) found that waterfowl foraging activity increased straw decomposition by 78% in untilled plots and 18% in wet-rolled plots compared to their respective un-foraged plots. Foraging and field tillage reduced nitrogen concentrations in the remaining straw residue at the end of the winter fallow period. Mallards did not incorporate the straw. Individual field plots (25 m^2) were subjected to two pot-harvest treatments: wet-rolled (field tillage) or untilled, replicated four times. Within these treatments, Mallard ducks *Anas platyrhynchos* were placed on one half of the plots, equivalent to 33 birds/ha from 1-18th February. Over five sample times, 10 soil samples were taken from each plot. Levels of residual rice straw and below-ground organic matter (carbon and nitrogen) were measured.

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4.13. Grow cover crops beneath the main crop (living mulches) or between crop rows

- **Biodiversity:** One randomized, replicated study from Spain[4] found that cover crops increased bacterial numbers and activity.
- **Erosion:** Two studies from France[2] and the USA[6] showed reduced erosion under cover crops. One controlled study[2] showed that soil stability was highest under a grass cover, and one randomized replicated study[6] found that cover crops reduced soil loss.
- **Soil organic matter:** Two controlled trials from India[5] and South Africa[1] (one also randomized and replicated[5]) found that soil organic matter increased under cover crops, and one trial from Germany[3] found no effect on soil organic matter levels.
- **Soil types covered:** gravelly-sandy loam[5], sandy loam[2, 4], sandy[1], silty loam[3].

Background

Organic nitrogen is found in plants and other living organisms. Inorganic or mineral nitrogen is a form of nitrogen available to plants to take up. Mineralization is the release of nutrients such as nitrogen (changing it to inorganic or mineral nitrogen) when plants and other organic matter decomposes. Soil aggregates are groups of soil particles that bind to each other more strongly than to adjacent particles. Aggregate stability refers to the ability of soil aggregates to resist disintegration when disruptive forces associated with tillage and water or wind erosion are applied. Wet aggregate stability suggests how well a soil can resist raindrop impact and water erosion

A controlled experiment from 1993 to 2003 on sandy soil in Lutzville, South Africa (1) found that after five years, soil organic matter to 30 cm depth was 60% higher in grazing vetch, pink Seradella *Ornithopus sativus* and 'Saia' oats *Avena strigosa* cover crops compared to the controls. Soil organic matter to 60 cm depth was higher under grazing vetch *Vicia dayscarpa* (52% greater) compared to either control treatment. Seven cover crop species were tested in 108 m^2 plots of grape *Vitis vinifera* vine in a vineyard, including: rye *Secale cereale*, oats *A. sativa*, 'Saia' oats, Parabinga medic *Medicago truncatula*, pink Seradella and grazing vetch. All cover crops were sown once or twice annually. All treatments received chemical control, applied before buds opened. There were two controls with no cover crop, one mechanically weeded between vines with chemical control within vines, and the other receiving full surface chemical control. Soil samples were taken from rows between vines and measured soil organic matter. This summary reports overall soil organic matter only, but the study also reported on separate components of organic matter.

A controlled experiment in 1991-2000 on a sandy loam in Champagne, France (2) found that soil particle stability was highest in the topsoil under a grass cover (index rating (*K)* = 21.7), followed by coniferous bark mulch (rating = 15.2) and poplar bark mulch (rating = 13.6), compared to the control (rating = 10.5). The conifer bark layer also increased stability in soils to 20 cm depth. Three treatments and a control were tested, comprising: a bluegrass *Poa pratensis* cover between vine rows only; organic mixed mulch of coniferous silver fir *Abies alba,* Norway spruce *Picea excelsa* and Scots pine *Pinus sylvestri* bark between and in vine rows (61 t/ha applied every three years); organic mulch of poplar *Populus* spp. bark (67 t/ha applied every three years); and bare soil between rows (control). Treatments and controls were tested in 35 x 8 m and 15 x 8 m plots, respectively. Soil under the grass cover was sampled in and between vine rows while the mulch and control treatments were sampled between vine rows only. All soils were sampled to 20 cm depth.

An experiment in 2001-2005 on silty loam soil in Villmar-Aumenau, Germany (3) found no changes in soil carbon or nitrogen when wheat *Triticum aestivum* was undersown with clover *Trifolium* spp. and grass (species not specified). Manuring and cover cropping treatments with various crops also had no effect. Trial 1 had eight treatments: (1-2) clover/grass ley, (3) wheat *Triticum aestivum* plus cover crops receiving farmyard manure (FYM) as slurry or effluents, (4) potatoes *Solanum tuberosum* receiving FYM and solid effluents, or silage maize *Zea mays* receiving FYM, (5) rye *Secale cereale* plus cover crops plus FYM, (6) peas *Pisum sativum* plus cover crops, (7) spelt *T. aestivum* ssp. *spelta* plus cover crops plus FYM and (8) wheat undersown with clover/grass ley plus FYM and solid effluents (wheat sown in February/March, cover crop sown at same time). Trial 2 included: (1) clover/grass ley,

(2) potatoes plus solid effluents, (3) winter wheat plus liquid effluents, (4) peas, (5) winter wheat plus liquid effluents, (6) spring wheat plus solid effluents. All manuring treatments were applied before ploughing. Five soil samples were taken from each plot to 30 cm depth and measured soil nitrogen and carbon.

A randomized, replicated experiment in 2008 on fine sandy loam soil in Spain (4) found that bacteria counts and activity were highest in the mowed cover crop (0.95 billion/g soil and 1,087 µg PNP/g/h) and lowest when herbicides were added (1.37 billion/g soil and 519 µg PNP/g/h). All treatments had a higher microbial diversity and soil organic carbon levels than the treatment with no cover. There were four long-term treatments in an olive *Oleo europaea* orchard: tillage (3-4 passes with disk harrow to 30 cm depth and tine harrowing (remove small weeds and smooth the soil surface ready for sowing) in summer), no-till, no cover crop (treated with glyphosate herbicide), cover crop (weeds left to grow) treated with herbicides (in March), and mown cover crop (herbicide-free). Each plot was 11 x 11 m and consisted of 16 olive trees. Each treatment was replicated four times. Two soil samples were taken from the centre of each plot. Soil bacterial numbers and community structure were measured. PNP (purine nucleoside phosphorylase) an enzyme which breaks down proteins, was used as an indicator of bacterial numbers.

A controlled, randomized, replicated experiment in 2009 on gravelly-sandy-loams in South Andaman Islands, India (5) found 41% more soil carbon and 46% more soil nitrogen in coconut palm *Cocos nucifera* plots with cover crops than in the control. Adding phosphorus to the cover crop increased nitrogen levels by 16%. Nitrogen mineralization (breakdown of organic matter, e.g. leaves, into mineral nitrogen) was 39% and 73% higher in soils with a cover crop, and a cover crop plus phosphorus respectively, compared to the control. There were six replicates of four treatments in a coconut plantation: no cover crop (control), no cover crop plus phosphorus (16% P at 24 kg/ha), cover crop (kudzu *Pueraria phaseoloides*), and cover crop plus phosphorus. Each plot was 40 x 40 m and contained 28 coconut palms, 7.5 m apart. Ten soil samples were taken monthly to 15 cm depth from each plot. Soil carbon, nitrogen and nitrogen mineralization were measured.

