RECARE
Preventing and Remediating degradation of soils in Europe through Land Care

Measures for Preventing, Mitigating and Remediating Soil Threats in Europe

A Literature Review

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RECARE partner list

No	Name	Short name	Country	Country
1	WAGENINGEN UNIVERSITY	WU	Netherlands	NL
2	TECHNICAL UNIVERSITY OF CRETE	TUC	Greece	GR
3	AARHUS UNIVERSITET	AU	Denmark	DK
4	UNIVERSITAT DE VALENCIA	UVEG	Spain	ES
5	THE CYPRUS INSTITUTE LIMITED	CyI	Cyprus	CY
6	NORWEGIAN INSTITUTE FOR BIOECONOMY RESEARCH	NIBIO	Norway	NO
7	UNIVERSIDADE DE AVEIRO	UA	Portugal	PT
8	LANDGRAEDSLA RIKISINS	SCSI	Iceland	IS
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26	UNIVERSITA DEGLI STUDI DI PADOVA	UNIPD	Italy	IT
27	KONGSKILDE INDUSTRIES AS	KONGSKILDE	Denmark	DK

About this document

The EU-funded RECARE project (Preventing and Remediating Degradation of Soils in Europe through Land Care, http://www.recare-project.eu) aims at the development of effective soil prevention, remediation and restoration measures using an innovative trans-disciplinary approach, actively integrating and advancing knowledge of stakeholders and scientists in 17 case study sites across different bio-physical and socio-economic environments across Europe. The soil threats addressed by this project are soil erosion by water, soil erosion by wind, decline of soil organic matter (SOM) in peat soils, decline of SOM in minerals soils, soil compaction, soil sealing, soil contamination, soil salinization, desertification, flooding and landslides, and decline in soil biodiversity.

This review has been compiled as part of RECARE Work Package (WP) 5 which looks into the selection of promising and innovative measures to be implemented at the 17 RECARE case study sites. It aims at reviewing existing measures for prevention, remediation and restoration of the identified soil threats in Europe and the world in order to identify and select promising and innovative measures that could be implemented in the case study sites, and later on up-scaled to EU level as part of WP8. This report is considered supplementary to the literature review report for the RECARE Project (Deliverable D2.1): Soil in Europe - threats, functions and ecosystem services.

For the present document, an extensive literature survey of measures for preventing, mitigating and remediating soil threats in Europe and the wider world has been conducted using a wide range of data sources and personal communications with all RECARE project partners. The review focuses on actual measures being applied to prevent, mitigate or remediate the soil threats as specified by RECARE. The existing measures are illustrated per RECARE soil threat.

Whereas measures for control of erosion by water and wind, desertification, and contamination can easily be found, much less information is available for arresting decline in organic matter in peat and mineral soils, flooding, landslides, soil sealing, or loss of soil biodiversity.

The amount of information available at the global scale is overwhelming, and not all of the information retrieved could be included. We have included what we believe to be accurate. Nevertheless, it is by no means an exhaustive document and no guarantee is provided about the content.

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Acronyms

CBC	Common Agriculture Policy, PHARE Cross Border Co-operation
CBD	United Nations Convention on Biological Diversity
CEC	Cation Exchange Capacity
CNKI	China Knowledge Resource Integrated
DRO	Diesel Range Organics
EC	The European Commission
ECE	Economic Commission for Europe
ECPA	European Crop Protection Agency
ERDF	European Regional Development Fund,
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GPS	Global Positioning Systems
IAEA	International Atomic Energy Agency
ISRIC	International Soil Reference and Information Centre
JRC	Joint Research Centre of the European Commission
MDA	Minnesota Department of Agriculture
PRO	Petroleum Range Organics
RECARE	EU-funded Project: Preventing and Remediation Degradation of Soils in Europe through Land Care
SAPARD	Special Action Programme for Agriculture and Rural Development
SCS-CN	Soil Conservation Service Curve Number
SDGs	Sustainable Development Goals
SIC	Soil Inorganic Carbon
SLM	Sustainable Land Management
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SVOCs	Semi-Volatile Organic Compounds
SWC	Soil and Water Conservation
UN	The United Nations
UNCCD	United Nations Convention to Combat Desertification
UN/ECE	United Nations and Economic Commission for Europe
USA EPA	The United States of America Environmental Protection Agency
USDA	The United States Department of Agriculture
VOCs	Volatile Organic Compounds
WOCAT	World Overview of Conservation Approaches and Technologies

0 Introduction

The world's carrying capacity roots in the soil, the living skin of the earth. Attention for this resource has focused on degradation of soils in its many forms: erosion, loss of soil organic matter, compaction, sealing, contamination, salinization, desertification, flooding and landslides, and loss of soil biodiversity which threaten soil functions and ecosystem services (Figure 1). This is a global development issue and land degradation neutrality has accordingly been suggested as one of the targets in the UN Sustainable Development Goals (SDGs) (OWG, 2014).

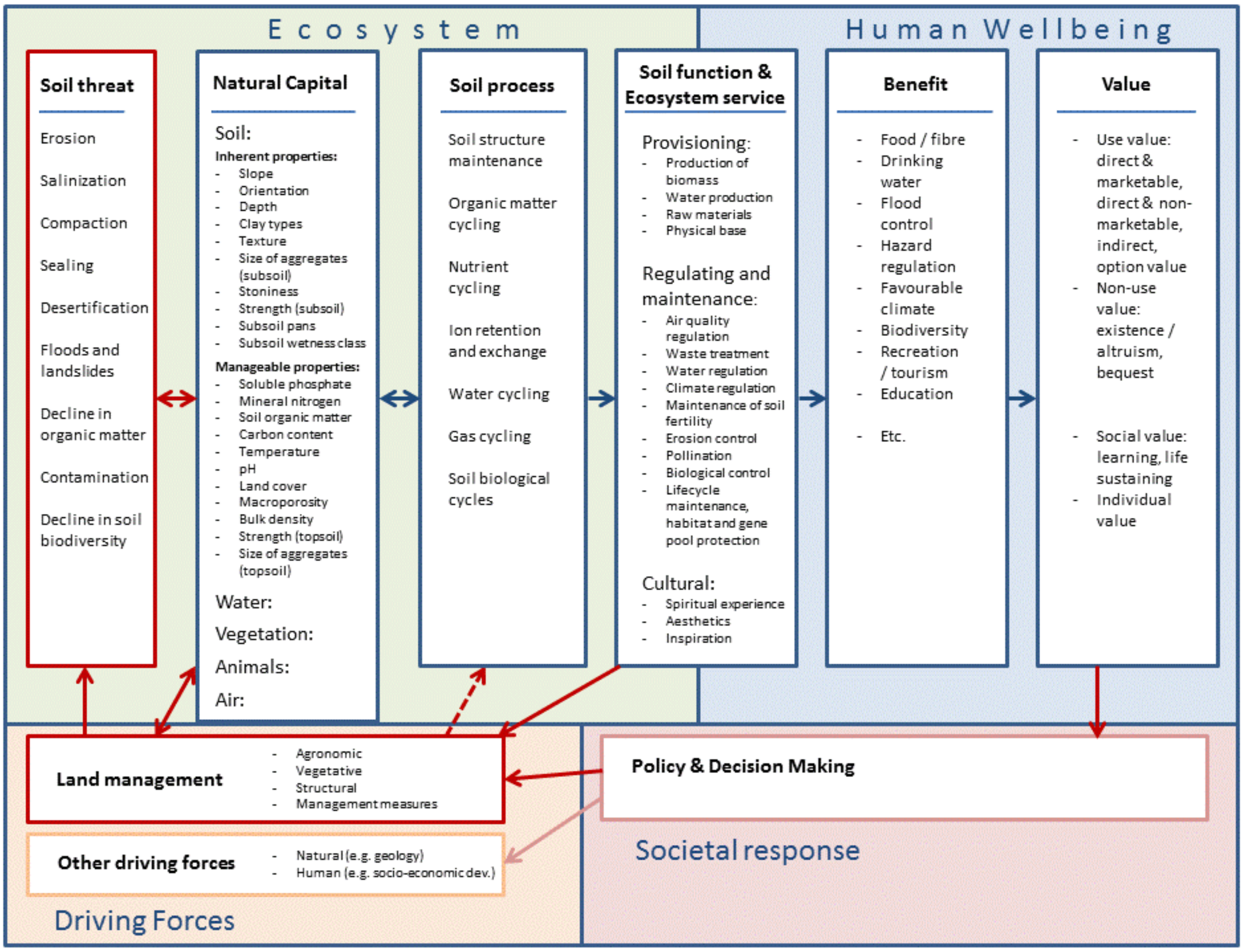


Figure 1.1. Soil threats and their impact on to soil functions and ecosystem services (from RECARE project report D2.1)

The EU-funded RECARE project *(Preventing and Remediating Degradation of Soils in Europe through Land Care)* aims at the development of effective prevention, remediation and restoration measures using an innovative trans-disciplinary approach, actively integrating and advancing knowledge of stakeholders and scientists in 17 case study sites across different bio-physical and socio-economic environments across Europe. The soil threats addressed by this project are soil erosion by water, soil erosion by wind, decline of soil organic matter (SOM) in peat soils, decline of SOM in minerals soils, soil compaction, soil sealing, soil contamination, soil salinization, desertification, flooding and landslides and decline in soil biodiversity. The project consists of 11 work packages (WP). ISRIC leads WP5 that looks into the selection of promising and innovative measures to be implemented at the 17 RECARE case study sites.

This literature review aims at reviewing existing measures for prevention, remediation and restoration of the identified soil threats in Europe and the world in order to identify and select promising and innovative measures that could be implemented in the case study sites, and later on up-scaled to EU level as part of WP8.

The literature review was carried out through an exhaustive literature survey of peer-reviewed and online publications using Google Scholar, ISI Web of Science, ResearchGate, ResearcherID, Scopus, AuthorID, ORCiD, Mendely.com, Scholarmate, Academia.edu, the China Knowledge Resource Integrated (CNKI) databases and the World Overview of Conservation Approaches and Technologies (WOCAT) database. The review focused on the identification of those measures that are currently being used for preventing and remediating soil degradation.

The WOCAT database (http://www.wocat.net) contains a large number of case studies of various sustainable land management (SLM) or soil and water conservation (SWC) technologies and approaches. Where available, WOCAT examples are cited at the end of each section. For each measure, the database contains location of application, natural and human environments, implementation activities, inputs and costs, maintenance/recurrent activities, impact of the measure, strengths and weakness, contact person and approach (code) for implementation, and so on.

This report is considered as supplementary to the literature review report for the RECARE Project (*Deliverable D2.1*): ***Soil in Europe - threats, functions and ecosystem services***, which illustrates for each soil threat definition and process involved, state, drivers/pressures (including climate, human activities, policies), key indicators, methods to assess the soil threat, effects of the soil threat on other soil threats, and effects of the soil threat on soil functions – literature review on measures is, however, not included in that deliverable.

1 Soil Erosion By Water

Soil erosion by water is the result of rain detaching and transporting vulnerable soil, either directly by means of rain splash or indirectly by rill and gully erosion (Boardman & Favis-Mortlock, 1998). It is a problem across Europe wherever erodible soil is combined with sloping land, low soil cover and heavy rainfall. Agricultural activities exacerbate erosion. Although the physics of water erosion process are well understood, the challenge is to combine measures with agricultural practices in such way that measures are effective and agriculture is profitable, This challenge is amplified by the large spatial and temporal variability of the erosion.

The principle to control soil erosion by water is maximisation of rainfall infiltration in soils in situ. For that various measures could be taken, *e.g.*, vegetation cover, mulching, tillage, terracing, or water harvesting. These measures could be combined in terms of local biophysical conditions, cost-benefits and impact on control of erosion on-site (*e.g.* splash, sheet, rill and gully) and off-site (sedimentation).

1.1 Vegetation cover

A dense vegetation cover can prevent splash erosion, increase surface roughness which reduces velocity of surface runoff and increases infiltration, facilitating accumulation of soil particles; root systems can stabilise soil aggregates and increase infiltration (Morgan, 1999; Hurni *et al.*, 2003) and strips of vegetation can filter and slow down surface runoff.

1.1.1 Planting grasses, shrubs and trees

Planting vegetation is efficient in reducing erosion and is a relatively inexpensive erosion control measure. Vegetative cover provides a canopy that covers the soil from the impacts of rain drops and a rooting system that holds soil particles together. Dense and short vegetative covers like grass are often more effective than tall and sparse vegetation for control of water erosion. Dense vegetation covers the soil surface and reduces the impact of energy of falling rain. The more vegetation area that is preserved, the less area exposed to erosion. Planting new vegetation that has a fibrous root system with fast establishment of roots and ground cover are good options. Permanent vegetative cover should be established on disturbed areas to stabilize the soil and reduce damages from runoff and sediment. Suggested shrubs for erosion control are listed in Table 1.1.

Table 1.1. Shrubs for control of soil erosion (Modified from: Kim Todd, UNL.).

Scientific Name	Common Name
Chrysopogon zizanioides	Vetiver grass, or khus
Sorbaria sorbifolia	Ural false-spirea
Rhus glabra	Smooth sumac
Rhus aromatica (Gro-Low cultivar)	Dwarf sumac
Symphoricarpos orbiculatus	Coralberry
Symphoricarpos x chenaultii	Coralberry
Prunus americana	American plum
Cornus racemosa	Gray dogwood
Diervilla sessilifolia	Southern bush honeysuckle
Prunus besseyi (Pawnee Buttes cultivar)	Sand cherry
Juniperus chinensis	Chinese juniper
Juniperus horizontalis	Creeping juniper
Juniperus sabina cultivars (Calgary Carpet is one of the best cultivars)	Savin juniper

Examples in WOCAT Database:
T_KEN659en; T_PHI011en; T_SWI001en

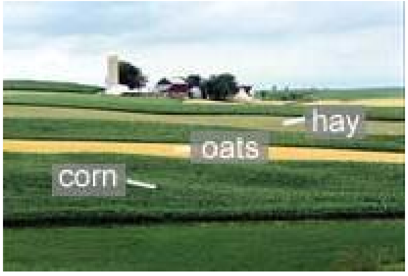
1.1.2 Contour cropping

Contour cropping is growing crops along the contour line of a slope. It increases water infiltration, reduces surface runoff and erosion by ploughing and planting across slope. Contour cropping works fine on gentle slopes, not on steep ones.

Hillside contour strawberry farming in Monterey County, CA (*Photo by USDA-NRCS*)

Farming on the contour, rows are perpendicular to the slope (*Photo by USDA NRCS*)

Strip contour cropping is the management practice of growing two or more crops in alternating strips along the contour of the land. In this system, a row crop more susceptible to erosion, like corn or soybeans, is planted alternating with a cover crop less susceptible to erosion, like grass meadow, clover, or oats. Similar to contour cropping, crops are planted perpendicular to the wind or water flow. Soil detached from the row crops by the forces of wind or water will get trapped by the cover crop.



Strips of oats and hay are interspersed with strips of corn to save soil and improve water quality and wildlife habitat on this field in northeast Iowa (Photo by USDA-NRCS)

Aerial view of contour buffer strips on highly erodible cropland in Winneshiek County in northeast Iowa. Strips of green alfalfa help curb erosion by providing breaks from the more erodible corn fields (Photo by USDA-NRCS)


Vegetative strips (Source: WOCAT)

Examples in WOCAT Database:
T_RSA004en; T_UGA013en

1.1.3 Vegetative strips

A good example of vegetative strips is planting Vetiver grass. Vetiver grass is proven to be a very effective measure to control erosion, reduce and filter runoff, preserve sediment, stabilize and rehabilitate the degraded soils and improve agricultural production. Vetiver grass can also be used for construction and furnishing of houses,, cultivation of mushrooms, ceremonial handicraft and medicinal purposes and increase in income which contributes to improve farmers' socioeconomic status in the community; planting Vetiver grass can recharge dried wetlands, springs and rivers and groundwater. Planting Vetiver grass is simple, inexpensive and low maintenance (Terefe, 2011).

Vetiver grass (Source: Terefe, 2011)

Examples in WOCAT Database:
T_BAN001en; T_CPV003en; T_CPV006en; T_MEX002en; T_MOR015en; T_KEN659en; T_PHI011en; T_SWI001en; T_NEP022en; T_NIG002en; T_NIG024en; T_PHI003en T_RSA035en; T_TAJ006en; T_TAJ047en; T_TAJ103en; T_TAJ349en; T_THA001en

1.1.4 Temporary and permanent seeding

Temporary seeding is the planting of grasses or plant materials that will quickly germinate and grow into protective cover for the soil until a permanent planting is established. Temporary seeding is recommended during the land grading and construction processes. Rapidly growing plants such as annual grasses, legumes or small grains are appropriate temporary seeding options. Temporary seeding protects the soil and reduces mud and dust produced during construction. Thus, it is a short-term erosion control measure (<1 year).

Permanent seeding is the establishment of the appropriate grasses or plants in the construction sites. Unlike temporary seeding, permanent seeding requires that the construction phase is complete. Only then more appropriate and/or desired plants are established. Thus, permanent seeding is for long-term control of soil erosion. If the season is not appropriate for permanent seeding, temporary seeding options are often considered to minimize bare soil exposure until permanent seeding can be done. Either temporary or permanent seeding can be done through hand seeding and/or hydro-seeding. Hydro-seeding is done if the land is especially steep and irregular for hand seeding.

1.1.5 Grassed waterways

A grassed waterway is a natural or constructed ditch, usually broad and more shallow than the rest of the field, used to conduct surface water from or through cropland. Grassed waterways enhance water infiltration and trap eroded sediment, and also help in preventing the development of gullies in the fields because the grasses are purposely established in the lowest part of the landscape, where concentrated water flow will likely occur. They are less costly to implement but require periodic maintenance to work efficiently.

A network of grassed waterways.

Contour terraces draining into a grassed waterway.

Source: http://passel.unl.edu/pages/informationmodule.php?idinformationmodule=1088801071&topicorder=14&maxto=16

Examples in WOCAT Database:
T_ETH051en; T_IND020en; T_KEN010en; T_RSA011en; T_TAJ010en; T_THA024en; T_UGA005en

1.2 Mulching

Mulching is a measure of applying dead plant or non-plant materials to cover bare soil surface to protect soil from erosion; it also conserves water and reduces soil temperature fluctuations. Mulching can be plant-based or organic, it can also be other materials *e.g.,* plastic film, cobblestone. If mulching is plant-based or organic, it can improve soil organic matter and soil biodiversity. Table 1.2 lists advantages and disadvantages of various mulching.

Table 1.2. Mulching for controlling soil erosion.

Material	Type	Advantages	Disadvantages
Bark mulch	Organic (plant-based)	- slowly builds org. matter - relatively inexpensive	- periodic application needed - easily blown away under windy conditions - may not be aesthetic
Wood chips	Organic (plant-based)	- slowly builds org. matter - relatively inexpensive	- periodic application needed - easily blown away under windy conditions - may not be aesthetic
Leaves	Organic (plant-based)	- builds organic matter - relatively inexpensive - decomposes relatively fast - adds nutrients to the soil	- periodic application needed - Mixing may be necessary to avoid leaves being blown - may not be appealing aesthetically
Grass clippings	Organic (plant-based)	- builds organic matter - relatively inexpensive - decomposes relatively fast - adds nutrients to the soil	- periodic application needed - Mixing may be necessary to avoid leaves being blown - may not be appealing aesthetically
Newspaper	Organic (plant-based)	- slowly builds org. matter - relatively inexpensive	- periodic application needed - Mixing may be necessary to avoid leaves being blown - may not be appealing aesthetically
Compost	Organic (plant-based)	- builds organic matter - relatively inexpensive - decomposes quite fast - adds nutrients to soil	- periodic application needed - may not be appealing aesthetically
Crushed stone, gravel, volcanic rock	Inorganic (non-plant)	- periodic application not necessary - appealing aesthetically	- does not build org. matter - relatively expensive
Plastics	Inorganic (non-plant)	- periodic application not necessary - appealing aesthetically - relatively inexpensive	- does not build org. matter - may not be aesthetic - can increase soil surface temperature to the extreme - causes waste after use if not properly disposed of
Geotextiles	Inorganic (non-plant)	- especially useful in high velocity flows, such as creek and stream bank protection - periodic application not necessary - appealing aesthetically	- does not build organic matter - may not be appealing aesthetically - may need to be replaced periodically because of wear and tear - relatively expensive

1.2.1 Organic or plant-based mulching

Organic or plant-based residues is plant material, such as stems, leaves, and roots, left in the field after harvest. Leaving plant residue on the soil surface can protect the soil from both water and wind erosion. Residue covers soil particles so that they are less susceptible to being dislodged by the energy of water and wind. The degree of erosion control by residue cover depends on the residue type and amount. For example, in the chart below, a 50% residue soybean residue cover is as effective as a 50% corn residue cover. However, with less than 50% residue coverage, the corn residue is better at reducing erosion than soybean residue. This is because the size of leaves and stems of soybeans are smaller than corn, and therefore, offer less protection from wind and water.

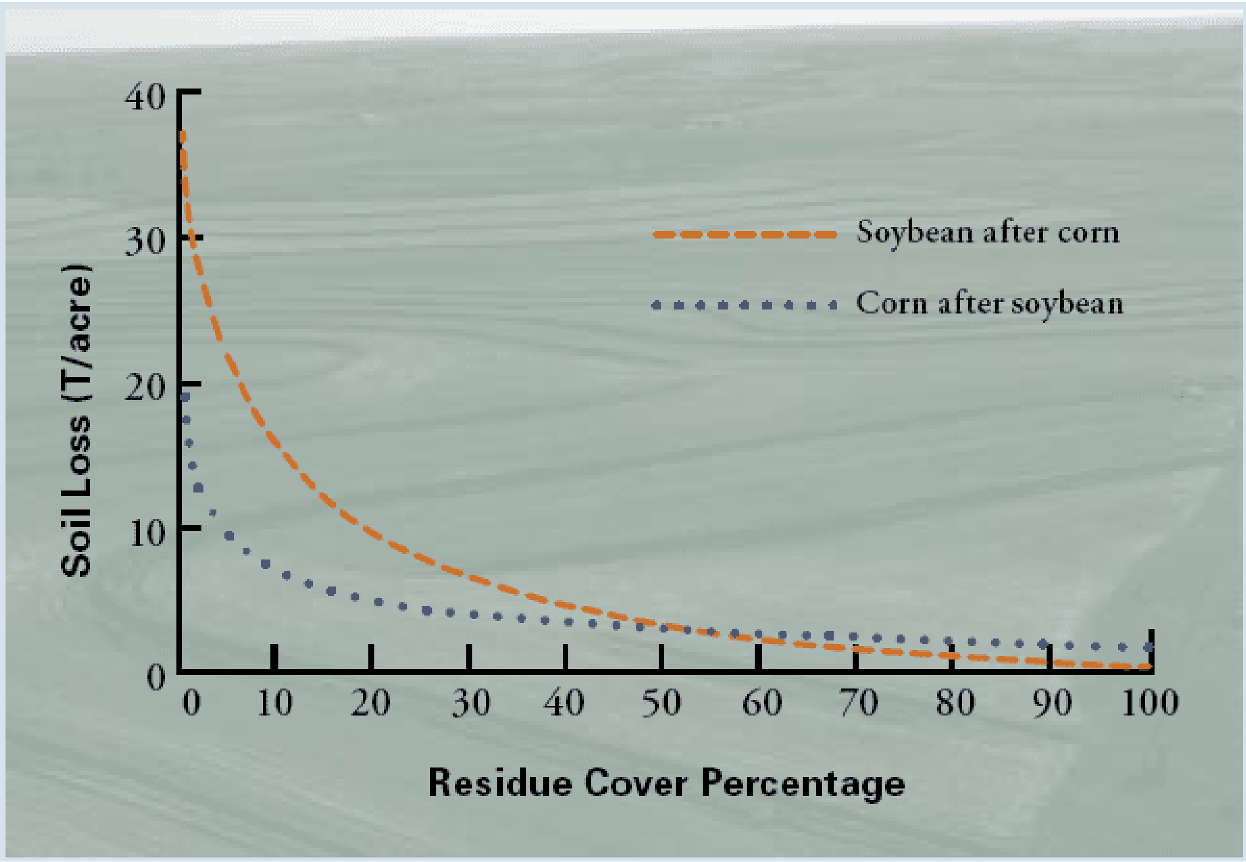


Figure 1.2. Soil loss due to water erosion in relation to percent residue cover for Iowa, based on the Universal Soil Loss Equation (By Iowa State University)

1.2.2 Inorganic mulching

Inorganic mulching such as plastic films is widely used to cover soil surface to protect soil moisture, increase soil temperature and reduce soil erosion. It has also negative impact on soils *e.g.,* polluting soils due to hard or non-decomposition.

Selection of mulching depends on land use, topography as well as economic conditions.

Examples in WOCAT Database:
T_AUS003en; T_CBD003en; T_ETH010en; T_GHA001en; T_PHI008en; T_POL003en; T_SPA003en; T_TAJ105en; T_TAN014en; T_TAN022en; T_UGA006en; T_UNK001en; T_UNK003en

1.3 Tillage

Tillage practices help to loose soil enhancing infiltration and aeration, bury plant residue and weeds in the process and leave a rough surface that is then disked smooth to allow for better planting. Tillage can be grouped into two broad categories: conventional tillage and conservation tillage. Conventional tillage is ploughing soil after harvest or before seeding. These operations create soil disturbance which in turn leads to a higher erosion risk. Therefore a tillage system that minimises soil disturbance is desirable to reduce soil erosion.

A moldboard plough, part of a conventional tillage system, significantly incorporates and buries residue and leaves a rough soil surface (Source : *by M. Mamo)*

Chisel plough (*Image by M. Mamo)*

1.3.1 Conservation tillage

Conservation tillage reduces soil disturbance to a minimum by reducing tillage or sub-soiling and keeps more residue from the previous crop at the soil surface (such as corn stalks or wheat stubble) to reduce soil erosion and runoff. Conservation tillage can leave 30% or more of the soil surface covered with plant residue, thus the degree of soil mixing is less than the conventional tillage. In the photos above, disking and chisel ploughs bury some of the residue compared to no-till surface. Removing some of the residue by disking or chisel ploughing increases the area of soil exposed to erosion.

Examples in WOCAT Database:
T_BEL002en; T_CHN040en; T_CHN041en; T_GHA001en; T_GRE001en; T_HUN001en; T_KEN030en; T_KEN031en; T_PHI003en; T_PHI007en; T_PHI009en; T_PHI044en; T_POL001en; T_RSA043en; T_SWI004en; T_SWI006en; T_UNK001en; T_UNK002en; T_UNK005en; T_ZAM002en; T_ZAM004en

1.3.2 Contour ploughing

Contour ploughing is a widely used agronomic measure that contributes to soil erosion control (Krüger *et al*., 1997). Soil is ploughed along the contour instead of up- and downslope. This decreases the velocity of runoff and thus soil erosion by concentrating water in the downward furrows (Tidemann, 1996). Contour ploughing on the other hand purposely builds a barrier against rainwater runoff which is collected in the furrows. Infiltration rates increase and more water is kept in place. Contour ploughing is especially important at the beginning of the rainy season when biological conservation effects are poor (Krüger *et al*., 1997). The effectiveness of contour ploughing decreases with increase in slope gradient and length, rainfall intensity and erodibility of soils (Lal, 1995).

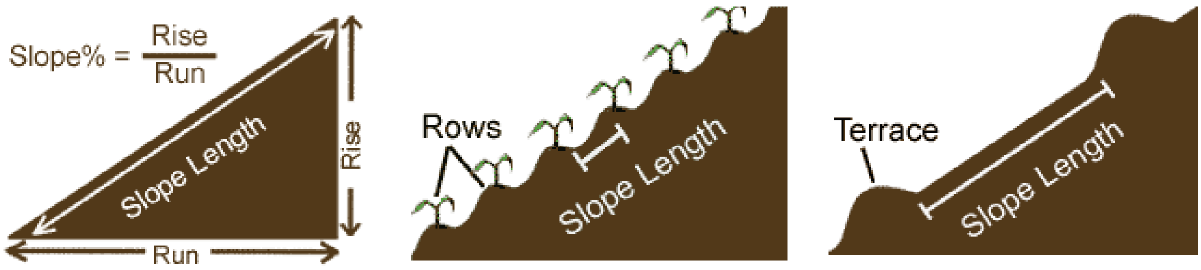
Examples in WOCAT Database:
T_HUN002en; T_SPA001en

1.3.3 No-tillage

No or zero tillage with mulching has been widely applied in Latin America and Asia. The secret to achieving no-tillage in the area is applying massive amounts of organic matter to the soil. Brazilian farmers, after some four years of applying green manure and cover crops to the soil, are able to quit ploughing. Interestingly, the farmers often use non-leguminous green manure and cover crops to increase biomass in order to quit ploughing sooner, they spend scarce income on nitrogen for three or four years in order to achieve zero tillage sooner. The no-tillage improved soil structure, reduced soil compaction, increased soil fertility and decreased cost (http://www.agriculturesnetwork.org/magazines/global/we-love-weeds/an-odyssey-of-discovery-principles-of-agriculture).

1.4 Terracing

Terracing refers to building a mechanical structure of a channel and a bank or a single terrace wall, such as an earthen ridge or a stone wall aiming to achieve a change in slope profile to reduce runoff and erosion. Terracing reduces slope steepness and divides the slope into short gently sloping sections (Morgan, 1986). It can considerably reduce soil loss by water erosion if well-planned, properly constructed and maintained.
The following diagrams show that terraces can reduce erosion by reducing the slope length:



The velocity of water increases as slope length increases. Decreasing slope length by planting rows perpendicular to the slope or by adding terraces can decrease the velocity of water and, as a result, decrease its erosive potential (Source: UNL)

There is a large variety of terrace types, each adapted to certain landscapes with various slopes gradients, but terraces can be divided in three groups: bench terraces, contour terraces and parallel terraces. All of these three terrace types could be effective regarding soil and water conservation, there is no such thing as the best terrace type, because it all depends on local conditions (Dorren & Rey, 2004).

The most important aspect of terracing is that it has to be combined with additional soil conservation practices, of which the most important one is the maintenance of a permanent soil cover. This latter is especially needed on the foot slope of the terrace, because terraces themselves could be easily eroded and they generally require a lot of maintenance and repair. Other disadvantages are the disturbance of the soil strata during construction, considerable decline in soil fertility in the first several years and considerable soil loss during construction. Hedgerows could be good alternatives for terraces, which eventually work in the same way through gradual build-up of sediments behind the hedgerows. A great limitation of construction of terraces or any soil and water conservation practice is the loss of productivity and most farmers are more concerned with production than with conservation. The challenge therefore is to develop conservation practices that are also productive (Dorren & Rey, 2004).

Level terraces in the Chinese Loess Plateau (Source: Yu, 2006)

Stone wall terrace (Source: WOCAT)

Level terracing is practised on areas with steep slopes with sufficiently deep soil, it requires considerable labour input for implementation and maintenance. Building only walls that reduce slope length is not sufficient to reduce the power of the runoff. Additionally, it is necessary to modify the degree of slope by half-excavating a channel and half-filling a bank. The original ground will be converted into level, step-like fields. Maintenance of terrace walls is important, which can be aided by vegetation cover with indigenous grass species (Lesschen *et al*, 2008; Varotto & Lodatti, 2014), or economic shrubs *e.g.*, pepper trees. The constructed terraces can be applied together with several vegetative and /or agronomic measures.

Terracing requires substantial inputs of labour or money when first installed but are of long duration.

Examples in WOCAT Database:
T_CHN009en; T_CHN045en; T_CHN050en; T_CHN051en; T_CHN053en; T_ETH004en; T_ETH009en; T_ETH044en; T_IDS090en; T_KEN005en; T_RSA003en; T_RWA003en; T_SPA002en; T_SYR001en; T_TAJ005en; T_TAJ362en; T_THA025en; T_YEM001en

1.5 Water and silt harvesting

1.5.1 Dams and silt fencing

A silt fence is a temporary barrier placed along the perimeter of a construction site. Silt fencing does not serve to prevent erosion; rather, it traps soil or sediments. To be effective, a silt fence must be constructed carefully and be in place before construction begins. Silt fences are primarily intended for trapping sediment from water erosion.

Examples in WOCAT Database:
T_BAN003en; T_BAN004en; T_BOL004en; T_CHN042en; T_CHN047en; T_CHN052en; T_ETH027en; T_ETH028en; T_ETH029en; T_ETH030en; T_ETH032en; T_ETH033en; T_ETH034en; T_ETH035en; T_ETH036en; T_ETH037en; T_ETH039en; T_ETH042en; T_ETH604en; T_KEN013en; T_KEN020en; T_KEN023en; T_KEN027en; T_KEN053en; T_KEN660en; T_NEP014en; T_NIC004en; T_PHI005en; T_RSA014en; T_RSA023en; T_TAJ356en; T_TAN010en; T_TON010en; T_TUN011en

1.5.2 Bunds

A bund is a single line of stones or earth along a contour (see photos below). It helps to control erosion by water and allows surface water to infiltrate into soils which can lead to better crop yields. Bunds can reduce soil loss up to 68% (Gebrermichael *et al.,* 2006).

Stone bunds with grass and trees (Source : WOCAT)

Stone line (Source: http://www.farmingfirst.org/2012/09/stone-bunds-as-soil-and-water-conservation-measures-in-sahelian-countries).

