Soil Management for Sustainable Agriculture

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Introduction

The thin layer of soil at the earth's surface is essential for maintaining life. This layer of soil is the basis of most agriculture around the globe and is related with many factors (Fig. 1). If soil is lost or degraded, the potential of an area to support both plant and animal life is greatly reduced. It is the property of everyone, now and in the future. It may take many thousands of years for a soil to form, but only a few years for it to be degraded or lost due to poor management practices (Fig. 2, 3). For this reason it is critical that the techniques we use to manage our soils will maintain them in a manner that ensures that they are at least as productive for future generations as they are now, and hopefully are even improved.

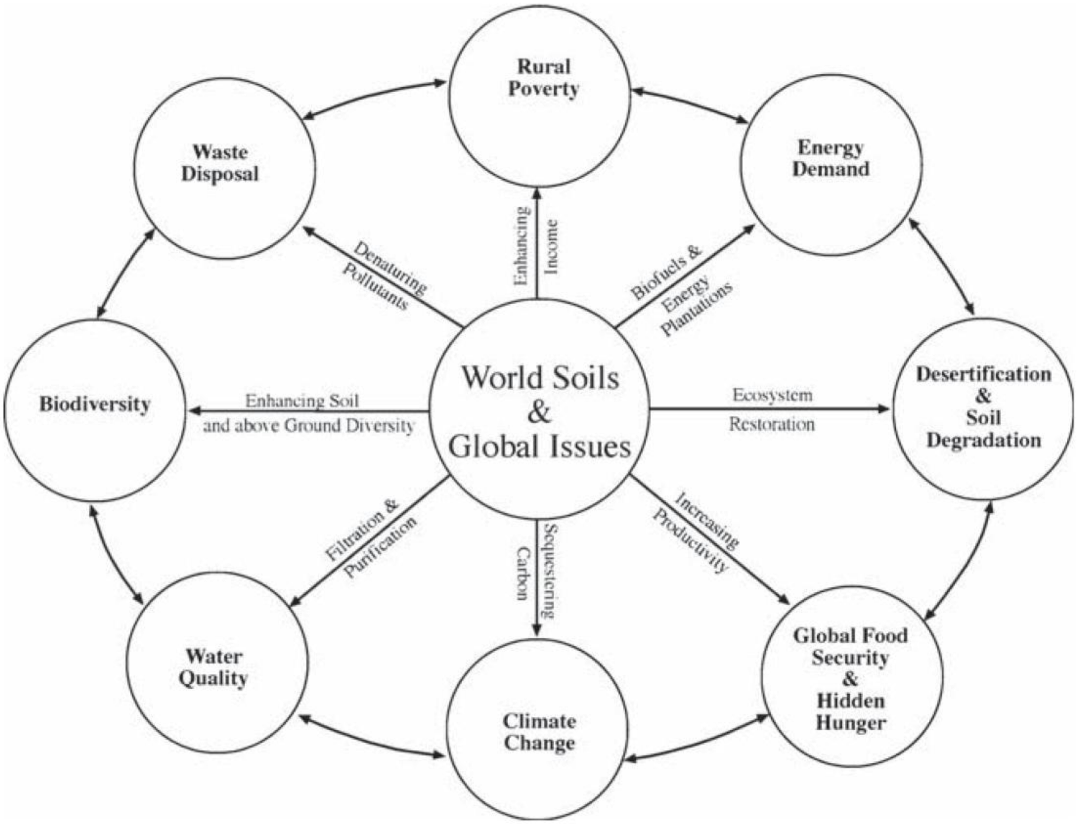

Fig. 1 World soils and global issues of twenty first century (Lal, 2009)

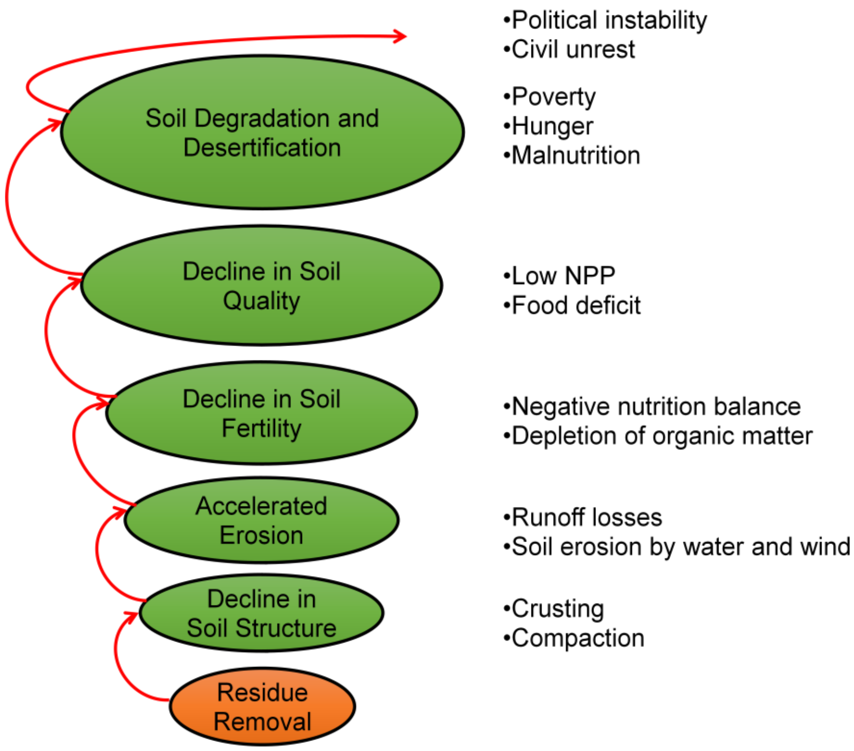

Fig. 2 The classic collapse

Intensified land use in the areas of shifting cultivation leads to shorter rest times for fallow fields and, ultimately, to soil degradation and reduced crop yields. This will inevitably give rise to a non-sustainable system, incapable of supporting a growing community (Fig. 3).