A controlled, randomized, replicated study in 1988-1989 in Oklahoma, USA (6) found that cabbage *Brassica oleracea* plots with rye *Secale cereal* cover crops retained more soil (25% drop in bed height over nine months) than bare ground controls (35% drop). Beds with hairy vetch *Vicia villosa* cover crops dropped in height by 29% over nine months but mean bed height was similar to beds in rye cover-cropped plots and bare controls. Above ground, rye produced more dry vegetation (4,754 kg/ha after six months) than hairy vetch (1,213 kg/ha). Raised cabbage beds (90 cm wide, 20 cm tall) were planted with cover crops (rye, hairy vetch or left bare) in mid-October 1988. Plots were sprayed with glyphosate on 5 April 1989 and cabbages were planted into cover crops on 17 April. Cover crop treatments were replicated three times in plots of 1.8 x 6.1 m. Bed height was measured on 3 November 1988, 27 March and 12 July 1989.

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(3) Möller, K. 2009. Influence of different manuring systems with and without biogas digestion on soil organic matter and nitrogen inputs, flows and budgets in organic cropping systems. *Nutrient Cycling in Agroecosystems*, 84, 179-202.

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(5) Pandey, C. B. & Begum, M. 2010. The effect of a perennial cover crop on net soil N mineralization and microbial biomass carbon in coconut plantations in the humid tropics. *Soil Use and Management*, 26, 158-166.

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4.14. Grow cover crops when the field is empty

- **Biodiversity:** One controlled, randomized, replicated experiment in Martinique[1] found that growing cover crops resulted in more diverse nematode communities. One replicated trial from the USA[2] found greater microbial biomass under ryegrass compared to a ryegrass/vetch cover crop mix.
- S**oil structure:** Three randomized, replicated studies from Denmark[3], Turkey[4] and the UK[6] found that growing cover crops improved soil structure and nutrient retention. One trial[3] found higher soil porosity, interconnectivity and one[4] lower resistance in soil under cover crops, and one[6] found reduced nitrate leaching.
- **Soil organic carbon:** One replicated study from Denmark[4] and one review based mainly in Japan[5] found increased soil carbon levels under cover crops. One study also[4] found soil carbon levels increased further when legumes were included in cover crops.
- **Soil organic matter:** Two controlled, randomized, replicated studies from Australia[10] and the USA[7] found increased carbon and nitrogen levels under cover crops, with one[10] showing that they increased regardless of whether those crops were legumes or not. Two studies from Europe[9] (including one controlled, replicated trial[8]) found no marked effect on soil organic matter levels.
- **Yield:** One replicated trial from the USA[2] found higher tomato yield from soils which had been under a ryegrass cover crop.
- **Soil types covered:** clay[1], loam[2], sandy clay[10], sandy-loam[3, 6, 7], silty-clay[4], silty-loam[8, 9].

Background

The Shannon diversity index or diversity indices generally are a measure of how many different species there are in a given sample, and how many individuals are present in each species. Soil pore interconnectivity is a measure of how connected air spaces in the soil are. High pore interconnectivity is an indicator of good soil health. Arbuscular mycorrhizal fungi are a group of fungi that live around the roots of plants. By living together, the fungi and host plant benefit each other: the fungi can live in a habitat without having to compete for resources and have a supply of carbon from the plant, while they provide an enhanced supply of nutrients to the plant, improving plant growth, the ability to reproduce and tolerance to drought. Arbuscular mycorrhizal fungi colonize a wide variety of host plants, including grasses, herbs, agricultural crops and legumes (Bardgett 2005). Measuring the level of arbuscular mycorrhizal proteins present in the soil enables us to estimate how abundant it is. Soil microbial respiration is the production of carbon dioxide (CO^2) from soil organisms as they break down molecules to produce energy, and can be used as a general measure of microbial activity.

Bardgett (2005) *The Biology of Soil: A community and ecosystem approach*. Oxford University Press, Oxford.

A controlled, randomized, replicated experiment in 2010-2011 on clay soil, in central Martinique (1), found more diverse soil nematode communities under cover crops (0.8 Shannon index) than in the no cover crop control (0.45 Shannon index), with grass cover crops having the highest soil nematode diversity (1.2 Shannon index). The study used six treatments in an old banana *Musa spp.* system: control without cover crop, a self-seeded cover crop, a grass *Paspalum notatum* cv. common, and three legumes (perennial soybean *Neonotonia wightii*, tropical kudzu *Pueraria phaseoloides*, and Brazilian Lucerne *Stylosanthes guyanensis*). There were three replicate plots of each treatment, giving a total of 18 plots. Four soil samples were taken from each plot twice, once at 16 and again at 20 months after the experiment was established. Soil samples were then mixed prior to analysis in the laboratory.

A controlled, replicated experiment in 2005-2009 on loam in Michigan, USA (2) found higher microbial biomass under perennial ryegrass *Lolium perenne* and compost (195-210 µg/g dry soil) than under ryegrass without compost, or ryegrass/vetch *Vicia sativa* with and without compost (145-160 µg/g dry soil). Microbial respiration was highest in soil under the ryegrass-compost combination (282 µg carbon dioxide/g dry soil), compared to ryegrass/vetch with no compost (126 µg carbon dioxide). Tomato *Lycopersicon esculentum* yield was higher in soils after the ryegrass-compost treatment (44 kg/ha) than in ryegrass/vetch with no compost (22 kg/ha). It was not clear whether these effects were due to the cover crop or compost treatments. Two cover crop treatments were sown into soil between crops: ryegrass and ryegrass with vetch. Within these were two compost treatments: compost (25 t/ha dairy compost, but reduced to 12.5 t/ha in 2009) and no compost. There were four replications. Cover crops were mowed and incorporated into the soil before tomato seedlings were transplanted into 7.6 x 0.6 m beds. Four soil samples were taken to 15 cm depth from each treatment during the growing season.

A randomized, replicated study in 2008-2009 on a sandy-loam soil in Foulum, Denmark (3), found a higher number of air spaces in the soil and how connected they are under fodder (animal feed) radish *Raphanum sativus*, compared to dyer's woad *Isatis tinctoria*.. Root growth in the 12-16 cm layer was limited by high soil resistance in directly drilled (-100 kPa) or harrowed (-30 kPa) soil, compared to ploughed soil. A spring barley *Hordeum vulgare* crop was the main experimental area, replicated three times. It was part of a longer term rotation (not specified). The cover crops were dyer's woad and fodder radish. Tillage treatments consisted of two 3 × 72.2 m plots within the crop, which were divided into smaller 3 × 13.7 m sub-plots. Tillage was direct drilling, harrowing or ploughing. Soil samples were takento16 cm depth from each sub-plot.

A controlled, randomized, replicated experiment between October 1998 and July 2001 on silty-clay soil in Samsun, eastern Turkey (4) found improved soil structure, increased soil organic carbon content between 1 and 37%, and reduced soil penetration resistance between 15 and 36% under forage (animal feed) cropping, relative to unplanted fallow controls. Bromegrass *Bromus inermis* was the most effective forage and perennial ryegrass *Lolium perenne* the least. After autumn ploughing (to 15 cm depth) and rototilling, perennial ryegrass, bromegrass, alfalfa *Medicago sativa*, small burnet *Sanguisorba minor*, subterranean clover *Trifolium subterraneum* and purple crownvetch *Coronilla varia* forage treatments were established and compared with unplanted fallow controls. Forages were grown on three 2 × 5 m plots and seeded in rows 40 cm apart. Soil characteristics were measured on samples taken from the top 15 cm of soil.