Examples in WOCAT Database:
T_ETH008en; T_ETH014en; T_ETH015en; T_ETH019en; T_ETH021en; T_IND004en; T_UGA029en

1.5.3 Impoundments

Impoundments are man-made ponds or lakes constructed to control storm run-off and/or trap sediments. Before soil or sediment reaches the drainage system, detention ponds can be placed to trap and settle sediments. This in effect is not an erosion preventive measure but a measure to minimize the already detached or eroded soil from entering waterways. It is a sediment control measure. There are two kinds of impoundments: permanent retention ponds and temporary detention ponds.

Retention ponds (Source: *WOCAT, T_CBD005en)*

Plastic-lined retention ponds (Source: Bai, 2014)

Detention ponds are small in area because they drain a relatively smaller area. Because construction changes the topography, or lay of the land, drainage characteristics of the land change. Detention ponds are often constructed during road or building construction because the removal of topsoil and compaction reduces water infiltration into the soil and increases the risk of runoff. In addition, paved roads and streets are impervious to water and often become a conduit for runoff and sediment to move into drainage systems.
The image below shows a detention ponds collecting runoff and sediments from small areas during land disturbance such as construction.

Plastic-lined detention ponds (Source: WOCAT, T_NEP022en)

Examples in WOCAT Database:
T_IND004en; T_IND008en; T_NEP022en; T_PHI004en; T_PHI005en; T_RWA006en; T_TAN017en; T_TUN009en; T_TUN013en T_ZAM001en

1.5.4 Gravel access path

Gravel or rock driveways in construction sites can minimize tracking of soil or sediment into the streets by vehicles and equipment. In addition, compaction of soil on the rest of the construction areas is reduced by limiting vehicle movement to the gravel or rock driveway.

1.6 Combination of measures

In many cases, measures are combined with each other, *e.g.* terracing is combined with vegetation cover. The combinations vary from place to place depending on local biophysical and economic conditions.

Terrace with crop growing in the Loess Plateau, China (Source: John Liu, http://eempc.org)

Effects of measures/techniques on control of soil erosion by water are different: In Europe and the Mediterranean, vegetation cover *i.e.* buffer strips, mulching and cover crops are generally more effective than tillage measures *i.e.* no-tillage, reduced tillage and contour tillage (Maetens *et al.,* 2012). Time-series analyses of runoff during multiple years of the measures application strongly indicate that no-tillage and conservation tillage become less effective in reducing runoff over time but such an effect is not observed for soil loss (Maetens *et al.,* 2012). Despite being generally less effective, no-tillage, reduced tillage and contour tillage have received substantially more attention than the other measures (Maetens *et al.,* 2012). All these measures are generally less effective in reducing runoff than in reducing soil loss, which is an important consideration in areas where water is a key resource and in regions susceptible to flooding; furthermore, all these measures lead a more consistent and effective reduction of both runoff and soil loss with increasing runoff and soil loss magnitude, which is attributed to the reduced influence of measurement uncertainties (Maetens *et al.,* 2012).

Examples in WOCAT Database:
T_CHN021en; T_COL002en; T_ETH001en; T_GHA001en; T_GRE003en; T_KEN024en; T_KEN657en; T_KEN658en; T_NEP002en; T_NEP010en; T_NEP011en; T_NEP013en; T_NIG002en; T_RSA001en; T_RSA052en; T_RWA004en; T_SYR629en; T_SWI003en; T_TAJ115en; T_TAJ365en; T_TAN005en; T_TAN007en; T_TAN012en; T_TUM001en T_ZAM004en

1.6.1 Integrated management of small watershed

Integrated management of small watersheds or micro-catchments has been proven a successful way to control soil erosion in many countries (Healthcote, 1998; Shi *et al*., 2012). The catchment should be considered holistically when planning soil erosion control programs (Croke *et al.,* 2007). The programs should consider all factors related to soil erosion, *e.g*., basic farmland construction, plantation of cash trees, firewood and conservation wood, roads, water banks, changes in land use and the needs of local residents. This comprehensive measure should emphasise both control of the soil erosion in the watershed and local economic development at the same time.

Examples in WOCAT Database:
T_CHN012en; T_ETH045en; T_KEN022en; T_RSA042en; T_TAJ370en

1.7 Institutional measures

Policy measures can promote adoption of the measures for the soil threats in various ways, such as laws, regulations, and economic incentives. In EU, land users have to deal with many regulations that originate from policies at different levels: EU, national, regional and local. Some of these regulations or policies directly aim at the control of erosion; others can have an indirect influence on the extent of erosion, both positive and negative. There is also a distinction in the degree of legal obligation. Some existing measures are mandatory requirements under national and regional policies. Compensatory payments are offered in some member states in the context of the agro-environmental measures and forestry measures. It is arguable, nonetheless, whether those public funds should be used to reward farmers in return for measures taken to control wind erosion. However in case of off-site effects of water erosion the source remains often difficult to identify, and individual farmers cannot be held responsible. This complicates the monitoring of measures taken by the farming community and of the benefits of controlling water erosion. The difficulties of linking measures taken by farmers to the occurrence of water erosion hamper the application of cross compliance because it constitutes of environmental conditions for direct payments. Proper monitoring of water erosion would be essential if a link were to be established between the measures taken out the provision of payments to compensate farmers for their foregone income (Riksen *et al*., 2003b).

1.8 Applicability of the measures to control soil erosion by water

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 1.3). How: applicability in terms of the main action that needs to be taken towards soil improvement. When: applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. Where: applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions e.g. cost-benefits or adaptability.

Table. 1.3. Applicability of the measures for soil erosion control

	How ?	When ?			Where ?						
		Stage			Land-use type				Location		
Measure category	Measures	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1)]	Landform[2)]	Altitude[3)]
Vegetation cover	Planting grass/shrub/tree	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
	Contour cropping	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
	Vegetative strips	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
	Temporary & permanent Seeding	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
	Grassed waterways	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Mulching	Crop residue	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
	Plant-based or organic	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
	Other materials	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Tillage	Conservation tillage	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
	Contour ploughing	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
	No-tillage	+	+	++	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Terracing	Bench terrace	++	+	+	+	+	+	+	Hu, SH, SA, A	RI, MO, HS, FS	I, II, III, IV, V, VI, VII, VIII, IX
	Contour terrace	++	+	+	+	+	+	+	Hu, SH, SA, A	RI, MO, HS, FS	I, II, III, IV, V, VI, VII, VIII, IX
	Parallel terraces	+	+	++	+	+	+	+	Hu, SH, SA, A	RI, MO, HS, FS	I, II, III, IV, V, VI, VII, VIII, IX

Water/silt harvesting	Dams and silt fencing	++	-	-	+	+	+	+	Hu, SH	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V
	bunds	++	-	-	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
	Impoundment	++	-	-	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
	Gravel access path	++	-	-	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Combined measures	Integrated management of micro-catchment	+	-	-	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Institutional measures	Policy & regulation	+	-	-	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX

1) HU: Humid (length of growing period (LGP) > 270 days); SH: Sub-humid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days);AR: Arid (LGP 0–74 days).

2) PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow);CV (Concave: depression (conversion of water flow)).

3) I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI: 2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.

4) ++: Application occurs only in this stage (on this land use type); +: Application occurs in this stage; -: Application is not recommended in this stage.

2 Soil Erosion By Wind

The movement of soil occurs when forces exerted by wind overcome the gravitational and cohesive forces of soil particles on the ground surface (Bagnold, 1941), and the surface is mostly devoid of vegetation, stones or snow (Shao, 2008). Wind erosion easily occurs when soil is dry, loose, bare and strong wind and often occurs in arid or semi-dry or seasonally dry areas. There are two crucial factors for control of soil erosion by wind: protecting surface of soils and reducing wind velocity. Measures include covering soil surface as much as possible with either crop residues or growing plants - these measures also conserve soil moisture therefore increase crop and pasture production; tilling soils in an appropriate way *e.g.,* reducing tillage, sub-soiling; and avoiding overgrazing. Wind speed can be reduced by, *e.g.* windbreaks or shelterbelts.

2.1 Planting vegetation

The best and surest way to prevent wind erosion is a permanent soil cover by plants. Measurements have shown that soil covers below 10 percent increase wind erosion (Morgan & Finney, 1987; Funk, 1995; Sterk, 2000), but soil cover greater than 10 percent reduces wind erosion rapidly. Forty percent soil coverage is regarded as sufficient to protect a susceptible soil (Fryrear, 1985). The same is more or less valid for coverage by non-erodible material (such as flat plant residues) or growing plant canopies. Concerning the wind velocity reduction at the ground, standing plants or plant residues are ten-times more effective than material lying on the surface (Bilbro & Fryrear, 1994). Therefore, plant residues or stubbles should be left as long as possible at the surface or change their management practices to reduced or no-tillage systems. Tillage operations can be replaced by use of herbicides to maintain residues at the surface, but care should be taken of the effects of herbicides on groundwater and the environment.

2.1.1 Shelterbelts

Planting shelterbelts or windbreaks is a common measure to prevent wind erosion(see picture below). Especially in the regions with high wind speeds there are many traditional systems of hedges, which separate and protect the fields. Hedges have influence on the local wind field and on many other components of the micro- and macroclimate.

Shelterbelts or windbreaks (Source: WOCAT by Ding Rong)

Shelterbelts should be arranged perpendicularly to the prevailing wind direction. They give protection downwind for a distance of about 10 to 25 times their height depending on the porosity, kind of trees and number of rows (Nägeli, 1943). Most effective are triple rows, with a tree row in the centre flanked by shrubs, with a triangular cross-section (Chepil & Woodruff, 1963). Increasing permeability with height prevents 'wall effects' on the leeward side. The distances between shelterbelts depend on erodibility of soil. Highly erodible soils need a dense network of hedges, which is contrary to an effective work rate of field machinery (Riksen *et al*., 2003a, b). The installation of shelterbelts is quite expensive, needs a long-time of support and becomes effective only after a number of years. Therefore, shelterbelts can be only a supporting measure to prevent wind erosion in combination with other measures in the field.

The positive effect of shelterbelts at the landscape level could be proven in a study of Funk *et al.* (2001) for the Federal State of Brandenburg in Germany. The vulnerable area to wind erosion was reduced by about 60 percent by the current state of landscape elements (shelterbelts, alleys, rows of bushes, forests and so on).

The shelterbelt principles can be used on a much smaller scale by planting appropriate crops (cereals, grasses) alternating with susceptible crops (sugar beet, corn) at one field. Alignment of the crop rows perpendicular to the prevailing wind direction improves the efficiency of this measure.

Examples in WOCAT Database:
T_CHN001en; T_CHN002en; T_CHN048en; T_TAJ110en

2.1.2 Intercropping

Intercropping is widely used in many arid regions, and several systems have been developed. Intercropping is growing two or more crops close together, because they do not compete with each other, or are mutually beneficial. The crops could be a fast-growing one between a slower-growing one. Intercropping could also be "vertical" layers of vegetation grow *e.g.*, palm-tree layer, an understorey of fruit-trees and a ground-level crop layer.

Walnut - wheat intercropping in Hetan County, Xinjiang. Photo by Zhu Yuwei (Source: WOCAT)

Intercropping (Source: WOCAT)

Examples in WOCAT Database:
T_CBD008en; T_CHN010en; T_MOR014en; T_SPA006en; T_PHI008en

2.1.3 Crop rotation

Crop rotation is a system of growing different kinds of crops in recurrent succession on the same land (Martin *et al*., 1976). Thus, in the strictest sense, crop rotation is more than just changing crops from year to year based on current economic situations. Rather, it is a long-term plan for soil and farm management.

Incorporating legumes in the rotation cycle, especially those with a deep and prolific root system and a high capacity to fix nitrogen is an important strategy to arrest desertification and enhance soil quality (Lal, 2001). Choice of an appropriate rotation is also critical to adoption of a conservation tillage system, whose effectiveness in soil and water conservation in arid and semi-arid regions depend on the amount of surface area covered by crop residue mulch. rotations of mixed pasture (5.5 years) and annual crops (4.5 years) maintained 17.3 Mg/ha of SOC compared with 11.2 Mg/ha in continuous cultivation with a wheat-sunflower (Helianthus annulus) rotation in semi-arid regions of Argentina (Galantini & Rosell, 1997). SOC content was high in wheat-grassland and wheat-alfalfa (*Medicago sativa*) rotations, especially with a conservation tillage system (Miglierina *et al.*, 1993, 1996). Subsoiling and incorporation of cover crops in rotation enhances soil quality (Barber, 1994). Introducing alfalfa in rotation with wheat grown on a sandy soil decreased salinity and increased SOC content three fold as compared with continuous wheat (Shahin *et al.*, 1998). Intercropping sorghum (*Sorghum bicolor*) with legumes and application of manure increased SOC content and aggregation (Lomte *et al.*, 1993). Crop rotations are used to:

- manage weed, insect, and disease pests
- reduce soil erosion by wind and water
- maintain or increase soil organic matter
- provide biologically fixed N when legumes are used in rotation
- manage excess nutrients

The above factors all serve to increase crop yields, but there often is a yield increase to rotation above what can be accounted for by these factors (http://soilquality.org/practices/row_crop_rotations.html).

Crop rotation avoids the undue exposure of the soil to dryness and wind erosion and it can also improve soil fertility. Grain followed by a legume, then by a row crop or fallow, and then back to grain adds residues to the soil which bind soil particles. However, with the availability of inorganic fertilizers, crop rotation is losing popularity.

Examples in WOCAT Database:
T_CHL002en; T_MOR012en; T_TAJ051en

2.2 Mulching

2.2.1 Crop residues

Crop residues can be retained after harvest to reserve soil moisture and reduce wind erosion. Residues, however, are not always available in arid regions and are often eaten by free-ranging livestock or used as fuel. In areas where two crops grow, a no-till machine for seeding is needed and herbicides should also be in place in order to avoid burning stubble after harvest, thus depriving soils of protective cover.

Straw mulching (Source: Bai, 2014)

When soil surface residues are depleted and a wind erosion hazard exists, emergency tillage is often the last resort (Woodruff *et al*., 1957). The use and type of emergency tillage varies with locality and climatic condition (Fryrear & Skidmore, 1985). If surface soil clods are broken down by rainfall, a sand fighter or rotary hoe is used to disturb the soil and leave new clods on the surface. The sand fighter and rotary hoe could be considered emergency tillage implements since they are used to control wind erosion, but they are not effective if the soil has been blowing and the surface few millimetres of soil is dry (Fryrear & Skidmore, 1985).

Clods are compact, coherent masses of soil formed by tilling the soil. To effectively reduce wind erosion, most of the soil surface must be covered with non-erodible clods. This is possible for most soils if they are properly tilled before wind erosion begins. Generally, the finer the soil texture the greater the number and stability of clods formed. Coarse-textured soils must be tilled after each rain to bury loose sand grains and bring more clods to the surface. Because most crops are seeded in the surface 0.05 m of soil, the farmer must compromise to have the minimum clods to control wind erosion and still have a satisfactory seedbed (Fryrear & Skidmore, 1985).

Examples in WOCAT Database:
T_BEL001en; T_AUS003en; T_CBD003en; T_ETH010en; T_GHA001en; T_POL003en; T_SPA003en; T_TAJ105en; T_TAN014en; T_TAN022en; T_UGA006en; T_UNK003en

2.2.2 Synthetic stabilizers

There are different commercial products available which stabilise a soil after application by a thin protective layer. The effect is a fast protection of the soil surface and can hold for some weeks. In use are products based on liquid polymers, lignite wax or by-products of the sugar and paper industry like CMS (Condensed Molasses Soluble) or cellulose sludge. Application limits arise from high costs and governmental permissions. Synthetic stabilisers are also in use in mining areas (Funk & Riksen, 2007).

2.2.3 Liquid manure or slurry

Liquid manure can be applied in the same way and results in similar effects. Slurry from ruminant animals contains more adhesive fibres and gives better results than slurry from other livestock (Riksen *et al*. 2003a). Limitations for the application of slurry are often given in drinking-water areas as well as by hygiene factors (Funk & Riksen, 2007).

2.3 Roughening the soil surface

Rough soil surface can increase turbulence close to the ground and dissipate kinetic energy of wind therefore slow wind velocity (Stull, 1988). Shelter of leeward side of roughness clods or furrows against the wind action and particle impacts (Potter & Zobeck, 1988). It can be distinguished between a non-directional rough, cloddy surface and a soil-ridge roughness and soil-ridge roughness depends on the tillage direction, so, as one of the basic rules, the direction of tillage has to be perpendicular to the wind direction to optimize the effect(Funk & Reuter, 2006). A soil-ridge roughness of 6 cm reduces wind erosion by 50 percent (Skidmore, 1986). Above a roughness of 11 cm no further reduction of wind erosion could be found (Fryrear, 1985).
Farmers can protect their susceptible fields by tillage operations which leave a rough surface. This depends mainly on the used tillage tool and the soil moisture at the time of tillage. Restrictions are due to the demands of some crops for a fine seedbed. Because no special equipment is needed, these are the easiest realisable measures. In many cases these measures are accompanied with a reduction of the tillage operations. Roughness in connection with the increase of the resistance of a soil means the establishing of a rough, cloddy surface with aggregates which are too heavy to be removable by the wind. In general particles or aggregates greater than 0.6 to 1 mm in diameter are regarded as non-erodible (Funk & Riksen, 2007).

Tillage practices should create soil roughness by leaving clods in the soil or by making ridges and furrows perpendicular to the prevailing wind direction. For soil ridges and furrows to be most effective they must have resistant soil clods on the surface. Cloddy furrows will limit wind erosion until the clods are broken down by additional tillage, weathering or erosion. Disadvantage of the tillage for roughing soils would increase in loss of soil moisture and destroy soil structure. The effectiveness of tillage in reducing wind erosion is improved when residue crops or crops with extensive root systems are grown to increase organic matter content of the soil. In the case of sandy soils this tillage practice is not effective, because of soil texture and lack of cohesiveness (Salem, 1991).

Measures to increase the resistance of the soil surface (Source: WOCAT)

Pits with mulch cover (Source: WOCAT)

Example in WOCAT Database:
T_UGA016en

Shelterbelts, crop strips, or crop barriers are very effective in reducing wind erosion in areas with a dominant prevailing wind direction during the wind erosion period. Most trees or shrubs require several years before they attain their design height, and the establishment of trees in semiarid regions is difficult. Because trees must live on available rainfall during prolonged droughts, mortality within the shelterbelt can be a problem. The sheltered area provides homes for wildlife and may improve the microclimate for adjacent crops, but it can also harbour non-beneficial insects. In warm, semiarid areas the perennial barrier must extend its root system laterally to survive and thus competes with the cash crop for soil water and nutrients.

2.4 Combination of measures

2.4.1 Mulching and sub-soiling

Stubble mulching is often combined with no-till seeding, or sub-soiling. This combination could reduce erosion by wind, and also increase soil organic matter.

Straw mulching and sub-soiling (Source: Bai, 2014)

Examples in WOCAT Database:
T_BEL002en; T_CHN040en; T_CHN041en; T_GHA001en; T_GRE001en; T_HUN001en; T_KEN030en; T_KEN031en; T_PHI003en; T_PHI007en; T_PHI009en; T_PHI044en; T_POL001en; T_RSA043en; T_SWI004en; T_SWI006en; T_UNK001en; T_UNK002en; T_UNK005en; T_ZAM002en; T_ZAM004en

2.5 Institutional measures

Some existing measures are mandatory requirements under national and regional policies. In the EU land users have to deal with many regulations that originate from policies at different levels: EU, national, regional and local. Some of these regulations or policies directly aim at the control of wind erosion. Other regulations can have an indirect influence on the extent of erosion, both positive and negative. Compensatory payments are offered in some EU member states in the context of the agro-environmental measures and forestry measures. It is arguable, nonetheless, whether those public funds should be used to reward farmers in return for measures taken to control wind erosion. However in case of off-site effects of wind erosion the source remains often difficult to identify, and individual farmers cannot be held responsible. This complicates the monitoring of measures taken by the farming community and of the benefits of controlling wind erosion. The difficulties of linking measures taken by farmers to the occurrence of wind erosion hamper the application of cross compliance because it constitutes of environmental conditions for direct payments. Proper monitoring of wind erosion would be essential if a link were to be established between the measures taken out the provision of payments to compensate farmers for their foregone income (Riksen *et al.*, 2003b).

2.6 Applicability of the measures to control soil erosion by wind

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 2.1). *How:* applicability in terms of the main action that needs to be taken towards soil improvement. *When:* applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. *Where:* applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions *e.g.* cost-benefits, or adaptability.

Table. 2.1. Applicability of the measures for control of soil erosion by wind

	How ?	When ?			Where ?						
		Stage			Land-use type				Location		
Measure category	Measures	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1)]	Landform[2)]	Altitude[3)]
Planting vegetation	Shelterbelts	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
	Strip cropping	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
	Intercropping	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
	Crop rotation	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Mulching	Crop residues	+	++	++	++	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
	Synthetic stabilisers	-	-	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Roughening soil surface	Clods and Tillage	-	-	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Combined measures	Mulching with sub-soiling	+	++	+	++	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Institutional measures	Policy & regulation	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX

1) HU: Humid (length of growing period (LGP) > 270 days); SH: Subhumid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days);AR: Arid (LGP 0–74 days).

2) PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow);CV (Concave: depression (conversion of water flow)).

3) I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI: 2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.

4) ++: Application occurs only in this stage; +: Application occurs in this stage; -: Application is not recommended in this stage.

3 Decline in Organic Matter In Peat Soils

Peat soils cover some 3% of the Earth's land surface (Strack, 2008) and are a carbon 'reservoir' containing 20–30% of the world's soil organic carbon (Moore, 2002). However, these valuable ecosystems are shrinking due to mineralization or oxidation of peat soils mainly caused by human activity: drainage, cultivation and conversion to arable land, liming, and fertilizer use (Kechavarzi *et al*., 2010).

Drainage to reclaim peat lands results in subsidence and degradation of peat soils by shrinkage and biological degradation (oxidation). Processes of the subsidence include: 1) consolidation and compaction; 2) loss of organic matter due to biochemical decomposition (oxidation); and 3) shrinkage by drying. Oxidation is the main factor responsible for subsidence over the long term. Usually drainage levels are adapted to the lowered surface from time to time, so in that way the oxidation and subsidence process can continue until the whole peat layer is oxidized and disappeared (Van den Akker *et al*., 2008). Peat soils under agricultural use are the most affected (Oleszczuk *et al*., 2008; Van den Akker *et al*., 2008).

Measures for preventing, mitigating and remediating degradation of peat soils are well summarized in the recent FAO report on "Towards Climate-responsible Peatlands Management" (FAO, 2014). Four steps for protecting peat soils and combating organic matter decline are recommended: conserve intact peatlands, rewet drained peatlands, apply climate-responsible peatlands management, and implement adaptive management where rewetting is not possible. The report emphasises that the priority is to safeguard and preserve natural peatlands from degradation. Rewetting of already drained peatlands conserves biodiversity, regenerates vegetation, replenishes freshwater resources and reduces GHG emissions. During rewetting, the stabilisation of high water levels can be achieved through hydrological practices targeted at enlarging water storage in the peatlands, decreasing water losses and increasing water supply. The following sections mainly draw on the measures presented in the FAO report.

3.1 Rewetting peat lands

Most of the negative environmental impacts caused by peatland drainage can be reversed by restoring stable water tables around the land surface, a process known as rewetting. There is no universal strategy for rewetting a drained peatland. There can be various causes for the drained conditions, and the rewetting options vary widely depending on climate, water availability and topography. Stable high water levels must be achieved by adequate hydrologic practices that include:

- decreasing water losses from the peatland;
- increasing water supply to the peatland; and
- enlarging water storage in the peatland.

In most cases, excessive water losses from installed surface or subsurface drainage structures are the main cause of excessively low water levels. Water losses can be decreased by:

- damming or infilling of drainage canals and ditches (e.g. with peat collected at site);
- raising overflow heights of weirs and sluices;
- raising groundwater level;
- establishing and allowing obstructions in water courses (trees, rocks, vegetation growth, beaver dams);
- removing subsurface drainage pipes by excavation or destruction;
- reducing evapotranspiration from tree growth in the peatland (only in originally treeless peatlands); and
- establishing hydrological buffer zones with higher water levels.

Rewetting peat *e.g.*, by raising groundwater level can diminish peat soil shrink through infiltration of ditch water via submerged drains to conserve peatland. This technique can halve subsidence and the resulting CO_2 emissions. Also, water quality is expected to improve; disadvantage might be that due to the extra water infiltration via drains, the water need in summer will increase. Infiltration via submerged drains is a promising technique to halve peat soil degradation, while it is also acceptable for a wide range of stakeholders.

In cases where substantial water supply of the peatland was originally provided by the surroundings, inflow can be increased by:

- decreasing groundwater extraction and/or increasing groundwater recharge in the catchment area (this can be done by reducing drainage, removing surface sealing, and converting the forest to less evaporating species);
- diverting water into the site;
- irrigating by pumping into the site; and
- perforating stagnating (secondarily humified and compacted) surface peat soil horizons to restore discharge of artesian groundwater.

Conservation of peat soils in use as grassland by infiltration via submerged drains (Source: Images from RECARE website)

Attention should be paid to the quality of the introduced water. Water rich in sulphates (e.g. some river water, sea water) aggravates peat oxidation and should be avoided.
Where peat extraction or soil degradation has led to the presence of compact top layers, the storage coefficient (porosity) of the peat is generally too low to maintain sufficiently high water levels during the dry season when there are high losses from evapotranspiration. In such cases, peatland internal storage can be increased by:

- installing bunds (elongated dams) to increase water storage over the peat surface;
- creating paddy field-like cascades to rewet sloping peatlands; and
- maintaining or creating hollows (*e.g.* dammed canals) to increase depression storage.

Flooding during the wet season should be deep enough to compensate for evapotranspiration losses during dry periods. To minimize wind and wave erosion, hollows and bunded areas should not be too large.

3.2 Cropping and afforesting on peat land - Paludiculture

Paludiculture (from Latin 'palus' for 'swamp') is drainage-based agriculture and forestry on peatlands (Joosten, 2014). Paludiculture makes use of any biomass from wet and rewetted peatlands by harvesting spontaneous vegetation on natural sites or artificially establishing crops on rewetted sites. Besides producing traditional agricultural products such as food, feed, fibre and fuel, the biomass can be used as a raw material for industrial biochemistry, for producing high-quality liquid or gaseous biofuels and for other purposes, such

the extraction and synthesising of pharmaceuticals and cosmetics. Paludicultures can also deliver substantial co-benefits by preserving and sequestering carbon, supporting climate change mitigation and adaptation activities, regulating water dynamics (flood control) and water quality (purification), and conserving and restoring peatlands' typical flora and fauna.
Combining bioenergy generation and the rewetting of drained peatlands makes paludiculture an extraordinarily cost-effective climate change mitigation option that can generate income both from carbon credits and from biomass production.

In the vast areas of drained and deeply subsided peatlands where flooding is a threat, paludiculture greatly reduces pumping costs. By providing sustainable income from abandoned or degraded sites, peatland rewetting and subsequent paludiculture can also generate employment and counteract social disintegration in rural areas.
Because the concept of paludiculture has (re-)emerged only recently, some of its various elements still have to be modified to permit large-scale implementation. Optimization is needed with respect to:

- the identification, selection and propagation of suitable (preferably perennial) species,
- provenances and cultivars;
- the technical challenges (low soil pressure machinery) and logistics for harvesting wet and inundated peatlands;
- the development of production lines adapted to new types of biomass;
- the improvement of agricultural consultation for site-adapted peatland use;
- the adaptation of laws, rules and regulations that can accommodate wet peatland agriculture;
- the removal of market distortions (*e.g.* when subsidies are given to support drainage-based peatland agriculture with no similar support provided for paludicultures); and
- the development of payment structures (payments for ecosystem services) that adequately consider external costs and benefits.

An animated film regarding paludiculture in Landschap Noord-Holland of the Netherlands is available: http://youtu.be/JIPVbxnFNnM.

Besides, planting grasses *e.g.*, alfalfa could diminish loss of carbon of organic soils (Bingeman *et al*., 1953).

3.3 Applicability of the measures to control decline in organic matter in peat soil

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 3.1). ***How:*** applicability in terms of the main action that needs to be taken towards soil improvement. ***When:*** applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. ***Where:*** applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions *e.g.* cost-benefits, or adaptability.

Table. 3.1. Applicability of the measures for control of decline in organic matter in peat soils

How ?	When ?			Where ?						
	Stage			Land-use type				Location		
Measures	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1]	Landform[2]	Altitude[3]
Conserving intact peat lands	+	-	-	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Rewetting drained peat lands	-	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Implementing adaptive management where rewetting is not possible	-	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Applying climate-responsible peat lands management	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Cropping and afforesting on peat land - Paludiculture	-	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Institutional measures	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI

[1] HU: Humid (length of growing period (LGP) > 270 days); SH: Sub-humid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days);AR: Arid (LGP 0–74 days).

[2] PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow);CV (Concave: depression (conversion of water flow)).

[3] I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI: 2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.

[4] ++: Application occurs only in this stage; +: Application occurs in this stage; -: Application is not recommended in this stage.

4 Decline in Organic Matter In Mineral Soils

Changes in soil organic matter (SOM) are driven by natural processes, human activity and socio-economic factors (Table 4.1).

Table 4.1. Drivers affecting soil organic matter content (*adapted from the RECARE Project report D2.1*).

a) Natural processes

- Climate (precipitation, temperature, solar radiation, etc.)
- Topography
- Soil type and properties (*e.g.* soil texture, soil temperature, moisture, pore structure)
- Land cover/vegetation type

b) Antropogenic/human activities

- Land management
  - Grazing intensity and grass coverage
  - Tillage and soil disturbance
  - Residues management/Bare fallow
  - Crop variety and species management
  - Intensive farming (*e.g.*Fertilisers/manuring/pesticides, simple crop rotation and high mechanisation)
  - Deforestation
  - Biomass burning
  - Drainage of wetlands
- Land use change/conversion (*e.g.* grasslands and woodlands to agriculture or urban areas – "soil sealing")
- Contamination/Pollution

c) Socio-economic factors

- Technological change/development
- Policies (Agricultural – Environment – Energy sectors)
- Economic growth and cost/price squeeze

The overall amount of organic matter stored in the world's soils is decreasing (Lal, 2004). Land use and management, *i.e.,* human activities, are likely to contribute most to these changes (Baldock & Nelson, 2000). Compared with natural ecosystems, the carbon content of cultivated soils is depleted by 30-40 tonnes/ha (Lal, 2015). Restoration of soil carbon stocks is essential to restoring soil performance and ecosystem services – including climate change adaptation and mitigation. This can be achieved through sustainable intensification of agro-ecosystems – producing more from less land, water, fertiliser, energy, and other inputs (Lal, 2015). The strategy is to increase biomass carbon, decrease losses by erosion, mineralisation and leaching, and reduce emission of greenhouse gases.

High SOM accumulation is favoured by management systems, which add high amounts of biomass to soil, cause minimal soil disturbance, improve soil structure, enhance activities and species diversity and strengthen mechanisms of element cycling (Lal, 2004). A long-term experiment at Rothamsted indicates that achieving a significant increase in the equilibrium level of SOM in a farming system under temperate climate requires continuous application of large inputs of organic matter (Johnston *et al*., 2009). Therefore whether soil is naturally high or low in organic matter, adding new organic matter every year is perhaps the most important way to improve and maintain soil quality because additions of organic matter can improve soil structure, enhance water and nutrient holding capacity, protect soil from erosion and compaction, and support a healthy community of soil organisms.

Practices that increase organic matter include: growing green manure crops or catch crops, perennial forage crops and cover crops; applying animal manure or compost; leaving crop residues in the field; applying reduced or conservation (minimum) or no tillage to minimize disruption of the soil's structure, composition and natural biodiversity and crop rotations with high residue plants with large amounts of roots and residue.

4.1 Apply animal manures, compound fertiliser, trash, recycled waste

Organic amendments such as animal manures, compound fertiliser or recycled organics (*e.g.* food wastes and composts) are usually added to supply plant nutrients. Addition of organic matter is generally a secondary concern. Recycled organics provide more carbon in the soil than manure or crop residues, because much of the easily decomposed carbon of recycled products has already been lost to the atmosphere as CO_2 during composting. Applying manure in excess of plant requirements increases the potential for serious environmental damage from runoff or leaching.

Examples in WOCAT Database:
T_KYR006en; T_NEP001en; T_NEP007en; T_NEP008en; T_NEP009en; T_NEP016en; T_NEP024en; T_TAN009en; T_TOG003en; T_UGA006en T_UGA021en

Many "waste" products or by-products from farm enterprises, food processors, municipalities or industry can be considered for soil organic amendment. These products can be applied raw or following some kind of processing like anaerobic digestion, composting or drying/pelletizing. Whether an organic soil amendment can be considered a fertilizer or general soil conditioner depends on its effect on plant nutrition. Fertilizers are a source of readily available nutrients and have a direct, short-term effect on plant growth. Soil conditioners affect plant growth indirectly by improving the physical and biological properties of the soil, such as water retention, aeration and microbial activity and diversity. Animal manures and biosolids (sewage sludge) are good examples of organic amendments with fertilizer value. Both can supply N, P and K needs of many crops because greater than 25% of their total N, P and K contents are in forms readily available for crop uptake. Amendments like municipal yard waste, bark and composts are examples of soil conditioners. They are not considered fertilizer substitutes, but mainly they improve soil properties by building soil organic matter. The potential organic matter sources are animal manures, crop residues, spoiled straw, hay and silage, municipal yard waste, biosolids (sewage sludge), wastes from dairy, vegetable, fish, meat and poultry processing industries; wastes from paper mills, timber and paper products, peat, compost (Cooperband, 2002).

