Water in the Critical Zone: Soil, Water and Life from Profile to Planet

M.J. Kirkby
School of Geography, University of Leeds, UK.
m.j.kirkby@leeds.ac.uk

Abstract

Earth is unique in the combination of abundant liquid water, plate tectonics and life, providing the broad context within which the critical zone exists, as the surface skin of the land. Global differences in the availability of water provide a major control on the balance of processes operating in the soil, allowing the development of environments as diverse as those dominated by organic soils, by salty deserts or by deeply weathered lateritic profiles. Within the critical zone, despite the importance of water, the complexity of its relationships with the soil material continue to provide many fundamental barriers to our improved understanding, at the scales of pore, hillslope and landscape. Water is also a vital resource for the survival of increasing human populations. Intensive agriculture first developed in semi-arid areas where the availability of solar energy could be combined with irrigation water from more humid areas, minimising the problems of weed control with primitive tillage techniques. Today the challenge to feed the world requires improved, and perhaps novel ways to optimize the combination of solar energy and water at a sustainable economic and environmental cost.

1. Water and critical zone typology

The earth provides a unique planetary environment in which liquid water, plate tectonics and life have co-evolved to create the critical zone. Many of the interconnected processes are well known, and described in greater detail elsewhere (e.g. Jacobson et al, 2000): the present review focusses on the role of water within the soil system. Human existence relies on the properties of this dynamic soil layer and the ways in which water helps to maintain and regenerate the ecosystem services that it provides. Soil properties have been described as depending on climate, biota, relief, parent material and time (Jenny, 1941). Although not explicit in this list, water plays a vital part in almost all soil processes, mediating their dependence on these five factors. In figure 1, the factors most directly linked to soil development have been re-arranged to show the central role played by water in soil processes (Hillel, 1971). Climate and parent material may be regarded as the most nearly independent external controls on soil development, atmospheric exchanges somewhat less so, while water plays a vital role as an intermediary, especially between climate, biota and soil. The close interdependence of all these processes demands multidisciplinary research (Brevik et al, 2015) to deepen our understanding.

The availability of water depends on the climate, defining the amount of precipitation, its form, seasonality and variability from year to year. Water typically spends months (soil water) to centuries (groundwater) within the critical zone, allowing it to interact effectively with soil and bedrock constituents. The areal distribution and seasonal pattern of rainfall and evapotranspiration are, therefore, the strongest global scale controls on critical zone development.

Water in the soil provides the essential working fluid for plant growth, being directly involved in photosynthesis and providing turgor, and is vital for all organisms in the soil (Bardgett et al, 2001). The way in which biota interact with and influence the critical zone is strongly linked to the intensity of water circulation through living organisms. Where water is freely available, and potential evapotranspiration is high, biomass is generally high, including both vegetation and soil organisms. Decaying vegetation provides soil organic matter and also provides an important resource for the soil organisms that enhance decomposition, as well as a dynamic reservoir for soil water.

Water, acting with gravity, drives many mechanisms that physically move soil grains and aggregates and transport the soil, progressively modifying the topography, and so the way in which the critical zone interacts with relief. As relief is progressively lowered, sediment transport is generally reduced, due to the lower potential energy of overland and subsurface flow, whereas chemical removal an water circulation remain important. This trend generally leads to a deeper and more weathered critical zone as relief is lowered, progressively modifying the soil structure and the pathways of water moving over and through the soil, and with organisms actively exploiting the system to their advantage. Within-slope effects are also observed as sediment and organic matter is transferred from upslope to downslope sites, particularly through tillage erosion (e.g. Wright et al, 1990, van Oost et al, 2005).

Water interacts with nutrients and weathering products, and its flow redistributes dissolved material. Water in the parent material acts as solute, dissolving weatherable minerals and making them available for advective transport in flowing water and diffusive transport in immobile water (Kirkby 1985). In arid conditions, material dissolved from parent material or deposited in the wind is often re-precipitated within the profile as, for example, sodium salts or calcrete. In humid conditions, solutes are largely carried away, progressively weathering the residual soil.