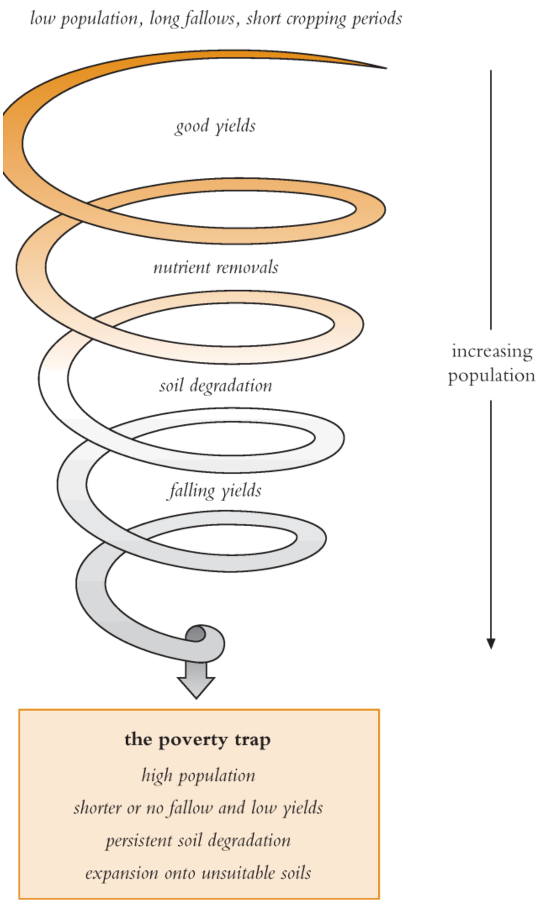

Fig. 3. The downward spiral to the poverty trap (FAO 1994)

Features of good soil

The best types of soil for most agricultural production can be described as having the following attributes:

- Well drained
- Deep root zone
- Easily penetrated by air, water and roots
- Good water-holding capacity
- Maintains a balanced nutrient supply
- Erosion resistant.
- Free from toxic elements.

Problems with soils

Soils are constantly affected by all that goes on around them, both by natural processes, and particularly in recent history, by human activity. Some of the more common human-induced changes include:

- Reduction in vegetation cover, opening up soils to increased rates of erosion
- Loss of soil structure due to poor cultivation techniques and the passage of heavy equipment, or regular traffic by hoofed animals (e.g. cows, horses)
- Reduction in soil fertility by not replacing nutrient losses from agricultural production
- An increase in saline-affected soils due to vegetation clearance or poor irrigation practices
- Waterlogging due to poor irrigation practices
- Soil acidification through the extensive use of acidifying fertilizers, or the extensive cropping of plants that remove large amounts of calcium from the soil.
- Pollution of some soils through the use of persistent or toxic agricultural chemicals.
- Salinity.

Major types of soil problems and their management

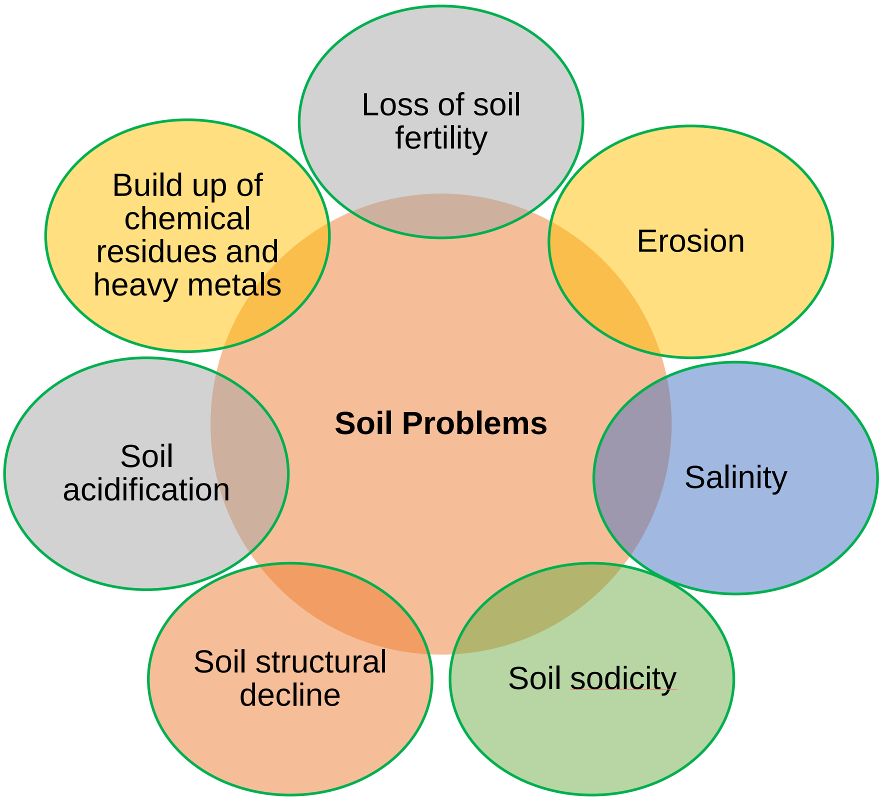

Fig. 4. Major soil-related problems

Loss of soil fertility

Sustainable soil fertility implies that soil nutrients will be available in the same quantity in the long term. For this to happen, nutrients that are removed from the soil need to be replaced. The main problem in terms of agricultural production is a loss of soil nutrients. There are a number of ways to reduce the loss of nutrients from the soil, including

- applying manure produced from the soil back to it and
- minimizing losses due to erosion, denitrification and leaching.