Examples in WOCAT Database:
T_NIC001en; T_NIG023en; T_SYR004en; T_TAJ354en; T_TAJ402en

4.2 Growing green manure crops

Green manure or catch crops are rotation crops that are ploughed in (or sprayed out) rather than harvested, to provide organic matter for the following crop. For instance, a crop will need less nitrogen if it follows a legume crop. Growing green manure crops are crucial for maintenance or improvement of soil fertility. It is often said that nature can only produce a few centimetres of topsoil in 100 years, but experience in country after country has shown that farmers using green manure can produce a centimetre of topsoil every three to four years (Bunch, 2015). In fact, when using edible legume species, the value of the grain often exceeds the costs of production, so the net cost of restoring soil fertility over decades is actually negative. In European farming system, growing catch crops and reducing fallow periods was shown to be an entirely positive option to manage SOM, increasing soil C storage and reducing erosion, and also reducing N_2O emissions and N leaching, while reducing the demand for mineral fertiliser (Wösten & Kuikman, 2014).

Chemical fertilizer will never compete with that price! But fertilizer can supplement green manure crops. When smallholder soils reach a productivity of about 3 tonnes per hectare, fertilizers can be profitably used. At this level of soil productivity, the fertilizer will produce a greater yield response with lower risks. Experience around the world shows that it takes about 20 to 25 tonnes per hectare per year (green weight) of leguminous biomass to maintain soil fertility over time. Never in 40 years a smallholder farmer using 20 tonnes of fresh compost or animal manure each year. Most smallholder farmers don't have enough animals to produce this amount of manure, and composting requires too much labour to be cost effective for most subsistence crops. But dozens of legumes can produce double or triple this amount of biomass. Runner beans (*Phaseolus coccineus*) and mucuna (*Mucuna spp.*) can easily produce 70 tonnes per hectare per year, lablab beans (*Dolichos lablab*) and jackbeans (*Canavalia ensiformis*) 50 to 60 tonnes per hectare per year, and pigeon peas (*Cajanus cajan*), densely planted, can produce about 30 tonnes (Bunch, 2015). (http://www.agriculturesnetwork.org/magazines/global/soils-for-life/conservation-agriculture).

The costs of green manure crops need to be assessed carefully, especially in terms of water use, since there is no direct financial return. Organic matter gains tend to be short-term, especially as the input of immature crops or legumes provides an easily decomposed biomass.

(An estimated 25 000 people, between Mexico, Honduras, Guatemala and Belize, have been using *Mucuna* as a green manure cover crop for over 50 years. Photo: Roland Bunch).

it is favorable to grow green manure or a catch crop and to avoid winter fallow. Such a crop will sequester carbon on farm – a difference with the import of carbon sequestered elsewhere such as compost. Because the catch crop is ploughed into the soil increasing SOM. Timing is crucial for growing green manure or a catch crop: the earlier the crop is sown in late summer or early fall, the better. A green manure crop sown after 1 October has usually little chance of success (Wösten & Kuikman, 2014).

Examples in WOCAT Database:
T_NEP003en; T_TUR004EN; T_UGA026en; T_UGA029en

4.3 Cover crops with plant-based materials

Cover crops are planted to provide ground cover between crops and have long been promoted for increasing soil organic matter, increasing nitrogen availability from nitrogen-fixing legume cover crops, scavenging residual nitrogen by small grains, improving water infiltration, providing species diversity in cropping systems, enhancing nutrient cycling, controlling early season weeds (by providing a physical barrier) and inhibiting weed seed germination (by producing allelopathic chemicals during decomposition) and reducing soil erosion from wind and water as well.

Cover crops provide continuous living vegetation in the field. Plant roots have their own particular effects on soil quality. Fibrous, fine root systems stimulate soil aggregation. Taproots help subsequent crop's roots explore subsoil and stimulate water infiltration and aeration of subsoil. Living plants in the soil at all times protect leachable nutrients against loss to the groundwater. In addition, many soil microbes live in the 'twilight zone' between root and soil (the rhizosphere) where they 'graze' on the root surface. They eat root exudates, secretions and decomposing root cells. A study suggests that the root systems of plants contribute twice as much organic material to the soil during the growing season as what remains in the root system at the end of the growing season (Sorensen, 2014). All this organic matter feeds life in the soil.

Cover crops are those crops planted after the main (cash) crop is harvested. Some cover crops are seeded over the standing cash crop so they can get a head start on growth while the cash crop is still in the field. Cover crops are usually killed the following spring, prior to planting the next season’s cash crop. Planting cover crops or green manures build soil organic matter in several ways. Both protect the topsoil completely and greatly decrease soil erosion by

reducing raindrop impact. Cover crops reduce leaching losses by utilizing excess nutrients, especially nitrogen, after the main crops are harvested. Green manures are cover crops that are managed to provide nutrients to the next season's cash crop by killing them while they are still green. Usually legumes and other nitrogen-fixing plants such as clover and vetch are used as green manures for their nitrogen supply. Decomposition is rapid and nitrogen is released. Grasses can also make good green manure crops if they are killed early.
The extensive root systems of cover crops contribute to the soil organic matter while the crop is still alive. If the cover crop survives the winter, most farmers kill the crop several weeks before the next crop is planted and till the residues into the soil. As the residues decompose, they build SOM (Schwenke & Jenkins, 2005).

Examples in WOCAT Database:
T_SPA005en; T_SPA007en; T_TAJ009en

4.4 Retain crop residues

Carbon management in soils must focus strongly on inputs. Retention of crop residues is a key management option currently available for farmers. Retaining crop residues produced onsite by crops is more cost effective than bringing in materials.

Examples in WOCAT Database:
T_PHI045en; T_RWA004en; T_UNK001en; T_UNK003en

4.5 Inter-planting

Planting a fast-growing crop between a slower-growing one can improve soil organic matter. Inter-planting can be crops and grass, or forest and crops, or orchard and crops.

Interplanting of maize with fodder grass (Source: Erik van den Elsen)

Example in WOCAT Database:
T_KEN033en

4.6 Reduce period of bare fallow

During a fallow period both winter and summer, no new organic material is being produced, but carbon continues to be lost from the soil as organic matter decomposes. Summer fallows are worst as the soil stays moist and warm – favourable conditions for decomposition. Keeping land covered ensures that soil organic matter decomposes more slowly than in the case of bare fallow. In addition, bare fallow misses the opportunity to capture carbon from the air in crops. It is therefore advisable to avoid fallow, both in summer and winter.

4.7 Crop rotation

Soil organic matter content decreases after a multiple year intensive cultivation, especially with intensive tillage and little residual return. Annual crop rotation can avoid this. Rotation with crops in the cropping pattern allows for accumulation of organic matter through crop residues and root systems. Rotation with grass or a green manure crop can be completely returned into soils not only for nutrient recycling but also increase in organic matter.

A crop rotation with corn is possible for pasture it is renewed (Wösten & Kuikman, 2014): The corn can take advantage of the released nutrients in the ploughed grassland, and grass clover grows well on a poor corn stubble. For soils under continuous corn cultivation it is beneficial to alternate the corn with some years of grassland. However, it is not recommended to plough permanent grassland to grow corn for only one or a few years. The losses of organic matter after ploughing are very large, and it takes a long time for this organic matter is built up again. In addition, the risk of losses of nitrogen through leaching after ploughing of permanent grassland is large (Klein Swormink et al., 2010).

4.8 Conservation agriculture

Conservation agriculture (CA) is an agricultural practice to achieve sustainable and profitable agriculture and subsequently aiming at improved livelihoods of farmers through the application of the three CA principles: minimal soil disturbance, permanent soil cover and crop rotations (FAO, 2015. http://www.fao.org/ag/ca/). CA could help to minimise or eliminate the degrading effects of inappropriate agricultural practices on the soil: 1) minimal or no mechanical soil disturbance, by seeding directly into untilled soil so as to maintain soil porosity and minimise loss of soil organic matter; 2) permanent, permeable ground cover with, *e.g.*, crop residues which not only protect the surface from extremes of rain-impact and temperature but are, also, a nutrient and energy source for soil-inhabiting organisms; 3) diversification of the cropping system through rotations, sequences or associations of crops, which minimises the effects and spread of disease organisms, both above and below the soil surface (Shaxson & Kassam 2015).

CA principles are universally applicable but there will always have to be site-specific adaptations to different localities. A good example of recent implementation of CA is the EcoGozo project in Gozo island of Malta (Sims, 2015). The EcoGozo project aims to promote the island as eco-island through a complete range of proposals for transforming all aspects of the island economy to produce a healthy, sustainable, environmentally nurturing ecosystem2020 (www.ecogozo.com). A key component of the project is the implementation of CA which covers 1) more rational use of fertilisers to reduce leaching and groundwater contamination; 2) A reduction in the use of pesticides and non-degradable plastics; 3) improving soil quality by reducing erosion through better maintenance of retaining walls, especially on hillside terraces, afforestation; 4) harvesting more rainwater and increasing water infiltration, enhancing soil storage capacity and reducing soil moisture losses to the atmosphere by not ploughing and maintaining soil cover (Sims, 2015).

Over the last 35 years, CA has been applied by more than 3 million farmers on 30 million hectares in Brazil and Paraguay, and has spread to some 30 other nations (Bunch, 2015). Farmers' yields have doubled or tripled, reaching up to eight tonnes per hectare of maize, and has resulted in soils with higher levels of organic matter and available nitrogen, phosphorus, potassium, calcium and magnesium, and with lower acidity. In the meantime, the per-hectare use of nitrogenous chemical fertilizer has fallen. In long term experiments, Conservation Agriculture produced a 64% increase in organic carbon in the top 10 cm of the soil. CA's increasing yields also show that we do not need to resort to subsidised chemical fertilizer – subsidies that are tremendously expensive (Bunch, 2015).

Conservation tillage (*e.g.* reduced or no-tillage) has been widely endorsed as reducing soil disturbance, preserving the soil structure and enhancing SOM content (Luo *et al.,* 2010). Measures for improvement of soil organic matter could again be grouped as agronomic, vegetative, structural, management and combination. Reduced or conservation tillage was argued to be preferable to zero tillage for most conditions, as it has benefits in terms of increased soil C storage, but with less chance of this being offset by increases in N_2O emissions, and is also less likely to reduce crop yields (Wösten & Kuikman, 2014).

Reducing or stopping cultivation altogether has several direct and indirect effects on organic matter. The residence time of carbon added to soil can be nearly twice as long under zero tillage than under intensive tillage. When crop residues remain on the soil surface, and the soil surface is not disturbed, rainwater infiltrates rather than runs off, so the soil is protected from erosion. All processes aimed at increasing organic matter are futile if the soil itself is lost. After erosion, the main process for carbon loss from soil is microbial decomposition. The physical disturbance of ploughing brings crop residues into the soil where conditions for microbial decomposition are more favourable than for residues left on the surface. As well, cultivation breaks up soil aggregates held together by organic matter and exposes the organic matter in the aggregates to decomposition by microbes. A less well-known direct effect of tillage is the degassing of CO_2 that naturally builds up within the soil air from microbes and plant roots.

Merely maintaining soil organic matter levels is difficult if soil is intensively tilled. Tillage is like stoking the fire, it burns up organic matter. Reducing tillage means leaving more residue, and tilling less often and less intensively than conventional tillage therefore reduces organic matter losses. No-till is the most extreme version of reduced tillage and it is firmly established that it can work on all soils in many parts of the world (Arshad *et al*., 1990; Karlen *et al*., 1994; Bayer *et al*., 2006). Eliminating tillage is important if we want to increase organic matter content. It is important to practice no-till continuously. In long term no-till soils, microbial activity is higher than in tilled soils. Fungi are also more prevalent in no-till soils than in tilled soils; their hyphae (hairlike structures) are an important component of the improved soil tilth found in no-till soils. Maintaining crop residues at the surface of no-till soil fields is essential for biological activity including earthworm habitat and feedstock.

The level of soil carbon is affected by the quantity and quality of the plants grown. The quantity of plant residue can be changed by growing crops of different biomass, improving the nutrition of and disease status of following crops through a beneficial rotation and growing crops with different rooting patterns that alter soil structure. The quality of crop residues can be improved by growing plants that are easy for microbes to decompose. Plants with high nitrogen levels are easier to break down than woody plants with high lignin levels. Legumes have the potential to bring nitrogen into the system from the atmosphere and can be grown as either a cash crop or green manure (Schwenke & Jenkins, 2005).

Pastures increase organic matter in the soil. A mix of grasses and legumes provides more organic matter than legume pastures such as lucerne or medic. The grasses have greater root biomass, and legumes are easily decomposable so their beneficial effect is soon lost.

Examples in WOCAT Database:
T_KAZ006en; T_NIG025en; T_TAJ003en; T_ZAM002en

In European agricultural land, the most promising measures to increase soil carbon contents and their effect at different time scales are listed in Table 4.2. Both reduced tillage intensity / frequency and avoiding fallow periods will take time to result in a clear increase in soil carbon content. Under the precondition that the productivity level is sustained, these two measures will have a considerable positive effect on the soil carbon content on a long term basis when they are implemented now. Both optimizing crop production and leaving behind crop residues will have an instant and clear positive effect on soil carbon content. Supply of organic matter from outside the farm will have an instant and clear positive effect on soil carbon content. However, this measure is not sustainable on a long run basis because availability of off farm organic matter is limited making it a scarce resource (Wösten & Kuikman, 2014).

Table 4.2. Effects of measures on soil carbon content at different time scales (from Wösten & Kuikman, 2014).

Measures	short	medium	long
Reduce tillage intensity / frequency	+	++	+++
Avoid fallow periods	+	++	+++
Optimize crop production	++	++	++
Leave behind crop residues	++	++	++
Supply organic matter	+++	++	+

Wösten & Kuikman (2014) summarised three categorises of increasing restricting breakdown of soil organic matter for arable and dairy farming: 1) supply of organic matter from outside the farm; 2) additional production of organic matter on the farm by sequestration of CO_2 from the air; and 3) reduction of organic matter loss by lowering the breakdown rate of organic matter in soils, concrete measures are listed in Table 4.3.

Table 4.3. Measures for increasing and restricting breakdown of SOM (Wösten & Kuikman).

Measures	Category*	For arable or dairy farming?
Measures related to tillage:		
Non inversion tillage	Z	Arable, Dairy
No tillage	Z	Arable, Dairy
Grassland renewal optimization	Y, Z	Dairy
No plough	Z	
Re- and overseeding (periodic or continuous)	Y, Z	
Measures related to cropping pattern:		
Avoid summer fallow	Y, Z	Arable, Dairy
Avoid winter fallow	Y, Z	Arable, Dairy
Green manure crop/nitrogen catch crop/mowing manure	Y, Z	Arable, Dairy
Crop rotation with annual crops	Y, (Z)	Arable
Crop rotation with perennials	Y, Z	Arable
Switch to woody crops	Y, Z	Arable
Placement of hedges	Y, Z	Arable, Dairy
Measures related to optimizing crop production:		

Optimize irrigation	Y	Arable, Dairy
Grazing management:		Dairy
Strip meadows and changing meadows	Y	
Additional seeding	Y	
Grassland herbs and improved grass mixtures		
More efficient fertilization	Y	Arable, Dairy
Other measures:		
Soil additives: compost, animal manure, mowing manure	X	Arable, Dairy
Leave crop residues	Y	Arable, Dairy

* X: supply of organic matter from outside the farm, Y: additional production of organic matter on the farm by sequestration of CO_2 from the air, Z: reduction of organic matter loss by lowering the breakdown rate of organic matter in the soil.

4.9 Applicability of the measures to improve SOM

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 4.2). *How*: applicability in terms of the main action that needs to be taken towards soil improvement. *When*: applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. *Where*: applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions e.g. cost-benefits, or adaptability.

Table. 4.4. Applicability of the measures for control of decline in organic matter in mineral soils

How ?	When ?			Where ?						
	Stage			Land-use type				Location		
Measures	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1)]	Landform[2)]	Altitude[3)]
Applying animal manure, compound fertiliser, trash, recycled waste	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Growing green manure crops	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Covering crops with plant-based materials	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Retaining crop residues	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Intercropping	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Crop-rotation & using pastures in rotation	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Reducing period of bare fallows	-	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Reducing tillage	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Conservation agriculture	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, FS, CX, CV	
Policy & regulation	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX

[1)] HU: Humid (length of growing period (LGP) > 270 days); SH: Sub-humid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days);AR: Arid (LGP 0–74 days).
[2)] PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow);CV (Concave: depression (conversion of water flow)).
[3)] I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI: 2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.
[4)] ++: Application occurs only in this stage; +: Application occurs in this stage; -: Application is not recommended in this stage.

5 Soil Compaction

Soil compaction is defined as densification and distortion of soil by which total and air-filled porosity is reduced, causing deterioration or loss of one or more soil functions (van den Akker, 2008). Overuse of machinery, intensive cropping, short crop rotations, intensive grazing and inappropriate soil management leads to soil compaction. Compact soils can also be found under natural conditions without human or animal involvement. Techniques for loosening compaction up to depths of 45 cm are well established but to correct deeper problems presents difficulties (Batey, 2009). There are four strategies commonly used in dealing with compaction: 1) avoidance, 2) alleviation, 3) controlled traffic, and 4) acceptance as well as the following practical techniques have used to avoid, delay or prevent soil compaction: (1) reducing pressure on soil either by decreasing axle load and/or increasing the contact area of wheels with the soil; (2) working soil and allowing grazing at optimal soil moisture; (3) reducing the number of passes by farm machinery and the intensity and frequency of grazing; (4) confining traffic to certain areas of the field (controlled traffic); (5) increasing soil organic matter through retention of crop and pasture residues; (6) removing soil compaction by deep ripping in the presence of an aggregating agent; (7) crop rotations that include plants with deep, strong taproots; (8) maintenance of an appropriate base saturation ratio and complete nutrition to meet crop requirements to help the soil/crop system to resist harmful external stresses (Hamza & Anderson, 2005).

These measures/techniques can be applied more efficiently when supported by a decision support tool on assessment of mechanical stresses and soil strength, *e.g.* by online Terranimo® (www.terranimo.dk, Lassen *et al*., 2013).

5.1 Avoidance

Avoidance is the most desirable option where it is physically and economically possible. Cato, 234-149 B.C. (cited by Birkas, 2008) recommended ‘Do not plough wet soil and do not drive cart or livestock on a rain-soaked field’. This is a sound principle but possible severe economic repercussions of delaying planting, harvesting, or other operations may outweigh compaction damage or loss. The dilemma the farmer faces in a wet spring or fall is not easy to resolve, although subsoil compaction in wet growing seasons leads to higher yield reductions than dry seasons (Alakukku, 2000). With mechanizations of farming practices, use of larger and heavier machines for tillage and harvest is inevitable and unless appropriate compensating measures are taken, related increases in the degree of compaction are unavoidable.

While large, heavy machinery is often blamed for soil compaction problems, it also offers opportunity to minimize compaction. Larger capacity machinery means fewer wheel tracks across the field because of wider working width. If wheel track spacing can be standardized among different pieces of equipment, soil compaction problems can be minimized. Tracks vs. tires: tracks, as an alternative for tires, are not new in agriculture. Tracks accounted for 6-10% of all tractor sales between the years of 1925-1966. However, in recent years, the change from steel to rubber tracks, improved ride-ability, increased traction, and research citing that tracks create less surface compaction than tires have increased the popularity of tracks.
Tractors equipped with either tracks or tires can create surface compaction. Both radial tires and tracks result in similar surface compaction if the radial tires are properly inflated. Tractors weighing less than 10 tons an axle usually keep compaction in the top 15-20 cm, which can be alleviated by tillage. By and large, even the biggest tractors weigh less than 10 tons an axle. However, combines and grain carts weigh much more and whether equipped with tracks or tires, they can create compaction as deep as 91 cm. see picture below.

Tractor with tracks

Tractor with tires

Combines and grain carts can create compaction as deep as 91 cm.

(Source: http://www.extension.umn.edu/agriculture/tillage/soil-compaction/)

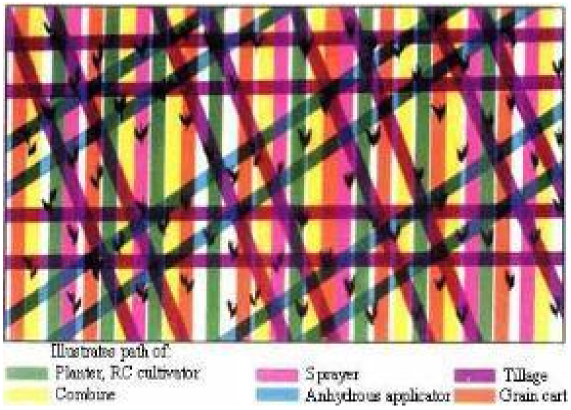
In general, contact pressure largely determines the potential for compaction in the plough layer, while total axle load determines the potential for subsoil compaction. This is important when comparing tracks and tires for compaction effects and depth. Tracks exert a ground pressure of approximately 5-8 pounds per square inch (psi) depending on track width, length, and tractor weight. Radial tires exert a pressure of 2 psi higher than their inflation pressure. For example, if a radial tire is inflated to 6 psi, the tire exerts a pressure of 7-8 psi on the soil. However, bias tires inflated to only 6-8 psi cannot operate efficiently and easily wear-out with such low tire pressures, consequently they have to be inflated to 20-25 psi. The simulations (Schjønning *et al.,* 2015) accord with measured data as reviewed by Hallett *et al* (2012) indicate significant implications for mitigation measures for soil compaction.

Axle loads are increasing and are increasingly causing severe damage to subsoils (Van den Akker *et al*., 2003). It seems prudent to plan ahead to use techniques which as far as possible minimise compaction but also to develop methods to assess the degree of deeper compaction in the soil and how it may be alleviated. Although the mass of tractors, harvesters and loaded trailers has increased substantially, the extra mass has been to some extent compensated for by the use of dual wheels on tractors, an increase in tyre widths, and on trailers by an increase in the number of axles; all steps which allow reductions in tyre pressures which is probably the most important factor controlling compaction under wheels (Davies *et al.,* 1973). Low tyre pressures proved to be very effective in preventing subsoil compaction (Van den Akker, 1998).
Other methods to reduce compaction include use of dual wheels, rubber tracks and flotation tyres (Antos, 2008). It has been proposed that axle loads should be restricted, to avoid compaction deeper than 40 cm, with a limit of 6 t on a single axle or 8–10 t on a tandem axle (Hakansson *et al.,* 1988). Tijink & van der Linden (2000), however, stress the danger when assessing compaction risk of considering axle loads alone. It is critical that both loads and pressures are considered together to enable a combination to be identified which will minimise compaction risk. The practical soil management approach must be to always use the lowest safest tyre pressure for the operation concerned.

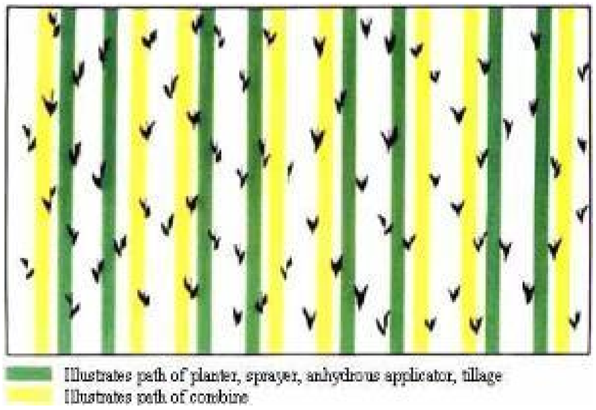
The Wheel Load Carrying Capacity Concept (Van den Akker, 2004; van den Akker & Schjønning, 2004; Schjønning *et al*., 2015) could be applied to identify ‘windows’ (soil type/water regime combinations), where sustainable traffic with specific machinery is possible, is crucial when discussing avoidance. Rules of thumbs have been created that allow the farmer to estimate the risk of compaction at least at field capacity water content (Keller *et al*., 2012; Schjønning *et al*., 2012). An online decision support tool (www.terranimo.dk) allows for such comparisons of stress and strength for nearly all combinations of machinery and soil/water conditions. The Terranimo will be described by the RECARE Case Study Soil Compaction team as the tool to identify potential measures to avoid soil compaction. The identification of a specific technology is not relevant across farming systems, so, a flexible instrument is needed to identify these windows.

5.2 Controlled traffic

Controlled traffic is the practice of running farm machinery over the same paths in the field, from event to event and year to year, so that compaction resulting from such passes will be confined to the smallest possible proportion of the field. The theory of controlled traffic is illustrated in the following figures obtained from the University of Nebraska:



Random wheel traffic patterns create compaction over the majority of the field



Controlled wheel traffic

Source: http://soilquality.org/practices/controlled_traffic.html

In a normal year, as much as 90% of the field may be tracked by equipment. The philosophy behind controlled traffic is to restrict the amount of soil travelled on by using the same wheel tracks. Seventy to 90 percent of the total plough layer compaction occurs on the first trip across the field. By controlling traffic, the tracked area will have a slightly deeper compaction but the soil between the tracks will not be compacted.

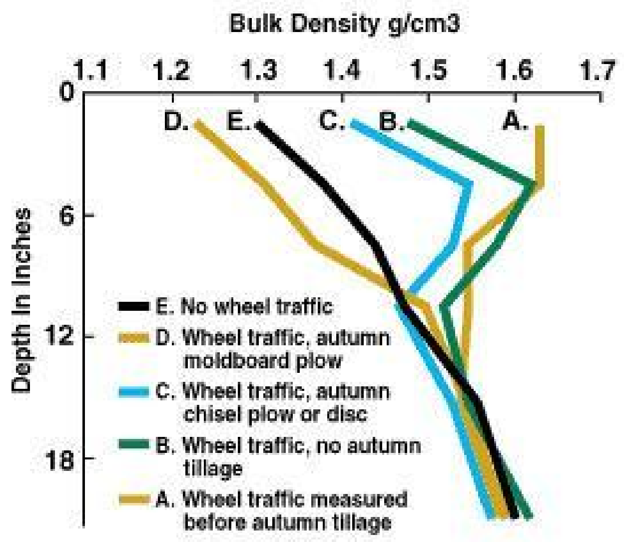
Corn and soybean farmers who use global positioning systems (GPS), ridge till, strip till, or no-till can confine traffic between certain rows and avoid compacting the row area. This requires proper matching of all machines including combines, grain carts, and manure-handling equipment to confine the compaction to the same between-row areas.

There are occasional reports of adverse effects on plant growth where the wheel tracks are on both sides of the row, but even then the damage is confined to certain rows. Benefits to controlled traffic, using permanent compacted lanes, are improved tractor efficiency and floatation, less powerful machinery needed, and improved timeliness of operations.

Example in WOCAT Database:
T_AUS002en

5.3 Alleviation

Although avoidance of compaction is a primary tenet of good soil management (Larsen *et al*., 1994; Hatley *et al*., 2005), alleviation is an essential component (DEFRA, 2005). Approaches to compaction alleviation are discussed in detail by Spoor (2006). There are two ways of alleviating and lessening the damage caused by compaction: 1) attempt to remove the compaction or 2) attempt to reduce the adverse effects of the compaction.



Alleviation of wheel traffic compaction by tillage and overwintering (Source: http://www.extension.umn.edu/agriculture/tillage/soil-compaction)

Subsoiling could loosen compacted soils and increase water infiltration. However, studies have shown that this would be not a sustainable management option,, because the loosening could reduce crop yields (Soane *et al.,* 1987; Munkholm *et al*., 2005; Olesen & Munkholm, 2007).

Examples in WOCAT Database:
T_KYR003EN; T_SWI001en; T_ZAM004EN

5.4 Acceptance

Acceptance is waiting for the detrimental effects to be removed by natural forces. However, this may not be practical if there is compaction below the plough layer. The deeper the compaction and higher the clay content, the longer it will persist.

As soils have been compacted, they can be removed and replaced, amended, or 'buried' under soil with better growing characteristics.

5.5 Replacing soils

Removal of soil and replacement with better soil is a drastic solution, but one that might be justified by the demands of the proposed landscape. Most often, soil replacement is feasible if the amount to be replaced is not very great. It is common to see topsoil brought onto a site and spread over an area so that two to four inches of new soil is added. This is most common on sites that have acted as the staging area for some construction project. The added topsoil helps to bury ruts and give a neater appearance. Its usual function is to aid in grass reestablishment. This amount of soil is of no benefit to trees and shrubs. For trees and shrubs, at least eighteen inches to three feet of new soil is necessary for good growth. Generally, the larger the plant and/or the more water it requires, the greater the replaced soil depth should be.

Although many might specify 'topsoil' as soil to use as a replacement, there is no standardised definition of the physical or chemical properties of topsoil. Topsoil could literally be any soil 'on top' of the ground. It is necessary to specify the physical and chemical properties of replacement soil so that you bring in a soil that can sustain plant growth.

5.6 Amending soils

It is possible to amend an existing poor soil so that its density is below a root-growth-limiting level and drainage is increased. To accomplish this with inorganic amendments such as sand, approximately 75% by volume, would need to be added to affect a positive change in drainage. Adding less actually decreases the porosity of the soil. It is important, too, that any amendment is predominantly uniform and preferably large-sized. If a well-graded sand is added, one with particles of all sizes, the smaller particles will nest within the larger ones, effectively reducing pore space. The best amendment is one of nearly equal size particles. When the equally sized sand particles become so numerous in an amended soil so that they begin to touch each other, large pores will begin to be formed. In practice it is very difficult to amend a soil with enough inorganic amendment to affect a meaningful improvement. Adding sand is useful if soils can be mixed away from the site and brought in, which is in essence the same as bringing in a new soil (http://www.gardening.cornell.edu/factsheets/soil/compaction.html).

By mixing in so much sand to a clayey soil, the texture of the soil is changed. The practice of amending a soil with organic matter is an ancient agricultural practice. Recent research has shown that organic amendment can have a beneficial effect in reducing soil density to below roots limiting levels, even in soils that had been re-compacted after the amendment was added. The correct way to add organic matter is over a site, not in a hole. The amendment should be tilled or dug in to a depth of 45cm and enough added to make a meaningful difference. With a compacted sandy loam, it is necessary to add at least 25% by volume to the entire 45cm depth profile to make a positive change in soil density and drainage. In a compacted heavy clayey soil, at least 50% of organic matter would have to be added to the same depth to decrease soil density below root limiting thresholds. Even with this level of organic matter, it is not clear whether drainage can be changed enough to remove that limiting factor in the planting site. Therefore, with a heavy, clayey soil, amendments should be added to reduce bulk density, however plants should still be chosen that could tolerate intermittently wet soils (http://www.gardening.cornell.edu/factsheets/soil/compaction.html).

There are many types of organic matter that may be used to amend soils. Peat humus, peat moss, food waste compost, composted brewers waste or other composted organic material can be usefully employed as long as the soluble salts and pH are compatible with the plants you will be growing. There may be other issues that will need to be addressed when using compost. Organic amendments should always be well-composted and a lab test run on them to verify pH, soluble salts, nutrient availability and organic matter content. Moreover, if the amendment is too fresh and not well-composted, there may be an abundance of weed seeds or wood chips which can tie up some soil nitrogen while they are decomposing.

5.7 'Burying' soils

Where it is not practical to remove soil and replace it, it is possible to bury the poor soil with a better, specified soil. This may be done over a large, continuous area or in discrete areas corresponding to where large plants are to be established. The most common way to do this is in the creation of berms, or raised planting areas. Too often, berms are created by scraping unspecified soil from an area to be levelled or lowered using a front- end loader or similar large machine. In this process, even reasonable soil may become compacted. A better way to create landforms is to bring in specified, compaction-resistant soil and place it on site. The depth of these forms should also be no less than

45cm, but preferably closer to 91cm if large plant material is to be established there (http://www.gardening.cornell.edu/factsheets/soil/compaction.html).

5.8 Drainage and aeration systems

It is important that the compacted soil under newly added soil or amended soils drains well. With the addition of amendments, or the use of good soil on a site, drainage should be fine within that depth of modified soil. However, below the better soil there are often layers of poorly draining, compacted soil that can force excess water to 'back up' into the plants root zone. A technique called sub-surface soil sculpting can aid in this process. With sub-surface sculpting, the slope of the soil to be buried under well-draining new or amended soil is graded in a way to move excess water away from the prepared planting sites. Water should drain freely through the replaced soil and when it reaches the old soil, it should be channelled away by the use of swales or drains via gravity. The grade or form of the replaced soil may look nothing like the shape of the buried soil that has been sculpted for positive drainage below. There are other techniques such as French drains and perforated pipe that may be used to move excess water away
(http://www.gardening.cornell.edu/factsheets/soil/compaction.html)
(http://www.extension.umn.edu/agriculture/Tillage/soil-compaction/index.html).
The option of mechanically loosening compacted subsoils has proven problematic, and the biological mitigation effects of roots are at best very slow (Schjønning *et al*., 2015); cost-benefit considerations point to avoid compaction rather than alleviate it by dubious management options (Hallett *et al.*, 2012). Therefore best way is to prevent subsoil compaction in advance rather than to attempt repairing it afterwards.