A review of 120 papers testing interventions on a range of soils largely in Japan (5), found enhanced soil organic carbon storage under cover crop management, no-tillage practices and manure (and other organic by-products) application. Longer-term cover crops resulted in considerable increases in soil organic carbon. In the review, research by Wagger (1988 & 1989) found that carbon input to the soil was greater under legumes due to their lower lignin and cellulose (substances which form cell walls in plants) content, and because legume growth is not limited by nitrogen availability in the soil. Balanced and integrated increases in the soil organic carbon pool, lessening of non-carbon dioxide emissions, and control of soil nutrients based on location-specific recommendations are also needed. No review methods were specified. Tillage systems reviewed included: no-tillage, conservation tillage (surface residues retained), conventional tillage (mouldboard plough, rotary tillage, disced). Cover crops reviewed included a mix of leguminous and grass covers: rye *Secale cereale*, hairy vetch *Vicia villosa*, and crimson clover *Trifolium incarnatum*.

A controlled, randomized, replicated site comparison study in 1990-1994 on a sandy loam in the UK (6) found 79% less nitrate leaching at site A and 42% less at site B when a winter cover crop was grown, compared with the fallow (104 and 50 kg N/ha for sites A and B respectively). There were two manure treatments at site A (Shropshire): pig/cattle slurry; cattle farmyard manure (FYM), and two manure treatments at site B (Nottinghamshire): broiler (poultry) litter; FYM. Manures were applied at 200 kg N/ha monthly between September and January to overwinter fallow or onto winter rye *Secale cereale*. An extra treatment was included to test the nitrification inhibitor DCD, which was applied at 20 l/ha. All treatments were replicated three times at both sites. Plots were 12 × 4 m and 15 × 4 m at sites A and B respectively. The total amount of nitrate lost through leaching and total soil mineral nitrogen was measured.

A controlled, randomized, replicated experiment in 2005 on fine sandy loam in Massachusetts, USA (7) found higher soil organic carbon and nitrogen levels under vetch *Vicia villosa*/rye *Secale cereale* cover crops (14.1 kg C/m^3 soil and 1.7 kg N/m^3) or rye cover alone (15 kg C/m^3 soil and 1.7 kg N/m^3), compared to soil with no cover crop (12.2 kg C/m^3 soil and 1.4 kg N/m^3 soil respectively), regardless of nitrogen fertilizer rate. There were three cover crop treatments, including: vetch /rye, rye alone, no cover crops (control). Each 3 × 7.5 m replicate was treated with nitrogen fertilizer at a rate of 0, 67, 135 or 202 kg N/ha. There were four replicates. Plots were seeded in September and cut at the end of May. The main crop corn *Zea mays* was seeded in June and harvested in August.

A controlled, replicated experiment in 2005-2009 on silty loam soil in eastern Spain (8) found no marked difference between the soil in the ploughed then sown oats *Avena sativa* treatment and the control, after five years. There were three replicates of five management treatments including: residual herbicide use; ploughing (4 times a year to 20 cm depth); ploughing then sown oats (as before, then oats sown in spring); addition of oat straw mulch; land abandonment (control). Plots were 6 × 10 m. Soil under native vegetation was used as a reference. Six soil samples from each plot were taken annually to 5 cm depth. Five rainfall simulations were also conducted during the summer drought period on 1 m^2 plots. Simulations lasted one hour at 55 mm/h (simulating thunderstorm rain levels). The study measured soil organic matter, arbuscular mycorrhizal proteins, aggregate stability and soil erosion.

An experiment in 2001-2005 on silty loam soil in Villmar-Aumenau, Germany (9) found no obvious changes in soil carbon or nitrogen despite different cover crop and manure management. There were two trials. Trial 1 had eight treatments: (1-2) Clover/grass ley; (3) wheat *Triticum aestivum* plus cover crops receiving farmyard manure (FYM) as slurry or effluents; (4) potatoes *Solanum tuberosum* receiving FYM and solid effluents, or silage maize *Zea mays* receiving FYM; (5) rye *Secale cereal* plus cover crops plus FYM; (6) Peas *Pisum sativum* plus cover crops; (7) Spelt *T. aestivum ssp. Spelta* plus cover crops plus FYM, and (8) wheat undersown with clover/grass ley plus FYM and solid effluents. Trial 2 included: (1) clover/grass ley; (2) potatoes plus solid effluents; (3) winter wheat plus liquid effluents; (4) peas; (5) winter wheat plus liquid effluents; (6) spring wheat plus solid effluents. Which applications of slurry were digested or not were not specified. All manuring treatments were applied before ploughing. Five soil samples were taken from each plot to 30 cm depth and measured soil nitrogen and carbon.

A controlled, randomized, replicated experiment in 2009-2010 on sandy clay soil in south-eastern Australia (10) found higher levels of soil carbon and nitrogen under all cover crops (vetch *Vicia villosa* (12.6 and 810.3), pea *Pisum sativum* (12.6 and 752.5), wheat *Triticum aestivum* (14.8 and 807.5), oat *Avena strigosa* (10 and 770), and mustard *Brassica juncea* (10.4.5 and 777.5)), compared to the control (6.8 mg C/kg dry soil, 622.5 mg N/kg dry soil respectively). There were no differences in carbon or nitrogen levels between legume and non-legume cover crops. Crop residue quantity was highest in wheat (143 g/m^2) compared to vetch (163 g/m^2), pea (110 g/m^2) and mustard (100 g/m^2). Six cover crop treatments (4 × 10 m) included: two legume crops (vetch, pea); three non-legume crops (wheat, Saia oat, Indian mustard); and a no-crop control. There were three replicates of each treatment. Five soil samples were taken from each plot to 10 cm depth.

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10. Zhou, X., Chen, C., Wu, H. & Xu, Z. 2012. Dynamics of soil extractable carbon and nitrogen under different cover crop residues. *Journal of Soils and Sediments,* 12, 844-853.

4.15. Retain crop residues

- **Biodiversity:** One replicated study from Mexico[4] found higher microbial biomass when crop residues were retained.
- **Erosion:** One review[2] found reduced water runoff, increased water storage and reduced soil erosion. One replicated site comparison from Canada[5] found mixed effects on soil physical properties, including penetration resistance and the size of soil aggregates. One replicated study from the USA[1] found that tillage can have mixed results on soil erosion when crop remains are removed.
- **Soil organic matter:** One randomized, replicated trial from Australia[3] found higher soil organic carbon and nitrogen when residues were retained, but only when fertilizer was also applied.
- **Yield:** One randomized, replicated trial from Australia[3] found higher yields when residues were retained in combination with fertilizer application and no-tillage.
- **Soil types covered:** clay[3], loam[5], sandy-loam[4], silt loam[1].