Minimizing dentrification

Soil denitrification (i.e. loss of nitrogen to the atmosphere) is affected by the nature and quantity of organic matter present, degree of soil aeration, soil moisture content, pH and temperature. Management practices can reduce nitrogen loss caused by these factors. For example, while farmers may have little control over rainfall, they can manipulate soil moisture content through irrigation and drainage practices. Saturated soils can produce the anaerobic environment required for denitrification, so irrigation practices can be timed to avoid waterlogging.

- Adding large amounts of organic matter to soils can result in high rates of microbial expansion, which in turn leads to an anaerobic environment which denitrifies quickly.
- Organic nutrients should be applied as close as possible to the time when they will be required by the crop.
- Nitrogen should be applied in an even concentration over the entire area. Localized buildups will accelerate denitrification.

Minimizing loss of nutrients due to leaching

To minimize loss due to leaching, it is advisable to only supply nutrients at a rate equal to the rate of uptake by the crop. In highly permeable soils, this can take the form of several applications of fertilizer rather than single application.

Erosion

Soil erosion, which is the movement of soil particles from one place to another by wind or water, is considered to be a major environmental problem. Erosion has been going on through most of earth's history and has produced river valleys and shaped hills and mountains.

This has resulted in a loss of productive soil from crop and grazing land, as well as layers of infertile soils being deposited on formerly fertile crop lands.

Common human causes of erosion

- Poor agricultural practices, such as ploughing soil that is too poor to support cultivated plants or ploughing soil in areas where rainfall is insufficient to support continuous plant growth
- Exposing soil on slopes
- Removal of forest vegetation
- Overgrazing – removing protective layers of vegetation
- Altering the characteristics of streams, causing bank erosion

Control of erosion

Erosion is generally caused by the effects of wind and water. It follows that erosion control methods are generally aimed at modifying these effects. Some of the most common control methods include:

- Prevention of erosion in the first place by careful land management
- Prevention of soil detachment by the use of cover materials such as trees, mulches, stubbles, matting and cover crops

- Crop production techniques (e.g. fertilizing) to promote plant growth and hence surface cover
- Strip cropping (strips of cereal alternated with strips of pasture or other crop), hence no huge expanse is bare at any time
- Terracing of slopes to reduce the rate of runoff
- Conservation tillage
- Armouring of channels with rocks, tyres, concrete, timber, etc to prevent bank erosion
- Ploughing into clod sizes too big to be eroded, or ploughing into ridges
- Avoiding long periods of fallow
- Working organic matter into the soil
- Establishing windbreaks to modify wind action.

Salinity

Among the abiotic stresses, salinity is the most destructive factors which limit the crop productivity considerably. A large area of land in the world is affected by salinity which is increasing day by day. Salinity is more prominent problem in irrigated crop lands. Worldwide, around 17% of the cultivated land is under irrigation and irrigated agriculture contributes more than 30% of the total agricultural production. It is estimated that at least 20% of total irrigated lands in the world is salt-affected. However, the statistics varies depending on sources. According to the FAO Land and Nutrition Management Service (2008), 6.5% of the total land in the world is affected by salt (either salinity or sodicity) which accounts for 831 M ha of land (Table 1).

Table 1: Variation in salt-affected areas in the world, in million hectares (M ha)

Region	Total area (M ha)	Saline soils		Sodic soils	
		M ha	%	M ha	%
Africa	1899	39	2.0	34	1.8
Asia, the Pacific and Australia	3107	195	6.3	249	8.0
Europe	2011	7	0.3	73	3.6
Latin America	2039	61	3.0	51	2.5
Near East	1802	92	5.1	14	0.8
North America	1924	5	0.2	15	0.8
Total	12781	397	3.1	434	3.4

Source: FAO Land and plant nutrition service (2008)