5.9 Using online decision support toolbox Terranimo

Subsoil stress caused by wheel load should not exceed the strength of the subsoil (Van den Akker & Schjønning, 2004). Mechanical stresses and soil strength can be assessed through an online decision support tool Terranimo® (www.terranimo.dk, Lassen *et al*., 2013; Stettler *et al*., 2014). Controlled traffic farming has been widely adopted in many parts of the World, like China and Australia (Tullberg *et al.,* 2007). The causes and prevention of soil compaction have been reviewed in more detail by Alakukku *et al*. (2003), Chamen *et al.* (2003), Håkansson (2005) and Hamza & Anderson (2005).

It should be emphasised that controlled traffic focuses topsoil compaction, while the non-resilient damage to subsoils is normally increased due to the need of large (heavy) machinery to operate in the wheel tracks. Also, most farming systems include some operations (typically harvest) that do not allow the use of the traffic lanes.

5.10 Applicability of the measures to reduce soil compaction

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 5.1). *How*: applicability in terms of the main action that needs to be taken towards soil improvement. *When*: applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. *Where*: applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions e.g. cost-benefits, or adaptability.

Table. 5.1. Applicability of the measures for reduction of soil compaction.

How ?	When ?			Where ?						
	Stage			Land-use type				Location		
Measures	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1)]	Landform[2)]	Altitude[3)]
Avoidance	+	+	-	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Controlled traffic	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Alleviation	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Acceptance	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Replacing soils	-	-	+	+	+	+	+	Hu, SH, SA, A	PL, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Amending soils	-	-	+	+	+	+	+	Hu, SH, SA, A	PL, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
"Burying" soils	-	-	+	+	+	+	+	Hu, SH, SA, A	PL, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Drainage & aeration	-	-	+	+	+	+	+	Hu, SH, SA, A	PL, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Using online decision support toolbox - Terranimo	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Policy & regulation	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI

[1)] HU: Humid (length of growing period (LGP) > 270 days); SH: Subhumid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days);AR: Arid (LGP 0–74 days).

[2)] PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow);CV (Concave: depression (conversion of water flow)).

[3)] I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI: 2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.

[4)] ++: Application occurs only in this stage; +: Application occurs in this stage; -: Application is not recommended in this stage.

6 Soil Sealing

Soil sealing refers to destruction or covering of soils by buildings, constructions and layers of completely or partly impermeable artificial material (asphalt, concrete, etc.), it is the most intense form of land take and is essentially an irreversible process (Huber *et al*., 2008; Prokop & Jobstmann, 2011). Soil sealing is driven by economic development in both urban and rural areas and increasing population which need more settlement areas for *e.g*., housing and infrastructure. Soil sealing often leads to economic benefits but decrease in soil functions and ecosystem services, this trade-off should be taken into consideration.

Processes of soil sealing can be interrupted by either reducing future land take or by implementing desealing measures. The latter is only rarely applied and very cost intensive. Reducing future land take can above all be realised by influencing planning policies and building rules, promoting reuse of already developed land and brownfields, strengthening inner urban development instead of urban sprawl, and implementing building techniques which consume less soil or maintain some soil functions (in particular permeability). These measures can be of binding or of voluntary nature.

6.1 Overview of best practices for limiting soil sealing or mitigating its effects in EU-27

A complete overview on practices to limit and mitigate the effects of soil sealing was published by European Commission in 2011 (Prokop *et al*., 2011) presenting land take and soil sealing trends in the EU. The report contains an exhaustive overview of existing member state policies and technical measures used to reduce and mitigate soil sealing. The full report can be downloaded here. The report recommends a three-tiered approach:

- Limiting the progression of soil sealing with improved spatial planning or by reassessing "negative" subsidies that indirectly encourage soil sealing;
- Mitigating damage when soil sealing cannot be avoided, through measures such as the use of permeable surfaces instead of conventional asphalt or cement and building green roofs;
- Compensating valuable soil losses by action in other areas to offset drawbacks in eco-function. Measures may take the form of payments, as in Czech Republic and Slovakia, or the restoration of already sealed soil. Good practices have been identified notably in the cities of Dresden (Soil Compensation Account) and Vienna.

6.2 Guidelines on best practice to limit, mitigate or compensate soil sealing

On the basis of the report on *Overview of best practices for limiting soil sealing or mitigating its effects in EU-27* and with the help of national soil sealing experts, European Commission departments have prepared *Guidelines on best practice to limit, mitigate or compensate soil sealing* (SWD(2012) 101 final/2) (*http://ec.europa.eu/environment/soil/sealing_guidelines.htm*). The guidelines collect examples of policies, legislation, funding schemes, local planning tools, information campaigns and many other best practices implemented throughout the EU. They are mainly addressed to competent authorities in the member states (at national, regional and local levels), professionals dealing with land planning and soil management, and stakeholders in general, but it may also be of interest to individual citizens. The best practice examples collected in the guidelines show that smarter spatial planning can limit urban sprawl. In fact, limiting soil sealing should have priority over mitigation or compensation measures, since soil sealing is an almost irreversible process. Development potential inside urban areas can be used instead, through the regeneration of abandoned industrial areas (brownfields), for example. Mitigating measures include using permeable materials , support of 'green infrastructure', and making wider use of natural water harvesting systems. Only where on-site mitigation measures are insufficient, compensation measures that enhance soil functions elsewhere should be considered. Two typical measures to mitigate soil sealing are permeable surfaces and green roofs. In the following examples for each tier are illustrated:

There are two ways to limit soil sealing: by reducing land take, the rate at which natural areas are converted into developed areas; or by continuing to seal soil, but only on land that has been previously developed. To "pave the way" for successful prevention of soil loss the following basic principles need to be implemented at the policy level:

- To establish the principle of sustainable development in spatial planning by following an integrated approach, requiring the full commitment of all governmental sectors (and not only spatial planning and environment)
  Best practice: The majority of the EU member states has established the principle of sustainable development in their key spatial planning regulations, referring to economic use of soil resources and avoidance of unnecessary urban sprawl. However, without binding measures, regular monitoring and critical assessment soil functions cannot be protected adequately;

- To define realistic land take targets at the national and the regional level
  Best practice: Quantitative limits for annual land take exist only in six Member States, as this is the case in Austria, Belgium (Flanders), Germany, Luxembourg, the Netherlands, and the United Kingdom. In all cases the limits are indicative and are used as monitoring tools. In the United Kingdom and Germany the national targets are taken most seriously and their progress is regularly assessed. Only in the United Kingdom are development targets also defined at the regional level;
- To streamline existing funding policies accordingly by freezing subsidies that encourage land take and soil sealing (i.e. public subsidies for private housing on undeveloped land, subsidies for developments on the green field sites, commuter bonuses, etc.);
  Best practice: So far no examples identified.
- To develop specific regional approaches according to the actual land use pressures:
  - To steer new developments to already developed land and provide financial incentives for the development of brownfield sites
    Best practice: Initial or supportive funding to encourage new infrastructure developments on brownfield sites exists in several Member States and is usually co-ordinated by designated brownfield organisations. Brownfield redevelopment projects are mostly realised in the form of private public partnerships: (1) The *English Partnerships* is probably the most experienced public land developer in the European Union and provides funding for social housing developments on derelict areas; (2) France has a network of more than 20 public land development agencies, which among other activities develop brownfield land for social housing; (3) The land development agencies *Czech Invest* and *Invest in Silesia* are in charge of developing major industrial brownfields for new industrial investors; (4) In Flanders specific contracts (brownfield covenants) are negotiated between the government and private investors to promote brownfield redevelopment.
  - To improve the quality of life in large urban centres
    Best practice: Several urban renewal programmes have been launched recently with the objective to attract new residents and create new jobs in central urban areas in decline. Best practice examples in this respect are (1) the urban renewal programmes of *Porto* and *Lisbon* and the neighbourhood renewal programme in *Catalonia* both of which are supported by the European Regional Development Funds, (2) the *Västra hamnen* project in Malmö which is built on derelict harbour premises providing 1,000 new dwellings with the lowest possible

environmental impact, (3) the *Erdberger Mais* development in Vienna which is built on five inner urban brownfield areas, providing housing for 6,000 new inhabitants and 40,000 work places, (4) the *Randstad* programme in the Netherlands which puts special emphasis on improving the attractiveness of inner urban areas in the metropolitan agglomeration of Amsterdam, Rotterdam, and Den Haag.

- To make small city centres more attractive in order to counteract dispersed settlement structures in rural regions with shrinking population.

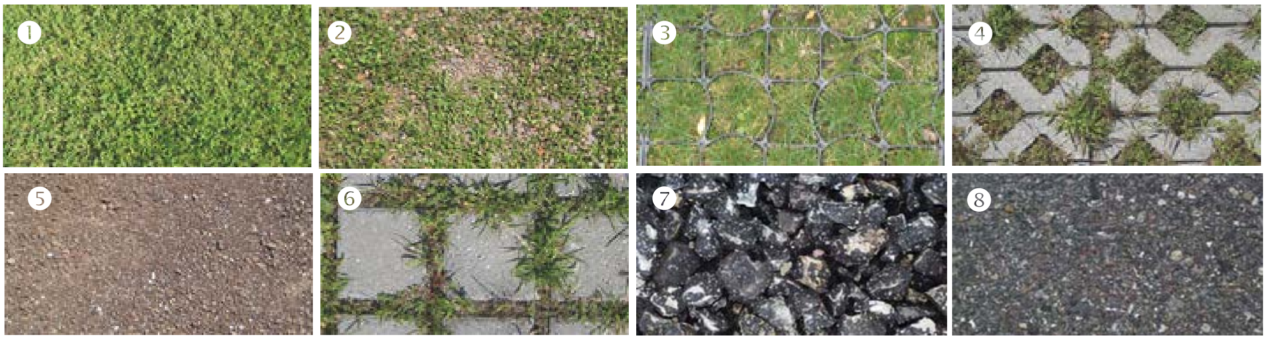
  Best practice: The Danish Spatial Planning Act puts clear restrictions on the construction of large shops and shopping centres on green fields out-side the largest cities and promotes small retailers in small and medium sized towns.
- To impose development restrictions on top agricultural soils and valuable landscapes

  Best practice: Several Member States have established specific policies to avoid further land take and sealing on their best agricultural soils and most valuable landscapes, as this is the case (1) in Spain where building activities within the first 500 meters from the sea are strictly controlled, (2) in France and the Netherlands where designated "green and blue" landscapes are protected from infrastructure developments, (3) in the Czech Republic and Slovakia where the conversion of top agricultural soils requires a fee.

Permeable surfaces can help to conserve soil functions and mitigate the effects of soil sealing to a certain extent. They contribute to the local water drainage capacity and can in some cases also fulfil biological or landscaping functions. Another advantage is their positive contribution to the micro-climate thereby trapping the heat and moderating temperatures in the area. Unsealed, green shaded surfaces have lower surface temperatures than sealed surfaces, the difference can amount to up to 20 °C. In the case of storm water a parking area built with permeable surfaces discharges the local sewage system by at least 50 % compared to a conventional asphalt surface. It can even be designed as independent system without discharges to the local sewage system.

A broad range of materials and concepts is available for permeable surfaces. In addition to their clear ecological advantages most types of surfaces have lower lifespan costs compared to conventional impermeable surfaces. With regard to sustainability most permeable surfaces are made of materials that are locally available and reusable. Key barriers to implementation are currently the fact that site specific know-how and building competence is required to construct them correctly. Furthermore, regular maintenance is needed to make sure that they function properly. Parking areas have the greatest potential for permeable surface application, in particular large parking areas in urban fringes. Most advanced in this respect is the United Kingdom, where permeable surfaces are broadly used – even in big cities – and where research is continuously developed and many guidelines exist.

In the following Figure, the most common surfaces for “artificial” open areas are shown. The surfaces are presented according to their permeability; i.e. the first picture shows conventional lawn which can be considered as 100 % unsealed, pictures 2 to 7 refer to various permeable surfaces, and the last picture shows asphalt, being 100 % sealed.



(1) Lawn, (2) Gravel Turf, (3) Plastic grass grids, (4) Concrete grass grids, (5) Water bound macadam, (6) Permeable pavers, (7) Porous asphalt, (8) Conventional asphalt.

Table 6.1. Comparison of benefits and limitations of most common permeable surfaces (in relation to asphalt) (Prokop *et al*, 2011).

	pedestrians	parking, small vehicles	parking, medium vehicles	road traffic	Visual appearance	Vegetation possible	High drainage capacity	Regional materials	Improves micro climate	High maintenance	Bad walking comfort	No disabled parking	Sludge accumulation	Dust formation	Unsealed surface	Run-off coefficient	Costs*: Asphalt = 100%
	Application range				Benefits					Limitations							
Lawn, sandy soil					+++	+++	+++	+++	+++			+++	+++		100%	<0.1	< 2 %
Gravel Turf	Y	Y	Y		++	++	++	+++	++	+	+	+			100%	0.1 - 0.3	50 - 60 %
Grass grids (plastic)	Y	Y			++	++	++	+	++	++	++	++	+		90%	0.3 - 0.5	75 %
Grass grids (concrete)	Y	Y	Y	Y	++	++	+	+++	++	++	++	++	+		40%	0.6-0.7	75 - 100 %
Water bound surfaces	Y	Y	Y		+		+	+++		++	+	+	++	++	50%	0.5	50%
Permeable pavers	Y	Y	Y		+		+	+++	+	+					20%	0.5-0.6	100 - 125 %
Porous asphalt	Y	Y	Y	Y			++								0%	0.5 - 0.7	100 - 125 %
Asphalt	Y	Y	Y	Y											0%	1.0	100 %

* Indicative costs in relation to asphalt are provided, in 2010 average costs for conventional asphalt layers amounted to approximately 40 €/m² (without VAT), including construction costs. For each surface type material costs and labour costs were considered.

Missed opportunities. Parking areas have the greatest potential for permeable surface application. In Europe there are definitely more parking lots than cars. The number of cars is increasing from year to year and together with this trend also the number of parking lots.

- Recreational sites. The application of reinforced grass systems with gravel or grass grids is ideal for large short-term used parking areas, like in ski resorts, football stadiums, golf courts, touristic sites, and trade fairs. Such surfaces improve the local drainage capacity and contribute positively to the landscape.
- Households. Private driveways have great potential for the application of permeable surfaces. For this type of use almost all surfaces types are applicable.
- Supermarkets. The use of permeable concrete pavers in combination with drainage ditches is a long lasting solution which allows heavy traffic. This type of surface is more and more applied at supermarket parking areas.

Limitations. Areas with sensitive groundwater resources or shallow groundwater (below 1 meter) are in general not suitable for surface drainage.

Costs. Apart from natural stone pavements, it can be said that permeable surfaces do not bear higher costs than conventional asphalt and are not dependant on the crude oil price (unlike asphalt).

Sustainability. Gravel turf and concrete bricks are made of sustainable materials, which are readily available in most European regions. As these materials can easily be reused their life span is almost unlimited. Conventional asphalt on the contrary has to be recycled for re-application with more energy input.

Trends. Many planning authorities in Europe are currently revising their technical regulations towards surface sealing. Increased drainage capacity has many advantages, in particular in areas with flood risk or overloaded sewage systems. The fact that permeable surfaces can reduce or even avoid costs related to flood prevention, flood damage repair or enlargement of existing sewage systems is attractive for local planning authorities. For example, planning authorities in England, in the Alto Adige region (Italy), and selected cities in Germany and Austria already restrict surface sealing for new building activities.

Compensation. The idea behind compensating for soil sealing is to make up for sealing in one place by restoring soil functions elsewhere in the same area. As a rule, compensation measures should be equivalent to the ecosystem functions lost.

Environmental impact assessments of large projects and for planning purposes can be used to identify the most appropriate compensation measure. Examples of compensation schemes include:

- Reuse of topsoil. Topsoil can be removed from a construction site and used, for example, to upgrade agricultural sites, or to regenerate contaminated land and encourage seed germination, on a golf course, or to improve soil quality in gardens.
- Desealing (soil recovery). Removing asphalt or concrete and replacing them with topsoil on subsoil can help renew the soil functions of a previously sealed site, as well as restoring the beauty of the landscape. Desealing is mainly used in urban regeneration projects, following the removal of derelict buildings to create green spaces, for example. Sadly, this option is not taken up often enough because the costs are perceived to be too high.
- Sealing fee. Authorities can impose fees for land take and soil sealing. This could be used as a tool to limit soil sealing, but in practice fees are rarely high enough to discourage land take. Instead, the money collected is used to support soil-protection projects. Some countries in Europe use sealing fees to protect the best farmland.
- Eco-accounts and trading development certificates. In an eco-accounts system, the ecological cost of soil sealing is determined and developers have to ensure that compensation measures of equal value to sealing are carried out elsewhere. Official compensation agencies oversee the system.

6.3 Applicability of the measures to soil sealing

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 6.2). *How*: applicability in terms of the main action that needs to be taken towards soil improvement. *When*: applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. *Where*: applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions e.g. cost-benefits, or adaptability.

Table. 6.2. Applicability of the measures for control of soil sealing

How ?	When ?			Where ?						
Measures	Stage			Land-use type				Location		
	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1)]	Landform[2)]	Altitude[3)]
Green roofs		+	+	+	+		+	All	All	All
Permeable surfaces, e.g., driveways		+	+	+	+		+	All	All	All
Inner urban development	+		+	+	+		+	All	All	All
Development restrictions on top agricultural soils	+		+	+	+		+	All	All	All
Reuse of topsoil		+	+	+	+		+	All	All	All
Sealing fee		+	+	+	+		+	All	All	All
Desealing		+	+	+	+		+	All	All	All
Policies and regulations	+	+	+	+	+	+	+	All	All	All

1) HU: Humid (length of growing period (LGP) > 270 days); SH: Sub-humid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days);AR: Arid (LGP 0–74 days).

2) PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow);CV (Concave: depression (conversion of water flow)).

3) I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI:"2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.

4) ++: Application occurs only in this stage; +: Application occurs in this stage; -: Application is not recommended in this stage.

7 Soil Contamination

Soil contamination is presence of contaminants in soil above a certain level causing deterioration or loss of one or more soil functions (JRC, 2014). The contaminants occur in various forms such as organic and inorganic or particulate contaminants[1] (Mirsal, 2008).
Although some soil contaminants derive from natural sources, *e.g.*, parent rock or volcanic emissions, most of them are the result of human activities (Alloway, 2013), such as point pollution *e.g.* metal mining and smelting, industrial production, waste disposal and diffuse pollution by industrial activities, car emissions, application of agrochemicals, manure containing veterinary drugs, etc. Special attention is still being given to hazardous sites with large amounts of heavy metals, combustible and putrescible substances, hazardous wastes, explosives and petroleum products from abandoned mines, mine spoils, tailings and other metal-bearing wastes (Adriano, 2001).

Major component of inorganic contaminates are heavy metals (Adriano, 1986; Alloway, 1990). They present a different problem than organic contaminants. Soil microorganisms can degrade organic contaminants, while heavy metals in soils cannot be degraded, and clean up usually requires their removal by chemical, physical and biological techniques which can be grouped into two categories: *ex-situ* and in- *situ* methods (Bake *et al.*, 1990). Most of the conventional remedial technologies, such as soil excavation and dumping, ex-situ and in-situ soil washing/flushing, electro-kinetics, vitrification and asphalt capping, ground freezing are expensive and inhibit the soil fertility; this subsequently causes negative impacts on the ecosystem.

7.1 Phytoremediation

Phytoremediation is the direct use of living green plants in situ or in place to absorb or, break down pollutants in soils, sludge, sediment, surface water and groundwater. Phytoremediation is a cost effective, environmentally friendly, aesthetically pleasing approach most suitable for developing countries (Ghosh & Singh, 2005). Phytoremediation includes phytoextraction, phytodegradation,

[1] Organic contaminants are substances whose molecules contain one or more carbon atoms covalent bonded with another element or radical (including hydrogen, nitrogen, oxygen, the halogens as well as phosphorus, silicon and sulphur) whereas an inorganic contaminant is any compound not containing carbon atoms such as heavy metals. Inorganic pollutants do not underlay decay and therefore once released into the soils stay, whereas organic pollutants underlay a process of decay.

rhizofiltration, hytostabilisation, phytovolatilization and phytotransformation techniques (Table 7.1).

Table 7.1. Phytoremediation processes and mechanisms of contaminant removal (modified from Ghosh & Singh, 2005).

Process	Mechanism	Contaminant
Phytoextraction	Hyper-accumulation	Inorganics
Phytostabilisation	Complexation	Inorganics
Phytodegradation		
Rhizofiltration	Rhizosphere accumulation	Organics/Inorganics
Phytovolatilization	Volatilisation by leaves	Organics/Inorganics
Phytotransformation	Degradation in plant	Organics

Phytoextraction or phytoaccumulation

Plants remove metals from soils and concentrate them in the harvestable parts of plants. It is the best approach to remove the contamination primarily from soil and isolate it, without destroying the soil structure and fertility (USA EPA, 2000). It is best suited for the remediation of diffusely polluted areas, where pollutants occur only at relatively low concentration and superficially (Rulkens *et al*., 1998). Two basic strategies of phytoextraction are 1) chelate assisted phytoextraction or induced phytoextraction, in which artificial chelates are added to increase the mobility and uptake of metal contaminant; 2) continuous phytoextraction in this the removal of metal depends on the natural ability of the plant to remediate; only the number of plant growth repetitions are controlled (Salt *et al*., 1995, 1997). Species with hyper-accumulations are listed in Table 7.2.

Table 7.2. Several hyper-accumulators and their bio-accumulation potential

Plant species	Metal	Leaf content (ppm)	Reference
Thlaspi caerulescens	Zn	39,600 (shoot)	Reeves & Brooks , 1983; Brown *et al*., 1994
Thlaspi caerulescens	Cd	1800	Baker & Walker , 1990
A. racemosus	Se	14900	Beath *et al*. 1937
P. vittata	As	27000	Wang *et al*., 2002
Berkheya coddii	Ni	5500	Robinson *et al*. 1997
Iberis intermedia	Ti	3070	Leblanc *et al*. 1999
Noea mucronata	Pb, Zn, Cu, Cd and Ni		Chehregani *et al*., 2009

Plant species	Metal	Leaf content (ppm)	Reference
Amaranthus retroflexus	Fe		Chehregani *et al.*, 2009
Polygonum aviculare	Pb, Zn, Cu, Cd and Ni		Chehregani *et al.*, 2009
Gundelia tournefortii	Cu, Fe, Zn, Pb and Ni		Chehregani *et al.*, 2009
Scariola orientalis	Cu, Fe, Zn, Pb and Ni		Chehregani *et al.*, 2009
Ipomea alpina	Cu	12,300	Baker & Walker (1989)
Haumaniastrum robertii	Co	10,200	Brooks (1998)
Astragalus racemosus	Se	14,900	Beath *et al.* (1937)
Sebertia acuminata	Ni	25% by wt dried sap	Jaffre *et al.* (1976)
Willow (*Salix viminalis*)	Cd	Unsuited on strongly polluted soils. promising on moderately polluted soils	Jensen *et al.*, 2009, Kumar *et al.*, 1995

Phytostabilization

Phytostabilization uses higher plants and associated microorganisms to immobilize contaminants in soil, through absorption and accumulation by roots, adsorption onto roots or precipitation within the root zone and physical stabilization of soils. It is mostly used for the remediation of soil, sediment and sludge (Mueller *et al.*, 1999; USA EPA, 2000) and depends on roots ability to limit contaminant mobility and bioavailability in the soil. Phytostabilization can occur through the sorption, precipitation, complexation, or metal valence reduction. The plants primary purpose is to decrease the amount of water percolating through the soil matrix, which may result in the formation of hazardous leachate and prevent soil erosion and distribution of the toxic metal to other areas. It is very effective when rapid immobilisation is needed to preserve ground and surface water and disposal of biomass is not required. However the major disadvantage is that, the contaminant remains in soil as it is, and therefore requires regular monitoring. Table 7.3 shows promising species for stabilization of pollutants in soils.

Table 7.3. Species for stabilization of pollutants in soils (modified from Padmavathiamma & Li, 2007).

Plant species	Metal	Treatments	Results	Limitations	Reference
Horedeum vulgare, Lupinus angustifolius, Secale cereale	As	Different P amendment products (organic and inorganic)	P amendment of <3 gm^{-2} caused As leaching of 0.5 mg l^{-1} from unplanted lysimeters and up to 0.9 mg l^{-1} on average in planted lysimeters. Arsenic accumulated in plant biomass to 126 mg/kg in shoots and 469 mg/kg in roots.	Variable species – amendment combinations produced differences in the amount of As leached and uptake.	Mains et al. 2006a,b
Lolium italicum and *Festuca arundinaceae*	Pb and Zn	Compost at two rates (10%, and 30% v/v)	The concentration of Pb and Zn in aerial parts and in roots of *L. italicum* and *F. arundinacea* decreased more than five times in presence of compost. Pb content decreased from 218 to 32 mg/kg in shoot and 7,232 to 1,196 mg/kg in root. Zn decreased from 4,190 to 624 mg/kg in shoot and 7,120 to 1,993 mg/kg in root.	The level of contaminants in aerial parts of plants was still too high to be grazed by herbivores.	Rizzi et al. 2004
B. juncea	Cd	Soil amendments – liming materials, phosphate compounds and biosolids	Phosphate immobilized Cd, thereby reducing the phytotoxicity of Cd. The tissue metal concentration of Cd, Cu and Cr(VI) with biosolids application was 253, 157 and 12.4 mg/kg. (i.e. a decrease over nil amendment.)		Bolan et al. 2003
B. juncea	Zn, Cu, Mn, Fe, Pb and Cd	organic amendments (cow manure and compost) and lime	Active phytoremediation followed by natural attenuation, was effective for remediation of pyrite-polluted soil. Soil concentration decreased from: 363 to 166 mg/kg for Zn, 36 to 31 mg/kg for Cu, 1.94 to 1.48 mg/kg for Pb, 1.6 to 0.86 mg/kg for Cd, 679 to 303 mg/kg for Fe and 245 to 303 mg/kg for Fe and 245 to 120 mg/kg for Mn. Available As concentration in soil decreased from 2.5–13.5 mg/kg after the first crop to 0.5–2.6 mg/kg after the second.	Bioavailability of Cu did not decrease with either soil pH increase or with lime.	Clemente et al. 2003; Clemente et al. 2006
Anthyllis vulneraria, Festuca arvernensis, Koeleria vallesiana, Armeria arenaria.	Zn, Cd and Pb	Local metallicolous legume and grass species.	Festuca and Koeleria in co-culture with Anthyllis showed a decreased concentration of heavy metals (Zn Pb Cd) in their leaves compared with monocultures. For Festuca, decreases of 2885 to 1469 mg/kg for Zn, 1002 to 376 mg/kg for Pb and 19 to 8 mg/kg for Cd were reported. For Koeleria, a decrease of 3,514 to 2,786 mg/kg for Zn, 1,960 to 1,477 mg/kg for Pb and 34 to 26 mg/kg for Cd were reported.	Armeria, one of the plants used in the study reduced the recruitment of Anthyllis seedlings.	Frérot et al. 2006
H. hirta and *Z. fabago*	Pb, Zn and Cu	Characterization of soil and plant samples from a mine tailing located in South-East Spain for further phytostabilisation research	*H. hirta* accumulated around 150 mg kg^{-1} Pb in both shoots and roots. Zn concentration was 750 mg kg^{-1} in *Z. fabago* shoots.	The plant species, *H. hirta* and *Z. fabago*, colonize only parts of the tailings with low electrical conductivity	Conesa et al. 2006

Phytodegradation

Plants and associated microbes degrade organic pollutants. Hybrid poplar trees can uptake, hydrolyze and dealkylate atrazine to less toxic metabolites (Burken & Schnoor, 1997). Reed could effectively degrade heavy oil hydrocarbons in the polluted soils (Ji *et al*., 2004). Horseradish, potato (*Solanum tuberosum*), and white radish (*Raphanus sativus*) that contains peroxidase can degrade phenols (Dec & Bollag, 1994; Roper *et al*., 1996). Poplar trees (*Populus* spp.) are capable of transforming trichloroethylene in soils (Strand *et al*., 1995).

Phytovolatilization

Phytovolatilization is the process of volatilisation of pollutants into the atmosphere via plants (Bañuelos *et al*., 1997). Some metal contaminants such as Se, As and Hg may exist as gaseous species in soils. In recent years, researchers have sought naturally-occurring or genetically-modified plants capable of absorbing elemental forms of these metals from the soil, biologically converting them to gaseous species within the plant, and releasing them into the atmosphere. Selenium accumulator *Astragalus racemosus* was identified as dimethyl diselenide (Evans *et al*., 1968). Selenium released from *alfalfa*, a selenium non-accumulator, was different from the accumulator species and was identified as dimethyl selenide. Members of the Brassicaceae are capable of releasing up to 40g Se ha^{-1} day^{-1} as various gaseous compounds (Terry *et al*., 1992). Some aquatic plants, such as cattail (*Typha latifolia L*.), have potential for Se phytoremediation (Pilon-Smits *et al.,* 2005). The volatilization of Se and Hg is also a permanent site solution, because the inorganic forms of these elements are removed, and gaseous species are not likely to redeposit at or near the site (Atkinson *et al*., 1990; Heaton *et al*., 1998). Furthermore, sites that utilize this technique may not require much management after the original planting. This remediation method has the added benefits of minimal site disturbance, less erosion, and no need to dispose of contaminated plant material; it is suggested that the transfer of Hg (O) to the atmosphere would not contribute significantly to the atmospheric pool. This technique appears to be a promising tool for remediating Se- and Hg- contaminated soils (Heaton *et al*., 1998). Volatilization of arsenic as dimethylarsenite has also been postulated as a resistance mechanism in marine algae. However, it is not known whether terrestrial plants also volatilize arsenic in significant quantities. Arsenic predominantly accumulates in roots and that only small quantities are transported to shoots. However, plants may enhance the biotransformation of arsenic by rhizospheric bacteria, thus increasing the rates of volatilization (Salt *et al*. 1998). Unlike other remediation techniques, once contaminants have been removed via volatilization, there is a loss of control over their migration to other areas. Addition to atmospheric levels through phytovolatilization would not contribute significantly to the atmospheric pool, since the contaminants are likely to be subject to more effective or rapid natural degradation processes such as photodegradation (Azaizeh *et al.*, 1997). However, phytovolatilization should be avoided for sites near population cantres and at places with unique meteorological conditions that promote the rapid deposition of volatile compounds (Heaton *et al.,* 1998). Hence the consequences of releasing the metals to the atmosphere need to be considered carefully before adopting this method as a remediation tool.

Rhizofiltration

Rhizofiltration is the use of plant roots (phytofiltration) or seedlings (blastofiltration) to absorb or adsorb pollutants, mainly metals, from water and aqueous waste streams (Prasad & Freitas, 2003). Table 7.4 lists potential species for rhizofiltration of pollutants in soils.

Table 7.4. Species for rhizofiltration of pollutants in soils (Padmavathiamma & Li, 2006)

Plant species	Metal	Treatments	Results	Reference
B. juncea, H. annuus	Cu, Cd, Cr, Ni, Pb, and Zn	Roots of hydroponically grown terrestrial plants used to remove toxic elements from aqueous solutions	Roots of B, juncea concentrated these metals 131–563-fold (on a DW basis) above initial solution concentrations. The recoveries of heavy metals were 45 % for Cd, 55% for Zn, 50% for Cr, 45% for Ni, 97% for Cu and 100 % for Pb.	Dushenkov et al. 1995
Sunflower plants	U	Rhizofiltration of U in water by roots of sunflower plants	U concentration in water reduced from 21–874 ug/l to <20 ug/l by rhizofiltration	Dushenkov et al. 1997a,b
Water Hyacinth	As, Cd Cr, Cu, Ni, and Se	The abilities of water hyacinth to take up and translocate six trace elements – As, Cd, Cr, Cu, Ni, and Se were studied under controlled conditions	The highest levels of Cd in shoots and roots were 371 and 6,103 mg/kg dry wt., and those of Cr were 119 and 3,951 mg/kg dry wt., Cadmium, Cr, Cu, Ni, and As were more highly accumulated in roots, whereas Se accumulated more in shoots.	Zhu et al. 1999
Duckweed	Hg	Effects of pH, copper and humic acid	Duckweed strongly absorbed Hg from water and after 3 days contained 2,000 ppm of Hg by weight	Mo et al. 1989
Duckweed (*Lemna minor* L.) and water velvet (*Azolla pinnata*).	Fe and Cu	Solutions enriched with 1·0, 2·0, 4·0, and 8·0 ppm of these 2 metal ions, renewed every 2 days over a 14-day test period.	When duckweed was kept in a solution containing Cu alone at 8·0 ppm level, the value of the metal concentration factor (i.e. the ratio of metals in the plant to the growth media) after 14 days was 51. However, in the presence of an equal concentration of Fe the value of this factor was 27, indicating the influence of Fe on the uptake rate of Cu.	Jain et al. 1989

Genetic engineering has been considered useful for improvement of plants for phytoremediation of metal polluted soils (Kärenlampi *et al.*, 2000).