Over time, the critical zone progressively evolves over similar time spans to the evolution of the entire landscape. In some shield areas, this process appears to continue for many tens of millions of years, but, more commonly the critical zone appears to approach a near steady state of almost constant mechanical and chemical denudation in which the structure and form of the critical zone is only very slowly changing while the landscape is continuously lowered at a steady rate (Riebe at al, 2003) over time spans of 10^4-10^5 years. Until it reaches such a steady state, the critical zone is in a state of transient change, either in response to external shocks such as deforestation and climate change, or through the slow evolutionary changes in vegetation. Human population growth and technical development are applying many other stresses that seem to threaten the maintenance of stable earth systems, violating the planetary boundaries within which humanity can safely operate (Steffen et al, 2015). During such periods of transience or instability, many of the most immediate changes in internal processes are strongly driven by changes in soil hydrology

At a global scale, the dominant control on soil development is the balance between climate and atmospheric inputs. Climate controls the overall soil hydrology, that can be expressed by the relationship between precipitation and potential evapotranspiration. Atmospheric mineral inputs or outputs are partially dependent on the climate. Dust is perhaps the most important single mineral component, source areas being associated with little vegetation cover and at least some dry periods when the surface material can be entrained. Desert areas are the most important source areas, but current and former glacial outwash areas are also significant, currently generating about 10% of the global dust budget (Bullard, 2013). Areas downwind of source areas receive dust, which is widespread globally, but most concentrated close to source areas due to selective transportation of silt-sized material. Particularly high concentrations form the areas of extensive loess accumulation, for example in China, northern Europe and the American Mid-west. Other significant atmospheric exchanges are associated with erosion and deposition of inorganic salts that are most concentrated close to the ocean or exposed evaporate deposits (themselves more prevalent in current or former arid areas). The relative importance of atmospheric inputs as agents of soil formation is strongly dependent on the hydrological balance, between precipitation and evapotranspiration. (FAO, 1961; Prentice et al, 1992) In figure 2, the hydrological balance is compared with the atmospheric exchange balance to define broad regimes of soil development. Where the hydrological balance is very strongly positive (precipitation greater than potential evapotranspiration) throughout the year, then organic material accumulates at the surface and persistent waterlogging creates anoxic conditions that minimise decomposition of organic matter, which accumulates as an organic soil. With a less positive and/or more seasonal hydrological balance, the critical zone is dominated by loss of dissolved weathering products and, given sufficient time, develops a deeply weathered profile, often lateritic. Once almost all nutrients have been leached from the upper layers of soil, plants may eventually become largely dependent on atmospheric inputs of nutrients dissolved in rainfall.

Under arid conditions, where the hydrological balance is negative, most of the precipitation that enters the soil is lost in evapotranspiration, re-depositing any products of chemical weathering within the soil, most frequently as calcrete layers, in some cases increased through inputs of wind-blown dust. Extremely arid areas provide ideal conditions for deflation, and, at the extremes, tend towards a rocky desert from which all fines near the surface have been removed. If, however, there is accumulation of salts, from the sea or from evaporites, then surfaces are instead dominated by salt accumulation and undergo rapid weathering as salts crystallise within the rock (Lavee et al, 1998; Howell, 2009).

Thus, at a global scale, water relations provide the strongest control on evolution of the critical zone. Important differences are, however, also due to the age of soils, for example allowing accumulation of weathering products throughout the Cainozoic in some low latitude shield areas, and incomplete re-cycling of material in areas of Pleistocene glaciation. . Observed differences also reflect differences in parent materials (e.g. Dere at al, 2010; Vitousek et al, 2016).