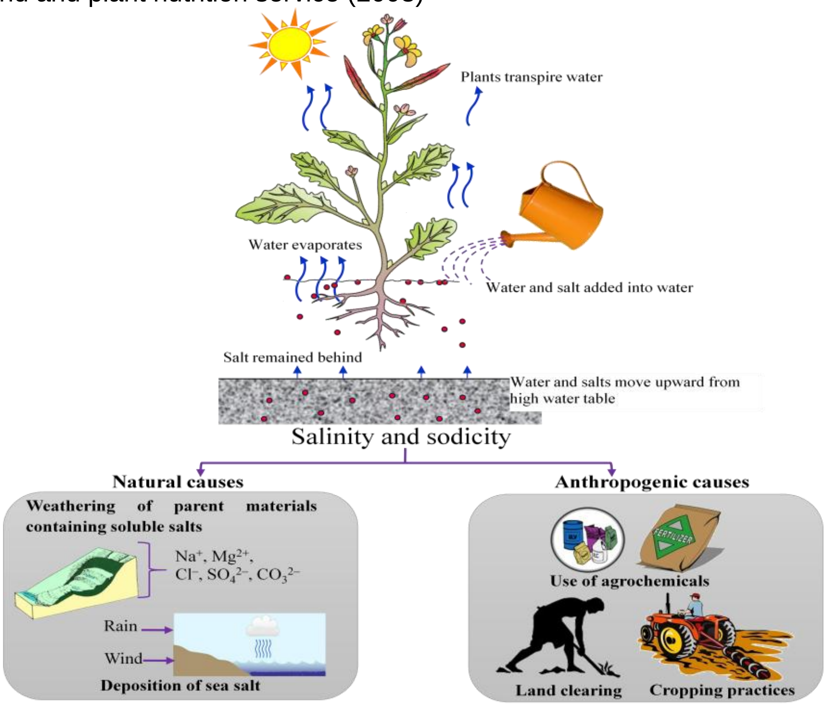

Fig. 5 Salinization in crop lands caused by salty irrigation water or rise of water table with salt water (Hasanuzzaman et al. 2013)

The presence of salinity is often indicated by:

- Yellowing of pasture (NB: waterlogging or drought can cause this effect also)
- Decline in crop plants, including yellowing, or burning of the tips of foliage
- Bare patches developing
- Reddish leaves on plantains
- The appearance of certain weeds and grasses (known as indicator plants)
- Salt deposits appearing at the soil surface (in more severe cases)

Control methods for salinity

Some of the main methods of controlling salinity are:

- Pumping to lower groundwater levels, with the groundwater being pumped to evaporation basins or drainage systems.
- Careful irrigation practices to prevent a rise in, or to reduce, groundwater levels.
- Revegetation of recharge areas and discharge sites.
- Engineering methods designed to remove saline water from crop land.
- Leaching suitable soils (e.g. raised crop beds).
- Identifying high recharge areas, which are often unproductive ridges and planting them with trees.
- Applying gypsum to surface soils with high NaCl levels; the calcium and magnesium in the gypsum will displace the sodium ions from soil particles, allowing them to be more readily leached by heavy irrigation or flood irrigation.
- Use of salt-tolerant species (e.g. barley)

Soil sodicity

Saline soils typically have a buildup of sodium chloride. In sodic soils, much of the chlorine has been washed away, leaving behind sodium ions (sodium atoms with a positive charge) which are attached to tiny clay particles in the soil. This makes the clay particles less able to stick together when wet – leading to unstable soils which may erode or become impermeable to both water and roots.

Affected soils erode easily and, in arid regions, sodic soils are susceptible to dust storms. In sloping areas, water easily removes the topsoil. Where the subsoil is sodic, water flowing below ground level can form tunnels which later collapse into gullies. The biggest problems occur when the top 5 cm of soil are sodic. However, when lower soil layers are affected it can also be a problem, as drainage is affected.

Control of Sodicity

Sodic soils are usually treated with calcium-containing substances such as gypsum. Other ameliorants such as sulphur, aluminium and iron sulphates or iron pyrite can be effective. Gypsum is the most cost effective treatment that is readily available for treating large areas. In some cases, soils need to be deep ripped to allow penetration.

Soil structural decline

- This causes a reduction in soil pore space, reducing the rate at which water can infiltrate and drain through the soil.
- It also reduces the available space for oxygen in the plant root zones, and makes it difficult for plant roots to penetrate through the soil.
- Some of the major consequences of soil structural decline are poor drainage, poor aeration, and hard pan surfaces which result in poor infiltration rates, and thus increased surface runoff and erosion.

Causes of loss of soil structure

- Loss of soil structure is commonly caused by compaction due to human use of the soil (i.e. foot traffic on lawn areas, or repeated passage of machinery in crop areas).
- Poor cultivation techniques (e.g. cultivating wet soils and overcultivating) lead to a breakdown of soil structure and this also increases the likelihood of compaction.

Control of soil structure loss

Soil structural decline can be prevented by farming practices that minimize cultivation and the passage of machinery. These include conservation tilling, selection of crops that require reduced cultivation and use of machinery at times less likely to cause compaction (i.e. when soils aren't too wet or when some protective covering vegetation may be present). For heavily compacted soils deep ripping may be necessary.

Soil acidification

This is a problem becoming increasingly common in cultivated soils. Soil acidification is the increase in the ratio of hydrogen ions in comparison to 'basic' ions within the soil. This ratio is expressed as pH, on a scale of 0–14 with 7 being neutral, below 7 acid, and above 7 alkaline. The pH of a soil can have major effects on plant growth, as various nutrients become unavailable for plant use at different pH levels. Most plants prefer a slightly acid soil, however an increase in soil acidity to the levels being found in many areas of cultivated land renders that land unsuitable for many crops, or requires extensive amelioration works to be undertaken.

Causes of soil acidification

Acid soils can occur naturally but a number of agricultural practices have expanded the areas of such soils. The main causal factor is the growth of plants that use large amounts of basic ions (e.g. legumes); particularly when fertilizers that leave acidic residues (such as superphosphate or sulphate of ammonia) are used. Soil acidity is generally controlled by the addition of lime to the soil, by careful selection of fertilizer types and sometimes by changing crop types.

