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Land husbandry: an agro-ecological approach to land use and management
Part 2: Consideration of soil conditions

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> *"Porosity was defined and calculations were made relating porosity to bulk density, and so on. What was missed was that it is the pore space, and more specifically the water films in the pores, that are the spaces used by life in the soil. Pore space is where the action is!"* (Anderson, 2006).

Abstract

This paper, complementing the first part (Shaxson et al., 2014), sketches the outlines of an ecologically-based approach to better care of soils, within the overarching context of 'land husbandry', contributing to more-effective conservation of soil and water. It suggests an up-dated paradigm which concentrates more on renewing and conserving the biologically-moderated spaces in the soil in the root-zone rather than on the solid soil-particles themselves. When read in sequence, the two papers offer contributions to better understanding of both the problems and the possibilities for solving the ongoing uncertainties of how best to repair damaged lands, to maintain and improve those areas already in use, and to safeguard the potentials of those as-yet-unopened areas which surely will be brought into production in the future, by the planning and executing of optimum strategies for assuring sustainability of their uses into the future. These two papers do not set out to challenge existing knowledge, but rather to suggest additions to, and alternative interpretations of, what may already be known. The conclusions suggest some important amplifications to any curriculum for the training and/or up-dating of people involved in those subject-areas which contribute to better land husbandry and more-effective conservation of soil and water, as well as to the buffering of soils' productive capacities against the possible adverse effects of climate change.

Key Words: Organic matter, Soil porosity, Paradigm-shift

1 Introduction

Within the context of modern concepts of soil conservation, as described in previous issues of this journal, (e.g. WOCAT, 2007; Motavalli et al., 2013; Dumanski & Peiretti, 2013; de Freitas & Landers, 2014), this article follows-on from its first part (concerning landscape) (Shaxson et al., 2014), which described conceptual and practical means for harmonising proposed types of land use with the significant characteristics of a particular catchment within a landscape. This second part considers aspects of the soils which clothe such landscapes, and some means by which these soil/plant agro-ecosystems should be appropriately managed for them to provide – and maintain – optimum conditions for yielding plants and water on a sustainable basis.

The paper draws on and expands on topics considered in Shaxson (2006).

2 Causes for concern

As human populations continue to rise towards a plateau of some 10 billion people in the second half of this century, there are major concerns about the Earth's capacity to satisfy associated demands for regular supplies of water, food and other products of the land (Oldeman et al., 1991); Reserves of unused but potentially productive

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land have been diminishing: by 2005, some two-thirds of the world's ecosystems had already been severely degraded, and only about 11% remained in reasonable condition (MEA, 2005). Coupled with the effects of inappropriate land use and/or management methods, more-intense rainstorms and more-severe droughts contribute to rising production costs under conventional tillage systems of agriculture, and diminish such systems' potential for sustainability in the future under a changing global climate (Maslin, 2013). The global challenges to be faced now and into the future regarding global food security have been concisely summarized in Beddington and Warham (2014).

Although much effort in soil conservation has been expended since before the 1930's (see e.g. Bennett, 1939 to WOCAT, 2007) and to the present day, erosion and floods continue. Despite good efforts, repeated damage to the lands from which they still emanate has often not been lastingly repaired, nor has their repeated degradation been automatically avoided. Where inappropriate selection and management of land and soil continues, in coming years the sustainability of their potential for production of plants will continue to be compromised. In addition, the regularity, volume and quality of streamflows from such areas are likely to be prejudiced, even as demands for dependable and clean water supplies continue to rise (Fig. 1).

Fig. 1 River-water contaminated with soil eroded from the upland catchment: Lake Malawi (Photo: courtesy of T. R. Jackson)

Three errors are commonly made in discussions about how best to address the problem of soil erosion. First, it is unhelpful to conceive of erosion using statements such as: "*the war against erosion*", as if "*erosion*" is an invisible force in its own right. In reality, erosion is an ecological consequence – not a primary cause – of soil damage. Second, it is similarly unhelpful to state that the three main causes of erosion are "*deforestation, overgrazing and excessive cultivation*" (even though they are certainly contributing factors). Many governments have legislated against these supposed causes, though with little success in diminishing the erosion problem, because neither the reasons for the occurrence of runoff and erosion, nor the most-appropriate means of minimizing them, are widely-enough appreciated. The underlying cause of erosion by water is the force of water's downwards impact (of rainfall and/or irrigation) interacting with a somewhat fragile soil matrix whose aggregate-stability and -structure have been disrupted and whose absorptive capacity has been diminished, resulting in "avoidable" runoff and soil erosion. A third common fault is the failure to anticipate the possibility and nature of future problems, and only to react, if at all, after they have arisen. From this, it may be stated that soil erosion is not necessarily an automatic consequence of using land for agriculture.