Background

Crop residues are the remains of the crop after the valuable part has been harvested. For this intervention, residue retention is considered to be crop remains which are left in the field, rather than crop remains which are brought in from elsewhere and added to the soil (see 'Amend the soil with fresh plant material or crop remains'). Soil aggregates are groups of soil particles held together by moist clay, organic matter (such as roots), organic compounds (from bacteria and fungi) or fungal hyphae (long, branching structures of a fungus). Some soil particles fit closely together, some do not, creating different-sized spaces. These spaces (or pores) within and between soil aggregates can store air and water, microbes, nutrients and organic matter. Large aggregations of particles retain the most nutrients. Soil penetration resistance is the soil's ability to withstand penetration by water or roots. Often with low penetration resistance comes higher hydraulic conductivity, which is the ease with which a fluid (usually water) can move through pore spaces in the soil. A fertile soil has good hydraulic conductivity. Soil microbial biomass is the amount of tiny living microorganisms within a given area or amount of soil and is measured by levels of carbon or nitrogen in the soil.

A replicated experiment in 1992 on silt loam at three sites in Illinois, USA (1) found decreased water infiltration rates and increased soil loss under both no-tillage (from >70 to 47.1 mm/h and 0.01-0.15 $kg/m^2/h$) and tillage (from 64.1 to 37.2 mm/h and 0.1-0.6 $kg/m^2/h$ respectively) when crop remains were removed at site 1. Removing crop remains from a no-till system increased soil loss at site 2 from 0.01-0.13 $kg/m^2/h$ and site 3 from 0.01-0.16 $kg/m^2/h$. The three sites were under corn *Zea mays*-soybean *Glycine max* rotations. Site 1 was under conventional tillage and treatments were: tilled vs. tilled with crop remains removed. Sites 2 and 3 had been under no-tillage for more than 15 years. Site 2 treatments were: no-tillage, no-tillage with crop remains removed, tillage residue replaced on the soil surface, and tillage residue removed. Site 3 treatments were: no-tillage, no-tillage with crop remains removed, tillage with residue removed, and tillage residue removed after three soil-drying days. Plots were 1 x 2 m and treatments were replicated six times at each site. Rainfall was simulated at an intensity of 70 mm/h on each plot for 90 minutes.

A review of 76 papers in 1991 (2) described a study (Russel, 1939) that found no water runoff under straw residue no tillage (0 mm) and highest runoff under disc tillage with no straw (60 mm). Another study (Greb, 1979) found higher water storage (157 mm) and wheat *Triticum aestivum* yield (2.16 Mg/ha) under stubble mulch with minimum tillage than under conventional tillage with dust mulch (a loose dry layer of soil) (102 mm, 1.07 Mg/ha respectively). Papendick (*et al.* 1990) found that the soil loss ratio (comparing loss from covered to loss from bare soil) decreased with increasing soil cover by crop residues (ratio of 0.8 at 10% cover,0.2 at 35% cover and 0 at 65% cover).

A randomized, replicated experiment from 1968 to 2008 on clay soil in Australia (3) found higher soil organic carbon when crop residues were retained (20.5 Mg/ha) rather than burned (19.5 Mg/ha) in the topsoil. Crop residue retention only affected carbon levels when fertilizer was also applied (1.8 Mg C/ha more carbon with residues and a high fertilizer application rate, compared to no residue and no fertilizer). Nitrogen was 125 kg N/ha higher with retained residues than when burned and total soil nitrogen increased with fertilizer rate when residues were retained. Average grain yield was higher when crop residue was retained under no-tillage plus 90 kg N/ha/year (2.9 Mg/ha) compared to retaining residue under conventional tillage without fertilizer (2.3 Mg/ha). Wheat *Triticum aestivum* was the principle crop bar three years which were cropped with barley *Hordeum vulgare.* Treatments included: tillage (conventional tillage to 10 cm depth vs. no-tillage), crop residue management (burned or retained), and nitrogen fertilizer application (none, low (30 kg N/ha/year) or high (90 kg) application). Plots were 61.9 x 6.4 m and treatments were replicated four times. Soil was sampled in each plot at the end of the experiment to 1.5 m depth.

A replicated experiment in 2005 on a sandy-loam in El Batán, Mexico (4) found greater soil microbial biomass when crop residues were retained (shown by 387 mg C/kg of microbial activity and 515 mg C/kg of microorganism growth), than when they were removed (319 mg C/kg and 384 mg C/kg, in both tillage treatments. Soil microbial biomass was higher in wheat *Triticum aestivum* compared to maize *Zea mays*. Zero and conventional tillage treatments were tested. Within tillage treatments were two residue treatments (retained or removed) and within these were plots of maize and wheat crops. Crop plots (continuous wheat, continuous maize, and rotated wheat and maize) were 7.5 x 22 m and fertilized at 120 kg N/ha. There were two replications of each treatment combination. Soil samples were collected to 15 cm depth from all plots. Total nitrogen and organic carbon were measured.

A replicated, site comparison in 1984-1989 on loam soils in Alberta, Canada (5) found lower soil resistance (942 kPa) when residues were retained compared to removing residue (1,195 kPa) in no-tillage plots. Residue management had mixed effects on the proportion of larger soil aggregates within the soil and did not affect soil density or water infiltration. Treatments were replicated four times and included no-tillage (direct drilling) tillage with rototilling (to 10 cm depth), and two residue levels: straw removed and straw retained. Plots were 6 x 2.7 m. The crop rotation was barley *Hordeum vulgare*/rape *Brassica napus*. Soil density, penetration resistance, particle aggregation and water infiltration were measured.

(1) Bradford, J. M. and Huang, C. 1994. Interrill soil erosion as affected by tillage and residue cover. *Soil & Tillage Research,* 31, 353-361.

(2) Unger, P. W., Stewart, B. A., Parr, J. F. and Singh, R. P. 1991. Crop residue management and tillage methods for conserving soil and water in semi-arid regions. *Soil & Tillage Research*, 20, 219-240.

(3) Dalal, R. C., Allen, D. E., Wang, W. J., Reeves, S. and Gibson, I. 2011. Organic carbon and total nitrogen stocks in a Vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation. *Soil & Tillage Research*, 112, 133-139.

(4) Govaerts, B., Mezzalama, M., Unno, Y., Sayre, K. D., Luna-Guido, M., Vanherck, K., Dendooven, L. & Deckers, J. (2007). Influence of tillage, residue management, and crop rotation on soil microbial biomass and catabolic diversity. *Applied Soil Ecology,* 37, 18-30.

(5) Singh, B. & Malhi, S. S. (2006) Response of soil physical properties to tillage and residue management on two soils in a cool temperate environment. *Soil & Tillage Research,* 85, 143-153.

4.16. Use alley cropping

- **Biodiversity:** A controlled, randomized, replicated study from Canada[1] found that intercropping with trees resulted in a higher diversity of arbuscular mycorrhizal fungi.
- **Soil types covered:** sandy-loam[1].

Background

This agroforestry intervention grows crops between hedgerows or tree lines planted at regular intervals across crop fields or along slope contours. Hedges may be pruned and the foliage used as mulch or green manure on the adjacent crop alleys. The technique may control weeds and insect pests in a number of ways, for example by modifying the field's climate, disrupting pest movement and weed growth, increasing crop vigour, providing habitat for natural enemies and using the insecticidal properties of hedgerow foliage. Studies that plant/allow trees around the edges of fields are included in 'Plant new hedges'. Arbuscular mycorrhizal fungi are a group of fungi that live around the roots of plants. By living together, the fungi and host plant benefit each other: the fungi can live in a habitat without having to compete for resources and receive a supply of carbon from the plant, while they give an enhanced supply of nutrients back to the plant, improving plant growth, the ability to reproduce and tolerance to drought. Arbuscular mycorrhizal fungi colonize a wide variety of host plants, including grasses, herbs, agricultural crops and legumes (Bardgett 2005). A phylotype is a way of classifying an organism by its phylogenetic (or evolutionary) relationship to other organisms.