Build up of chemical residues and heavy metals

The presence of chemical residues can be quite a problem in many soils. These residues derive almost entirely from long-term accumulation after repeated use of pesticides, or use of pesticides or other chemicals with long residual effects. Some problems that result from chemical residues include toxic effects on crop species and contamination of workers, livestock and adjacent streams. Control is often difficult and may involve allowing contaminated areas to lie fallow, leaching affected areas, trying to deactivate or neutralize the chemicals, removing the contaminated soil, or selecting tolerant crops.

Heavy metals

From a chemical point of view, the term 'heavy metal' is strictly ascribed to transition metals with atomic mass over 20 and has a specific gravity of above 5 g cm^{-3} or more. In biology, "heavy" refers to a series of metals and also metalloids that can be toxic to both plants and animals even at very low concentrations.

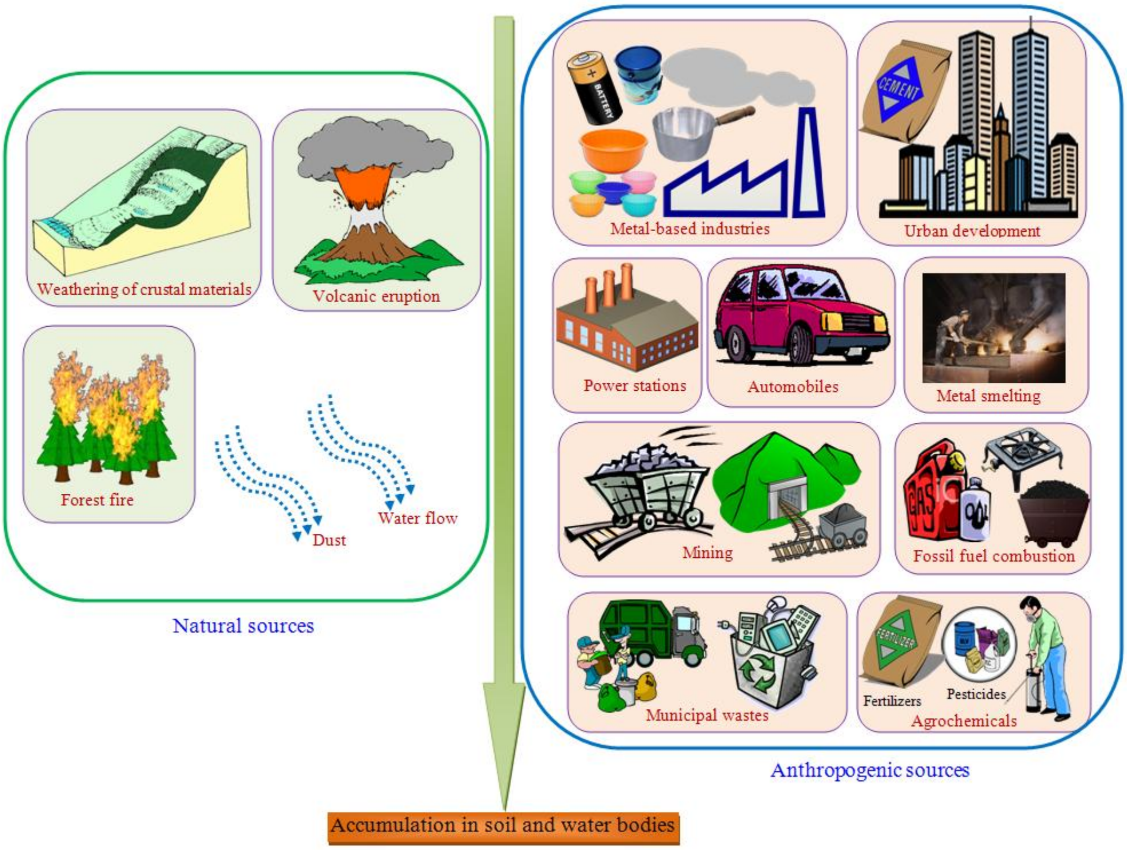

Fig. 6 Sources of heavy metals (Hasanuzzaman and Fujita 2012)

Fig. 7 Common effects of toxic metals in plants (Hasanuzzaman and Fujita 2012)

Phytoremeiation: A sustainable way to remove heavy metals

Phytoremediation is defined as "the engineered use of plants *in situ* and *ex situ* for environmental remediation". These strategies refer to the use of higher plants and their associated microbiota for the *in situ* treatment of soil, sediment, and ground water.

The phytoremediation is a cost-effective 'green' technology based on the use of metal-accumulating plants to remove HMs from soil and water. Phytoremediation has been reported to be an effective, non-intrusive, aesthetically pleasing, socially accepted technology to remediate polluted soils. Biologically based remediation strategies, including phytoremediation, have been estimated to be 4 to 1000 times cheaper, on a per volume basis, than current non-biological technologies.