3 Where should we go from here?

Rather than only intensifying common efforts at erosion control by allocating more money to soil & water conservation and putting more people "on the ground" to reinforce current actions, some "lateral thinking" (de Bono, 1970) helps us to dissect the current situation and informs the search for better ways forward. This means separating facts from fiction, re-interpreting what has already been observed, and considering new aspects that might prove to be relevant. As this paper will argue, understanding soil porosity as one of the key features in defining the productive capacity of a soil will help us to understand the origins of runoff and erosion and lead to a better-defined paradigm of more-effective soil and water conservation.

3.1 *A biological definition of "soil"*

"Arguably, society might take better care of soil if it were considered less as an inorganic physical unit of mineral particles, air, water, and nutrient ions that happens to contain life, but more descriptively as a living system, a complex and dynamic subsurface ecosystem of diverse living organisms (including plant roots), non-living organic matter and biologically-transformed organic/humic products, which inhabits, modifies and interpenetrates an inorganic mix of mineral particles, air, water and nutrient ions, and which changes dynamically over the fourth dimension of time" (Shaxson, 2006).

3.2 *Soil porosity*

A soil in good condition which yields vegetation on the one hand, and moderates water-movement on the other, is made up of a combination of solid particles of sand, silt, clay and non-living organic matter, which, because of their often-irregular individual shapes, have – in between them – three-dimensional spaces of a range of sizes, which may change in the fourth dimension of time. The particles may be "glued together" at their points of contact by inorganic ligands such as iron oxide and/or by carbon-rich organic mucilages or gums derived from the metabolic actions of soil-inhabiting living organisms such as microbes, fungi and plant roots. Such a soil is an ordered and complex composite of solids, glues/cements, liquid, gases and spaces of various dimensions. The presence and relative proportions of each size-group of pore-space within a given volume of soil are important, as these affect (a) the volume of water which can be stored within a given volume of soil at plant-available tensions; (b) the ease with which roots and other soil-inhabiting organisms can physically permeate the potential root-zone; and (c) the rate at which infiltrated water (beyond plants' requirements), can percolate down to any deeper groundwater.

3.2.1 Attributes of soil pores

Roots can penetrate, and extract water from, soil pores and fissures in soil aggregates which are of mean diameter greater than 0.1 mm; root hairs can penetrate those as small as 0.005 mm.

Pores of diameter greater than 0.05 mm allow water to drain out and air to enter; unless the soil is saturated, they may be filled with air. Those of smaller diameter – between 0.05 mm and 0.0002 mm – can retain water against the pull of gravity that plants can use; but the very smallest pores – less than 0.0002 mm diameter – retain water against both gravity and any suction that can be exerted by plant roots. At that point the water-retaining force exerted by the menisci at the boundaries between the water and surrounding solid soil-particles is about 15bar, known as "Wilting Point" (derived from Schwab et al., 1966; Russell, 1988; Hamblin, 1989).

A good quality loamy soil may be 50%–60% pore-space, of which two-thirds can be filled with water, of which 50% is available moisture. So 1 meter depth of such a soil can hold some 170–200 mm of plant-available soil moisture. However, when soils lose their normal porosity and structure due to tillage, the pore-space can reduce to 10%–20%, severely affecting most soil ecosystem functions and soil productive capacity.

The "glues", such as glomalin (derived from soil-inhabiting fungi), are of particular significance in the formation and stability of porous soil aggregates (USDA, 2014). For this process of formation and re-formation to be continuous, a supply of "raw" non-living organic materials such as dead roots, fungal hyphae, leaf-litter, animal excreta etc., is necessary, and needs regular replenishment. On this the soil micro-organisms and fungi organisms can "feed". From this it can be deduced that living organisms have – and demonstrate – the capacity to restore damaged soils back to a state of integrity and ordered functioning (Flaig et al., 1977).

This interplay between living and non-living organic materials is thus among the keys to both soil "fertility" and to the sustainability of soils as potentially-productive entities. On the one hand, the complex dead organic matter is dis-associated by soil-inhabiting organisms back to its simpler components with the "liberation" of nutrient ions into the soil solution, enabling re-absorption by other organisms. On the other hand, its decomposition also ‘liberates’ energy from the carbon linkages, which becomes a source of living organisms’ own energy and life-processes within which more complex compounds are re-combined again, in the ongoing carbon-based cycle of build-up of complex molecules in living organisms, followed by simplification after death, and then by re-cycling.

Assemblages of particles (aggregates, comprising both solids and spaces) give the soil its porosity, through which air and the respiration-gases of the organisms (microbes, plant roots etc.) can exchange with the above-ground atmosphere, and through which water, roots and other meso-organisms, such as earthworms, can physically extend and move. Through these same pores of various sizes and shapes, incident water from rain or irrigation can, on the one hand, percolate downwards under the influences of gravity and, on the other, be detained by the strength of surface-tension forces of the air-liquid boundary meniscus at the contact angles of solids etc. bounding each soil pore. The microbial components of the soil-inhabiting biota subsist in the water films coating the particles and aggregates that form the walls of the soil pores.