Bardgett R. (2005) *The Biology of Soil: A Community and Ecosystem Approach*. Oxford University Press, Oxford.

A controlled, randomized, replicated study in 2008 on sandy-loam soil in Ontario, Canada (1) found a greater diversity of arbuscular mycorrhizal fungi (AMF) under tree-based intercropping (6 phylotypes) compared with conventional cropping (4.7 phylotypes). Colonization of corn *Zea mays* roots was greater than 50% in both intercropped and conventional treatments, and AMF richness was similar in both treatments. Different tree species supported distinctive AMF communities. Trees were intercropped annually with corn, soybean *Glycine max*, winter wheat *Triticum aestivum* or barley *Hordeum vulgare* using no-till cultivation. The tree rows accounted for 16% of the crop area and were spaced 12.5-15 m apart. Tree species included silver maple *Acer saccharinum* , white ash *Fraxinum americana* , hazelnut *Corylus avellana* , black walnut *Juglans nigra* , Norway spruce *Picea abies*, hybrid poplar *Populus deltoides*, red oak *Quercus rubra*, black locust *Robinia pseudoacacia*, willow *Salix discolor* and white cedar *Thuja occidentalis*.

(1) Bainard, L.D., Koch, A.M., Gordon, A.M. & Klironomos, J.N. (2012) Temporal and compositional differences of arbuscular mycorrhizal fungal communities in conventional monocropping and tree-based intercropping systems. *Soil Biology and Biochemistry*, 45, 172–180.

4.17. Use crop rotation

- **Biodiversity:** Three randomized, replicated trials from Canada[1, 8] and Zambia[2] measured the effect of including legumes in crop rotations and found the number of microbes and diversity of different soil animals increased.
- **Erosion:** One randomized, replicated trial from Canada[4] found that including forage crops in crop rotations reduced rainwater runoff and soil loss, and one replicated trial from Syria[3] showed that including legumes in rotation increased water infiltration (movement of water into the soil).
- **Soil organic carbon:** Three studies from Australia[5], Canada[6], and Denmark[7] (including one controlled replicated trial[6] and one replicated site comparison study[7]), found increased soil organic carbon under crop rotation, particularly when some legumes were included.
- **Soil organic matter:** Two of four replicated trials from Canada[8, 10] and Syria[11] (one also controlled and randomized[8]) found increased soil organic matter[8], particularly when legumes were included in the rotation[11]. One study[10] found lower soil organic matter levels when longer crop rotations were used. One randomized, replicated study[9] found no effect on soil particle size.
- **Soil types covered:** Clay[5, 6, 11], clay-loam[8], fine clay[3], loam[10], loam/silt loam[1], sandy clay[2], sandy-loam[7, 9], silty-loam[4].

Background

Many different measures are used to determine the health or structure of soil. Soil porosity is the volume of air in soil (or number of pores) and high porosity indicates good soil structure, as does high microbial biomass, and low penetration resistance. Often with low penetration resistance comes higher hydraulic conductivity, which is the ease with which a fluid (usually water) can move through pore spaces. Soil microbial biomass is the amount of tiny living microorganisms within a given area or amount of soil. Soil penetration resistance is the soil's ability to withstand penetration by water or roots. Soil aggregates are groups of soil particles held together by moist clay, organic matter (such as roots), organic compounds (from bacteria and fungi) or fungal hyphae (long, branching structure of a fungus). Some soil particles fit closely together, some do not, creating different-sized spaces. These spaces, or pores, within and between soil aggregates can store air and water, microbes, nutrients and organic matter. Large aggregations of particles retain the most nutrients.

A randomized, replicated experiment, established in 1992 on loam/silt-loam soil at Fort Vermilion, Canada (1) found higher soil microbial biomass in rotations with legume crops (red clover *Trifolium pratense*: 593.99 mg/kg soil, field pea *Pisum sativum*: 448.40 mg/kg soil) compared to fields left fallow (322.68 mg/kg soil) or cropped continuously with wheat *Triticum aestivum* (432.25 mg/kg soil). The trial treatments were zero tillage and conventional tillage (3-4 mechanical cultivations/year), combined with four different crop rotations: wheat-field peas, wheat-red clover, wheat-summer fallow, or continuous wheat. The trial included three replicate plots of each treatment combination, and 10 soil samples were taken from each plot during wheat cropping and mixed before analysis.

A controlled, randomized, replicated study in 1999-2007 on sandy-clay soil in Zambia (2) found higher soil animal diversity and improved maize *Zea mays* yield in crop rotations including legumes (3.7 orders and 4 t/ha, respectively) compared to a continuously cropped maize control (2.9 orders and 2.7 t/ha). There were no differences in overall soil animal abundance and crop yield between single- and two-species legume treatments, but the abundance of earthworms and millipedes were higher in pure stands of pigeon pea *Cajanus cajan* (4.3 earthworms, 2.4 millipedes) and earthworms in sesbania *Sesbania sesban* (1 earthworm), compared to continuously-cropped maize (<1 earthworm, <0.5 millipedes per plot). Two fallow and cropping cycles and one control treatment (continuous maize with two applications of 200 kg/ha NPK fertilizer) were established on 10 × 10 m plots. The treatments in the two cropping cycles were: pure stands of sesbania, tephrosia *Tephrosia vogelii*, or pigeon pea; 1:1 mixtures of sesbania/pigeon pea, and sesbania/tephrosia. The fallow consisted of native legume and grass species. During the cropping phase, fertilizer was only applied to continuously cropped maize. There were three replicates.

A replicated experiment from 1983 to 1995 on fine clay soil in Syria (3) found that soil organic matter increased in medic *Medicago sativa* and vetch *Vicia sativa* legume-cereal rotations (12.5-13.8 g/kg), compared to continuous wheat *Triticum aestivum* and wheat-fallow (10.9-11 g/kg). Higher levels of water filtered into the soil and hydraulic conductivity (see background section) was higher in legume rotations (16.2-21.8 cm/h and 8.7-12.4 cm/h) compared to continuous wheat and wheat-fallow (13.9-14.4 cm/h and 6.2-7.4 cm/h). Cropping sequences included: (1) durum wheat (var *durum)* grown in rotation with lentil *Lens culinaris*, chickpea *Cicer arietinum,* medic and vetch and watermelon *Citrullus vulgaris;* (2) continuous wheat; (3) wheat with a clean-tilled fallow. Each crop treatment was 36 x 150 m. There were seven replicates. Within these plots were secondary grazing treatments and tertiary nitrogen fertilizer treatments, but no results were presented. Soils were sampled annually prior to planting to 20 cm depth.

A controlled, randomized, replicated experiment in 1991-1992 on a silty loam in Ontario, Canada (4) found that including forage crops in crop rotations and minimizing tillage reduced rainwater runoff by 70% and 27%, and soil loss by 87% and 63%, respectively, compared to continuous cropping of maize *Zea mays*. Treatments included alfalfa *Medicago sativa* or bromegrass *Bromus inermis* followed by maize, and a continuously cropped, conventionally tilled maize control. Forage crops were grown for either two, four or six years prior to the reintroduction of maize. There were four replicates. A rainfall simulator was used to simulate rain events at 16 mm/h in 1 m^2 subplots within each treatment. Runoff and soil lost from plots were collected manually. The results did not distinguish between forage crops.