Different kinds of phytoremediation/Mechanisms

Many plant species possess the genetic potential to remove, degrade, metabolize, or immobilize a wide range of contaminants by different process (Fig. 9). The phytoremediation process may be divided into following heads based on their nature of remediation process:

1. Phytoextraction/Phytoaccumulation
2. Phytostabilization
3. Phytodegradation/Phytotransformation
4. Rhizofiltration
5. Rhizodegradation
6. Phytovolatilization
7. Phytorestauration

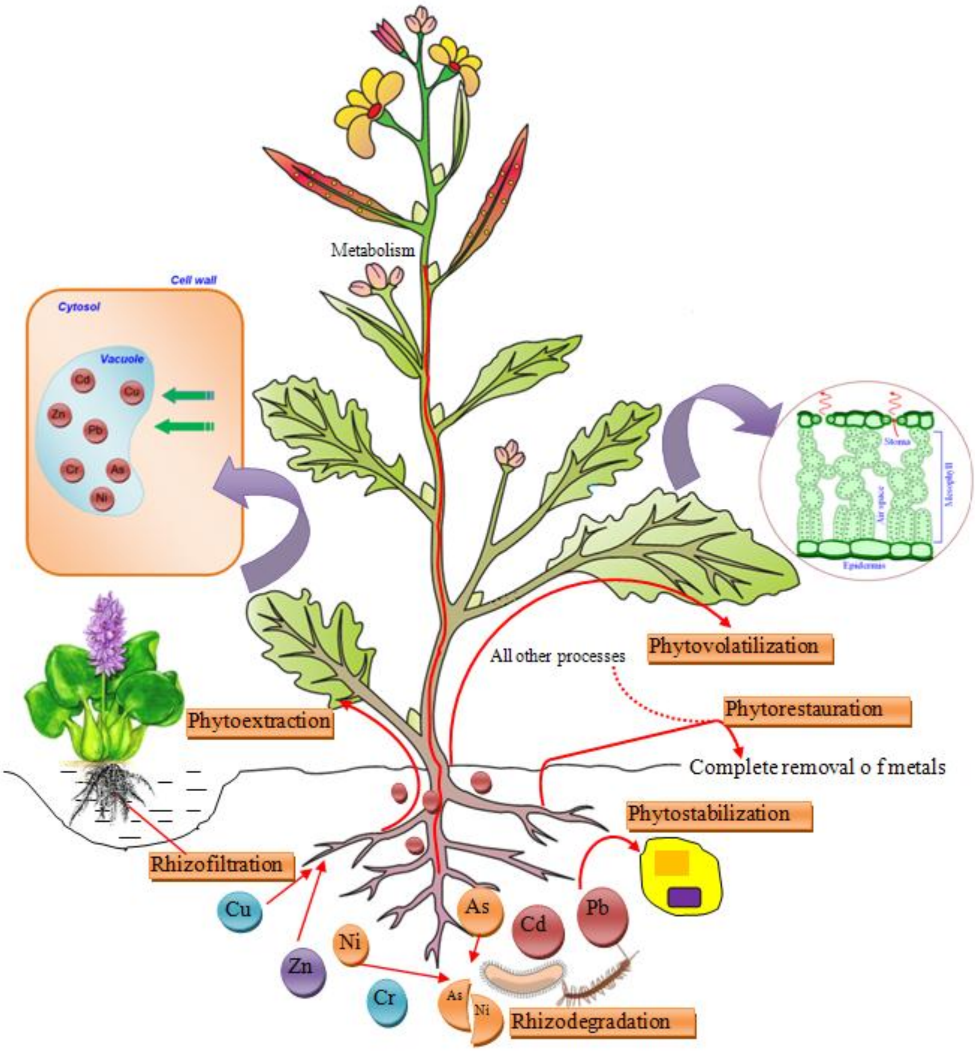

Fig. 8. Major components of phytoremediation of toxic metals (Hasanuzzaman and Fujita 2012)

Improving soils to make it sustainable

Adding organic matter

Most soils will benefit from the addition of organic matter, except those rare soils that are already high in organic matter such as peaty soils. Soils with good levels of organic matter are generally have a good ‘tilth’.

Organic matter will improve the soil by:

- Helping to improve soil structure; this will also improve water penetration and drainage, as well as improving aeration.
- Helping to retain moisture in well drained soils, e.g. sandy soil; every percentage point of soil organic matter is considered capable of holding the equivalent of 25 mm of rainfall.
- Acting as a buffer against sudden temperature or chemical changes which may affect plant growth
- Encouraging the activity of beneficial soil organisms such as earthworms

Adding non-organic materials to soil

Adding lime

This is the main way to raise the soil pH if it is too acid. Soils can be naturally acid, or may become too acidic when (i) fertilizers such as sulphate of ammonia have been extensively used, (ii) where excessive manures or mulches are applied, or(iii) if plants that deplete the soil of calcium (e.g. legumes) have been grown. Lime might also be used if you are growing lime-loving plants such as cabbage, cauliflower and broccoli.

Adding gypsum

Gypsum is commonly applied to hard packed or poorly structured clay soils. It has the ability to cause clay particles to aggregate together in small crumbs (or peds), thereby improving structure. It is also used to reclaim saline or sodic soils. It will not affect soil pH to any great extent. Rates of up to two tonnes per hectare are used to treat hard-setting cereal growing soils, and up to 10 tonne per hectare to reclaim saline-sodic clay soils.

Cultivation techniques

Conservation tillage

This aims to reduce tillage operations or cultivations to only one or two passes per crop. Conservation tillage has been shown to give sustained, improved yields. There are also considerable benefits in reduced labor costs and decreased fuel costs, as a result of the reduced number of passes required.

The biggest barrier to the use of conservation tilling has been the cost of buying or modifying tillage and seeding machinery. Conventional seeding machinery has had difficulty coping with the retained stubble. As this method of cultivation has increased in popularity, there has been extensive development of new machinery that can cope with such demands.

Choosing the right fertilizer

Using the right fertilizer helps to (i) minimize wastage, (ii) reduce costs, and (iii) reduce negative effects on the environment, while (iv) maximizing plant growth.