Under the influence of gravity, soil pores will drain out progressively over time downwards to a water-table and thence to streams and rivers. A preponderance of large pores may permit rapid through-flow and little storage; a preponderance of small pores initiates quicker saturation of the uppermost layer of soil during rainstorms when the rate of rainfall exceeds the rate of infiltration, thus producing higher volumes of surface run-off during such periods; beneath the surface, a high proportion of small pores limits the rate of removal of the water by plants and by soil drainage due to gravity.

To ensure water can be retained at a range of tensions between Field Capacity (when the soil can hold no more against the pull of gravity) and Wilting Point (at which plants can no longer extract sufficient water to avoid wilting), a sufficiently large volume of pores, made up of a range of different sizes, needs to be maintained in a given volume of soil.

Runoff and erosion may occur when the rate of water income – from rainfall, irrigation or overland flow – exceeds the rate at which it can pass down into the soil. Destruction of the pores – and thus of porosity – in the upper layers of soil contributes to the frequency with which such infiltration rates are exceeded and overland flow of runoff is generated.

Some of the macroscopic attributes of the land thus depend – for many aspects of their dynamics – on some of the microscopic features of the soil/plant systems represented. Therefore, the role of life-forms and their self-reproduction capacity in soil is critical for reversal, repair, improvement, stabilization, and maintenance of soil structural conditions.

3.3 *Loss of soil porosity*

Several factors acting on the soil can damage its porosity to different depths and with different degrees of severity, which will affect the relative proportions of incoming rainfall that are diverted among various destinations, and the soil’s overall ability to accept and hold water which can be used by plants and other soil-inhabiting organisms. These destinations include: soak-in, storage, runoff, direct evaporation, evapotranspiration, through-flow.

By collapsing the structure, most of the useable spaces are lost (“densification”). The absolute amount of solid materials may remain, but in a different, more-compact arrangement. This results in reduced amounts of plant-available water, and in diminished aeration, and movement of respiratory gases between soil and atmosphere. All these effects, taken together, reduce a soil’s capacities for yielding useful plant materials for harvesting and water for streamflow.

Whatever the cause of densification/compaction, this loss of soil porosity has an economic effect. Under continuous cropping in New Zealand, repeated soil compaction progressively reduced grain-growers’ gross profit margins over time, due to: (a) increasing costs for tillage, increasing fertilizer costs, costs of re-sowing, and uneven ripening dates, and, simultaneously, (b) decreasing gross receipts because of poor germination, poor plant growth and vigour, low grain quality, soil erosion, and fungal infection (e.g. Shepherd, 1992). Activities that cause damage to soil porosity factors include:

3.3.1 Oxidation of organic matter due to mechanical tillage

The depth, frequency, type and/or severity of tillage materially affects the rate of breakdown of soil organic matter and consequent loss of CO_2 into the atmosphere. This is because a higher concentration of oxygen in the soil voids following tillage enables faster biological respiration and breakdown of the soil organic matter by the soil-inhabiting organisms.

Field experiments reported by Reicosky (2001) indicated that rates of loss of CO_2 from a field soil varied from 10 g m^{-2} in 24 hrs. from un-tilled soil, to 229 g m^{-2} in 24 hrs. from soil ploughed to a depth of 280 mm. Glanz, recorded in FAO (2008), showed that tillage-induced rates of decomposition of organic matter, recorded as weight of o.m. lost in 19 days, ranged from 860 kg ha^{-1} from direct-seeding to 4,300 kg ha^{-1} under heavy-duty ploughing+disc-harrowing.

Loss of humic colloids, their precursors, and other soil organic matter by oxidation and release of CO_2 into the atmosphere is particularly damaging, since any net loss of carbon in this way deprives soil life of energy sources and nutrients involved in dynamic re-structuring, maintenance and improvement of soil physical conditions. The activities of living organisms contribute not only to the formation of soils capable of providing yields of plants and of water from a landscape, but also to the soil's biological capacity for self-repair into living-spaces optimized to their different needs, with bounded spaces for protection and for life-processes to proceed and organisms to reproduce.

This oxidative breakdown of carbon-rich organic matter in these situations reduces the cohesion between soil particles provided by the humic colloid glues which bind them, thereby reducing the stability of soil aggregates and contributing to loss of porosity. In addition, net loss of carbon from the soil diminishes the adequacy of other benefits derived from soil organic matter, such as the sufficiency of food materials for soil-inhabiting micro- and meso-organisms, and the slow release of nutrient ions into the soil solution.

Networks of fungal hyphae, such as those of the symbiotic arbuscular mycorrhizas, form wide-spreading biological networks in the soil and make intimate associations with plant-roots. They improve the roots' access to plant nutrients beyond the immediate vicinity of the roots' rhizosperes, as well as contributing glomalin gum to the stabilisation of soil aggregates. Tillage disrupts and diminishes such networks (Habte, 2006).

The changing of a soil's colour from darker to lighter hue, and a decline in physical stability of the soil's structural condition over time, are visible qualitative indicators of diminishing content of carbon-rich soil organic matter.