7.2 Chemical remediation

Metals and arsenic in contaminated soils can be stabilised using various oxides as stabilizing amendments, which by chemical means reduces contaminant mobility, bioavailability and bioaccessibility. This stabilisation techniques can be combined with phytostabilization (Kumpiene *et al.,* 2008; Komárek *et al*., 2013). Table 7.5 lists examples for stabilising pollutants in the contaminated soils.
In situ remediation technologies for Lead, Zinc, and Cadmium in soil have been reviewed by Martin & Ruby (2004).

Table 7.5. Examples of studies dealing with metal(loid) stabilization in contaminated soils using various oxides and their precursors (from Komárek *et al.*, 2013).

Metal(loid) concentrations (mg kg^{-1})	Treatment (wt.%)	Effect	Reference
Cd (18) Pb (1112) Zn (1434)	- Fe(0) (1%) - hydrous Mn oxide (1%)	- decreased water-soluble Cd, Pb and Zn - decreased Cd uptake by plants (ryegrass, tobacco, bean) - decreased Cd, Pb and Zn uptake by ryegrass - no significant changes in biomass production	Mench et al. (1994a,b) Sappin-Didier et al. (1997)
Pb (250)	- hydrous Mn oxide (1%)	- reduced water-soluble and acetic acid (0.43 M) extractable Pb - decreased Pb uptake by ryegrass - increased biomass yields of ryegrass	Mench et al. (1997)
Cd (7)	- steel sludge (Fe + FeO + Fe_2O_3 at 3.5–10.5%) + CaO, SiO_2, MgO	- decreased Cd uptake by wetland rice, Chinese cabbage and wheat - positive influence on biomass production of Chinese cabbage	Chen et al. (2000)
Cd (26–48) Pb (1521–3291) Zn (4463–8649)	- synthetic cryptomelane (0.25–0.5%)	- reduction of Pb bioavailability (PBET) - reduced soluble Pb (TCLP) - reduced phytoavailable Pb (Swiss chard) - lower influence on Cd and Zn	Hettiarachchi et al. (2000) Hettiarachchi and Pierzynski (2002)
Cu (3430)	- birnessite (10%) - ferrihydrite (10%) - $Al(OH)_3$ (5%)	- birnessite lowered free Cu^{2+} activity in soil solution, but phytotoxicity persisted due to elevated total soluble Cu concentrations as a result of increased DOC - birnessite slightly improved corn growth - ferrihydrite and $Al(OH)_3$ reduced soluble Cu	McBride and Martínez (2000)
As (683–4814)	- $FeSO_4$ + lime (Fe:As molar ratio 0–50)	- significantly decreased water soluble As (e.g., at Fe:As = 2 from 3790 to 0.79 μg L^{-1}) - mobilization of Cu and Zn in the non-limed variant as a result of pH decreases	Moore et al. (2000)
As (1215–1327)	- synthetic FeOOH (1–5%) - limonite (1–10%) - synthetic $Al(OH)_3$ (1–5%)	- reduced water-soluble As (55–100%) - higher efficiencies for the synthetic phases	García-Sanchez et al. (2002)
Cd (19–42) Cu (78–1245) Pb (230–842) Zn (1756–2920)	- red mud (2%)	- increased soil pH - decreased metal fluxes from the soil solid phase to solution - redistribution of metals from the exchangeable to the reducible (oxide-bound) fraction - reduced phytotoxicity of metals, increased biomass yields and decreased metal concentrations in plants (oilseed rape, pea, wheat, lettuce) - increased soil microbial biomass	Lombi et al. (2002a,b)
As (1325) Pb (170)	- Fe(0) (1%) + compost (5%) + beringite (5%)	- beneficial for pine growth in the long-term (3 years) - decreased As in aboveground biomass - decreased As leaching - successful revegetation of the treated soils	Bleeker et al. (2002) Mench et al. (2003)
Cd (7–120) Zn (700–2713)	- red mud (1%)	- reduced Cd and Zn extractability (1 M NH_4NO_3) by 70% and 89%, respectively - Cd and Zn plant uptake reduced by 38–87% and 50–81%, respectively - redistribution of metals from the exchangeable to the reducible (oxide-bound) fraction	Friesl et al. (2003)
As (577)	- $FeSO_4$ (0.2–1.1%) + lime	- reduction of As concentrations in lettuce (e.g., at 1.1% $FeSO_4$ from 13.8 to 1.45 μg kg^{-1}) - no significant changes in biomass production	Warren and Alloway (2003)
As (748)	- $FeSO_4$ + lime (0.2–2.0% of Fe oxides) - Fe(0) (0.2% of Fe oxides)	- $FeSO_4$ application (at 0.5% and 1.0% of Fe oxides) reduced As uptake by several crops (by 32% in average) - Fe(0) application did not decrease As concentrations in plants	Warren et al. (2003)
As (60–78) Cd (1–36) Cu (69–118) Pb (127–360) Zn (33–508)	- $FeSO_4$ (1%) + lime - $Fe_2(SO_4)_3$ (1%) + lime - goethite (1%) - Fe(0) (1%)	- all treatments reduced As concentrations in leachates - increased concentrations of Cd, Cu, Pb, Zn in leachates after the addition of Fe sulfates - Fe(III) sulfate > Fe(II) sulfate > Fe(0) > goethite - long-term stability	Hartley et al. (2004)
As (115–14,200)	- Fe(0) (1%)	- large-scale project - As concentrations decreased in soil solution by 39–95%	http://www.difpolmine.org (2006)
As (30–68) Cd (5–34) Cu (58–95) Pb (913–8306) Zn (500–2039)	- ferrihydrite (2%) - goethite (2%) - red mud (0.25%, 0.5%) + gravel sludge (2%, 2.5%)	- ferrihydrite amendment reduced Cd and Pb uptake by barley - immobilization of most metals (Cd, Cu, Pb, Zn) - red mud increased soil pH - risks of As mobilization due to elevated pH after the application of red mud	Friesl et al. (2006)
Cd (79) Cu (311) Pb (4210) Zn (3970)	- red mud (3%, 5%)	- increased soil pH - decreased metal concentrations in soil pore water - promoted growth of *Festuca rubra* (metal tolerant grass) - decreased metal concentrations in *F. rubra*	Gray et al. (2006)
As (5904) Cr (3829) Cu (1509)	- Fe(0) (1%)	- As and Cr concentration decreased in leachates (by 98% and 45%, respectively), in soil pore water (by 99% and 94%, respectively), in plant shoots (by 84% and 95%, respectively) - no positive influence on Cu	Kumpiene et al. (2006)

Metal(loid) concentrations (mg kg^{-1})	Treatment (wt.%)	Effect	Reference
As (169)	- Fe(0) (1%) + beringite (5%)	- 6-yr experiment - decreased exchangeable As concentrations - promoted growth of lettuce, cabbage and dwarf bean - reduced As bioaccessibility (PBET) and bioavailability for earthworms - increase in microbial biomass, but no increase in microbial species richness	Mench et al. (2006a) Ascher et al. (2009)
Cu (2600)	- Fe(0) (2%) + organic matter (compost, activated carbon)	- increased soil pH - decreased Cu concentrations in soil solution - improved growth of dwarf bean when Fe(0) was applied with compost - the lowest Cu concentration in leaves of dwarf bean when Fe(0) was applied with compost	Bes and Mench (2008)
As (60–78) Cu (33–508)	- $FeSO_4$ (1%) + lime - $Fe_2(SO_4)_3$ (1%) + lime - goethite (1%) - Fe(0) (1%)	- decreased pH after sulfate addition - no significant changes in Cu fractionation - reduced exchangeable As fraction, switch to less labile fractions (reducible, residual) - goethite application promoted the growth of ryegrass, tomato and spinach; however, higher biomass yields were only observed on ryegrass - reduced As uptake by ryegrass, tomato and spinach after Fe treatments	Hartley and Lepp (2008a,b)
Cr (42) Cu (630)	- basic slag containing Fe_2O_3, Al_2O_3 (1–4%)	- increased soil pH and conductivity - improved growth of bean - decreased Al, Cr, Cu uptake by bean	Negim et al. (2010, 2012)
Cd (1–3) Cu (309–1027) Zn (314–819)	- Fe(0) (1%)	- decreased NH_4NO_3-exchangeable Cd and Cu (Cu > Cd > Zn) - no significant effect on metal uptake by spinach under field conditions - no adverse effect on soil pH	Hanauer et al. (2011)
Cu (2080)	- Fe(0) (2%)	- reduced exchangeable Cu, switch to less labile fractions (especially reducible) - positive influence on the growth of *Agrostis castellana* Boiss. & Reut. - decreased shoot Cu concentrations in *A. castellana*	Kumpiene et al. (2011)
Cd (4) Pb (214) Zn (260)	- Fe(0) (2%)	- reduced TCLP- and $Ca(NO_3)_2$-extractable Cd and Zn - reduced bioaccessible (PBET) Pb and Zn - reduced exchangeable Cd, Pb and Zn fractions - similar biomass yields of lettuce compared to the control - reduced Cd, Pb and Zn uptake by lettuce - no effect on Cd, Pb and Zn concentrations in earthworms - increased dehydrogenase activity in soils	Lee et al. (2011)
As (1033) Cr (371)	- water treatment residue containing mainly ferrihydrite (2.5%, 5%)	- reduced As and Cr leaching by 98% and 91%, respectively - decreased As and Cr concentrations in pore waters in a 3-yr field experiment	Nielsen et al. (2011)
Tl (5)	- birnessite (0.5%)	- reduced easily mobilizable Tl, switch to less labile fractions (reducible) - decreased Tl uptake by white mustard - positive influence on biomass production of white mustard grown on a sandy soil	Vaněk et al. (2011)
As (179) Cd (6) Pb (3564) Zn (3127)	- not precisely defined Fe oxides (1%, 3%)	- significant decrease of As in pore water; not for Cd, Cu, Pb and Zn - no positive influence on lettuce seeds germination and root growth	González et al. (2012)
As (145)	- $Fe(OH)_3$ (5%) - mine sludge containing goethite (5%)	- a 30% and 50% reduction of As leaching when using mine sludge and $Fe(OH)_3$, respectively	Ko et al. (2012)
As (1457)	- Fe(0) (2%) + compost (5%) + coal fly ash (5%)	- 10-yr experiment - decreased total As concentrations through leaching in the long-term - decreased exchangeable As fraction and fraction associated with poorly crystalline Fe oxides, increased residual fraction	Kumpiene et al. (2012)

7.3 Encapsulation or Dig-and-dump

Dig and dump or encapsulation is to excavate contaminated soils and remove to an authorized landfill. This technique is too expensive and not sustainable for a large area (Van Ginneken *et al.*, 2007). In the UK and the rest of Europe, there remains a heavy reliance on dig and dump as a management method for contaminated soils, despite a range of legislative, cost and sustainability drivers to develop alternative treatment methods (Cundy *et al.*, 2008).

7.4 Soil washing

Soil washing is a water based process for remediation of excavated soils. There are two ways to wash contaminants from soils: 1) by dissolving and/or separating, suspending contaminants on soil particles into the wash water, wash water can be dosed with chemicals to improve the washing characteristic (such as pH adjustment, surfactants *etc.*); 2) by concentrating contaminants into a smaller volume of soil through particle size separation and attrition scrubbing. The most important factor affecting the soil washing process is the percentage of fines (particles with a diameter less than 0.063mm) in the soil, if the percentage of fines is high then there will only be a small volume reduction in the amount of contaminated material and the efficiency of the soil washing process will be low. Generally it is considered that if the fine content of the soil is above 25% then soil washing will not be effective. More granular soils are better suited to soil washing than cohesive or semi cohesive soils.
Soil washing has been shown to be able to remediate/reduce the volume of contaminated soil, contaminated with diesel range organics (DRO); petroleum range organics (PRO); volatile organic compounds (VOCs); semi- volatile organic compounds (SVOCs); heavy metals (lead, chromium etc.) and pesticides and so forth.

7.5 Limiting application of inorganic fertilisers, pesticides and herbicides

Application of Inorganic fertilizers, pesticides and herbicides can increase crop production and protect from harmful organisms, farmers cannot stop to use them. However, overuse of chemical fertilizers, pesticide and herbicides occur - soil will be polluted. This will lead to the loss of soil fertility and crop failure. The question is how to use these toxic chemicals so that their use may be fruitful but may not adversely affect soil fertility and the related environment. The following measures may be suggested to control soil pollution (source: http://www.preservearticles.com/2012011320631/the-following-measures-may-be-suggested-to-control-soil-pollution.html.):

- Development of such pesticides should be encouraged, which may save crops from pests and rodents but should not contaminate soil with toxic chemicals.
- Pesticides and fertilizers should be applied on croplands only in recommended dose, prescribed by experts. It will help in reducing the level of water and soil pollution caused through these chemicals.
- There should be sufficient duration between the harvesting of crops and time of last spray of pesticides. This will help in reducing contamination

of pesticides, directly to the crop. It will also cause less contamination of chloride and other chemicals to the soil.
- There must be arrangement for educating farmers regarding the proper use of pesticides and fertilizers. Only those fertilizers could be used for growing crops, which are deficient in soils.
- After every two or three years soils percentage should be analysed, so that it can be observed that what is the percentage of nutrients in the soils. This will help in maintaining the required amount of nutrient in the soils.
- Waste water from industries should not be used for irrigation without eliminating toxic chemicals from the effluent. This will also reduce the concentration of unwanted substances in the soil.
- Garbage should not be disposed of on cultivated land without covering it with soil.
- Soil conservation practices should also be adopted so as to avoid loss of valuable nutrients through soil erosion.

In addition, governments should encourage research programs examining the effects of pesticides and fertilizers on soils, wild plants and animals, and human beings. This will help in devising suitable measures to control soil pollution and restore soil fertility.

7.6 Controlling animal manure pollution

Good manure management has the following aspects (Hugo van der Meer, personal communication):
- Calculation of N, P, K (and other nutrients) excretion in faeces and urine per animal per year;
- Good collection and storage of faeces and urine produced, limiting losses in the building and manure storage system as much as possible;
- Complete recycling of manure nutrients to crops, considering the following aspects:
    - Period of field application: shortly before or at the start of crop growth;
    - Rate of manure application to the crops: determined by the requirements for N, P, K of the crop;
    - Method of manure application: rapid incorporation of manure into the soil to avoid N losses by ammonia volatilization.

These aspects can be considered as universal guidelines, details are referred to the Guidelines for Sustainable Manure Management in Asian Livestock production Systems', published as IAEA-TECDOC-1582 (IAEA, 2008; van der Meer, 2008), but only the European Union has compulsive legislation on these aspects, because it considers a clean environment (atmosphere, water, soil) as essential elements of a prosperous society.

7.7 Applying electric field

Application of a direct-current electric field in soils that contain contaminated liquid can restore contaminated soils. The electric field induces a motion of the liquid and dissolved ions that transports the contaminant to wells for removal. Electrode chemistry plays an important role, and reagents can be introduced at the electrodes to enhance contaminant removal rates. A study shows high degrees of contaminant removal, propagation of sharp acid and base wave fronts from the electrodes, and a "focusing" effect by which metals accumulate in regions of the soil (Probstein & Hicks, 1993).

7.8 Controlling contamination by laws and regulations

There is no general Acts world-wide on soil contamination counter measures but country by country. In Japan, Agricultural Land Soil Pollution Prevention Law has been enacted (Ministry of the Environment, Japan, 1970), system of implementing the Law has been developed (http://www.emecs.or.jp/01cd-rom/section_3_e/section3d_e/3top_a_ha_1_2_e.html).
The Soil Protection Act of the Netherlands which is only a skeleton is gradually filled in with general administrative orders (Vegter, 1995).

7.9 Applicability of the measures to control soil contamination

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 7.6). ***How***: applicability in terms of the main action that needs to be taken towards soil improvement. ***When***: applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. ***Where***: applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions e.g. cost-benefits, or adaptability.

Table. 7.6. Applicability of the measures for remediation of soil contamination.

How ?	When ?			Where ?						
Measures	Stage			Land-use type				Location		
	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1)]	Landform[2)]	Altitude[3)]
Bioremediation		+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Chemical remediation			+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Encapsulation (Dig-and-dump)			+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Soil washing		+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Limiting application of inorganic fertiliser, pesticides and herbicides	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Controlling animal manure pollution	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Applying electric field		+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Policy and regulation	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX

1) HU: Humid (length of growing period (LGP) > 270 days); SH: Sub-humid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days); AR: Arid (LGP 0–74 days).

2) PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow);CV (Concave: depression (conversion of water flow)).

3) I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI: 2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.

4) ++: Application occurs only in this stage; +: Application occurs in this stage; -: Application is not recommended in this stage.

8 Soil Salinization

Salinization refers to accumulations of water soluble salts in soils, causing a deterioration or loss of one or more soil functions. The accumulated salts contain sodium-, potassium-, magnesium- and calcium- chlorides, sulphates, carbonates and bicarbonates (Huber *et al.,* 2008). There are two major types of salinization - primary and secondary which are induced by climate and human activities, respectively. Primary soil salinization accumulate salts through natural processes such as physical or chemical weathering and transport from parent material, geological deposits or groundwater; and secondary salinization is caused by human interventions such as use of salt-rich irrigation water or other inappropriate irrigation practices, and/or poor drainage conditions (Tóth *et al*., 2008). Salty groundwater may also contribute to salinization as groundwater table reaches plant root zone. Fertilising and other inputs in association with irrigation and insufficient drainage cause soil salinization, especially where land under intensive agriculture has low permeability and limited possibilities of leaching.

Practices to control soil salinity include improving drainage, minimising saline water irrigation, leaching salts, isolating salts, growing halophytes, and employing good soil/water management (drip irrigation, irrigation scheduling, seedbed placement, applying organic matter). Drainage is a primary method of controlling soil salinity. Policy could play a key role in preventing and remediating salinization of soils.

8.1 Improving drainage

Drainage should be improved in saline areas; in particular if salinity problems are associated with a rising water table and saline groundwater. If soils are waterlogged, removing excess water can help leach salt from the root zone to lower levels in the soil profile. Consideration must be given to management of the drainage water.

- Cut-off drains can divert and remove surface water that would otherwise become groundwater recharge. Surface drains should be stabilized with fencing and vegetation cover.
- Raised beds with adjoining furrow drains can improve surface drainage and salt leaching.
- Sub-surface drainage can reduce waterlogging and increase the leaching of salt.

- Care is needed when considering drainage options as drains in dispersive soils can lead to soil instability and severe erosion.
- Bio-drainage

Example in WOCAT Database:
T_KYR001en

8.2 Minimising saline water irrigation

An option to minimise the effects of salinity is to minimise irrigation applications with saline water and the subsequent accumulation of salts in the soils. This can be accomplished through converting to a rain-fed production system; maximizing effectiveness of precipitation to reduce the amount of irrigation required; adopting highly efficient irrigation and tillage practices to reduce irrigation applications required; and/or using a higher quality irrigation water source (if available). Since some salts are added through fertilisers or as components (or contaminants) of other soil additives, soil fertility testing is warranted to refine nutrient management.

8.3 Drip irrigation

Surface drip irrigation and subsurface drip irrigation methods can be very effective in applying irrigation without leaf wetting. Some salts, including calcium and magnesium carbonates that contribute to water hardness, merit special consideration for subsurface drip irrigation systems. These salts can precipitate out of solution and contribute to significant clogging of drip emitters and other components (such as filters). Water quality analysis, including acid titration, is necessary to determine appropriate SDI maintenance requirements. Common maintenance practices include periodic acid injection (shock treatment to prevent and/or dissolve precipitates) and continuous acid injection (acid pH maintained to prevent chemical precipitation).

Example in WOCAT Database:
T_GRE002en

Managing irrigation schedules (amounts and timing) helps to keep salt accumulations dispersed and away from plant roots, provides for better root uptake of nutrients, and offers improved protection from short-term drought conditions.

Light, frequent irrigation applications can result in a small wetted zone and limited capacity for dilution or leaching of salts. When salt deposits accumulate near the soil surface (due to small irrigation amounts combined with evaporation from the soil surface), crop germination problems and seedling damage are more likely. In arid and semi-arid conditions a smaller wetted zone generally results in a smaller effective root zone; hence the crop is more vulnerable to salt damage and to drought stress injury.

8.4 Leaching salts

Leaching is the only practical way of removing excess salts. This is effective only to the extent that water moves down through the soil profile and below the root zone (drainage must be good). This is often accomplished by occasional excessive irrigation applications to dissolve, dilute and move the salts. The amount of excess irrigation application required (often referred to as the "leaching fraction") depends upon the concentrations of salts within the soil and in the water applied to accomplish the leaching. The amount of salts removed depends on the quantity and quality of water leached through the soil profile during a single irrigation period. Water should be low in salts (high quality) and must not run off the surface. It should be applied slowly so amounts do not exceed the ability of the soil to take in water (infiltration rate).

Rainfall may act as a leaching fraction. However, excessive leaching fractions can worsen the process of salinization by causing the water table to rise, so they need to be carefully managed. Where irrigation water quantity is limited, sufficient water for leaching may not be available. The combined problem of limited water volume and poor water quality can be particularly difficult to manage. Soil additives and field drainage can be used to facilitate the leaching process. Site specific issues, including soil and water chemistry, soil characteristics and field layout, should be considered in determining the best approach to accomplish effective leaching. For instance, gypsum, sulphur, sulphuric acid, and other sulphur containing compounds, as well as calcium and calcium salts may be used to increase the availability of calcium in soil solution to "displace" sodium adsorbed to soil particles and hence facilitate sodium leaching for remediation of sodic soils. In soils with insufficient internal drainage for salt leaching and removal, mechanical drainage (subsurface drain tiles, ditches, etc.) may be necessary.
(http://www.saiplatform.org/uploads/Modules/Library/sai-technical-brief-14-salinity-control-2.pdf)

8.5 Isolating salts

Straw interlayer burial is a measure to bury straw layer in soil as a interlayer to isolate salts move upwards. A straw interlayer is buried in 20-40cm beneath soil surface by tillage with some 6 tonnes of straw per hectare from e.g., maize straw; ideally straw interlayer burial with plastic film mulching could lead to best effect on stopping upward salt movement and preventing salt accumulation to surface soil layer, increasing soil organic matter and reducing evaporation hence increasing soil moisture (Wang et al., 2012; Zhao et al., 2013a, b).

	
Check	Isolated by straw interlayer

8.6 Growing halophytes

Halophytes could be used for human food consumption, for forage and animal feeds, as oilseed and energy crops; they could also be used for desalination and phytoremediation purposes. There is a considerable number of species of halophytes which may be a viable commercial alternative to conventional cropping systems and the utilization of saliniszed soils (Panta *et al.*, 2014).

Example in WOCAT Database:
T_UZB004en

Some relatively salt tolerant crops (such as barley and sugar beet) are more salt sensitive at emergence and early growth stages than in their later growth stages. Currently crop breeding programmes are addressing salt tolerance for several crops, including small grains and forages. Some field crops are particularly susceptible to particular salts or specific elements or to foliar injury if saline water is applied through sprinkler irrigation methods.

8.7 Seedbed placement

In some operations, seed placement can be adapted to avoid planting directly into areas of highest salt accumulation. Row spacing and water movement within the soil can affect the amount of water available for seedlings as well as the amount of water required and available for the dilution of salts.

8.8 Applying organic matter

Use of organic amendment could be a strategic remediation for saline soil (Tejada *et al.*, 2006). Adding organic matter into soils can improve soil structure and permeability supporting movement of water through the soil and maintain higher water holding capacity and higher cation exchange capacity (CEC) of soils therefore lower the exchangeable sodium percentage, thereby helping to mitigate negative effects of sodium. Manure and compost made from manure may be high in salts, therefore adding manure or compost into salty soils should be done with caution. On marginally salty soils, concentrate on gradually improving the soil organic content and activity of soil microorganisms and earthworms. Do not exceed recommended rates per application as large quantities of organic matter can hold salts next to plant roots and cause injury. Organic amendments applied over time improve soil tilth, which then will improve the potential for effective leaching as well as plant growth.

Where feasible, organic mulches also can reduce evaporation from the soil surface, thereby increasing water use efficiency (and possibly lowering irrigation demand). Because some organic mulch materials can contain appreciable salts, sampling and analysis for salt content of these products are recommended. Vegetation can assist in preventing and managing salinity, particularly salinity associated with rising water tables. Deep-rooted plants can assist in preventing rising water tables, by utilising water deep in the soil profile but the plants grown on salty soils are less tolerant of dry soil conditions requiring more frequent irrigation, with reduced amounts of water.

8.9 Policy and regulations

Policy instruments against soil salinization can be applied at different levels of authority and management. At the European level, the 5th Environment Action Programme (EAP) legislation in the late 1990s has set environmental objectives that are built up on scientifically sound-based action plans that integrate scientific disciplines, policies, and stakeholder consultations and has helped ensure that these objectives are backed by environment legislation. Within the 5th EAP, the Water Framework Directive (WFD) 2000/60/EC1 established a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater, including relevant information on the superficial deposits and soils at catchment scale, thus illustrating the importance of the holistic approach of soil and water management as well as the data collection.

Nevertheless, the WFD treats soil merely as a medium of achieving "good status" of all waters, mostly concerning point and diffuse pollution sources which may affect the aquatic ecosystems (Quevauviller & Olazabal, 2003), thus overlooking the essential functions and services it provides. Tackling this shortcoming, the 6th EAP (2002-2012) established the Soil Thematic Strategy aiming specifically at preventing and diminishing the soil degradation and threats. Later, the Thematic Strategy for Soil Protection recognised salinization among all other soil threats and in 2012, the EU recognised the increasing soil degradation trends and structured its strategy on the pillars of awareness raising, research, integration, legislation. It is important to note that salinisation can pose a major risk for the long-term objectives of the Common Agricultural Policy (CAP) ("viable food production, sustainable management of natural resources and climate action and balanced territorial development") and provision in the new CAP's "targeted agri-environment schemes" has been proposed by several NGOs (BirdLife International, 2009).

Nevertheless, salinization is never mentioned but only implied even in the current CAP's Good Agricultural and Environmental Conditions (GAEC). In the 7th EAP that came into force in 2014 and will be guiding the European environment policy until 2020, fertile soil and the productive land are considered part of the "natural capital" to be managed sustainably and adequately protected, while action for the remediation of contaminated areas, reduce soil erosion and increase soil organic matter is encouraged. These policy and soft law texts indicate the intention of EU for further and more specific protection of the soil; nevertheless, a hard law text (directive, regulation) is vitally important in order to set the limit values of the salinization soil threat.

8.10 Applicability of the measures to control soil salinization

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 8.1). *How*: applicability in terms of the main action that needs to be taken towards soil improvement. *When*: applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. *Where*: applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions e.g. cost-benefits, or adaptability.

Table. 8.1. Applicability of the measures for soil salinization

How ?	When ?			Where ?						
Measures	Stage			Land-use type				Location		
	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1)]	Landform[2)]	Altitude[3)]
Improving drainage	-	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Minimising saline water irrigation	-	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Drip irrigation	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Leaching salts	-	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Growing halophytes	-	+	-	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Seedbed placement	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Applying organic matter	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Policy & regulation	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX

1) HU: Humid (length of growing period (LGP) > 270 days); SH: Sub-humid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days);AR: Arid (LGP 0–74 days).

2) PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow);CV (Concave: depression (conversion of water flow)).

3) I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI:"2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.

4) ++: Application occurs only in this stage; +: Application occurs in this stage; -: Application is not recommended in this stage.

9 Desertification

Desertification has been defined by UNCCD as land degradation in arid, semi-arid and dry sub-humid regions resulting from various factors, including climatic variations and human activities (http://www.unccd.int/en/about-the-convention/Pages/Text-Part-I.aspx).
It is a process of fertile land transforming into desert due to deforestation, drought or inappropriate agriculture and other activities. Decreasing water losses by runoff and evaporation is critical to enhancing vegetation cover therefore arresting desertification. Residue management and choice of appropriate tillage methods are important to reduce surface water loss and increase water use efficiency. An integrated approach is increasingly adopted through sustainable land use practices to prevent or reduce desertification of land.

9.1 Growing vegetation

Removal of vegetative cover exacerbates desertification (Castillo *et al*., 1997); it also damages physical, chemical, and biological properties of soils, especially disturbing plant-microbe symbioses which are a critical factor in helping reestablishment of plant growth in degraded ecosystems (Requena *et al.,* 2001). Thus, establishing a vegetative cover is the key to controlling soil desertification.

Planting trees and grasses
Planting trees and grasses is often viewed as an appropriate measure to combat desertification. Different strategies are adopted in different regions. In the severely desertified farming regions, the main measure is to convert desertified cropland into woodland or grassland. However, because part of the land is used for the planting of trees and grasses, the carrying capacity of the remaining land in the same region will have to be greatly increased (Cao, 2008).

Examples in WOCAT Database:
T_KAZ003en; T_KAZ030en; T_NIG015en; T_PHI013en; T_TAJ114en; T_TUM002en; T_UGA007en; T_UZB001en

Planting economic trees, forage grass with livestock cultivation
Combining vegetative recovery and improving farmers' or local stakeholders income has been proved to be a sustainable way to combat desertification. Planting economic trees, or fruit trees which are suitable to grow in the local

conditions while grow forage grass in the same area for feeding livestock *e.g.* chicken, sheep/goat etc., both can increase farmers' income.

Planting medical herbs

Planting medical herbs *e.g.,* honeysuckle, bellflower, heterophylla has been proven feasible and efficient for halting soil desertification, also, increasing farmers' income – a win-win approach (Bai X.Y. *et al.*, 2014, personal communication).

9.2 Leaving crop residuals and mulching

Leaving crop residuals can reserve soil moisture and reduce wind or water erosion and also increase soil organic matter. This could be combined with no-till seeding or sub-soiling. In Niger, application of 2 Mg/ha of crop residue mulch decreased erosion by about 50% (Eltrop *et al.*, 1996a,b), also, application of millet residue mulch at 2 Mg/ ha significantly reduced wind erosion and increased SOC content and CEC of the surface layer (Michels *et al.,* 1995). An additional benefit of erosion control by mulching is decreased loss of water by runoff and evaporation. Residue mulching decreases soil temperature which contributes to a reduction in evaporation. In Niger, crop residue mulching decreased maximum daily temperature at the 0.1 m depth by 8 °C. The temperature at this depth in unmulched bare soil was 50 °C (Buerkert *et al.*, 1996a,b). Spreading crop residue and deadwood etc. also stimulates termite activity which improves soil structure, and increases SOC and SIC contents (Lal, 1987).

Leaving crop residues in the field (Source: Bai, 2014)

Examples in WOCAT Database:
T_KAZ031en; T_SPA001en; T_TOG008en; T_TUR002en

9.3 Improving farming systems

Unproductive and inefficient farming systems should be replaced by efficient and productive systems if soils are to be protected against deforestation. Important components of farming systems are agroforestry, crop rotations, fallowing and grazing management.

9.3.1 Agroforestry

Afforestation is an important strategy to restore vegetal cover and arrest desertification. There are several multi-purpose trees which can grow under the harsh environments of drylands, improve soil quality. Kair (*Capparis decidua*) is one such tree adaptable to the drylands (Gupta *et al*., 1989). Some promising species for soil quality improvement and desertification control include *Tamarix, Eucalyptus, Leucaena, Cupressus, Casuarina, Capparis, Prosopis, Azadirachta, Acacia, Tectona, Cassia, Dalbergia, Khaya, Albizia, Parkia, Terminalia, Pongamia, Sesbania, Morus* and *Populus* (Le Houerou, 1975; Gupta *et al*., 1989; Lattore, 1990; Mainguet, 1991; Singh *et al*., 1994; Alstad & Vetaas, 1994; Singh & Singh, 1995; Patil *et al*., 1996).

9.3.2 Planted fallows

Taking land out of agricultural production and permitting natural vegetation to grow leads to restoration of deserted land. Although natural regeneration can enhance soil quality (Ruecker *et al.,* 1998), fallowing efficiency can be greatly improved by the use of appropriate cover crops (Barber & Navarro, 1994). Planted tree or shrub fallows can help increase the fertility of degraded soils (Phiri *et al*., 2001). However, herbaceous fallows are more efficient and promising than tree-based fallows (Hauser *et al*., 2006).

Examples in WOCAT Database:
T_IND005en; T_IND006en; T_KYR002en; T_TAJ113en; T_TOG008en

9.3.3 Supplemental irrigation

Development of small-scale irrigation using ground water, runoff storage through water harvesting, micro-catchment farming, and other cost-effective and simple watershed management techniques could reduce soil desertification. There is great potential to improve irrigation efficiency in drylands.

Examples in WOCAT Database:
T_IND008en; T_NEP005en; T_UZB003en

9.4 Grazing management

Excessive and uncontrolled grazing accelerates desertification. Increase in vegetation cover can increase water infiltration capacity, decrease soil bulk density and increase soil organic matter content but grazing could cause a significant decline in infiltration capacity by reducing the protective vegetal cover and increasing the surface area of the bare ground and erosion (Pluhar *et al*., 1987; Thurow *et al*., 1988). Therefore, controlled grazing and planting improved species are important considerations of enhancing biomass production therefore preventing or reducing soil desertification.