- Timing is important so as not to waste fertilizer. In winter, some plants may be dormant so the fertilizer will not be taken up. Heavy feeding at the wrong time of year can also cause fruit trees to produce plenty of leaves at the expense of fruit.
- Quick-release or soluble fertilisers are very mobile, which makes them easier for the plants to access, but unfortunately most of the nutrients can be leached into streams or ground water,

eventually ending up in rivers, bays, dams and estuaries, causing problems such as algal blooms.
- Using slow-release fertilizer can be a more efficient way of feeding plants.
- Home-made fertilizers can be prepared using compost, animal manures and mulch material. Some plants themselves are excellent sources of nutrients, including legumes.

Mulches

Mulching will do the following:

- Reduce the need for watering (by preventing evaporation from the soil surface)
- Minimize temperature fluctuation in roots, i.e. reduces frost damage, keeps roots cool in summer and warm in winter
- Control weed growth
- Reduce wind and water erosion
- Improve the appearance of a garden
- Organic mulches provide nutrients as they decompose.

Role of crop residues management on soil and environment quality

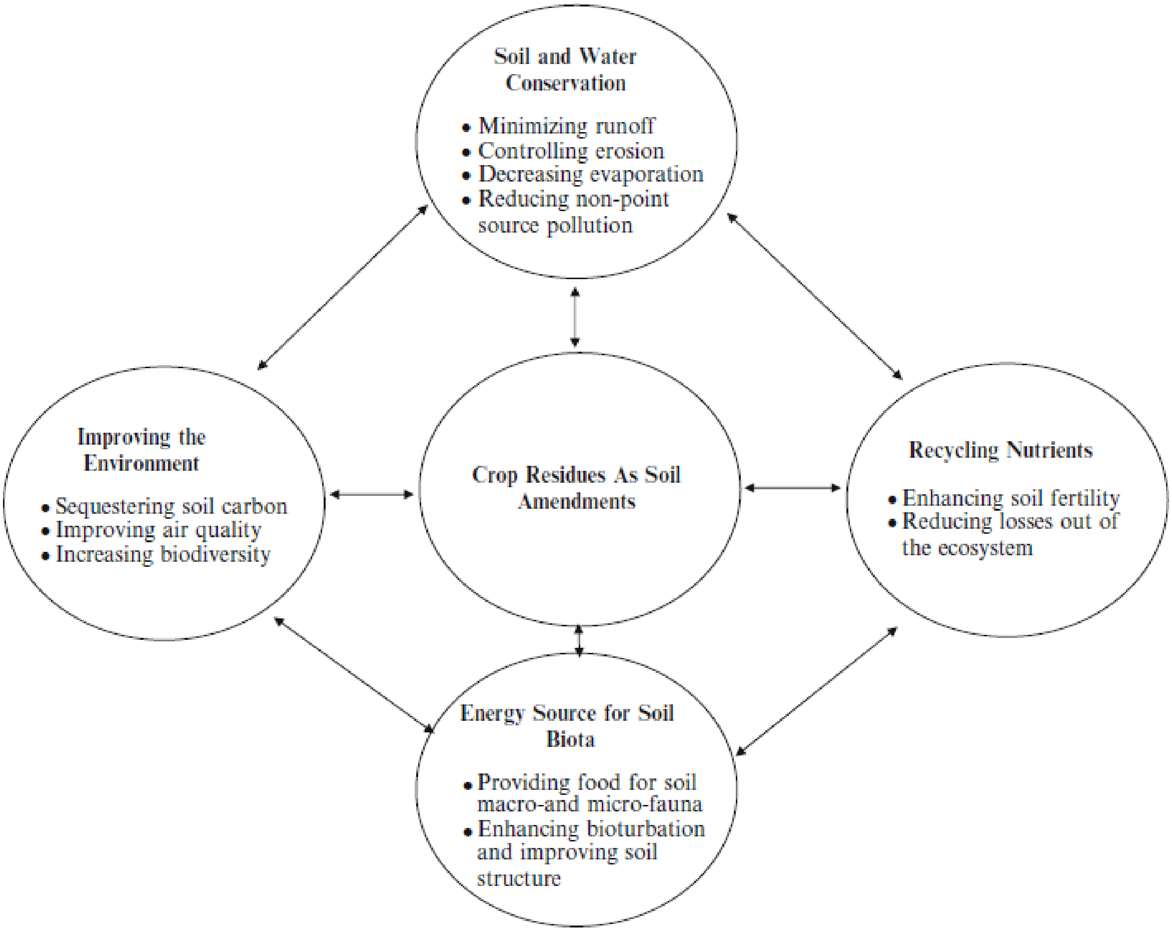

Fig. 9 Site and ecosystem specific effects of crop residue management on soil & environment quality

Components of sustainable soil management systems

<table>
<tr><th>Humid tropics</th><th>Sub-humid tropics</th><th>Semi-arid tropics</th><th>Wetlands</th></tr>
<tr>
<td>Trees
• To avoid erosion
• To recycle nutrients

For mulch:
• To maintain organic matter
• To suppress weeds

Fertilizers
• To increase yield
• To replace nutrients

Lime
• To control acidity
• To replace Ca (and Mg)

Relay and intercropping
• To minimize soil exposure
• To control erosion

Terracing and contour bunding
• To control erosion
• To remove excess water</td>
<td>Trees
• To avoid erosion
• To recycle nutrients