3.3.2 Pulverisation

Tillage of dry soil can also physically destroy the porous integrity of soil aggregates by mechanical pulverisation (e.g. Montgomery, 2007). At the other (macro) end of the scale, while the use of rippers/ subsoilers may be justified to break impermeable layers and allow water into the subsoil, the large voids created are of too great a size to be colonised rapidly and densely by roots or micro-organisms, are prone to subsequent collapse, and therefore are unlikely to remain open after a short time. In dryland conditions, overgrazing of natural rangelands is accompanied by soil pulverisation, compaction, decline of plant vigour, and wide-spreading dust-storms, following the loss of soil porosity, as, for instance in Inner Mongolia (Williams, 2006).

3.3.3 Compaction

Topsoil compaction is caused by contact pressure; lower-subsoil compaction is related to axle load (Penn State, 2014). Frequent passage of wheels, people's feet, and/or animals' hooves cause significant problems by "squashing" soil voids out of existence. By contrast with the respiration-increasing effects of the disruption by tillage, soil compaction slows the rates of exchange of the subsurface microbial respiration gases oxygen and carbon dioxide between the soil and the above-ground atmosphere.

Such loss of porosity is evidenced by puddles forming in wheel-tracks, footpaths and earth roads after rain. Repeated passage of people's feet along gaps between rows of hand-cultivated crops during the rainy season can cause similar problems, resulting in the uppermost soil layer becoming almost impermeable to rain or irrigation water. And long durations of high concentrations of grazing animals on pasture-land can also make the soil surface layer impermeable by the actions of their hooves, a clear symptom of overgrazing with respect to the rate of recovery of both vegetation and soil.

The upward-lifting force of farming equipment (such as mouldboard ploughs, disc-ploughs, disc harrows, rotavators and hand-hoes) on the soil above its operating-depth is balanced by an equal and opposite downward force from the equipment on the soil beneath. This can be severe enough to limit the effective depth of a given soil to only a few centimeters, providing serious hindrance to the penetration of rainwater and crop roots (Figs. 2 and 3).

Fig. 2 Subsurface compaction ("panning") due to repeated annual disc-tillage on a (pedologically "deep") soil in the Brazilian cerrado region (Soil auger for scale)
(Photo: T. F. Shaxson)

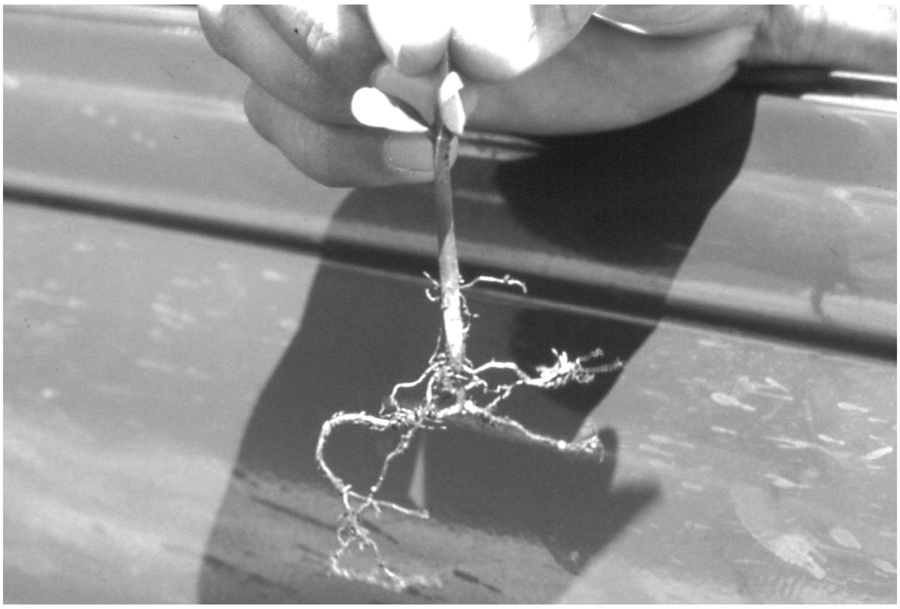

Fig. 3 Close-up of a soya seedling's root-system which has been unable to break through the "disc-pan"
(Photo: T. F. Shaxson)

As illustrated in both Fig. 2 and Fig. 3, compaction has diminished the optimum functioning of biological processes within the soil body.

Crops grown in tillage-agriculture systems may thus suffer a triple jeopardy: (i) indirect effects of loss of organic matter from the disturbed upper rooting-zone, as well as (ii) the loss of adequate aeration in the lower zone of rooting, plus (iii) decreased availability of soil moisture.

3.3.4 Raindrop impact

The impact of large water-drops can cause serious damage to the soil porosity, whether directly from intense, energetic rainfall or irrigation-projection onto a bare soil surface, or from water-drops which have coalesced on the leaves of high cover (such as tall bushes and trees) and have also gained terminal velocity before striking a bare soil-surface. On hitting the surface, the force of impact may be sufficient to damage porous soil aggregates by breaking bonds between component soil particles, resulting in the crusting illustrated below (Fig. 4). It is a salutary observation that each one mm of rain falling on one hectare equates to 10 tonnes of water. Thus an intensive rainstorm of 30 mm of rain is producing 300 tonnes of minute hammer blows per hectare on the soil surface or the vegetation above it.