9.4.1 Controlled grazing at an optimal stocking rate

Controlled grazing is to regulate the amount of time and the amount of grazing that should take place within a particular paddock or pasture in order to either increase/optimize animal performance or forage quality or both. Controlled grazing is mainly used to control the quality, yield, consumption and persistence of forage from pasture and it has a great influence on soil characteristics with major effects on soil carbon and nitrogen cycling in grazing lands. A time-controlled grazing system, *i.e.,* short, intensive grazing followed by a long period of rest has become popular among many graziers in Australia and elsewhere (Sanjari *et al*., 2008). The grazing system can increase soil organic carbon and nitrogen compared with continuous grazing; also increase ground-litter accumulation; reduce nitrate and extractable P concentrations and decrease the contamination potential for downstream water bodies (Sanjari *et al*., 2008). In the Mediterranean region controlled grazing can increase both biomass and species diversity (Margaris *et al*., 1996).

Examples in WOCAT Database:
T_AUS001en; T_ITA001en; T_RSA007en; T_RSA100en; T_TAJ004en; T_TAJ012en; T_TAJ048en; T_TAJ051en; T_TAJ368en; T_TAJ400en; T_UM003en; T_TUR001en; T_UZB002en

9.4.2 Enclosing pasture

Enclosing pasture is dividing grazing land into several plots and forbid livestock grazing in order to recover pasture naturally through self-recovery. It is generally used as a measure to combat soil desertification (Li, 1995; Li, 1996). The self-recovery capacity of desertification depends on the degree of desertification and biophysical conditions (Fan & Zhou, 2001).

Examples in WOCAT Database:
T_ETH013en; T_ETH042en; T_RSA037en; T_TAN002en; T_TUN011en

Other measures for prevention and restoration of soil desertification include fire management like prescribed burning (Schuman *et al*., 2002; Rice & Owensby, 2001), growing improved species like Sowing legumes (Chan *et al*., 1997) and integrated management (Lal, 2001; Conant *et al*., 2001).

9.5 Combining global best practises with local stakeholder's skills and experiences

Recent desertification control practices indicate an integrated approach is needed to combine global best practices with skills and experiences of local key stakeholders affected by and acting on the desertification issue, including land users, policy makers, managers, researchers and rural development technicians (Schwilch *et al*., 2009; de Pina Tavres *et al*., 2014; Hessel *et al*., 2014). To do so it is necessary to bring all key local stakeholders (farmers, local association of land users and local nongovernmental organizations) with scientific knowledge of external stakeholders such as technicians, environmental advisors and researchers in a participatory way to appraise and select desertification control strategies and implement jointly selected promising desertification mitigation options (de Pina Tavres, *et al*., 2014).

9.6 Commercialisation of desertification control

Commercial soil desertification control has been proven and promising: A Chinese dairy giant Elion Group has created a green development path with balanced driving among "desertification control, ecology, society and economy", established a model for the desertification control in other countries, and brought more confidence and inspiration for global desertification control works (http://www.unep.org/resourceefficiency/Portals/24147/scp/business/dialogue/2012/pdf/Case_Studies/Elion.pdf; http://www.uncsd2012.org/content/documents/380Elion.pdf).

The overall objective of the model is to reduce population pressure on land and to form a stable ecosystem. Three stages of change are suggested: ***First,*** new techniques should be adopted to transform current production methods, to lead to increased yields on desertified land. Efforts are also needed to revert from croplands to woodlands and grass-lands, to popularize sandy-land afforestation techniques, and to establish protective forests to form a preliminary sand-control system. Growing plants to improve the carrying capacity of desertified land should be combined with other activities for desertification control. *Second,* efforts should be made to change current farming structures, to popularize grain-grass intercropping, to introduce fodder grasses into the cropland farming system, to develop a three-crop planting rotation for grain, forage, and other cash crops to enhance soil fertility, to develop animal husbandry, and to form a stable eco-agricultural system. *Third*, efforts should be made to promote industrialization in desertified regions. Not all desertified regions face the problem of food shortage, some grain-producing regions have surplus grain, and local farmers are reluctant to revert from croplands to woodlands and grassland, thus, readjustment of the current agricultural structure is difficult to introduce. Promoting the development of regional economies and improving farm incomes could help to solve some desertification problems.

The economy of most desertified regions is poor and is mainly dominated by agricultural production. The development of light processing industries which use agricultural products as raw materials is one means of forwarding readjustment of the farming structure, which could enable desertified regions to move from agriculture to industry. Only when desertification control reaches the third stage that can desertification control be said to have succeeded (Fan & Zhou 2001).

9.7 Applicability of the measures to control of soil desertification

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 9.1). *How*: applicability in terms of the main action that needs to be taken towards soil improvement. *When*: applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. *Where*: applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions e.g. cost-benefits, or adaptability.

Table. 9.1. Applicability of the measures for combating desertification.

How ?		When ?			Where ?						
		Stage			Land-use type				Location		
Measure category	Measures	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1)]	Landform[2)]	Altitude[3)]
Growing vegetation		+	+	+	+	+	+	+	SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI
Leaving crop residuals and mulching		+	+	+	+	+	+	+	SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Improving farming systems	Agroforestry	+	+	+	+	+	+	+	SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
	Planted fallow	+	+	+	+	+	+	+	SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
	Supplemental irrigation	+	+	+	+	+	+	+	SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Grazing management	Controlling grazing at an optimal stocking rate	+	+	+	+	+	-	+	SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
	Enclosing pasture	+	+	+	-	+	-	+	SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Commercialisation of desertification control		+	+	+	+	+	+	+	SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX
Policy & regulation		+	+	+	+	+	+	+	SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII, VIII, IX

[1)] HU: Humid (length of growing period (LGP) > 270 days); SH: Sub-humid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days); AR: Arid (LGP 0–74 days).

[2)] PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow); CV (Concave: depression (conversion of water flow)).

[3)] I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI: 2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.

[4)] ++: Application occurs only in this stage; +: Application occurs in this stage; -: Application is not recommended in this stage.

10 Flooding

Flooding refers to the overflowing by water of the normal confines of a watercourse or water body and/or the accumulation of drainage water over areas which are not normally submerged (WMO, 2012). Flooding results from a complex interaction between natural and socio-economic forces *e.g.*, intensity of precipitation, snowmelt, and changes in land use. The topic has been subject to collaborative research in Europe, e.g. through the CRUE program (see http://www.crue-eranet.net/ for an overview and the database).

Policy plays a key role in preventing and remediating flooding. In this regard, European and national policies on flooding provide a broad interlinked framework for mainstreaming flooding risk management mainly through agriculture, water and climate change mitigation policies. At EU level a comprehensive set of policies addressing such risks exists, which is implemented into national policies/legal frameworks. The most relevant in the EU are the EU Water Framework Directive (WFD), the EU Floods Directive (FD), the EU Common Agricultural Policy (CAP) and Structural and Cohesion Funds. The WFD recommends to take climate change into account in River Basin Management Plans and FD requires flood risk management plans and flood risk assessments.

While the CAP does not directly address flood and landslide risks, its recent reforms present mainstreaming opportunities through cross-compliance regulations that require on-farm measures (e.g. small retention ponds, shelter belts which can reduce runoff and changes in tillage practices to maintain soil moisture). The Agro-Environment Program plans to compensate farmers for implementing on-farm water-retention and other ecological investments with indirect impacts on flooding and landslides. The European Commission also stresses the need of mainstreaming climate change mitigation into flood/landslide risk policy.

A Blueprint to Safeguard Europe's Water Resources stressed the importance of natural water retention measures and planned policy integration tools for the 2014–2020 period.

10.1 Communication on flood risk management: flood prevention, protection and mitigation in Europe

Flooding has the potential to undermine the EU's drive towards sustainable development and the flood risks are increasing. Severe flood events in 2002 triggered the European Commission (EC) to launch concerted action at community level to help reduce the severity of flood events and the damage caused by the floods. In the Communication on Flood risk management; Flood prevention, protection and mitigation (COM(2004) 472 final of 12.7.2004) the EC proposed to develop and implement a concerted EU Action Programme on flood risk management. It proposed that the Member States and the Commission work together to develop and implement a coordinated flood prevention, protection and mitigation action programme. The issue of flood protection including the Communication were discussed at both the Informal Environment Council on 18 July 2004 and at the Environment Council on 14 October 2004. In October the Council has adopted Conclusions on flood risk management and agreed that based on the Communication, the Member States and the European Commission, in the context of the regular meetings of the EU Water Directors in co-operation with other stakeholders and relevant parties, should prepare the contents of such concerted European action. The Council invited the Commission to submit an appropriate proposal taking into account the Council conclusions and the work of the Informal meeting of the Water Directors. The Commission also invites the Member States to:

- support the assessment made by the Commission concerning the importance of flood protection;
- take note of the actions ongoing, or planned, at EU, national, regional and international level;
- support the need for a concerted EU action on flood prevention, protection and mitigation;
- endorse the essential features of the concerted EU action as presented by the Commission and to agree on the steps which should be taken to develop and implement such a concerted action (COM, 2004).

More European flood action programme are available via:
http://ec.europa.eu/environment/water/flood_risk/key_docs.htm

10.2 Best practices on flood prevention, protection and mitigation in Europe

Due to severe floods between 1998 and 2002 in Europe, an informal meeting of EU Water Directors, Norway, Switzerland and Candidate Countries was held in Copenhagen in November 2002, and agreed to take an initiative on flood prediction, prevention and mitigation. A core group led by the Netherlands and France had prepared a report on flood prevention, protection and mitigation, and presented to the Water Directors meeting in Athens in June 2003. The report is an update of the United Nations and Economic Commission for Europe (UN/ECE) Guidelines on sustainable flood prevention (2000). The guidelines aim to recommend measures and best practices to prevent, control and reduce the adverse impact of flood events on human health and safety, on valuable goods and property, and on the aquatic and terrestrial environment. They are intended to assist the Parties to the Convention, other UN/ECE countries and joint bodies in developing and implementing sustainable measures and good management practices for flood prevention and protection that take account of economic, environmental and social considerations. As this depends on the specific conditions and circumstances in the respective catchment areas, the proposed guidelines are non-binding, and the character of the guidelines is strategic rather than technical. They attempt to provide the essential elements to be considered when drawing up concerted action plans. The guidelines is a living document that needs continuous input and improvements as application and experience build up in all countries of the European Union and beyond (EU report on best practices on flood prevention, protection and mitigation in Europe, 2002).

The report consists of three parts: the more basic principles and approaches; how to translate and implement the principles and approaches; and conclusions. Several important points for controlling flooding have been illustrated:

- Integrated river basin approach
- Public awareness, public participation and insurance
- Research, education and exchange of knowledge
- Retention of water and non-structural measures
- Land use, zoning and risk assessment
- Structural measures and their impact
- Flood emergency, and
- Prevention of pollution.

The report recommends that :

1) Effective measures for flood prevention and protection have to be taken at the level of river basins and that it is necessary to take into account interdependence and interaction of effects of individual measures implemented along water courses.
2) It is absolutely necessary to organise the water management systems and improve forecasting, flood defence measures and crisis management on a river basin basis, cutting across regional boundaries and country borders.

This will be done in co-operation with the relevant organisations in the fields of hydrology and mete-orology, mitigation planning, river control, civil protection and crisis management units.

Need of an integrated approach

3) For flood prevention, protection and mitigation, a good combination of structural measures, preventive measures and operative measures during flood events are necessary: building codes and legislation to keep structures away from flood-prone areas, appropriate land use, adequately designed floodplains and flood-control structures planning, mitigation, early-warning systems, correct risk communication and preparedness of the populations how to act during floods. In some cases even relocation of extremely endangered activities and buildings may be advisable. Development of preliminary flood protection strategy should include respectively evaluation of associated costs, technical feasibility assessment, environmental impact assessment, social acceptability and thus in a sustainable way by taking a river basin integrated and long term view, probably of the order of 50 or 100 years.
4) The Water Framework Directive, and the 11 water-related Directives associated to it, could be considered as a support to implement a floodplain regulation in the development of River Basin Management Plans, based on an as good as possible ecological and chemical status of wetlands and floodplains.
5) The reduction of flood risks has to be based on the principles of solidarity and precaution by not passing on water management problems, and not passing on administrative responsibilities.
6) There is a need for interdisciplinary co-operation at all government and local levels for a coordination of sectoral policies regarding environmental protection, physical planning, land use planning, agriculture, transport and urban development, and a co-ordination regarding all phases of risk management: risk assessment, mitigation planning and implementation of measures. Therefore, a holistic approach is necessary throughout the river basin.
7) This would contribute to the implementation of a holistic approach with in-creased knowledge about responsibility, function and capacity of the concerned parties, better understanding, and a better support for decision making.
8) Societal developments and expansion of water management policy demand new knowledge including new insights into social studies, spatial planning and public administration. In this way, societal and administrative aspects, in addition to technological solutions, can be

investigated and the social support for the solutions can be assessed in advance.

Need of an integrated and comprehensive action plan

9) All envisaged measures concerning flood prevention and protection should be compiled in a comprehensive action plan covering up to several decades. An integrated action plan for reducing flood damage must: (a) draw long-term conclusions for preventive action in water management, land use, settlement policy and finance, (b) define the scope of responsibilities in the flood protection system at levels of the government and local administration, responsibilities of public (individuals) and business companies. Such a plan is a tool which: (c) ensures permanent and integrated planning of functions and use of the river basin, (d) specifies principles for its organisation and co-ordinates investment activities and other activities affecting the river basin. It should also form conditions for ensuring permanent harmony of all natural, civilisation and cultural functions in the basin.

10) An effective co-operation between state authorities, the communities, water regulation enterprises and other interested parties, for example by creating a local water commission, is more than needed for a regional co-ordination and the implementation of a holistic approach.

Need of international and trans-boundary cooperation

11) Strengthening international co-operation aiming at securing a sustainable future for the river basin, especially in terms of shared approaches to river basin management, preparation of risk analyses and flood forecasts at transnational level, improving the co-ordination of the existing forms of assistance, sustainable use of biodiversity, are one of the components of an anticipatory approach.

12) Progress has been achieved by existing river commissions in developing joint strategies involving aspects of regional planning and land use regulation. The objective of an international co-operation is to develop joint documents specifying strategies and action programmes aimed at improving protection against floods.

Need of financial instruments

13) Relevant projects could financially be supported from programmes and funds of European Union, such as Common Agriculture Policy, PHARE Cross Border Co-operation (CBC), INTERREG, European Regional Development Fund, Special Action Programme for Agriculture and Rural Development (SAPARD), EU solidarity fund or LIFE, however, actions of individual co-operating countries and sectors have to be co-ordinated.

14) A financial instrument that can both reduce the financial risk for individuals, enterprises and even whole societies and increase the awareness of being at risk, is flood insurance.

15) The establishment of national funds could be considered to partially cover damage of floods.

The comprehensive report on "Best practices on flood prevention, protection and mitigation" is available at http://ec.europa.eu/environment/water/flood_risk/pdf/flooding_bestpractice.pdf.

10.3 Local experiences in preventing and mitigating floods

Measures for preventing and mitigating floods can be classified in various ways. The following is a division with explanations by Eva Skarbovik (personal communication):

- Flood mitigation by land use changes.
- Structural mitigation measures, which again can be divided into
  - measures that retain the water (reservoirs/dams, expanded floodplains (increasing the room for the rivers), emergency flood reservoirs, preserved areas for flood water); and
  - measures that divert water or keep the water within channels (dikes, artificial or enlarged levees, gabions).
  - Adaptation and mitigation measures to reduce damage (economic, loss of lives), which again can be divided into
  - flood forecasting and warning systems (awareness raising, risk reduction);
  - area planning (avoid building houses in flood-prone areas);
  - private (household) measures (e.g., improve building stability, avoid expensive items in flood-prone stores).

Large-scale land use changes to reduce flooding can involve afforestation or reforestation, or exchanging pastures with less disturbed grassland or natural vegetation (Wheather & Evans, 2009; Marshall *et al.*, 2014; Schilling *et al.*, 2014). Such large-scale changes in vegetation cover can reduce flood peaks due to increased evaporation, improved infiltration and groundwater storage capacity. land use changes have to affect the dominant runoff pattern if they are to result in significant reductions in storm runoff and thereby reduce flooding problems (Naef *et al*, 2002). The potential effect of land use changes on flood reductions for entire catchments usually needs to be modelled (Brath *et al.*, 2006; Schilling *et al.*, 2014), as few catchments have experienced large-scale land use changes in recent years. However, on the plot scale, increased infiltration rates were observed when heavily grazed pastures were exchanged with ungrazed grassland or forest (Marshall *et al.*, 2014). More small-scale land use changes occur both in urban and rural areas: in urban areas green roofs, park areas and rain beds (the latter can also be classified as a structural measure) can be found. In rural agricultural areas, such land use changes can involve reduced tilling or no-till, or establishment of grass-covered buffer zones and waterways. These measures are to increase the infiltration of water, reduce overland flow, increase roughness, and thereby delay the water flow. There is less evidence that they work on a catchment scale but this does not imply that impacts on catchment scale do not exist, only that there are not enough studies to confirm this (O'Connel *et al*., 2007).

Structural measures are built aiming to either retain or (re)direct the water. The devices to retain the water can be anything from large dams and expanded floodplains, to smaller impoundments or areas designated for receiving flood water during events. Barriers such as dams constructed of wood in steep slopes, intended to slow down water flow and therefore also debris flow, are also included in this group, as are any constructed devices to reduce water flow in agricultural fields (*e.g*., hay barriers). The other main purpose of structural measures is to keep running flood water "within walls", such as dikes, artificial levees or gabions. Often, these measures are recommended to be employed in lowlands, whereas the retaining measures more often are used in upstream locations (Falloon & Betts, 2010). Dikes and gabions can result in an increase in water velocity, which again can have negative impacts downstream (De Kok & Grossman, 2010). Many types of structural measures are less suited in a perspective of sustainable development, and non-structural measures would be more environmental friendly in the long run (Kundezewicz, 2002). However, non-structural measures may not be enough to reduce the impacts of floods on soil and property.

The adaptation measures *e.g.,* warning systems, area planning and measures to secure private property are mainly intended to protect buildings, property and lives, and are seldom designed to ensure soil protection (Bubeck *et al*., 2012; Poussin *et al*., 2012). Soil Conservation Service Curve Number (SCS-CN) method could be employed to predict direct runoff volume for a given rainfall event (Soulis *et al*., 2009; Tedela *et al*., 2012).

An adaptation measure is possible in agriculture if farmers choose to grow grass instead of cash crops in flood prone areas in order to minimize risks of crop losses due to erosion, sedimentation or anaerobic conditions.

In general, mitigation approaches that take the entire catchment into consideration are recommended (Falloon & Betts, 2010). This is also true in terms of flood measures to protect soils. Farm scale measures to reduce floods will be considerably more effective if flood measures are implemented in the entire catchment. In such a perspective, measures to reduce urban runoff can be important for agricultural soil protection, if the urban measures can retain flood water and thereby reduce the downstream flood peaks in rivers draining agricultural land.

Example in WOCAT Database:
T_TAJ607en

10.4 Applicability of the measures for flood control

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 10.1). *How*: applicability in terms of the main action that needs to be taken towards soil improvement. *When*: applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. *Where*: applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions e.g. cost-benefits, or adaptability.

Table. 10.1. Applicability of the measures for flood control.

How ?	When ?			Where ?						
	Stage			Land-use type				Location		
Measures	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1)]	Landform[2)]	Altitude[3)]
Communication on flood risk management: flood prevention, protection and mitigation in Europe*	+	++	+	+	+	+	+	Hu, SH	PL, HS, FS, VF, CX, CV	I, II
Best practices on flood prevention, protection and mitigation in Europe**	+	+	++	+	+	+	+	Hu, SH	PL, HS, FS, VF, CX, CV	I, II
Local experiences in preventing and mitigating floods	+	+	+	+	+	+	+	Hu, SH	PL, HS, FS, VF, CX, CV	I, II
EU Floods Directive (WD) ***	+	+	+	+	+	+	+	Hu, SH	PL, HS, FS, VF, CX, CV	I, II

1) HU: Humid (length of growing period (LGP) > 270 days); SH: Subhumid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days); AR: Arid (LGP 0–74 days).

2) PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow);CV (Concave: depression (conversion of water flow)).

3) I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI: 2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.

4) ++: Application occurs only in this stage; +: Application occurs in this stage; -: Application is not recommended in this stage.

* EU report on Communication on flood risk management: flood prevention, protection and mitigation in Europe.

** EU report on best practices on flood prevention, protection and mitigation in Europe, 2002.

*** also EU Water Framework Directive (WFD), EU Common Agricultural Policy (CAP) and Structural and Cohesion Funds.

11 Landslides

A landslide is defined as the movement of a mass of earth, rock, debris or artificial fill down a slope, under the force of gravity, causing a deterioration or loss of one or more soil functions (Huber *et al*., 2008). Landslides are usually classified on the basis of their type of material involved like earth (fine/coarse soil) or rock and type of movement (fall, topple, slide, lateral spread, and flow) (Varnes, 1978; Cruden & Varnes, 1996; Hungr *et al*., 2001). Landslide occurrence can be triggered by forces similar to that of flooding (see chapter 10). There are three major ways to prevent new landslides or re-activation of pre-existing landslides:

- Removal of material from the upslope portions of unstable areas (to reduce the mass that would provide a driving force);
- Placement of soil/dirt at the base of unstable slope to act as a buttress (adding mass to create a resisting force);
- Reduce the amount of surface water that can percolate through the rock and add weight to the unstable bedrock. This can be done by constructing concrete drainage ditches to collect and divert the water or by covering the slope with an impermeable barrier (*i.e.* plastic). If this is the main condition that is driving landsliding, a system of wells drilled into the unstable material can be set-up to pump water out.

In some cases, the unstable bedrock material can be removed with heavy equipment and the slope can be rebuilt with the excavated dirt being replaced as compacted fill.

11.1 Preserving vegetation

Trees, grasses, and vegetation can minimize the amount of water infiltrating into the soil, slow the erosion caused by surface-water flow, and remove water from the soil. Although vegetation alone cannot prevent or stop a landslide, removal of vegetation from a landslide-prone slope may initiate a landslide.

11.2 Improving surface and subsurface drainage

Because water is a main factor in landslides, improving surface and subsurface drainage at the site can increase the stability of a landslide-prone slope. Surface water should be diverted away from the landslide-prone region by channelling water in a lined drainage ditch or sewer pipe to the base of the slope. The water should be diverted in such a way as to avoid triggering a landslide

adjacent to the site. Surface water should not be allowed to pond on the landslide-prone slope.
Ground water can be drained from the soil using trenches filled with gravel and perforated pipes or pumped water wells. Swimming pools, water lines, and sewers should be maintained to prevent leakage, and the watering of lawns and vegetation should be kept to a minimum. Clayey soils and shales have low hydraulic conductivity and can be difficult to drain.

Example in WOCAT Database:
T_TAJ353en

11.3 Excavating head

Removing the soil and rock at the head of the landslide decreases the driving pressure and can slow or stop a landslide. Additional soil and rock above the landslide will need to be removed to prevent a new landslide from forming upslope. Flattening the slope angle at the top of the hill can help stabilize landslide-prone slopes.

11.4 Buttressing toes

If the toe of the landslide is at the base of the slope, fill can be placed over the toe and along the base of the slope. The fill increases the resisting forces along the failure surface in the toe area. This, in turn, blocks the material in the head from moving toward the toe. However, if the toe is higher on the slope, adding fill would overload the soil and rock below the toe, thus causing a landslide to form downslope of the fill.

11.5 Constructing piles and retaining walls

Piles are metal beams that are either driven into the soil or placed in drill holes. Properly placed piles should extend into a competent rock layer below the landslide. Wooden beams and telephone poles are not recommended for use as piles because they lack strength and can rot. Because landslides can ooze through the gaps between the piles, retaining walls are often constructed. Retaining walls can be constructed by adding lagging (metal, concrete, or wooden beams) horizontally between the piles. Such walls can be further strengthened by adding tiebacks and buttressing beams. Tiebacks are long rods that attach to the piles and to a competent rock layer below the ground surface. Buttressing beams are placed at an angle downslope of the piles to prevent the piles from toppling or tilting. Retaining walls also are constructed of concrete, cinder blocks, rock, railroad ties, or logs, but these may not be strong enough to resist landslide movement and could topple.

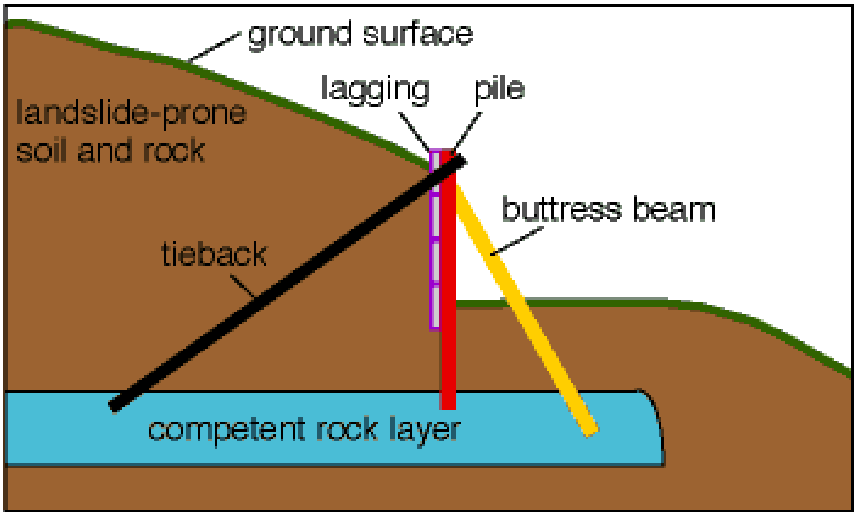


Diagram of a retaining wall with tiebacks and buttress beams. Tiebacks are metal rods that extend from the piles to a competent rock layer below the ground surface. Buttress beams are metal beams that are inclined downslope from the piles that prevent the piles from toppling. Lagging consists of wooden, metal, or concrete beams placed upslope and between the piles to fill in the gaps.
(Source: http://www.kgs.ku.edu/Publications/pic13/pic13_5.html)

11.6 Removal and replacement

Landslide-prone soil and rock can be removed and replaced with stronger materials, such as silty or sandy soils. Because weathering of shales can form landslide-prone soils, the removal and replacement procedure must include measures to prevent continued weathering of the remaining rock. Landslide material should never be pushed back up the slope. This will simply lead to continued motion of the landslide.

11.7 Rock fall protection

Rock falls are contained by (1) ditches at the base of the rock exposure, (2) heavy-duty fences, and (3) concrete catch walls that slow errant boulders that have broken free from the rock outcrop. In some cases, loose blocks of rock are attached to bedrock with rock bolts, long metal rods that are anchored in competent bedrock and are threaded on the outside for large nuts. A metal plate with a centre hole, like a very large washer, is placed over the end of the

rod where it extends from the loose block, and the nut is then added and tightened. Once constructed, remedial measures must be inspected and maintained. Lack of maintenance can cause renewed landslide movement.
"Restraint works" controls the movement of landslide using the power. "Control works" controls the movement of landslide through the control of natural condition, such as groundwater level.
A homeowner's guide to landslide recognition, prevention, control and mitigation compiled by Burns *et al.*, (2008) illustrates methods to remedy landslide problems. The best solution is to avoid landslide-prone areas altogether. Before purchasing land or an existing structure or building a new structure, the buyer should consult an engineering geologist or a geotechnical engineer to evaluate the potential for landslides and other geology-related problems. Below are some common remedial methods used when landslide-prone slopes cannot be avoided. There is no guarantee that any one method or combination thereof will completely stabilize a moving hillside. The following sections are mainly derived from Kansas Geological Survey, Public Information Circular (PIC) 13 (http://www.kgs.ku.edu/Publications/pic13/pic13_5.html).

11.8 Applicability of the measures for preventing landslides

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 11.1). ***How***: applicability in terms of the main action that needs to be taken towards soil improvement. ***When***: applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. ***Where***: applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions e.g. cost-benefits, or adaptability.

Table. 11.1. Applicability of the measures for flood control.

How ?	When ?			Where ?						
Measures	Stage			Land-use type				Location		
	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1)]	Landform[2)]	Altitude[3)]
Preserving vegetation	+	-	-	+	+	+	+	Hu, SH, SA, A	RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Improving surface and subsurface drainage	+	+	+	+	+	+	+	Hu, SH, SA, A	RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Excavating head	+	+	+	+	+	+	+	Hu, SH, SA, A	RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Buttressing toes	+	+	+	+	+	+	+	Hu, SH, SA, A	RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Constructing piles and retention walls	+	+	+	+	+	+	+	Hu, SH, SA, A	RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Removal and replacement	+	+	+	+	+	+	+	Hu, SH, SA, A	RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Rock-fall protection	-	+	+	+	+	+	+	Hu, SH, SA, A	RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
EU Water Framework Directive (WFD *	+	+	+	+	+	+	+	Hu, SH, SA, A	RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII

[1)] HU: Humid (length of growing period (LGP) > 270 days); SH: Subhumid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days);AR: Arid (LGP 0–74 days).

[2)] PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow);CV (Concave: depression (conversion of water flow)).

[3)] I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI: 2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.

[4)] ++: Application occurs only in this stage; +: Application occurs in this stage; -: Application is not recommended in this stage.

[*] EU Water Framework Directive (WFD), EU Common Agricultural Policy (CAP) and Structural and Cohesion Funds.

12 Decline in Soil Biodiversity

The Convention on Biological Diversity (CBD) defined soil biodiversity as "the variation in soil life, from genes to communities, and the ecological complexes of which they are part, that is from soil micro-habitats to landscapes" (http://eusoils.jrc.ec.europa.eu/library/themes/biodiversity). Decline in soil biodiversity is a reduction of forms of life living in soils, both in terms of quantity and variety (Jones *et al*., 2005).
It does not decline independent of other factors and is usually related to some other deterioration in soil quality, due mainly to land use change, loss of organic matter, removal of crop residues, tillage, application of pesticides and chemical fertilizers, salinization, contamination, or compaction. Climate change is considered a potential important factor in driving future soil biodiversity decline (Suarez *et al*., 2002). Decline in soil biodiversity is often 'hidden' and invisible and it is easily being 'ignored'; but it significantly affects soil function and ecosystem services. Soil biodiversity can be improved by soil management strategies supplemented with more concrete measures. Proper agricultural activities *e.g.* conservation tillage, crop rotation and organic matter application, limited use of chemicals and appropriate policies are crucial for the protection and rehabilitation of soil biodiversity.

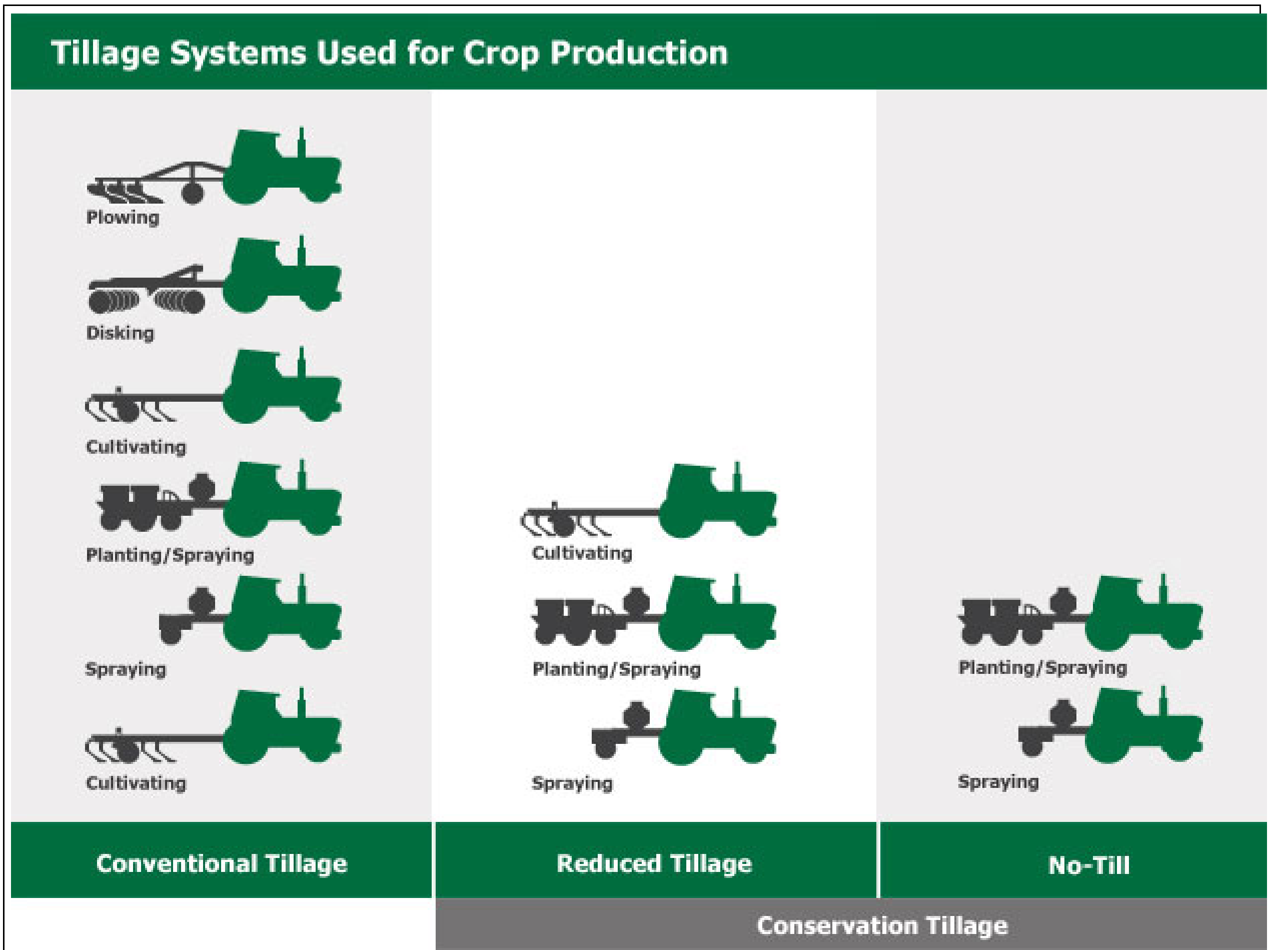
12.1 Establishing regional/national strategies

Soil biodiversity must be included in national strategies for long-term preservation of biodiversity to be developed following the Rio-Convention on Biodiversity (Hågvar, 1998) and the UN Sustainable Development Goals (SDGs). Development of national or regional guidance for protection of soil biodiversity are strongly encouraged. A good example is the UK Government Guidance on Soil management standards for farmers (https://www.gov.uk/soil-management-standards-for-farmers).