For mulch:
• To maintain organic matter
• To suppress weeds

Fertilizers
• To increase yield
• To replace nutrients

Lime
• To control acidity
• To replace Ca (and Mg)

Green manures
• To provide nitrogen
• To maintain organic matter
• To minimize soil exposure

Contour bunding
• To control erosion</td>
<td>Animals
• To transfer nutrients
• To provide manure

Fertilizers
• To increase yield
• To replace nutrients

Grassed contour strips, hedgerows or bunds
• To control erosion
• To provide animal feed

Raised beds
• To control water on heavy clays

Tree windbreaks
• To control erosion by wind

Irrigation and drainage
• To supplement rainfall
• To avoid salinity and waterlogging</td>
<td>Terracing or bunding
• To retain water

Puddling
• To minimize drainage
• To control weeds

Irrigation
• To supplement rainfall and natural floodwaters

Fertilizers
• To increase yield
• To replace nutrients

Surface drainage
• To remove excess water</td>
</tr>
<tr>
<td>Example:
• Plantation crops with legume groundcovers
• Long-fallow shifting cultivation</td>
<td>Example:
• Agroforestry systems where trees provide an economic return
• Zero-till mulch farming with fertilizers and lime, and an economic source of organic matter</td>
<td>Example:
• Fertilized legume-based pastures with controlled grazing, either continuous or alternating in space and time with arable cropping</td>
<td>Example:
• Flooded rice systems with controlled water supply and fertilizer</td>
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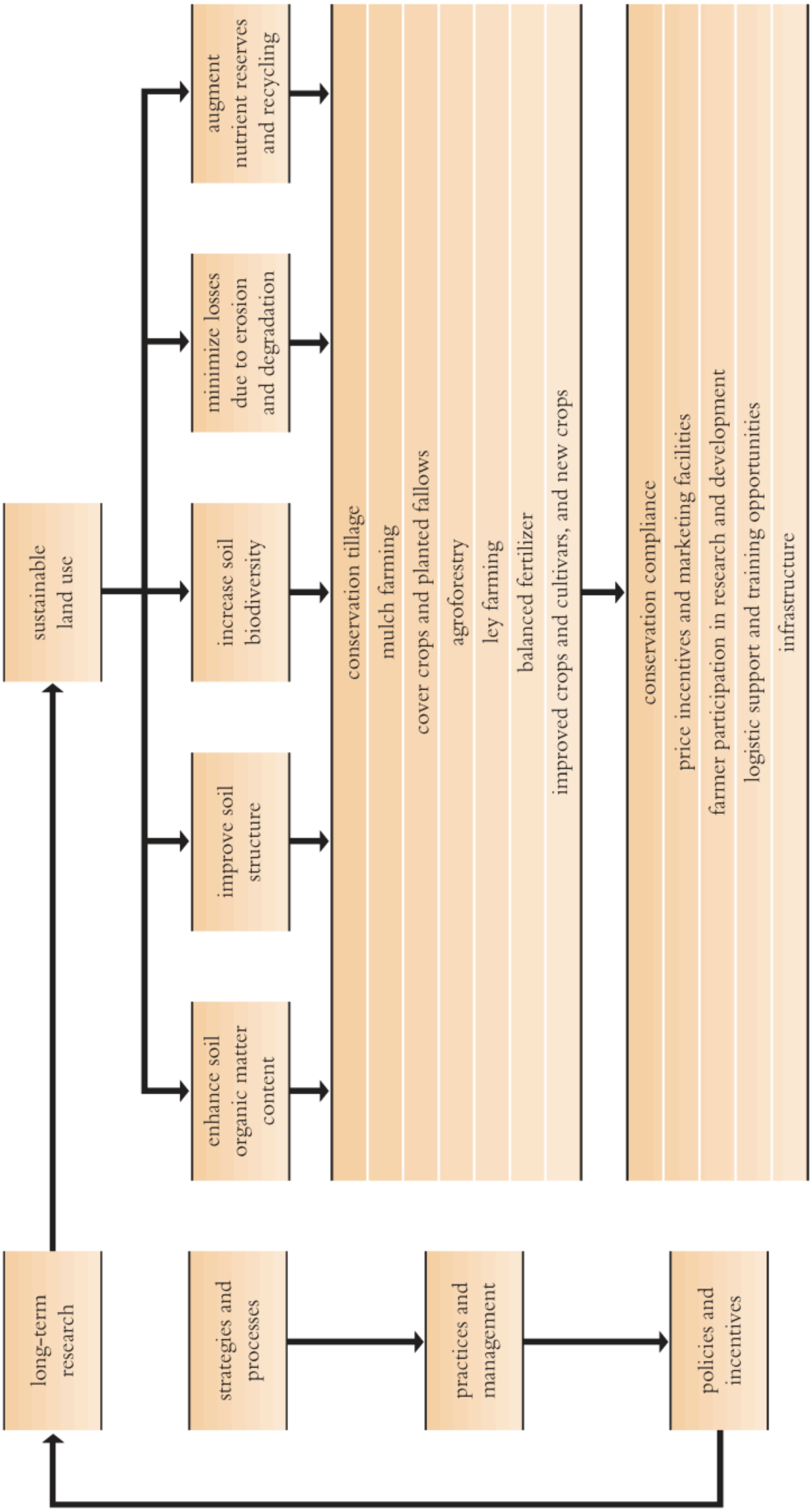

Fig. 10 Processes, practices and policies involved in land use and soil resilience (FAO 1994)