Fig. 4 Top-side and under-side of a bare soil-surface rammed and crusted by the impact of large raindrops (Photo: T. F. Shaxson)

The implications are clear for potential effects of multitudes of such large drops falling from great heights onto weakly-structured bare soil during intense rainstorms. The photograph below illustrates the crux of the problem for soil degradation: the loss of optimum soil porosity. At rainfall intensities of between 115–165 mm/hr, the mean diameter of raindrops in a storm is between 2 and 3 mm, and may reach a terminal velocity of ca. 7 m/sec., (Hudson 1981, pp. 56, 58) with energy of about 29 joules per sq.m. per mm. of rain (Hudson, 1981; Hudson, 1995). Falling onto a bare soil surface, this can cause dis-placement of different soil particles upwards and sideways ("splash erosion"). Each large drop of ca. 3 mm diameter is capable of splashing soil particles at least 260 mm laterally, and at least 270 mm vertically. However, in addition to splashing of soil particles, the force of impact can also ram dislodged individual smaller particles of an un-covered soil surface downwards into the spaces between larger particles, producing an almost impermeable soil crust. This hinders the infiltration of the rainwater into the soil profile, thus increasing runoff of the rainfall in excess of infiltration across the surface of sloping land.

A mixture of inert soil mineral materials may have many particles of different shapes and sizes, but – if once collapsed or rammed together – pore-spaces between them cannot be easily generated, regenerated and maintained between them if disturbed by any of the factors described above, without the influence of organic matter and biological activity.

Without adequate volume and range of sizes of pore-spaces, the combinations of the four components of soil – physical, chemical, biological and hydrologic – cannot function effectively as a productive plant/soil system. The overall effect is that, by losing its spaces, the soil's structure is diminished in usefulness, both for plant growth and for the acceptance, storage and yielding of water to plants and streamflow.

There is, however, one exception to the generalised suggestion that improvement in porosity and permeability of compacted soils is beneficial. In regions of ancient soils, such as in parts of Australia, permeable topsoils may have developed above highly-impermeable subsoils. On sloping sites, excess upper-soil moisture can lead to development of tunnel-erosion along the interface between the permeable and impermeable layers. This, in turn, can lead to the formation of gullies when such tunnels collapse. Usually tunnel erosion becomes apparent some years after the land has been cleared of its natural vegetation. Once tunnel erosion has commenced, it is difficult and expensive to remedy by mechanical methods. Re-establishing deep-rooted perennial vegetation that grows actively during the periods of highest rainfall, and pumps out excess soil water by evapo-transpiration, may be the best background-action for soil reclamation. However, it would have been better if the land had been properly assessed as to its capability/incapability for the chosen use (in the manner indicated in the first paper of this series) prior to being cleared in the first place.

The effects of demolishing a block of apartments with dynamite explosions are analogous to those of destroying soil porosity: Loss of useful spaces diminishes flows of air, water and communications; living-spaces are constricted or lost, and the remaining disorganised solids lose their value. In addition, the remains may be washed away by rainfall and floods. Loss of voids within the soil's architecture results in the decline of its productivity, stability, and usefulness for the chosen purpose.

3.4 *Reversing the damage*

In the context of management of natural resources, soil degradation and erosion are ecological problems, to which physical means of control – on their own – are not effective or lasting solutions (Downes, 1982). If soils are treated as inanimate entities, then – under the influences of gravity, disruptive forces such as fire, rainfall-impact, tillage etc. – they tend to break down into simpler and more-disordered components. This implies a gain in entropy in the system, and a lessening of usefulness in terms of ecological functioning (Shaxson, 2006), with no indication of how sustainability of a soil's usefulness could be achieved realistically. The erosion of soil, by whatever cause, is an example of such loss of order and of complexity, and of a gain of entropy by the plant/soil/water system, and illustrates the working of the Second Law of Thermodynamics. In this scenario, the situation for the sustained production of crops and water is, over time, unsustainable.

However, this is not an inevitable consequence, because of life's capacities to reverse the trend, increasing order and complexity in the system, in seeming opposition to the Second Law of Thermodynamics. Life's ability to establish itself in different forms, even in unlikely places, is something of which we need to take advantage (see Uphoff, 2006).

A key fact to note is that all true soils with productive potential are inhabited by a wide range of soil-inhabiting organisms. Optimally-sized and – distributed pore-spaces in soil are generated, regenerated and maintained by living organisms, many of whom have a role also of accessing and mobilizing nutrients and water, and imparting resilience to biotic and abiotic stresses. Some have endophytic relationships with crop plants that can increase photosynthesis rates and resistance to pest attack, and many have a role in the process of humification and carbon sequestration.