Moonen & Barberi (2008) developed a methodological framework to assess functional biodiversity for action taking. The frame work focuses on diversity or richness, ecosystem functions provided by the biological community; three steps are recommended: 1) define objectives of biodiversity research and policies including species, community, habitat or overall biodiversity conservation regardless of its functions ; biodiversity conservation to attain production and environmental protection services and use of bio-indicators for agro-ecosystem monitoring; 2) choose appropriate target elements for conservation based on an agro-ecosystem approach; 3) select adequate biodiversity measures of composition, structure and function for each target element.

12.2 Applying conservation tillage

Tillage is often mentioned in soil conservation strategies as major cause of human induced disturbance in soils. Conventional tillage has a significantly negative impact on earthworm populations (Chan, 2001); use of a chisel instead of a conventional plough could reduce this impact (Kuntz *et al*., 2013). Conservation tillage is an agricultural practice that leaves previous year's crop residue (such as e.g. wheat stubble) on fields before and after planting the next crop using reduced tillage, sub-soiling or no-till seeding; it also can reduce soil erosion and increase soil organic matter (see section 12.3), thereafter increase soil biodiversity.



Different tillage methods (source: http://www.advancefarming.com)

Reduced tillage management effects on soil biodiversity depending on season, soil type and the type of crop that is grown (Adl *et al*, 2006; Lupwayi *et al*., 1998). Natural and planted fallows can regenerate earthworm populations in a degraded soil (Tian *et al.*, 2000).

No-till farming strategies generally exhibit increased aggregation of soil organic matter (Six *et al.*, 2000) and often led to improved soil biodiversity in soil organisms in comparison with conventional tillage and effects of reduced tillage on soil biodiversity depend on season, soil type and the type of crop that is grown (Adl *et al*, 2006; Chan, 2001; Lupwayi *et al.*, 1998). Occasionally no significant effects of tillage were found on soil bacteria in a dry land cropping system (Bissett *et al.*, 2013).

Examples in WOCAT Database:
T_PHI044en; T_UNK003en; T_ZAM002en; T_ZAM003en; T_ZAM004en

12.3 Increasing soil organic matter

All dead biologically derived matter in the soil is called soil organic matter (Brady & Weil, 2007). Soil organic matter can greatly improve physical, chemical and biological properties of soils (Pérez-Piqueres *et al.*, 2006). Application of compost is commonly used in agricultural practise to improve soil organic matter content as well as to manage organic waste. Soil organic matter is an important source organic carbon which is an energy source for soil microorganisms and carbon supply in combination with environmental conditions have a predominant effect on soil organisms (Kimble *et al.*, 2007). Mulch and compost can be applied on a larger scale by blower methods and tillage (Kimble *et al.*, 2007).

Examples in WOCAT Database:
T_TAJ402en; T_TAN009en

12.4 Intercropping

Intercropping can lead to benefits for soil micro-organisms by contributing to the nutrient balance in the soil (Machado, 2009; McDaniel *et al.*, 2013). Intercropping with trees can increase diversity and stability in soil microbial systems in a contained area (Lacombe *et al.*, 2009; Manna & Sing, 2001; Wang *et al.*, 2014).

Several intercropping design methods for intercropping have been developed and tested and for each design optima can be calculated for different crop combinations (Vandermeer, 1992). Intercropping has not been an effective measure under all conditions, great variations exist between ecosystems (Khan *et al.*, 1997). Legume-cereal interactions are particularly popular in intercropping (Hauggaard-Nielsen *et al.*, 2008).

12.5 Sequential cropping

In sequential cropping two or more crops are grown in sequence on the same field per year (Gliesmann, 1985). This leads to an increase in SOM and thus improves soil biodiversity. Double, triple and quadruple cropping systems represent the number of crops that are grown in sequence in one year. Furthermore, ratoon cropping is about cultivating crop regrowth after harvest. Logically, not all crops are suitable for ratoon cropping. Sequential cropping has advantages *e.g.*, saving fertilisers and reducing nutrient leaching; its disadvantages could be not always work with conventional machinery and acceptance by farmers.

12.6 Limiting application of inorganic fertilizers, pesticides and herbicides

There are a number of undesirable environmental impacts associated with fertilizer, pesticide and herbicide usage. Chemical fertilizer loadings must be better budgeted to not exceed local needs, and pesticide inputs should be reduced to a minimum, preferably be avoided (Hågvar, 1998).

Examples in WOCAT Database:
T_NEP004en; T_SWI546en; T_TAJ380en

12.7 Creating buffer zones: green and blue veining

Green and blue veining has the potential to create so called "buffer zones" for soil biodiversity. Green and blue veining is a network of semi-natural landscape elements that cross rural areas, green veining consist of dry elements such as hedgerows, dikes, tree rows and blue veining are water elements such as ditches (Geertsema, 2002). This idea of green and blue veining suggests that soil biota in healthy soils can recolonize in less favourable soils. A well-structured network can be beneficial for overall agro-biodiversity, including soil biodiversity (ECPA, 2010). Strategic planning of landscape elements can increase efficiency (Grashof-Bokdam *et al.*, 2009; Schippers *et al.*, 2009).

12.8 Applicability of measures for protection of soil biodiversity

The applicability of the above measures is mainly determined by three factors: how, when and where (Table 12.1). *How*: applicability in terms of the main action that needs to be taken towards soil improvement. *When*: applicability of measures in terms of the site soil status, or stage of implementation. Prevention is about maintaining natural resources and their productivity; mitigation is about interventions intended to reduce ongoing degradation, and rehabilitation is considered where soil has been degraded to such an extent that its original use is no longer possible and the soil is considered unproductive. *Where*: applicability of measures in terms of land use types, agro-climatic zones, landforms and altitudes. The applicability can be extended to other conditions e.g. cost-benefits, or adaptability.

Table. 12.1. Applicability of the measures for protection of soil biodiversity.

How ?	When ?			Where ?						
	Stage			Land-use type				Location		
Measures	Prevention	Mitigation	Rehabilitation	Cropland	Grazing land	Forest	Mixed	Agro-climate zone[1)]	Landform[2)]	Altitude[3)]
Establishing regional/national strategies	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Applying conservation tillage	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Increasing soil organic matters	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Intercropping	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Sequential cropping	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Limiting application of inorganic fertilisers, pesticides and herbicides	+	+	+	+	+	+	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII
Creating buffer zones: green and blue veining	+	+	+	+	+	-	+	Hu, SH, SA, A	PL, RI, MO, HS, FS, VF, CX, CV	I, II, III, IV, V, VI, VII

[1)] HU: Humid (length of growing period (LGP) > 270 days); SH: Subhumid (LGP 180–269 days); SA: Semi-arid(LGP 75–179 days); AR: Arid (LGP 0–74 days).

[2)] PL(Plateau /plains: extended level land (slopes less than 8%); RI (Ridges: narrow elongated area rising above the surrounding area, often hilltops or mountain-tops; MO (Mountain slopes (including major escarpments): extended area with altitude differences of more than 600m per 2km and slopes greater than 15%; HS (Hill slopes (including valley and minor escarpment slopes): altitude difference of less than 600 m per 2km and slopes greater than 8%; FS (Foot slopes: zone bordering steeper mountain / hill slopes on one side and valley floors / plains / plateaus on the other side; VF (Valley floors: elongated strips of level land (less than 8% slope), flanked by sloping or steep land on both sides; CX (Convex: swell (diversion of water flow);CV (Concave: depression (conversion of water flow)).

[3)] I: 0-100m; II: 100-500m; III: 500-1000m; IV: 1000-1500m; V: 1500-2000m; VI: 2000-2500m; VII: 2500-3000m; VIII: 3000-4000m; IX: >4000m a.s.l.

[4)] ++: Application occurs only in this stage; +: Application occurs in this stage; -: Application is not recommended in this stage.

[*] EU Water Framework Directive (WFD), EU Common Agricultural Policy (CAP) and Structural and Cohesion Funds.

Recommendations

There is a wide range of measures available for preventing, mitigating and remediating soil threats throughout the EU, and world-wide. However, each of the measures has its specific suitability in terms of biophysical conditions (such as climate, topography, soil land use), as well as economic and social-cultural factors. Therefore, when selecting a certain measure make sure that

- *firstly,* it fits your local environmental setting;
- *secondly*, it is appropriate to address the severity of your issue (take the various implementation stages into consideration, *i.e.*, is the measure for prevention, mitigation or rehabilitation of the soil threats);
- *thirdly,* you take all costs and benefits into consideration; this will be crucial to sustainably adopt the selected measures.

The measures themselves also have their advantages and disadvantages. To explore these, you can take the WOCAT database (https://www.wocat.net/en/methods.html) as a starting point. Each of these measures could either be applied alone, or they could – in most cases – be combined to combat one or more soil threats.

The selection of measures for combating threats to soils should respect relevant regional or national laws and regulations. In this regard, European and national policies on soil threats related regulations provide a broad interlinked framework for mainstreaming soil management mainly through agriculture, water and climate change mitigation policies. At EU level a comprehensive set of policies addressing soil threats exists, which are implemented into national policies/legal frameworks. The most relevant in the EU are the EU Water Framework Directive (WFD), the EU Floods Directive (FD), the EU Common Agricultural Policy (CAP) in its recent reforms present mainstreaming opportunities through cross-compliance regulations that require on-farm measures (e.g. small retention ponds, shelter belts which can reduce runoff and changes in tillage practices to maintain soil moisture). In the Netherlands, e.g., application of animal manure is constrained to a limited level for preventing nutrient leaching into the ground water and emitting in air.

An integrated approach to combatting one or several of the soil threats has been proven promising in EU-funded projects such as DESIRE (http://desire-project.eu; Hessel *et al.,* 2014) and is strongly recommended. To do so, an integrated and comprehensive plan is needed, preferably at (small) watershed level. Any actions should combine global best practices with the skills and experiences of stakeholders affected by and acting on soil threats, including land users, policy makers, managers, researchers and rural development workers. It is important to bring together all key stakeholders for problem appraisal and develop the design and implementation of promising soil threat control strategies in a participatory way. As part of the DESIRE and RECARE projects, guidelines and tools have been developed to assist case study site teams in organising stakeholder workshops, and test-implementing promising measures at their sites. To learn more on this aspect, visit the project websites, or get in touch with the authors of this report.

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References

Adl, S.M., Coleman, D.C. & Read, F., 2006. Slow recovery of soil biodiversity in sandy loam soils of Georgia after 25 years of no-tillage management. *Agriculture, Ecosystems & Environment* 114, 323–334. doi: http://dx.doi.org/10.1016/j.agee.2005.11.019.

Adriano, D.C., 1986. Trace elements in the terrestrial environment. – Springer-Verlag, New York. pp, 533.

Adriano, D.C., 2001.Trace elements in terrestrial environments. Biogeochemistry, Bioavailability, and Risk of Metals, 2nd edition. Springer-Verlag, NewYork.

Alakukku, L., 2000. Response of annual crops to subsoil compaction in a field experiment on clay soil lasting 17 years. In: Horn, R. *et al*. (Eds.) Subsoil compaction: Distribution, processes and consequences. Advances in GeoEcology 32, Catena Verlag, Reiskirchen, Germany, pp. 205–208.

Alakukku, L., Weisskopf, P., Chanmen, W.C.T., Tijink, F.G.J., van der Linden, J.P., Pires, S., Sommer, C. & Spoor, G., 2003. Prevention strategies for field traffic induced subsoil compaction: a review. *Soil Tillage Research* 73, 145–160.

Alloway, B.J., 1990. In Heavy metals in soils (ed. Alloway B.J.), Blackie, Glasgow.

Alloway, B.J., 2013. Sources of heavy metals and metalloids in soils. In: B.J. Alloway (Ed). Heavy metal in soils. Trace metals and metalloids in soil and their bioavailability. Third edition Springer, pp 11–50.

Alstad, G. & Vetaas, O.R., 1994. The influence of *Acacia tortilis* stands on soil properties in arid northeastern Sudan. *Acta-Oecologica,* 15, 449–460.

Antos, G., 2008. Tillage – energy requirement and soil damage; technical and operational factors. Ch.3.1 in Birkas M. Environmentally sound adaptable tillage. Akademia Kiado, Budapest, Hungary.

Arshad, M.A., Schnitzer, M., Angers, D.A., Ripmeester, J.A.., 1990. Effects of till vs no-till on the quality of soil organic matter. *Soil Biology and Biochemistry* 22, 595–599.

Atkinson, R., Aschmann, S.M., Hasegawa, D., Eagle-Thompson, E.T. & Frankenberger, J.R., 1990. Kinetics of the atmospherically important reactions of dimethylselenide. *Environmental Science and Technology* 24, 1326–1332.

Azaizeh, H.A., Gowthaman, S. & Terry, N., 1997. Microbial selenium volatilization in rhizosphere and bulk soils from a constructed wetland. *Journal of Environmental Quality* 26, 666–672.

Bagnold, R.A., 1941. The physics of wind-blown sand and desert dunes. Methuen, London, 265.

Baker, A.J.M. & Walker, P.L., 1990. Heavy metal tolerance in plants: evolutionary aspects. (ed. Shaw A.J.). Boca Raton: CRC Press, 155–177.

Baldock, J.A. & Nelson, P.N., 2000. Soil organic matter. In: Sumner, Malcolm E., (ed.) Handbook of Soil Science. CRC Press, Boca Raton, FL, USA, B25–B84.

Bañuelos, G.S., Ajwa, H.A., Mackey, L.L., Wu, C., Cook, S. & Akohoue, S., 1997. Evaluation of different plant species used for phytoremediation of high soil selenium. *J. Environ. Qual.* 26, 639–646.

Barber, R.G. & Navarro, F., 1994. The rehabilitation of degraded soils in eastern Bolivia by subsoiling and the incorporation of cover crops. *Land Degradation & Rehabilitation* 5, 247–260.

Barber, R.G., 1994. Soil degradation in the tropical lowlands of Santa Cruz, eastern Bolivia. *Land Degradation & Rehabilitation* 6, 95–108.

Batey, T., 2009. Soil compaction and soil management – a review. *Soil Use and Management*, 25, 335–345. doi: http://dx.doi.org/10.1111/j.1475-2743.2009.00236.x.

Bayer, C., Martin-Neto, L., Mielniczuk, J. Pavinato, A. & Dieckow, J., 2006. Carbon sequestration in two Brazilian Cerrado soils under no-till. *Soil and Tillage Research* 86, 237–245.

Beath, O.A., Eppsom, H.F. & Gilbert, G.S., 1937. Selenium distribution in and seasonal variation of vegetation type occurring on seleniferous soils. *Journal of the American Pharmaceutical Association* 26, 394–405.

Bergmann, E.P., 1979. Compaction. *Journal of Terramechanics* 16, 23–32. doi: http://dx.doi.org/10.1016/0022-4898(79)90013-.2

Bilbro, J.D. & Fryrear, D.W., 1994. Wind erosion losses as related to plant silhouette and soil cover. *Agron. J.* 86, 550–553.

Bingeman, C.W., Varner, J.E. & Martin, W.P., 1953. The effect of the addition of organic materials on the decomposition of an organic soil. *Soil Sci. Soc. Am. Pro.* 29, 692–696.

Birkas, M., 2008. Environmentally sound adaptable tillage. Akademia Kiado, Budapest, Hungary.

Bissett, A., Richardson, A.E., Baker, G., Kirkegaard, J. & Thrall, P.H., 2013. Bacterial community response to tillage and nutrient additions in a long-term wheat cropping experiment. *Soil Biology and Biochemistry* 58, 281–292. doi: http://dx.doi.org/10.1016/j.soilbio.2012.12.002.

Boardman, J. & Favis-Mortlock, D., 1998. Modelling Soil Erosion by Water. NATO ASI series, vol. 55. Berlin: Springer-Verlag.

Brady, N.C. & Weil, R.R., 2007. The nature and properties of soils. Fourteenth Edition. Prentice Hall, Inc. Upper Saddly River, NJ. 980 pp.

Brath, A., Montanari, A. & Moretti, G., 2006. Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty). *Journal of Hydrology* 324, 141–153.

Brooks, R.R., 1998. Plants that hyperaccumulate heavy metals (p. 384). Wallingford: CAB International.

Brown, S.L., Chaney, R.L., Angle, J.S. & Baker, A.J.M., 1994. Phytoremediation potential of *Thlaspi Caerulescens* and *Bladder Campion* for Zinc- and Cadmium-contaminated soil. *J. Environ. Qual*. 23, 1151–1157.

Bubeck, P., Botzen, W.J.W., Kreibich, H. & Aerts, J.C.J.H., 2012. Long-term development and effectiveness of private flood mitigation measures: an analysis for the German part of the river Rhine. *Nat. Hazards Earth Syst. Sci.* 12, 3507–3518.

Buerkert, A., Michels, K., Lamers, J.P.A., Marschner, H. & Bationo, A., 1996a. Anti-erosive, soil physical and nutritional effects of crop residues. In Buerkert, B., Allison, B.E., and Von Oppen, M. (eds.), *Wind Erosion in Niger: Implications and Control Measures in a Millet-Based Farming System*, Kluwer Academic, Dordrecht, Germany, pp. 123–138.

Buerkert, B., Allison, B.E. & Von Oppen, M. (eds.). 1996b. *Wind Erosion in Niger: Implications and Control Measures in a Millet-Based Farming System*, Kluwer Academic, Dordrecht, Germany, pp. 255.

Bunch, R., 2015. Restoring our soils by learning from history. Restoring the soil, A guide for using green manure/cover crops to improve the food security of smallholder farmers (Winnipeg: Canadian Food grains Bank, 2012).

Burken, J.G. & Schnoor, J.L., 1997. Uptake and metabolism of atrazine by poplar trees. *Environmental Science & Technology 31*, 1399–1406. doi: http://dx.doi.org/10.1021/es960629v.

Burns, S.F., Harden, T.M. & Andrew, C.J., 2008. A homeowner's guide to landslide – recognition, prevention, control and mitigation. Portland State University.

Cao, S.X., 2008. Why large-scale afforestation efforts in China have failed to solve the desertification problem. *Environmental Science & Technology* 42, 1826–1831.

Castillo, V.M., Martinez, M. & Albaladejo, J., 1997. Runoff and soil loss response to vegetation removal in a semi-arid environment. *Soil Sci. Soc. Amer. J.* 61, 1116–1121.

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

Chan, K.Y., 2001. An overview of some tillage impacts on earthworm population abundance and diversity — implications for functioning in soils. *Soil and Tillage Research* 57, 179–191. doi: http://dx.doi.org/10.1016/S0167-1987(00)00173-2

Chan, K.Y., Bowman, A.M. & Friend, J.J., 1997. Restoration of soil fertility of degraded vertisols using a pasture including a native grass (*Astrebla lappacea*). *Tropical Grasslands* 31, 145–155.

Chehregani, A, Noori, M. & Yazdi H.L., 2009. Phytoremediation of heavy-metal-polluted soils: screening for new accumulator plants in Angouran mine (Iran) and evaluation of removal ability. *Ecotoxicol Environmental Safety* 72, 1349–53. doi: http://dx.doi.org/10.1016/j.ecoenv.2009.02.012.

Chepil, W.S. & Woodruff, N.P., 1963. The physics of wind erosion and its control. *Adv. In Agron.* 15, 211–302.

COM, 2004. COMMUNICATION FROM THE COMMISSION TO THE COUNCIL, THE EUROPEAN PARLIAMENT, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS (2004): Flood risk management Flood prevention, protection and mitigation. COM(2004)472 final.

Conant, R.T., Paustian, K. & Elliott, E.T., 2001. Grassland management and conversion into grassland: effects on soil carbon. *Ecological Applications* 11, 343–355.

Cooperband, L., 2002. Building Soil organic matter with organic amendments. Center for Integrated Agricultural Systems. University of Wisconsin-Madison (http://www.cias.wisc.edu/wp-content/uploads/2008/07/soilorgmtr.pdf).

Croke, B.F.W., Ticehurst, J.L., Letcher, R.A., Norton, J.P., Newham, L.T.H. & Jakeman, A.J., 2007. Integrated assessment of water resources: Australian experiences. *Water Resources Management* 21, 351–373.

Cruden, D.M., Varnes, D.J., 1996. Landslide types and processes. In: Turner, A.K., Schuster, R.L. eds. Landslides: investigation and mitigation (Special Report). Washington, DC, USA: National Research Council, Transportation and Research Board Special Report 247, 36–75.

Cundy, A.B., Hopkinson, L. & Whitby, R.L.D., 2008. Use of iron-based technologies in contaminated land and groundwater remediation: A review. *Science of The Total Environment* 400, 42–51.

Davies, D.B., Finney, J.B. & Richardson, R.J., 1973. Relative effects of tractor weight and wheelslip in causing soil compaction. *Journal of Soil Science* 24, 399–409.

De Kok, J.-L. & Grossmann, M. 2010. Large-scale assessment of flood risk and the effects of mitigation measures along the Elbe River. *Nat. Hazards* 52, 143–166.

De Pina Tavres J., Ferreia, A.J.D., Reis, E.A., Baptista, I., Amoros, R., Costa, L., Furtado, A.M. & Coelho, C., 2014. Appraising and selecting strategies to combat and mitigate desertification based on stakeholder knowledge and global best practices in Cape Verde Archipelago. *Land Degradation & Development* 25, 45–57. doi: http://dx.doi.org/10.1002/ldr.2273.

Dec, J., Bollag, J.M., 1994. Use of plant material for the decontamination of water polluted with phenols. *Biotech. Bioeng*., 44, 1132–1139.

DEFRA, 2005. Cross compliance guidance for soil management. Defra Publications, London.

Dorren, L. & Rey, F., 2004. A review of the effect of terracing on erosion. In briefing papers of the second SCAPE workshop in Cinque Terre (IT), 13–15 April 2004, pp. 97–108.

ECPA, 2010. Soil biodiversity and agriculture: European Crop Protection Agency, European commission. Soil biodiversity. Luxembourg.

Eltrop, L., Allison, B.E. & Michels, K., 1996b, Effects of planted wind breaks on wind erosion and millet growth, and biomass production of the wind breaks. In Buerkert, B., Allison, B.E., and Von Oppen, M. (eds.), *Wind Erosion in Niger: Implications and Control Measures in a Millet-Based Farming System*, Kluwer Academic, Dordrecht, Germany, pp 67–83.

Eltrop, L., Allison, E., Michels, K. & Sivakumar, M.V.K., 1996a. Effect of Different Rates of Crop Residue Application on Wind Erosion, Soil Properties, and Millet Growth. In Buerkert, B., Allison, B.E. and Von Oppen, M. (eds.), *Wind Erosion in Niger: Implications and Control Measures in a Millet-Based Farming System*, Kluwer Academic, Dordrecht, Germany, pp 139–151.

European Commission, 2012. *Guidelines on best practice to limit, mitigate or compensate soil sealing* (SWD(2012) 101 final/2).

Evans, C.S., Asher, C. & Johnson, C.M., 1968. Isolation of dimethyl diselenide and other volatile selenium compounds from Astragalus racemosus (Pursh.) *Aust. Journal of Biological Sciences*, 21, 13–20.

Falloon, P. & Betts, R., 2010. Climate impacts on European agriculture and water management in the context of adaptation and mitigation – The importance of an integrated approach. *Sci. Tot. Environ*. 408, 5667–5687.

Fan, S.Y. & Zhou, L.H., 2001. Desertification Control in China: Possible Solutions. *AMBIO*, 30, 384–385.

FAO, 2014. Towards climate-responsible peatlands management, eds by Biancalani, R. & Avagyan, A. in Mitigation of climate change in agriculture series 9. http://www.fao.org/3/a-i4029e.pdf

FAO, 2015. Environmental and social management Guidelines. http://www.fao.org/3/a-i4413e.pdf

Fryrear, D.W. & Skidmore E.L., 1985. Methods for Controlling Wind Erosion. In Follett R. F. & Stewart, B.A. ed. 1985. *Soil Erosion and Crop Productivity.* ASA-CSSA-SSSA, 677, South Segoe Road, Madison, WI 5371 1, USA.

Fryrear, D.W., 1985. Soil cover and wind erosion. *Trans. ASAE* 28, 781–784.

Funk, R. & Reuter, H.I., 2006. Wind Erosion in Europe. In: Soil Erosion in Europe, eds. by Poesen J. & Boardman, J., 563-582.

Funk, R. & Riksen, M., 2007. Measures to reduce wind erosion and related dust emissions. In: DustConf 2007 'How to improve air quality' : International Conference in Maastricht, The Netherlands, 23-24 April 2007: 1–11; Maastricht (Maastricht Exhibition and Congress Centre).

Funk, R., 1995. Quantifizierung der Winderosion auf einem Sandstandort Brandenburgs unter besonderer Berücksichtigung der Vegetationswirkung. ZALF Bericht Nr. 16, Zentrum für Agrarlandschafts- und Landnutzungsforschung, Müncheberg.

Funk, R., Deumlich D. & Steidl J., 2001. GIS application to estimate the wind erosion risk in the federal state of Brandenburg. In: Soil erosion research for the 21st century, proceedings of the international symposium, January 3-5, 2001, Honolulu, Hawaii, 400–403.

Galantini, J.A. & Rosell, R.A., 1997. Organic fractions, N, P, and S changes in Argentine semi-arid haplustoll under different crop sequences. *Soil Tillage Res.* 42, 221–228.

Gardi, C., & Jeffery, S., 2009. Soil Biodiversity, JRC Scientific and Technical Report.

Gebrernichael, D., Nyssen, J., Poesen, J., Deckers, J., Haile, M., Govers, G. & Moeyersons, J., 2006. Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray Highlands, northern Ethiopia. *Soil Use and Management* 21, 287–297. doi: http://dx.doi.org/10.1111/j.1475-2743.2005.tb00401.x

Geertsema, W., 2002. Het belang van groenblauwe dooradering voor natuur en landschap *Achtergronddocument Natuurbalans2002*. Wageningen: ALTERRA.

Ghosh, M. & Singh, S.P., 2005. A review on phytoremediation of heavy metals and utilization of it's by products. *Asian Journal on Energy and Environment* 6, 214–231.

Gliesmann, S.R., 1985. Multiple cropping systems: a basis for developing an alternative agriculture.

Grashof-Bokdam, C.J., Chardon, J.P., Vos, C.C., Foppen, R.P.B., Wallis DeVries, M., Veen, M.v.d. & Meeuwsen, H.A.M., 2009. The synergistic effect of combining woodlands and green veining for biodiversity. *Landscape ecology* 24, 1105–1121.

Gupta, R.K., Harsh, L.N., Shankarnarayana, K.A. & Sharma, B.D., 1989. Wealth from Wastelands. *Indian Farming,* 38, 18–19, 24.

Hågvar, S., 1998. The relevance of the Rio-Convention on biodiversity to conserving the biodiversity of soils. *Applied Soil Ecology* 9, 1–7.

Håkansson, I., 2005. Machinery-induced compaction of arable soils. Incidence-consequences-counter-measures. SLU Department of Soil Sciences. Reports from the Division of Soil Management. No 109. pp153.

Håkansson, I., Voorhees, W.B. & Riley, H., 1988. Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes. *Soil & Tillage Research* 11, 239–282.

Hallett, P., Balana, B., Towers, W., Moxey, A., Chamen, T., 2012. Studies to inform policy development with respect to soil degradation. Sub project A: Cost curve for mitigation of soil compaction. Defra project SP1305.

Hamza, M.A. & Anderson, W.K., 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research* 82, 121–145. doi: http://dx.doi.org/10.1016/j.still.2004.08.009.

Hatley, D., Wiltshire, J., Basford, B., Royale, S., Buckley, D. & Johnson, P., 2005. Soil compaction and potato crops. *Research Review* R260, British Potato Council, Oxford, UK.

Hauggaard-Nielsen, H., Jørnsgaard, B., Kinane, J. & Jensen, E.S., 2008. Grain legume–cereal intercropping: The practical application of diversity, competition and facilitation in arable and organic cropping systems. *Renewable Agriculture and Food Systems* 23(Special Issue 01), 3–12. doi: doi:10.1017/S1742170507002025

Hauser, S., Nolte, C. & Carsky, R.J., 2006. What role can planted fallows play in the humid and sub-humid zone of West and Central Africa? *Nutrient Cycling in Agroecosystems* 76, 297–318.

Heathcote, I.W., 1998. Integrated Watershed Management: Principles and Practice. John Wiley, New York.

Heaton, A.C.P., Rugh, C.L., Wang, N. & Meagher, R.B., 1998. Phytoremediation of mercury- and methyl mercurypolluted soils using genetically engineered plants. *Journal of Soil Contamination* 74, 497–510.

Hessel, R., Reed, M.S., Geeson, N., Ritsema, C.J., Karavitis, C., Schwilch, G., Jetten, V., van Dijck, S.J.E., van den Elsen, H.G.M., 2014. From framework to action: the DESIRE approach to combat desertification. *Environmental Management* 54, 935-950.

Huber, S., Prokop, G., Arrouays, D., Banko, G., Bispo, A., Jones,R.J.A., Kibblewhite, M.G., Lexer, W., Möller, A., Rickson, R.J., Shishkov, T., Stephens, M., Toth, G., van den Akker, J.J.H., Varallyay, G., Verheijen,F.G.A., Jones A.R., 2008. Environmental assessment of soil for monitoring (eds), Volume I: Indicators & Criteria. Pub: Joint Research Centre of the European Commission, , Luxembourg, doi: http://dx.doi.org/10.2788/93515, 339pp ISBN 978-92-79-09708-9.

Hungr, O., Evans, S.G., Bovis, M., Hutchinson, J.N., 2001. Review of the classification of landslides of the flow type. Environmental and Engineering Geoscience, 7, 221–238.

Hurni, H., Herweg, K., Linger, H.; Maselli, D. & Klay, A., 2003. Nachhaltige Ressourcennutzung I: Integrale Betrachtung von einzelnen natürlichen Ressourcen, sowie Forschungsmethoden und Möglichkeiten zu deren nachhaltiger Nutzung.

IAEA, 2008. TECDOC-1582: *Guidelines for Sustainable Manure Management in Asian Livestock Production System*. A publication prepared under the framework of the RCA project on integrated approach for improving livestock production using indigenous resources and conserving the environments.

Jensen, J.K., Holm, P.E., Nejrup, J., Larsen, M.B. & Borggaard, O.K., 2009. The potential of willow for remediation of heavy metal polluted calcareous urban soils. *Environmental Pollution* 157, 931–937.

Ji, G.D., Yang, Y.S., Zhou, Q., Sun, T. & Ni, J.R., 2004. Phytodegradation of extra heavy oil-based drill cuttings using mature reed wetland: an in situ pilot study. *Environment International* 30, 509–517. JRC, 2012. the State of Soil in Europe. EC-JRC report.

Johnston, A.E., Poulton, P.R., Coleman, K., 2009. Chapter 1 Soil Organic Matter. Its Importance in Sustainable Agriculture and Carbon Dioxide Fluxes. *Advances in Agronomy* 101, 1-57.

Jones, A., Montanarella, L. & Jones, R., 2005. Soil Atlas of Europe. European Commission, 128 p.

Joosten, H., 2014. Croplands and paludicultures. In *towards climate-responsible peatlands management*, eds Biancalani R & Avagyan A., FAO Mitigation of Climate Change in Agriculture Series 9.

JRC, 2014. Soil themes: soil contamination. http://eusoils.jrc.ec.europa.eu/library/ themes/contamination/.

Kärenlampi, S., Schat, H., Vangronsveld, J., Verkleij, J.A.C., van der Lelie, D., Mergeay, M. & Tervahauta, A.I., 2000. Genetic engineering in the improvement of plants for phytoremediation of metal polluted soils. *Environmental Pollution* 107, 225–231.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S. & Jordahl, J.L., 1994. Crop residue effects on soil quality following 10-years of no-till corn. *Soil and Tillage Research* 31, 149–167. doi: http://dx.doi.org/10.1016/0167-1987(94)90077-9

Kechavarzi, C., Dawson, Q, Bartlett, M, Leeds-Harrison, P.B., 2010. The role of soil moisture, temperature and nutrient amendment on CO_2 efflux from agricultural peat soil microcosms. *Geoderma* 154, 203–210.