An experiment in 1997 on clay soils in New South Wales, Australia (5) found that crop rotation decreased soil organic carbon across all crop rotations (in two soil types) up to 71% compared to un-cropped controls. Including legumes like clover *Trifolium subterraneum* and lucerne *Medicago sativa* in rotations increased soil organic carbon levels by 41% and 32% respectively compared to wheat *Triticum aestivum* and long fallow controls, and 25% more than when grain legumes were included. Stability of soil aggregates was higher in continuous wheat than in rotations including lucerne, clover, and snail medic *Medicago scutellata*. A long-term rotation started in 1966 included six rotation treatments with three phases arranged in a 6 x 6 m plot (size/replication not specified), 1): lucerne followed by wheat. 2): lucerne or sorghum *Sorghum bicolor* on three plots, and a chickpea *Cicer arietinum*-wheat rotation, a wheat-long fallow rotation and continuous wheat on the remaining three. 3): cowpea *Vigna unguiculata*, clover or snail medic on three plots, and the same wheat rotations as for 2). Soil porosity was measured and soil samples were taken.

A long-term controlled, replicated experiment between 1959 and 1994 on clay loam soil in Ontario, Canada (6) found that cultivating maize *Zea mays* in crop rotations increased soil carbon (20 Mg/ha more carbon than in maize monoculture) and increased maize yield by 30% in fertilized plots, and 360% in unfertilized plots, compared to maize monoculture. In 1959, 12 plots (76.2 x 12.2 m) were established comprising three cropping treatments were maize in monoculture, bluegrass *Poa pratensis* in monoculture, and a maize-oat *Avena sativa*-alfalfa *Medicago sativa*-alfalfa rotation. The 12 plots comprised six replicate plots with fertilizer (16.8 kg N, 29.3 kg P and 27.4 kg K/ha) and six without. Three soil cores were taken from each plot to measure soil density and carbon.

A replicated, site comparison study in 2001-2003 on a sandy-loam in Denmark (7) found that soil organic carbon was higher under crop rotation (2.14 g/100g) relative to continuous cereal at Foulum (2.01 g/100 g). At Flakkebjerg, organic carbon was highest in the cereal plus manure treatment (1.06 g/100 g) compared to continuous cereal (0.91g/100 g). Soil porosity at Flakkebjerg was much higher under crop rotation (0.120 m^3m^{-3}) compared to continuous cereal (0.094 m^3m^{-3}), and cereal with manure (0.090 m^3m^{-3}). There were three 4-year crop rotations at two sites: cereal (oats *Avena sativa*, barley *Hordeum vulgare*, lupin *Lupinus angustifolius*, wheat *Triticum aestivum*) no manure; cereal plus manure; cereal-grass *Lolium perenne*-clover *Trifolium repens* and *Trifolium pratense* rotation without manure. Part of each plot was compacted by a medium-sized tractor. There were two replicates of 216 m^2 plots at Foulum, and 169 m^2 plots at Flakkebjerg. Soils were sampled to 13 cm depth at Foulum and 10 cm depth at Flakkebjerg in the wheat plots, from compacted and uncompacted plots.

A controlled, randomized, replicated experiment in 1988 on a loam/clay loam soil in Saskatchewan, Canada (8) found that crop rotations including grain crops and alfalfa *Medicago sativa* decreased soil organic matter in fallow and grain crop phases, but increased soil organic nitrogen in 4- (37.7 kg/ha/yr) and 6-year (43.9 kg/ha/yr) barley rotations in comparison to continuous wheat (31.1 kg/ha/yr). Microbial biomass was increased by including alfalfa in the rotation (by 26.6 mg C/kg and 10 mg N/kg), as was carbon release into the soil (by 6 mg C/kg). The experiment was part of a long term crop rotation study started in 1964, and over the course of the trial included wheat *Triticum aestivum* (replaced with canola *Brassica campestris*), barley *Hordeum vulgare* (replaced with oats *Avena sativa*) and alfalfa. There were 10 rotations of 2-5 crop types for four or six years, replicated four times in plots of 7.3 x 30.4 m. There were two, three, four, and six year rotations. Crop management followed recommended field practice. Soil samples were taken to 15 cm depth. Organic carbon and nitrogen, carbon release, and microbial biomass were measured.

A randomized, replicated experiment in 2003 on a sandy-loam soil in Quebec, Canada (9) found similar sized soil aggregates in continuous maize *Zea mays* (1.89 mm) and in a soybean *Glycine max*-maize rotation (1.90 mm). There were four replicates of two tillage systems: conventional; and no-tillage. Within these were continuous maize, soybean -maize, and maize-soybean rotations (in 20 x 24 m plots). Within these were four fertilizer treatments: inorganic fertilizers, composted cattle manure, and the two mixed together (tested in 20 x 6 m plot sections). Soil samples (to 10 cm depth) were taken after crop harvest from the maize phase in October 2003. The size of soil aggregates was measured using a wet-sieving procedure. Soil carbon, nitrogen, and phosphorus were measured using finely ground soil samples.

A replicated experiment in 2001-2006 on loam soil in Saskatchewan, Canada (10) found that nitrate-N was lower in arable rotations (82 kg N/ha) and grain and forage crop rotations (60 kg N/ha) than in in low diversity crop rotation (92.3 kg N/ha). Three treatments were replicated four times: an arable rotation comprising wheat *Triticum aestivum*-oilseed (mustard *Brassica juncea* or canola *Brassica napus*), a grain-forage rotation comprising barley *Hordeum vulgare*-perennial forage crop (sweet clover *Melilotus officinalis*, pea *Pisum sativum*, flax *Linum usitatissimum* or alfalfa *Medicago sativa*), and a grain-perennial forage crop comprising mustard-wheat-barley-alfalfa-hay. Fallowing (and green manuring) followed each crop stage for one season, creating six cropping phases over each six-year rotation period. Each treatment plot measured 40 x 12.8 m. Each year, two soil samples were taken during each crop phase, and a third taken in 2006. Nitrate-N, carbon, nitrogen, phosphorus, and yield were measured.

A replicated experiment from 1989 to 1997 on a clay soil in northern Syria (11) found that a wheat *Triticum aestivum*-fallow rotation had the lowest level of soil organic matter (235 t/ha) while a wheat-medic *Medicago* spp. (no species specified) rotation had the highest level (290 t/ha). The other rotations, listed according to the level of soil organic matter they maintained and starting with the lowest, were: wheat-melon *Citrullus vulgaris* (235 t/ha), continuous wheat (246 t/ha), wheat-lentil *Lens culinaris* (249 t/ha), wheat-chickpea *Cicer arietinum* (257 t/ha), and wheat-vetch *Vicia sativa* (266 t/ ha). Rotations of wheat with fallow, wheat with other crops and a continuous wheat control were replicated three times in plots of 36 x 120 m. The wheat rotation treatment included wheat with lentil, chickpea, vetch, pasture medic or watermelon. Within each rotation were four smaller 36 x 30 m sub-plots with 0, 30, 60 or 90 kg N/ha applied. Within these were 12 x 30 m grazing treatments: no grazing, medium and heavy grazing. Soil organic matter, phosphorus, nitrogen and nitrates were measured each cropping season.