3.4.1 Aggregates in five dimensions

Using physical, chemical and hydrological components of soil, and their interactions, micro-organisms make their self-agreeable habitats[1] in among the empty spaces (voids) between particles. Here their exudates from hyphae, plus those from roots, worms and other organisms, provide bonds between individual particles with a tendency to produce multi-porous aggregates of a range of sizes (Genxing Pan et al., 2013; Tivet et al., 2013; Seguy et al., 2006).

3.4.2 Regaining soil porosity

Soil porosity can be regained, but for that to happen two actions are needed:

(i) Diminish the rate of degradation by avoiding future losses, through minimising the severity and frequency of factors that caused the loss in the first place.

a. Maximising protective cover on or close above the soil to mitigate raindrop impact and splash effects; The closer to the soil surface and the more evenly-spread is a permeable cover (of e.g. a mulch of grass or leaves) that protects the soil surface, the less the soil will be damaged by splash and impact of rain drops (Fig. 5) (see

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[1] This perception is consistent with the origins of the words "ecology" (Greek: "oikos" = house); and "husbandry": (Old English) "Husbonda" ("hus"= house + "buandi" = Old Norse : "bua"=to dwell) (Chambers 20th Century Dictionary, 1983; p.613).

also Elwell, 1981).

b. Improving the proportion of organic matter as a soil component;

c. Minimising pulverisation from excess tillage;

d. Minimising the compressive impacts by tillage equipment, wheels, feet and hooves.

1/250 sec

Fig. 5 Effective cover disperses the energy of falling raindrops

(Photo: T. F. Shaxson)

(ii) At the same time, actively improving soil porosity by favouring the living-conditions of appropriate organisms of the soil's microbiome.

Optimally-sized and -distributed pore-spaces in soil are generated, regenerated and maintained by living organisms, including earthworms, whose significance includes (a) physically dragging leaves etc. down in their burrows; (b) the mixing of soil particles with organic matter; (c) by their presence/absence as indicators of the health or otherwise of the soil. Soil therefore has physical, chemical and hydrological properties whose interactions are "animated" by its biological component, the soil-inhabiting organisms (which includes plants). Seen in this way, soils deserve to be treated as living organisms, rather than just as "dirt" (Montgomery, 2007).

The biological activities of the soil micro-biome will be limited where the appropriate association of available water (hydrator of cells and solvent for nutrient-supply) with air-movement (affecting proportions of oxygen and carbon dioxide) is unbalanced. This occurs when the spaces within which they subsist are disrupted. An ongoing supply of sufficient organic matter is, therefore, essential for maintaining the vitality and reproduction of the soil organisms, and thus for the ongoing re-formation and repair of soil-structural units whose pores they fashion to provide habitable spaces (Flaig et al., 1977). The same processes are essential to providing the (self-) sustainability of productive soils. There is growing evidence that plants and soil are interdependent, as "plant/soil systems": "*Recent literature amplifies the contention that plants should be understood as systems, not as organisms, as composites of the genes of flora and myriad micro-organisms*" (N.

Uphoff, pers. comm., Oct. 2009; Berendsen et al., 2012; Uphoff et al., 2013; Money, 2014). For example, the superior response of rice plants grown under the system of rice intensification (SRI) cannot be explained in conventional terms that views soil fertility as a quality that resides in the soil itself based on favourable chemical and physical conditions that may be enhanced by biological activity. In reality, there appears to be a large number of endophytic and epiphytic symbiotic relationships operating between crop plants and soil microorganisms that greatly improves the phenotypic expression of plants and their reproductive success. The symbiotant microbial endophytes do more than improving access to soil nutrients. They inhabit the rhizosphere and also live within root interiors and within their sheaths and leaves which changes the expression of tissue cells' genetic potentials, offering much higher rice productivity from soils whose fertility would be regarded as "poor" (Uphoff et al., 2013).

4 Indications of concept validity

4.1 *East Africa: Hydrological effects of changes in land-use in some East African catchment areas*

In 1956 a major project was initiated to make detailed studies of the effects of changes in use and management of land in catchments in four different situations:

a. Development of tea estates in tall rain forest;
b. Grazing control in semi-arid rangeland;
c. Development of softwood plantations in softwood forest;
d. Effects of peasant cultivation practices on steep stream-source valleys.

The studies were conducted between 1958 and 1976, during which a mass of valuable information (relevant to the concept of this present paper) was collected and analysed (Pereira, 1962; Blackie et al., 1979). In the latter final report, the results emphasised the particular importance of maintaining soil porosity (in any situation): "*...it is apparent that soil structure, and the possible effects of land-use change on it, must be considered carefully…If the change reduces the infiltration rates, wet season water yields will increase, whilst ground-water recharge, and hence dry-season water yields, will be reduced. Examples of such adverse effects are all too common in East Africa and elsewhere…*" (p. 275)

Comments which later confirm the effects of worsening soil-structure conditions – over a period of up to 50 years on small farms in rainforest catchments in Kenya – complement those of the EAAFRO studies: "*On the average for both years* (2007, 2008) *the 'flashiness index'* (of the runoff) *after forest conversion* [to cultivation by small farmers] *was 30 times higher after 5 years of cultivation and 45 times higher after 50 years of cultivation.*" (Recha et al., 2012).