Keller, T., Arvidsson, J., Schjønning, P., Lamandé, M., Stettler, M. & Weisskopf, P., 2012. In situ subsoil stress-strain behavior in relation to soil precompression stress. *Soil Sci*. 177, 490–497.

Khan, Z.R., Ampong-Nyarko, K., Chiliswa, P., Hassanali, A., Kimani, S., Lwande, W. & Woodcock, C.M., 1997. *Intercropping increases parasitism of pests*. 388(6643), 631–632.

Kimble, J., Rice, C., Reed, D., Mooney, S., Follet, R. & Lal, R., 2007. *Soil carbon management,* CRC press.

Klein Swormink, B., van Eekeren, N., Philipsen, B., Graslandsignalen. Praktijkgids voor optimaal graslandgebruik. Roodbont B.V., Louis Bolk Instituut, 2008, 96p.

Komárek, M., Vanek, A. & Ettler, V., 2013. Chemical stabilization of metals and arsenic in contaminated soils using oxides - A review. *Environmental Pollution* 172, 9–22.

Krüger, H.J., Fantaw, B., Mihaeli, Y.G. & Kajela, K., 1997. Inventory of indigenous soil and water conservation measures on selected sites in the Ethiopian Highland. Soil Conservation Programme Ethiopia. Research Report 34. Bern, London.

Kumpiene, J. Lagerkvist, A. & Maurice, C., 2008. Stabilization of As, Cr, Cu, Pb and Zn in soil using amendments – A review. *Waste Management* 28, 215–225.

Kundezewicz, Z.,W., 2002. Non-structural flood protection and sustainability. *Water International* 27, 3–13.

Kuntz, M., Berner, A., Gattinger, A., Scholberg, J. M., Mäder, P. & Pfiffner, L., 2013. Influence of reduced tillage on earthworm and microbial communities under organic arable farming. *Pedobiologia, 56*, 251–260. doi: http://dx.doi.org/10.1016/j.pedobi.2013.08.005

Lacombe, S., Bradley, R. L., Hamel, C. & Beaulieu, C., 2009. Do tree-based intercropping systems increase the diversity and stability of soil microbial communities? *Agriculture, Ecosystems & Environment* 131, 25–31. doi: http://dx.doi.org/10.1016/j.agee.2008.08.010

Lal, R. 2001. Potential of desertification control to sequester carbon and mitigate the greenhouse effect. *Climate Change* 51, 35–72.

Lal, R., 1987. *Tropical Ecology and Physical Edaphology*, J. Wiley & Sons, Chichester, U.K.

Lal, R., 1995. Sustainable management of soil resources in the humid tropics. United Nations University Press. Tokyo, New York, Paris.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. *Science 304*, 1623–1627.

Lal, R., 2015. Managing soil carbon through sustainable intensification of agro-ecosystems, *Agriculture for Development* 24, 13–18.

Larsen, W.E., Eynard, A., Hadfas, A. & Lipiec, J. 1994. Control and avoidance of compaction in practice. In: Soil compaction in crop production (eds B.D. Soane & C. van Ouwerkerk), pp. 597–625. Elsevier, Amsterdam.

Lasat, M.M., 2000. Phytoextraction of metals from contaminated soils: a review of plant/metal interaction and assessment pertinent agronomic issues. *Journal of Hazardous Substance Research* 5, 1–25.

Lassen, P., Lamandé, M., Stettler, M., Keller, T., Jørgensen, M.S., Lilja, H., Alakukku, L., Pedersen, J., Schjønning, P., 2013. Terranimo® - A soil compaction model with internationally compatible input options. EFITA-WCCA-CIGR Conference "Sustainable Agriculture through ICT Innovation", Turin, Italy, 24–27 June 2013, 8pp.

Lattore, J., 1990. Reforestation of arid and semi-arid zones in Chile. *Agric. Ecosystems Env.* 33, 111–127.

Le Houérou, H.N., 1975. *Science Power and Desertization*, Meeting on Desertization, 22–28 Sept. 1975, Dept. Geogr., University of Cambridge, Cambridge, U.K., p. 26.

Lesschen, J.P., Cammeraat, L.H. & Nieman, T., 2008. Erosion and terrace failure due to agricultural land abandonment in a semi-arid environment. *Earth Surface Process & Landforms* 33, 1574–1584. doi: http://dx.doi.org/10.1002/esp.1676.

Li, J.J., 1996. Speech at the conference on the new Eurasian bridge and sustainable development in northwest China. *Arid Zone Geography* 1, 1–3.

Li, M.G., 1980. Principles and measures of shifting sand stabilization on both sides of railway. *Research on Shifting Sand Control.* Edited by the Institution of Desert Research, Chinese Academy of Sciences. Ningxia People's Publishing House, 27–48.

Li, Y.T., 1995. Several problems on grassland ecological construction in China. *Desertification and its Control.* Edited by China Executive Committee Secretariat on UN Convention to Combat Desertification. China Forestry Scientific Press, 51–52.

Lomte, M.H., Ateeque, M., Bharambe, P.R. & Kawarkhe, P.K., 1993. Influence of sorghum legume association on physico-chemical properties of soil. *J. Maharashtra Agric. Univ.* 18, 388–390.

Luo, Z., Wang, E. & Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. *Agriculture, Ecosystems & Environment* 139, 224–231.

Lupwayi, N.Z., Rice, W.A. & Clayton, G.W., 1998. Soil microbial diversity and community structure under wheat as influenced by tillage and crop rotation. *Soil Biology and Biochemistry* 30, 1733–1741. doi: http://dx.doi.org/10.1016/S0038-0717(98)00025-X.

Machado, S., 2009. Does intercropping have a place in modern agriculture? *Journal of soil and water conservation* 64, 55–57. doi: 10.2489

Maetens, W., Poesen, J. & Vanmaercke, M., 2012. How effective are soil conservation techniques in reducing plot runoff and soil loss in Europe and the Mediterranean? *Earth-Science Reviews* 115, 21–36.

Mainguet, M., 1991. *Desertification: natural background and human mismanagement*, Springer-Verlag, Berlin.

Makino, T., Sugahara, K., Sakuraia, Y., Takano, H., Kamiya, T., Sasaki, K., Itou, T. & Sekiya, N., 2006. Remediation of cadmium contamination in paddy soils by washing with chemicals: Selection of washing chemicals. *Environmental Pollution* 144, 2–10.

Manna, M.C. & Singh, M.V., 2001. Long-term effects of intercropping and bio-litter recycling on soil biological activity and fertility status of sub-tropical soils. *Bioresource Technology* 76, 143–150. doi: http://dx.doi.org/10.1016/S0960-8524(00)00088-2

Margaris, N.S., Koutsidou, E. & Giourga, Ch., 1996. Changes in traditional mediterranean land use systems, in Brandt, C.J. & Thornes, J. B. (eds.), *Mediterranean Desertification and Land Use*, J. Wiley & Sons, Chichester, U.K., pp. 29–42.

Marshall, M.R., Ballard, C.E., Frogbrook, Z.L., Solloway, I., McIntyre, N., Reynolds, B. & Wheather, H.S., 2014. The impact of rural land management changes on soil hydraulic properties and runoff processes: results from experimental plots in upland UK. *Hyrol. Proc.* 28, 2617–2629.

Martin, J.H., Leonard, W.H., Stamp, D.L., 1976. Principles of field crop production. 3rd edition, Macmillan, New York, pp 1118.

Martin, T.A. & Ruby, M.V., 2004. Review of *In Situ* Remediation Technologies for Lead, Zinc, and Cadmium in Soil. *Remediation Journal* 14, 35–53. doi: http://dx.doi.org/10.1002/rem.20011.

McDaniel, M.D., Tiemann, L.K. & Grandy, A.S., 2013. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecological Applications*, 24, 560–570. doi: http://dx.doi.org/10.1890/13-0616.1

MDA, 2014. Minnesota Department of Agriculture.

Michels, K., Sivakumar, M.V.K. & Allison, B.E., 1995. Wind erosion control using crop residue. I. effects on soil flux and soil properties', *Field Crops Res.* 40, 101–110.

Miglierina, A.M., Galantini, J.A., Iglesias, J.O., Rosell, R.A. & Glave, A., 1996. Crop rotation and fertilization in production systems of the semi-arid region of Buenos Aires. *Revista de la Faculatd de Agronomia*, *Universidad de Buenos Aires* 15, 9–14.

Miglierina, A.M., Landriscini,M.R., Galantini, J.A., Iglesias, J.O.,Glave, A. & Gallardo Lancho, J.F., 1993. Fifteen years of crop rotation and fertilization in the semi-arid pampas region. I. Effect on the chemical properties of the soil. *El estudio del suelo y de su degradacion en relacion con la desertification. Actas del 12 Congreso Latinamericano de la Ciencia del Suelo*, Sevilla (Espana), 19–26 Sept. pp. 751–758.

Mirsal, I.A., 2008. Soil Pollution. Origin Monitoring & Remediation. 2nd Edition. Springer-Verlag, Berlin.

Moonen, A.C. & Barberi, P.B., 2008. Functional biodiversity: An agroecosystem approach. Agriculture, *Ecosystems and Environment* 127, 7–21.

Moore, P.D., 2002. The future of cool temperate bogs. *Environmental Conservation* 29, 3–20.

Morgan, R.P.C. & Finney, H.J., 1987. Drag coefficients of single crop rows and their implications for wind erosion control. In: International Geomorphology 1986 Part II. Edited by V. Gardiner, Wiley and Sons Ltd, 449–460.

Morgan, R.P.C., 1986. Soil erosion and conservation. Longman Group UK Ltd., Essex: 295 pp.

Morgan, R.P.C., 1999. Soil Erosion and Soil Conservation, Longman.

Mueller, B., Rock, S., Gowswami, D. & Ensley, D., 1999. Phytoremediation decision tree. prepared by Interstate Technology and Regulatory Cooperation Work Group, 1–36.

Munkholm, L.J., Schjønning, P., Jørgensen, M.H. & Thorup-Kristensen, K., 2005. Mitigation of subsoil recompaction by light traffic and on-land ploughing II. Root and yield response. Soil Till. Res. 80, 159–170.

Murphy P.N. C. & Stevens R.J., 2010. Lime and gypsum as source measures to decrease phosphorus loss from soils to water. *Water Air Soil Pollution* 212, 101–111. doi: http://dx.doi.org/10.1007/s11270-010-0325-0.

Naef, F., Scherrer, S. & Weiler, M., 2002. A process based assessment of the potential to reduce flood runoff by land use change. *J. Hydrol.* 267, 74–79.

Nägeli, W., 1943. Untersuchungen über die Windverhältnisse im Bereich der Windschutzstreifen. Mitt. der Schweiz. Anst. f. forstl. Versuchswesen, Bd.XXIII, pp.223

Newman, L.A., Strand, S.E., Choe, N., Duffy, J., Ekuan, G., Ruszaj, M., Shurtleff, B.B., Wilmoth, J., Heilman, P. & Gordon, M.P., 1997. Uptake and biotransformation of trichloroethylene by hybrid poplars. *Environ. Sci. Technol*. 31, 1062–1067.

O'Connel, E., Ewen, J., O'Donnel, G., Quinn, P. 2007. Is there a link between agricultural land use management and flooding? *Hydrol. Earth Syst, Sci.* 11, 96–107.

Olesen, J.E. & Munkholm, L.J., 2007. Subsoil loosening in a crop rotation for organic farming eliminated plough pan with mixed effects on crop yield. Soil Till. Res. 94, 376–385.

Oleszczuk, R., K. Regina, L. Szajdak, H. Hoper, V. Maryganova, 2008. Impacts of agricultural utilization of peat soils on the greenhouse gas balance. In: M. Strack (editor). Peat lands and Climate Change, edited by, published by International Peat Society, 2008, Vapaudenkatu 12, 40100 Jyvaskyla, Finland, pages: 70–97.

OWG, 2014. Open Working Group proposal for Sustainable Development Goals. Full report of the Open Working Group of the General Assembly on Sustainable Development Goals is issued as document A/68/970, available at http://undocs.org/A/68/970

Padmavathiamma, P.K. & Li, L.Y., 2007. Phytoremediation technology: hyper-accumulation metals in plants. *Water Air Soil Pollution* 184, 105–126. doi 10.1007/s11270-007-9401-5.

Panta, S., Flowers, T., Lane, P., Doyle, R., Haros, G., Shabala, S., 2014. Halophyte agriculture: success stories, *Environmental and Experimental Botany* 107, 71–83. doi: http://dx.doi.org/doi:10.1016/j.envexpbot.2014.05.006.

Patil, S.G., Hebbara, M. & Devarnavadagi, S.B., 1996. Screening of multipurpose trees for saline vertisols and their bioameliorative effects. *Annals Arid Zone* 35, 57–60.

Pérez-Piqueres, A., Edel-Hermann, V., Alabouvette, C. & Steinberg, C., 2006. Response of soil microbial communities to compost amendments. *Soil Biology and Biochemistry* 38, 460–470. doi: http://dx.doi.org/10.1016/j.soilbio.2005.05.025.

Phiri, S., Barrios, E., Rao I.M. & Singh, B.R., 2001. Changes in soil organic matter and phosphorus fractions under planted fallows and a crop rotation system on a Colombian volcanic-ash soil. *Plant and Soil* 231, 211–223.

Pilon-Smits, E.A.H., 2005. Phytoremediation. *Annual Review of Plant Biology* 56, 15–39.

Pluhar, J.J., Knight, R.W. & Heitschmidt, R.K., 1987. Infiltration rate and sediment production as influenced by grazing systems in the Texas Rolling Plains. *Journal of Rangeland Management* 40, 240–243.

Potter, K.N. & Zobeck, T.M., 1988. Simulation of Soil Microrelief. ASAE Paper No. 88-2557.

Poussin, J. K., Bubeck, P., Aerts, J.C.J.H. & Ward, P.J., 2012. Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: case study for the Meuse. *Nat. Hazards Earth Syst. Sci.* 12, 3455–3471.

Prasad, M. N. V. & Freitas, H., 2003. Metal hyperaccumulation in plants – Biodiversity prospecting for phytoremediation technology. *Electronic Journal of Biotechnology* 6, 275–321.

Probstein, R.F. & Hicks, R.E., 1993. Removal of Contaminants from Soils by Electric Fields. *Science* 260, 498–503.

Prokop, G. , Jobstmann H. & Schonbauer, A., 2011. Report on best practices for limiting soil sealing and mitigating its effects - *Overview of best practices for limiting soil sealing or mitigating its effects in EU-27.* Publisher: European Commission, Brussels, Technical Report - 2011 – 050, ISBN: 978-92-79-20669-6 http://ec.europa.eu/environment/soil/pdf/sealing/Soil%20sealing%20-%20Final%20Report.pdf

Pulford, I.D. & Watson, C., 2003. Phytoremediation of heavy metal-contaminated land by trees—a review. *Environment International* 29, 529–540. doi: http://dx.doi.org/10.1016/S0160-4120(02)00152-6.

Quevauviller, P. & Olazabal, C., 2003. Links between the Water Framework Directive, the Thematic Strategy on Soil Protection and Research Trends with Focus on Pollution Issues. *Journal of Soils & Sediments* 3, 243–244.

Requena, N., Perez-Solis, E., Azcon-Aguilar, C., Jeffries, P. & Barea, J.M., 2001. Management of indigenous plant-microbe symbioses aids restoration of desertified ecosystems. *Applied and environmental microbiology* 67, 495–498. doi: http://dx.doi.org/10.1128/AEM.67.2.495-498.2001.

Rice, C.W. & Owensby, C.E., 2001. The effects of fire and grazing on soil carbon in range lands. Pages 323–341 *in* Follett, R.F., Kimble, J.M. & Lal, R. Eds, The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect. CRC/Lewis Publishers, Boca Raton, Florida.

Riksen, M., Brouwer, F. & de Graaf, J., 2003b. Soil conservation policy measures to control wind erosion in north-western Europe. *Catena* 52, 309–326.

Riksen, M., Brouwer, F., Spaan, W., Arrue, J.L. & Lopez, M.V., 2003a. What to do about wind erosion. In: Wind erosion on agricultural land in Europe. Ed. by A. Warren. European Commission, EUR 20370, 39–54.

Robinson, B.H., Brooks, R.R., Howes, A.W., Kirkman, J.H. & Gregg, P.E.H., 1997. The potential of the highbiomass nickel hyperaccumulator Berkheya coddii for phytoremediation and phytomining. *Journal of Geochemical Exploration* 60, 115–126.

Roper, J.C., Dec, J. & Bollag, J., 1996. Using minced horseradish roots for the treatment of polluted waters. *J. Environ. Qual*. 25, 1242–1247.

Ruecker, G., Sachad, P., Alcubilla, M.M. & Ferrer, C., 1998. Natural regeneration of degraded soils and site: changes on abandoned agricultural terraces in Mediterranean Spain. *Land Degradation & Development,* 9, 179–188.

Rulkens, W.H., Tichy, R. & Grotenhuis, J.T.C., 1998. Remediation of polluted soil and sediment: perspectives and failures. *Water Sci. Technol*. 37, 27–35.

Salem, B., 1991 Prevention and control of wind erosion inn arid regions In Unaslva (FAO), 42 (164), 33–39.

Salt, D.E., Blaylock, M., Nanda Kumar, P.B.A., Dushenkov, V., Ensley, B.D. & Raskin, I., 1995. Phytoremediation: A novel strategy for the removal of toxic metals from the environment using plants. *Biotechnol*. 13, 468–474.

Salt, D.E., Pickering, I.J., Prince, R.C., Gleba, D., Dushenkov, S., Smith, R.D. & Raskin, I., 1997. Metal accumulation by aquacultured seedlings of Indian Mustard. *Environ. Sci. Technol.* 31, 1636–1644.

Salt, D.E., Smith, R.D., & Raskin, I., 1998. Phytoremediation. *Annual Review of Plant Physiology and Plant Molecular Biology* 49, 643–668.

Sanjari, G., Ghadiri, H., Ciesiolka, C.A.A. & Yu, B., 2008.Comparing the effects of continuous and time-controlled grazing systems on soil characteristics in Southeast Queensland. *Soil Research* 46, 348–358. http://dx.doi.org/10.1071/SR07220.

Schilling, E.K., Gassman, W.P., Kling, L.C., Campbell, T., Jha, K.M., Wolter, F.C. & Arnold, G.J., 2014. The potential for agricultural land use change to reduce flood risk in a large watershed. *Hydrol. Process* 28, 3314–3325.

Schippers, P., Grashof-Bokdam, C.J., Verboom, J., Baveco, J. M., Jochem, R., Meeuwsen, H. A.M. & Adrichem, M.H.C., 2009. Sacrificing patches for linear habitat elements enhances metapopulation performance of woodland birds in fragmented landscapes. *Landscape Ecology* 24, 1123–1133. doi: 10.1007/s10980-008-9313-9.

Schjønning, P., Lamandé, M., Keller, T., Pedersen, J. & Stettler, M., 2012. Rules of thumb for minimizing subsoil compaction. Soil Use Manage. 28, 378–393.

Schjønning, P., van den Akker, J.J.H., Keller, T., Greve, M.H., Lamandé, M., Simojoki, A., Stettler, M., Arvidsson, J. & Breuning-Madsen, H. 2015. Driver-Pressure-State-Impact-Response (DPSIR) analysis and risk assessment for soil compaction – a European perspective. *Advances in Agronomy* (in review).

Schuman, G.E., Janzen, H.H. & Herrick, J.E., 2002. Soil carbon dynamics and potential carbon sequestration by rangelands. *Environmental Pollution* 116, 391–396.

Schwenke, G. & Jenkins, A., 2005. How to build organic matter in your soil. *Soil biology basics – Information series*. NSW Department of Primary Industries.

Schwilch, G., Bachmann, F. & Liniger, H.P., 2009. Appraising and selecting conservation measures to mitigate desertification and land degradation based on stakeholder participation and global best practices. Land Degradation and Development 20, 308–326. doi:http://dx.doi.org/10.1002/ldr.920.

Shahin, R.R., El-Meleigi, M.A., Al-Rokiba, A.A. & Eisa, A.M., 1998. Changes in organic matter and fertility of sandy soils as affected by wheat crop rotation. *Bull. Fac. Agric. Univ. Cairo* 49, 169–184.

Shao, Y. 2008. Physics and modelling of wind erosion. Springer, Cologne.

Shaxson, F. & Kassam, A., 2015 Soil erosion and conservation. *Agriculture for Development* 24, 21–25.

Shi, Z.H., Ai, L., Fang, N.F. & Zhu, H.D., 2012. Modeling the impacts of integrated small watershed management on soil erosion and sediment delivery: A case study in the Three Gorges Area, China. *Journal of Hydrology* 438–439, 156–167.

Sims, B., 2015. Conserving soils on the island of Gozo, Malta. *Agriculture for Development* 24, 18–20.

Singh, G. & Singh, G., 1995. Long-term effects of amendments on *Prosopis juliflora* and soil properties of a highly alkali soil. *J. Tropical Forest Sci.* 8, 225–239.

Singh, G., Singh, N.T. & Abrol, I.P., 1994. Agroforestry techniques for the rehabilitation of degraded salt-affected lands in India. *Land Degradation & Rehabilitation* 5, 223–242.

Six, J., Elliott, E.T. & Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry* 32, 2099–2103. doi: http://dx.doi.org/10.1016/S0038-0717(00)00179-6.

Skidmore, E.L., 1986. Wind-erosion climatic erosivity. *Climate Change* 9,195–208.

Smith, R.A.H. & Bradshaw, A.D., 1972. Stabilization of toxic mine wastes by the use of tolerant plant populations. Trans. Inst. Min. Metall., Sect. A 81, 230–237.

Soane, G.C., Godwin, R.J., Marks, M.J. & Spoor, G., 1987. Crop and soil response to subsoil loosening, deep incorporation of phosphorus and potassium fertilizer and subsequent soil management on a range of soil types. Part 2: Soil structural conditions. *Soil Use and Management* 3, 123-130.

Sorensen, L., 2014. Saving the soil 'Skin,' thriving with no-till. No-till farmer, Conservation tillage guidance

(http://www.notill.org/sites/default/files/098_rick_bieber_ctg_0814_v2.pdf)

Soulis, X.K., Valiantzas, D.J., Dercas, N. &d Londra, A.P., 2009. Investigation of the direct runoff generation mechanism for the analysis of the SCS-CN method applicability to a partial area experimental watershed. Hydrol. *Earth Syst. Sci*., 13, 605–615, www.hydrol-earth-syst-sci.net/13/605/2009/.

Spoor, G., 2006. Alleviation of soil compaction: requirements equipment and techniques. *Soil Use and Management* 22, 113–122.

Sterk, G., 2000. Flattened residue effects on wind speed and sediment transport. *Soil Sci. Soc. Am. J.* 64, 852–858.

Stettler, M., Keller, T., Weisskopf, P., Lamandé, M., Lassen, P., Schjønning, P., 2014. Terranimo® - a web-based tool for evaluating soil compaction. Landtech. 69, 132–137.

Strack, M., (editor). Peat lands and Climate Change, published by International Peat Society, 2008, Vapaudenkatu 12, 40100 Jyvaskyla, Finland, 223 pp.

Strand, S.E., Newman, L., Ruszaj, M., Wilmoth, J., Shurtleff, B., Brandt, M., Choe, N., Ekuan, G., Duffy, J., Massman, J.W., Heilman, P.E., Gordon, M.P., 1995. Removal of trichloroethylene from aquifers using trees. In: Innovative technologies for Site Remediation and Harzardous Waste management., Proceedings of the National Conference. R.D. and F.G. Pohland, eds. Environmental Engineering Division, America Society of Civil Engineers, New York, held in Pittsburgh, Pennsylvania, pp. 605–612.

Stull, R., 1988. *Introduction to Boundary Layer Meteorology.* Kluwer, Dodrecht, pp. 666.

Suarez, A., Watson, R.T. & Dokken, D.J., 2002. Climate change and biodiversity. Geneva, Switzerland: Intergovernmental Panel on Climate Change.

Tedela, N., McCutcheon, S., Rasmussen, T., Hawkins, R., Swank, W., Campbell, J., Adams, M., Jackson, C., and Tollner, E., 2012. Runoff Curve Numbers for 10 Small Forested Watersheds in the Mountains of the Eastern United States. *J. Hydrol. Eng.* 17, 1188–1198.

Tejada, M., Garcia, C., Gonzalez, J.L. & Hernandez, M.T., 2006. Use of organic amendment as a strategy for saline soil remediation: Influence on the physical, chemical and biological properties of soil. *Soil Biology and Biochemistry* 38, 1413–1421. doi: http://dx.doi.org/10.1016/j.soilbio.2005.10.017.

Terefe, T.N., 2011. Farmers' perception on the role of Vetiver grass in soil and water conservation in south western Ethiopia: *The Case of Tulube Peasant Association, Metu District. MA thesis* submitted to Indira Gandhi National Open University (IGNOU), Department of Rural Development in Partial

Fulfilment of the Requirements for the Degree of Masters of Arts in Rural Development (MARD).

Terry, N., Carlson, C., Raab, T.K. & Zayed, A., 1992. Rates of selenium volatilization among crop species. *Journal of Environmental Quality* 21, 341–344.

The United States of America Environmental Protection Agency Reports, 2000. Introduction to Phytoremediation. EPA, 600/R-99/107.

Thurow, T.L., Blackburn, W.H. & Taylor, C.A., Jr., 1988. Infiltration and inter-rill erosion responses to selected livestock grazing strategies, Edwards Plateau Texas. *Journal of Rangeland Management* 41, 296–302.

Tian, G., Olimah, J.A., Adeoye, G.O. & Kang, B.T., 2000. Regeneration of earthworm populations in a degraded soil by natural and planted fallows under humid tropical conditions. *Soil Science Society of America Journal* 64, 222–228.

Tidemann, E., 1996. Watershed Management. Guidelines for Indian conditions. New Delhi.

Tijink, F.G.J. & van der Linden, J.P., 2000. Engineering approaches to prevent subsoil compaction in cropping systems with sugar beet. In: Subsoil compaction: distribution, processes and consequences (eds R. Horn, J.J.H. van den Akker & J. Arvidsson), *Advances in Geoecology* 32, 442–452.

Tóth, G., Adhikari, K., Várallyay, Gy., Tóth, T., Bódis, K. & Stolbovoy, V., 2008. Updated map of salt affected soils in the European Union. In: Tóth, G., Montanarella, L. Rusco, E., (eds) Threats to Soil Quality in Europe., JRC.

Tullberg, J.N., N.J., D.F. Yule, D.F., McGarry, D., 2007. Controlled traffic farming—From research to adoption in Australia. *Soil and Tillage Research* 97, 272–28. doi: http://dx.doi.org/10.1016/j.still.2007.09.007.

USDA, 2010. Farming in the 21st century: a practical approach to improve soil health (s.q.n.t.d. team, Trans.): US Department of Agriculture.

Van den Akker, J.H.H., Arvidsson, J. & Horn, R., 2003. Introduction to the special issue on experiences with the impact and prevention of subsoil compaction in the European Union. *Soil and Tillage Research* 73, 1–8.

Van den Akker, J.J.H. & Schjønning, P., 2004. Subsoil Compaction and Ways to Prevent It. In: Schjønning, P., Elmholt, S. and Christensen, B.T. (Eds.) *Managing Soil Quality: Challenges in Modern Agriculture*. CABI Publishing, Wallingford, UK, chapter 10, pp. 163–184.

Van den Akker, J.J.H. & Schjønning, P., 2004. Subsoil compaction and ways to prevent it. In: Schjønning, Elmholt and Christensen (Eds.) Managing Soil Quality – Challenges in Modern Agriculture. CAB International, pp163–184.

Van den Akker, J.J.H., 1998. Prevention of subsoil compaction by defining a maximum wheel load bearing capacity. *Advances in Sugar Beet Research* IIRB, 1, 43–54.

Van den Akker, J.J.H., 2004. SOCOMO: a soil compaction model to calculate soil stresses and the subsoil carrying capacity. *Soil Till. Res*. 79, 113–127.

Van den Akker, J.J.H., 2008. Soil compaction. In: Huber *et al*. (Eds.) Environmental Assessment of Soil for Monitoring: Volume I Indicators & Criteria. EUR 23490 EN/1, Office for the Official Publications of the European Communities, Luxembourg, pp 107–124.

Van den Akker, J.J.H., Kuikman, P.J., De Vries, F., Hoving, I., Pleijter, M., Hendriks, R.F.A., Wolleswinkel, R.J., Simoes, R.T.L. and Kwakernaak, C., 2008. Emission of CO_2 from agricultural peat soils in the Netherlands and ways to limit this emission. In: Farrell, C and J. Feehan (eds.), 2008. Proceedings of the 13th International Peat Congress After Wise Use – The Future of Peat lands, Vol. 1 Oral Presentations, Tullamore, Ireland, 8–13 June.

Van der Meer, H.G., 2008. Production and utilization of livestock manure in The Netherlands. In T. Matsunaka and T. Sawamoto *(Eds.):* Animal Manure – Pollutant or Resource? 55–99.

Van Ginneken, L., Meers, E., Guisson, R., Ruttens, A., Elst, K., Tack, F.M.G., Vangronsveld, J., Diels, L. & Dejonghe, W., 2007. Phytoremediation for heavy metal-contaminated soils combined with bioenergy production, *Journal of Environmental Engineering and Landscape Management* 15, 227–236. http://dx.doi.org/10.1080/16486897.2007.9636935

Vandermeer, J., 1992. The ecology of intercropping: Cambridge University Press.

Varnes, D.J., 1978. Slope movement types and processes. In: special report 176: landslides: analysis and control (Eds. Schuster, R.L. & Krizek, R.J.). Transportation and road research board, National Academy of Science, Washington D. C., 11–33.

Varotto, M. & Lodatti, L., 2014. New Family Farmers for Abandoned Lands. *Mountain Research and Development* 34, 315–325.

Vázquez, S., Agha, R., Granado, A., Sarro, M.J., Esteban, E., Peñalosa, J.M. & Carpena, R.O., 2006. Use of white lupin plant for phytostabilization of Cd and As polluted acid soil. *Water, Air, and Soil Pollution* 177, 349–365. doi: http://dx.doi.org/10.1007/s11270-006-9178-y.

Vegter, J.J., 1995. Soil protection in The Netherlands. In W. Salomons, U. Forstner, & P. Mader (Eds.), Heavy Metals: Problems and Solutions, pp79–100.

Wang, J., Zhao, F., Meharg, A.A., Raab, A., Feldmann, J. & McGrath, P.S., 2002. Mechanisms of arsenic hyperaccumulation in Pteris vittata. Uptake kinetics, interactions with phosphate, and arsenic speciation. *Plant Physiology* 130, 1552–1561.

Wang, J., Pang H.C., Ren T.Z., Li, Y.Y. Zhao Y.G., 2012. Effect of plastic film mulching and straw buried on soil water-salt dynamic in Hetao plain. Transactions of the Chinese Society of Agricultural Engineering, 28, 52—59. (in Chinese with English abstract)

Wang, Z.G., Jin, X., Bao, X.G., Li, X.F., Zhao, J.H., Sun, J.H. & Li, L., 2014. Intercropping Enhances Productivity and Maintains the Most Soil Fertility Properties Relative to Sole Cropping. *PLoS ONE* 9, e113984. doi: 10.1371/journal.pone.0113984

Wemmer, T.H., 2002. Watershed Management to regulate erosion processes in tropical and subtropical regions. In: Schutt, B., Mekonen, A. & Forch, G.: Field Study *Landscape Sensitivity*. Landscape sensitivity of Hare River catchment area, South Ethiopia – with special focus on water budget and soil erosion. Field Guide. Arba Minch, Berlin, Siegen, pp 53–65.

Wheater, H. & Evans, E., 2009. Land use, water management and future flood risk. *Land Use Policy* 26S, S251–S264.

WMO, 2012. International glossary of hydrology. WMO-No. 385, World Meteorological Organization. ISBN 978-92-63-03385-8, 1–461.

Woodruff, N. P., Chepil, W.S. & Lynch., R.D., 1957. Emergency chiseling to control wind erosion. *Tech. Bull. 90*. Kansas Agric. Exp. Stn.

Wösten, H. and Kuikman, P., 2014. Report describing the practices and measures in European farming systems to manage soil organic matter. Deliverable 2.1 for EC-funded Project SmartSOIL.

Zhao, Y.G., Li Y.Y, Hu X.L., Wang J., Pang H.C., 2013a. Effect of plastic mulching and deep burial of straw on dynamics of soil water and salt in micro-plot field cultivation. ACTA Pedologica Sinica, 50, 62—70. (in Chinese with English abstract)

Zhao, Y.G., Wang J., Li Y.Y., Pang H.C., 2013b. Reducing evaporation from phreatic water and soil resalinization by using straw interlayer and plastic mulch. Transactions of the Chinese Society of Agricultural Engineering, 29, 109—117. (in Chinese with English abstract)

Appendix: WOCAT Technologies for RECARE