(1) Lupwayi, N.Z., Rice, W. A. & Clayton, G.W. (1999) Soil microbial biomass and carbon dioxide flux under wheat as influenced by tillage and crop rotation. *Canadian Journal of Soil Science*, 79, 273–280.

(2) Sileshi, G., Mafongoya, P., Chintu, R. & Akinnifesi, F. (2008) Mixed-species legume fallows affect faunal abundance and richness and N cycling compared to single species in maize-fallow rotations. *Soil Biology and Biochemistry*, 40, 3065–3075.

(3) Masri, Z. & Ryan, J. 2006. Soil organic matter and related physical properties in a Mediterranean wheat-based rotation trial. *Soil & Tillage Research,* 87, 146-154.

(4) Rasiah, V. & Kay, B.D. (1995) Runoff and soil loss as influenced by selected stability parameters and cropping and tillage practices. *Geoderma*, 68, 321–329.

(5) Blair, N. & Crocker, G. J. (2000) Crop rotation effects on soil carbon and physical fertility of two Australian soils. *Australian Journal of Soil Science*, 38, 71-84.

(6) Gregorich, E.G., Drury, C.F. & Baldock, J. a. (2001) Changes in soil carbon under long-term maize in monoculture and legume-based rotation. *Canadian Journal of Soil Science*, 81, 21–31.

(7) Schjønning, P., Munkholm, L. J., Elmholt, S. & Olesen, J. E. 2007. Organic matter and soil tilth in arable farming: Management makes a difference within 5-6 years. *Agriculture, Ecosystems and Environment,* 122, 157-172.

(8) Campbell, C. A., Brandt, S. A., Biederbeck, V. O., Zentner, R. P. & Schnitzer, M. (1992) Effect of crop rotation and rotation phase on characteristics of soil organic matter in a Dark Brown Chernozemic soil. *Canadian Journal of Soil Science,* 72, 403-416.

(9) Jiao, Y., Whalen, J. K. & Hendershot. (2006) No-tillage and manure applications increase aggregation and improve nutrient retention in a sandy-loam soil. *Geoderma,* 134, 24-33.

(10) Malhi, S. S., Brandt, S. A., Lemke, R., Moulin, A. P. & Zentner, R. P. (2009) Effects of input level and crop diversity on soil nitrate-N, extractable P, aggregation, organic C and N, and nutrient balance in the Canadian Prairie. *Nutrient Cycling in Agroecosystems,* 84, 1-22.

(11) Ryan, J., Masri, S., İbriçi, H., Singh, M., Pala, M. & Harris, H. C. 2008. Implications of cereal-based crop rotation, nitrogen fertilisation, and stubble grazing on soil organic matter in a Mediterranean-type environment. *Turkish Journal of Agriculture and Forestry,* 32, 289-297.

4.18. Incorporate leys into crop rotation

- **Nutrient loss:** One replicated study from Denmark[1] showed that reducing the extent of grass pasture in leys reduced the undesirable uptake of nitrogen by grasses, therefore requiring lower rates of fertilizer for subsequent crops.
- **Soil types covered:** sandy-loam[1].

Background

This action involves converting arable land to grass or legume pasture (leys) for at least one growing season. We found evidence for one study examining different extents of grass pasture in leys.

A replicated experiment from 1994 to 2006 on sandy-loam soil in Foulum, Denmark (1) found lower nitrogen uptake in 25% and 38% grassland leys than in a 75% grassland ley, therefore less fertilizer (average application 111 kg N/ha) was required to improve subsequent barley *Hordeum vulgare* crops, compared with after the 75% grassland ley (132 kg N/ha). Overall nitrogen uptake by perennial ryegrass was higher grown alone (126 kg N/ha), than in the perennial ryegrass-white clover *Trifolium repens* ley (109 kg N/ha) treatment. Four replicates of two crop rotations (in 576 m^2 plots) were established, including unfertilized ryegrass *Lolium perenne*-clover and fertilized (300 kg N/ha/y) ryegrass leys rotated with barley. Half of the barley plots were undersown with ryegrass. Each ley treatment was split into 25%, 38% and 75% grassland (remainder not specified). In 2002-2003, cattle slurry fertilizer was applied at three different rates: 0, 115 and 230 kg N/ha on 12 x 12 m plots. Up to 20 soil samples were taken periodically from each plot between 20-100 cm depth and soil carbon, nitrogen, nitrate and ammonium levels were measured.

(1) Eriksen, J., Askegaard, M. & Søegaard, K. 2008. Residual effect and nitrate leaching in grass-arable rotations: effect of grassland proportion, sward type and fertilizer history. *Soil Use and Management*, 24, 373-382.

5. Livestock and pasture farming

5.1. Reduce grazing intensity

- **Compaction:** One replicated study from Australia[1] found compacted soils recovered when sheep were excluded for 2.5 years.
- **Erosion:** Two replicated studies from New Zealand[2], and Syria[3] (one also controlled[2]) measured the effect of grazing animals on soil nutrient and sediment loss. Of these, one trial[3] found increased soil carbon and nitrogen when grazing animals were excluded. One trial[2] found higher soil phosphate levels, and less sediment erosion when grazing time in forage crops was reduced.
- **Soil types covered:** clay[3], clay-loamy[1], loamy[1], silt loam[2].

Background

Soil permeability is the ability of soil to transmit water.

A replicated experiment in 1993-1996 on loamy and clay-loamy soils in southern New South Wales, Australia (1), found that compacted soils recovered naturally when sheep were excluded for 2.5 years. Soil permeability (35 mm tension) and soil density (under low to high stocking rates: 1.20, 1.18 and 1.18 t/m3 respectively) in areas ungrazed for 2.5 years, were comparable to soils ungrazed for 27 years (25 mm and 1.17 t/m^3). However there was large year-to-year variation in soil permeability. Each plot (0.4 ha) had three stocking rates (established in 1983) – ungrazed, low (10 sheep/ha), medium (15 sheep/ha) and high (20 sheep/ha) – replicated four times. Sheep were excluded from two 1 x 2 m areas in each plot in September 1993. Rainfall and evaporation were recorded at a weather station 3 km from the site. The soil permeability was measured twice in each plot. Soil density was determined in 1996 by four soil cores taken from each plot.

A controlled, replicated experiment in 2004-2008 on silt loam soil in New Zealand (2) found that phosphorus loss from forage crop fields was reduced by 26% and 36%, and sediment loss by 35% and 53%, when cattle and sheep grazing was reduced to three/hours a day. Grazing cattle or sheep on forage crops increased phosphorus loss by approximately 100% (1.3 kg/ha) and 33% (0.9 kg/ha) respectively, relative to grazing sheep on pastures (0.6 kg/ha). Cattle or sheep grazing increased the amount of fine sediment washed from fields by 1,000% (0.7 mg/ha) or 500% (0.4 mg/ha), compared to grazing sheep on pastures (0.06 mg/ha). There were 28 plots (10 × 25 m) testing combinations of the following treatments: cattle or sheep grazing on winter forage crops (triticale *Triticosecale Wittmack*, then kale *Brassica oleracea*), sheep grazing on pasture, restricted grazing, and/or alum addition (20 kg/ha following grazing). Treatments were replicated four times.