4.2 *Southern Brazil – Rio Grande do Sul: effects of changes in soil management on water-infiltration rates*

The opposite trend of change – from damage to recuperation – was documented at Ibirubá, in Rio Grande do Sul state in southern Brazil. Here soil physical conditions indicative of porosity were compared in plots which had been under 4 different land-uses for up to 20 years (Wünsche et al., 1979).

On two experimental watersheds at Ibirubá, Rio Grande do Sul, Brazil, soil physical conditions which were indicative of soil porosity (bulk density; penetrometer resistance; and profile infiltration-rate – in mm/hr- through the upper 35 cm depth) were compared under four different conditions of soil management: permanent forest; cultivation with animal traction for the previous 7 years (least severe); no-till farming for four years following conventional (disc-) tillage for the previous fifteen years; conventional tillage for 20 years. Of significance to this paper, the infiltration-rates through the soil (treatments listed in the same order) were: 112.5; 28.9; 6.0; 0.2 mm/hr. It is apparent that the change from conventional (disc-) tillage to the no-till methodology resulted in an improvement in infiltration rate, but nowhere near sufficient to simulate good "'forest-floor' conditions".

4.3 *Malawi: Soil-recuperating effect of dense-rooted grass (Eragrostis curvula)*

In Southern Africa widespread soil degradation can occur on tobacco farms due to soil compaction during the weekly manual harvesting of the leaves during the rainy season. This can be remedied by growing the crop in a rotation: commonly, after each year under tobacco, the land spends three years under Weeping Lovegrass (*Eragrostis curvula),* whose dense and deep rooting-habit results in biological regeneration of a good permeable soil structure (Figs. 6a and b).

(a)

(b)

Fig. 6 (a) After one year's tobacco, this sandy-clay loam soil (ploughed once), still needed considerably more preparation before seeding it with Weeping Lovegrass; (b)The adjacent section of the field, on the same day ploughed once, but which had been under Weeping Lovegrass for three years, now needed very little extra preparation before planting the next tobacco crop, following the grass's biological optimisation of a porous soil structure

(Southern Malawi) (both photos: T. F. Shaxson)

4.4 *Southern Brazil - Paraná: effects of no-tillage farming on duration of plant-available soil moisture*

The early results from Ibirubá were complemented by a report on comprehensive studies of effects of different forms of soil preparation on soil conditions for planting crops. Experiments comparing conventional tillage with heavy disks versus scarification with tines versus direct-drilling of seed through residues of the previous crop were undertaken at Londrina and Rolândia in Paraná, southern Brazil, between 1977 and 1985 (Derpsch et al., 1991).

The experiments provided a wealth of detailed information on the effects of the treatments on physical soil conditions at different depths, including soil-moisture availability, the temperature ranges in the soil surface layers, soil-aggregate stability, rainfall infiltration rates, plant nutrient availability, biological activity and carbon dioxide emissions, splash erosion, weeds and pests, root-development, crop yields, and effects of rotations with green manure crops. The report covered technical, economic and social consequences.

During the April to September rainy season in 1981, a study was undertaken to compare the duration of plant-available soil moisture (held between Field Capacity and Wilting Point) from the incident rainfall under conditions of Conventional Tillage (CT) and Zero-Tillage (ZT), at depths of 0–10 cm, 10–20 cm, 40–60 cm.

Interpretation of the data in the original Table suggests that the advantage of ZT over CT (expressed as the number of days totaled over the 5-month period May to September during which available moisture remained in uncropped soil at each of the three depths was: 0–10 cm: +65 days; 10–20 cm: +71 days; 40–60 cm: +42 days.

Improved soil porosity under Zero Tillage methodology resulted in marked improvement in the length of time in which soil water remained at plant-available tensions before Wilting Point was reached. Now that the advantages of mulch-based, no-till systems are widely accepted (e.g. Kassam et al., 2013**;** Landers et al., 2013), an interpretation of the above information could be re-phrased in a question as: "*How much worse than no-till are the other (more-conventional) alternatives?*" (Figs. 7 and 8).

Fig. 7 Loss of soil porosity due to tillage, and associated increase in runoff, led to failure of physical conservation works and diminished plant-growth (photo is of lower end of the field shown in Fig. 2)

(Cerrado region, Brazil) (Photo: T. F. Shaxson)

Fig. 8 Young maize planted through wheat straw. An example of no-tillage Conservation Agriculture: productive and protective
(Southern Brazil) (Photo: T. F. Shaxson)

5 Improving the paradigm for achieving conservation of soils and water

"Soil conservation in any environment is fundamentally a problem of determining the correct form of land use and management. [This] is one which provides a higher level or different form of productivity than that available in the natural state, but this new productivity must be capable of being maintained indefinitely. This means that the balance of the natural environment must be replaced by another balanced system under the changed form of land use. The determination of correct land use is therefore a problem of applied ecology". (Downes, 1959).

5.1 *Saving spaces in order to save particles and water*

Across the world, undisturbed ecosystems exhibit degrees of resilience and stability in the face of variations in climatic conditions and other (often man-induced) stresses from year to year, showing a capacity for adaptation and ecosystem self-adjustment. Any ecosystem, whether managed or not, has a degree of meta-stability[1] in the face of such pressures, determined by the severity of the disturbing forces and the strength of its resilience and capacity to resist them. In soils, the living organisms which inhabit them confer resilience through the capacity to re-form porous soil structure after it has been damaged. Their capacity for reproduction and proliferation is what determines the sustainability of soil-plant systems (e.g. Greenland & Szabolcs, 1994; FAO, 2008; Doran & Zeiss, 2000; Uphoff et al., 2006).

The commonly held 'Soil & Water Conservation' paradigm has formerly been predicated on the idea that what was important was to conserve the solids in soils, mainly through erecting barriers and the physical rehabilitation of degraded land. This paper argues that – in a paradigm-shift – our first concern should, instead, be the need to conserve the SPACES within the soil, in order to:

- maintain appropriate mixes of the soil pores that favour the capacities of living organisms to resist degradation, and rebuild soils after deformation and/or loss;
- be able to store water in the soil at a range of plant-available tensions; and
- allow the excess to percolate into aquifers feeding into streams and rivers.

This is not to say that the conventional SWC paradigm is wrong, but that it is only part of a larger picture. Within a new paradigm for crop and soil sciences suggested by Sanchez in 1994 (cited in Uphoff et al., 2006), it could be suggested that "conventional" SWC approaches fulfil the role of "back-up" structures rather than being

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[1] *"A metastable equilibrium is when a body will only come back to its equilibrium position if not displaced too much."* (Hudson 1995, p.286)

the 'first line of defence'.

5.2 *A different paradigm of soil and water conservation*

By optimizing soil spatial conditions in favour of the soil-inhabiting biota (which includes plants), indicates the possibility of achieving conservation of soil particles, spaces, water, and sustainability more-effectively by stealth than by frontal attack.

In some cases this may be through improved water provision (e.g. enhanced soil moisture beneath dryland crops); in others by improved air provision in wetland crops (e.g. rice in SRI systems). In all such cases, improved conditions enable better expression of the potentials inherent in the crops' genotypes (Uphoff et al., 2013).

This switch of viewpoint suggests a different paradigm of soil and water conservation. Principles and practices should concentrate more on optimizing, protecting, and maintaining the biological self-sustaining capacity of the SPACES between soil aggregates before they are lost, and less on blocking the movement of the solids and water after these have started downhill.

The approach advocated here, as exemplified by stable Conservation Agriculture (FAO, 2011; Landers et al., 2013), has been shown to decrease the vulnerability of soils to climatic extremes and mis-management, by increasing both resilience and system-sustainability (Tenywa et al., 2013).

6 Conclusions

Future pressures on land to provide more food, water and other land-derived products – in ways which maintain productivity without further damaging the land as their production base – will need well-informed, motivated and dedicated technical researchers and advisory staff, working in laboratories ("Basic research" – "*What works?*"), on the ground ("In-field research" – "*Can it work?*") , and with farmers and others on the lands they control ("Operational research" – "*How does it work in practice?*"*).*

For such purposes, the World Soil Charter (FAO, 1982) (prepared by R. G. Downes) provides a framework of concepts and recommendations for achieving better land husbandry than at present commonly exists. It also provides a framework for optimising Government policies in support of such work. Achieving this will involve appropriate and co-ordinated interdisciplinary actions by organisations tasked with research, training, providing advisory services, monitoring and evaluation, publicity, legislation, and support services to land-users, among others.

Land Husbandry – as "an ecology of disciplines" – is an appropriate over-arching concept for augmented topics in the curricula for the pre- and in-service training of advisory and other technical staff who are entrusted with improving the management of land and the conservation of its resources and their productive potentials. In its wider sense, a concern for better land management provides a context and framework for interlinking the broad subjects of ecology, biology, chemistry, and physics of soils with the related subject of the hydrologic cycle, and for discussing their implications and the justification for encouraging and enabling better care of land.

These two interlinking papers provide indications of rational means for harmonising the details of the different but intertwined subjects with their client land-users' motivations, knowledge, understanding, and local experience.

Whereas in the past in many countries, any talk of "soil conservation" has had many overtones of "Government interference" and "regulations", the above approach also aligns more-closely with farmers' – and the wider society's – interests in production and its sustainability. As such, it enables better chances of good "*rapport*" and collaboration between farmers and their advisers, and of soils becoming better-safeguarded against damage by people and climate-change.

"*The outstanding scientific discovery of the twentieth century is not television, or radio, but rather the complexity of the land organism. Only those who know the most about it can appreciate how little is known about it*". [Aldo Leopold, quoted in Leopold (eds.), 1966]

"Think like a root – think like a river".

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