A replicated experiment from 1989 to 1997 on a clay soil in northern Syria (3) found that reducing grazing intensity generally increased soil organic matter levels, by 264 t/ha with zero grazing, 253 t/ha with medium intensity and 250.8 t/ha with high intensity grazing of crop residues. Three replications of 36 x 120 m plots included continuous wheat *Triticum aestivum*, and wheat-fallow, wheat- lentil *Lens culinaris*, wheat-chickpea *Cicer arietinum*, wheat-vetch *Vicia sativa,* wheat-pasture medic *Medicago* sp., and wheat-watermelon *Citrullus vulgaris* rotations. Within each rotation were four smaller 36 x 30 m sub-plots receiving 0, 30, 60 or 90 kg N/ha. Within these were three 12 x 30 m grazing treatments: no, medium and heavy grazing of crop stubbles. Soil organic matter, nitrogen/nitrates, and phosphorus were measured at the beginning of each cropping season.

(1) Greenwood, K. L., MacLeod, D.A., Scott, J. M. & Hutchinson, K. J. (1998) Changes to soil physical properties after grazing exclusion. *Soil Use and Management,* 14, 19-24.

(2) McDowell, R.W. & Houlbrooke, D.J. (2009) Management options to decrease phosphorus and sediment losses from irrigated cropland grazed by cattle and sheep. *Soil Use and Management*, 25, 224–233.

(3) Ryan, J., Masri, S., İbriçi, H., Singh, M., Pala, M. & Harris, H. C. 2008. Implications of cereal-based crop rotation, nitrogen fertilisation, and stubble grazing on soil organic matter in a Mediterranean-type environment. *Turkish Journal of Agriculture and Forestry,* 32, 289-297.

5.2. Restore or create low input grasslands

- **Biodiversity:** One randomized, replicated trial in the Netherlands[2] and one controlled trial from France[1] found that restoring grasslands increased the diversity of soil animals. One trial[1] also found higher microbial biomass, activity and carbon under grassland.
- **Soil types covered:** sandy-loam[2], silty[1].

A controlled experiment from 1968 to 2002 on silty soil in France (1) found greater microbial biomass under permanent grassland (557 µg C/g) compared to arable management (179 µg C/g). Fungal diversity increased by 2.3 to 6.4 times under grassland compared to arable management. Total carbon was highest under permanent (33.3 g/kg) followed by temporary (19.7 g/kg) then restored grassland (18.1 g/kg), compared to arable management (9.5 g/kg). Microbial activity, or the breakdown of carbon, was greater as grassland aged, with decomposed carbon ranging from 2.4% (of total carbon measured) under arable cropping to 5.6% in older temporary grassland. Treatments included: one long-term arable field (> 10 years of wheat *Triticum aestivum,* maize *Zea mays*, flax *Linum usitatissimum* or beetroot *Beta vulgaris*), one long-term grassland (> 25 years of pasture), two temporary grassland (previously had 2 years of wheat-maize rotations), and three restored grassland fields (re-established after at least eight years of cropping). The six permanent, temporary and restored grasslands were implanted with perennial ryegrass *Lolium perenne* and clover *Trifolium* spp. several times throughout the experiment. Each field was divided into three 2 x 40 m plots and soils were sampled in each plot to 10 cm depth.

A randomized, replicated experiment in 2001-2003 on sandy-loam in the Netherlands (2) found that restoring arable land to grassland increased the diversity of soil animals. There was a higher diversity of bacteria (68 DNA bands per experimental plot), nematodes (28 genera per experimental plot), earthworms (3 species per experimental plot), potworms (4 species) and predatory mites (10 species) in new grassland than new arable land (65 DNA bands, 21 genera, 0 species, 4 species, and 4 species respectively). There were four experimental systems: long-term grassland (dominant species included fescue *Festuca rubra,* velvet grass *Holcus lanatus*, sweet vernal grass *Anthoxanthum oderatum,* sorrel *Rumex acetosa,* and buttercup *Ranunculus* spp.), new grassland, long-term and new arable land (an oat *Avena sativa*, maize *Zea mays*, barley *Hordeum vulgare*, potato *Solanum tuberosum* rotation). There were three replicates of 10 x 12 m field plots. Soil samples were taken to 10 cm depth.

(1) Plassart, P., Vinceslas, M. A., Gangneux, C., Mercier, A., Barray, S. and Laval, K. 2008. Molecular and functional responses of soil microbial communities under grassland restoration. *Agriculture, Ecosystems and Environment*, 127, 286-293.

(2) Postma-Blaauw, M. B., de Goede, R. G. M., Bloem, J., Faber, J. H. & Brussaard, L. 2012. Agricultural intensification and de-intensification differentially affect taxonomic diversity of predatory mites, earthworms, enchytaeids, nematodes and bacteria. *Applied Soil Ecology*, 57, 39-49.

1. Annex 1: Search terms used for gathering studies

The search equation for obtaining studies from the Web of Science abstracts comprised six search strings. Results were sorted by relevance, then the first hundred hits were trawled, and relevant studies selected. This process was repeated while refining the search terms.

Search String 1: Soil compaction

1a.	Soil compaction, soil compaction AND manag*, soil compaction AND (manag* OR avoid*), soil compaction AND wheel rut*, soil compaction AND (management AND wheel rut*), oil compaction AND till*, soil compaction AND (management AND till*

Search String 2: Soil erosion

2a.	Soil erosion, soil erosion AND manag*, till*, soil erosion AND till*, soil erosion AND (manag* AND till*), Soil erosion AND terrace*, soil erosion AND (management AND terrace*), soil erosion OR crop residue, soil erosion AND crop residue, soil erosion AND (manag* AND crop residue), alley farming, alley farming AND soil, soil AND hedg*, soil AND hedg* AND UK

Search String 3: Soil organic matter loss

3.	soil organic matter OR SOM, soil organic matter AND manag*, soil organic matter AND manag* AND UK, soil organic matter AND legume cropping, soil organic matter AND fallow period, soil organic matter AND fallow period AND vegetation, soil organic matter AND organic manag*, soil organic matter AND organic manag* AND intervention*, soil organic matter AND crop residue*

Search String 4: Nutrient addition/depletion

1a.	nitrogen loss OR N loss, nitrogen loss AND fertiliser OR fertilizer, nitrogen loss AND farm yard manure, nitrogen loss AND cover crop*, nitrogen loss AND tim*, nitrogen loss AND crop rotation
OR	
1b.	phosphorus loss OR P loss, phosphorus loss AND fertiliser OR fertilizer, phosphorus loss AND mitigat*
OR	
1c.	cover crop*, cover crop* AND soil, crop rotation, crop rotation AND soil

Search String 5: Biodiversity loss

1a.	soil biodiv*, soil biodiv*AND manag*, soil biodiv* AND increase*, fung* biodiv*, soil biodiv* AND fung*
OR	
1b.	TS=(soil* SAME functional *diversity) AND TS=(farm* OR agri*)

Search String 6: Flooding

1a.	Soil AND flood*, soil mitigate* AND flood*, soil AND farm* AND flood*, soil AND farm* AND flood* AND UK, flood* AND agri*, flood* AND manag*, water manag* AND soil, flood* AND landuse OR land use
OR	
1b.	Retention pond*, retention pond* AND flood*, retention pond* AND agri*
OR	
1c.	dam* AND flood*mitigate*, dam* AND flood*mitigate* AND agri*