Although there are many alternative ways of conceptualizing the relationships between water and soil, the development of the critical zone concept has perhaps done more than any other to transform the study of the soil and to emphasise its essentially multidisciplinary nature (Brantley et al, 2007; Lin 201; Anderson & Anderson, 2010: Anderson, 2012: Brevik et al, 2015). Inevitably some aspects of this re-focussing overlap with existing components of earth science, the establishment of Critical Zone Observatories (CZOs), first in the United States (Anderson et al, 2008) and now internationally (Banwart et al, 2012), is doing much to foster new research and improve our understanding of how soil is related to the landscape at hillslope to global scales.

2. Movement of water within the critical zone

At finer scales, the relationships between water and soil are in the domain of soil hydrology and soil physics. In both of these fields, there are many questions that are not fully resolved and, because of their importance, a considerable literature.

At the finest scale, flow of water within the soil is most commonly described by the Richards (1931) equation, re-stating, for an unsaturated soil, Darcy's (1856) law that the rate of flow is proportional to the pressure gradient. However, the Darcy/Richards approach assumed that as flow passes through the soil, there is complete mixing between the flowing threads of water, and there are commonly substantial deviations from this assumption, because pore sizes and shapes vary, so that water travels faster through macropores when close to saturation, bypassing flow through the finer pores of the soil matrix (Beven and Germann, 1982, 2013). Macropores are widespread, due to the contrast in pore sizes between and within individual soil aggregates, as well as more extreme contrasts produced by cracking in clay-rich soils and open pore spaces around stones in the soil. In some cases the behaviour of the soil can be dominated by flow in either the matrix or the macropores, but this response varies with the moisture content as well as over time in swelling soils. In many cases therefore a more complex model is required, for example involving dual porosity and marked hysteresis. Experimental evidence is showing the intricate three dimensional patterns of wetting and draining in a block of soil (e.g. Weiler & Naef, 2003; Haber-Pohlmeier et al, 2009) but, to date, there is no simple model that adequately describes the range of observed behaviours. Simple infiltration equations are still being applied as a necessary phenomenological tool, but it is clear that they can only represent a single prior soil state, for example ponded infiltration into an initially dry soil.

Unsaturated flow in the soil takes place predominantly in the vertical direction, as rainfall percolates toward a saturated level (if there is one) where lateral flow occurs, predominantly in the saturated phase. This contrast reflects the lower hydraulic gradient and the much larger distances involved in lateral flow, so that only saturated flow is able to drive significant volumes of water.

Under climates, and during seasons, where precipitation is less than potential evapotranspiration the movement of water is predominantly vertical: infiltrating water supplies evapotranspiration, only penetrating deeply into the soil in the largest storms, and there is little or no surplus to drive lateral flow. When precipitation exceeds potential evapotranspiration, the excess can only be carried away by lateral flow, which may be overland, within the soil or in groundwater. This dichotomy, often with seasonal switching between these modes (Grayson et al, 1997), shows strong contrasts in the downslope connectivity that is established by lateral flow. In a place and season dominated by vertical fluxes, each point responds independently to the rainfall supply and evapotranspiration demand, and common responses are filtered by local heterogeneities. Lateral connectivity is only briefly established during relatively infrequent flow events, usually overland, so that, in general, behaviour at a point responds only to very local influences. Where lateral flow is dominant, there is a near-continual connection, commonly subsurface, and the hydrological response at any point integrates the effects of every point upslope that drains towards it.

At the soil surface, overland flow is generated either when rainfall exceeds the infiltration capacity (Horton, 1933) or when the surface soil is saturated (Hewlett & Hibbert, 1967; Dunne & Leopold, 1975; Kirkby, 1978; Beven, 2000). The former, infiltration excess overland flow, is dominant in semi-arid areas where rainfall exceeds potential evapotranspiration so that the soil is dry. Rainfall impact crusts the bare soil surface around the sparse vegetation, while shrubs may funnel water towards their roots (Cammeraat et al, 2010) setting up a strongly contrasting patchwork of infiltration. The latter, saturation excess overland flow, occurs mainly in humid areas, where rainfall is greater, generating substantial subsurface flow and a strong vegetation cover. However under many Mediterranean and other seasonal climates, there is switching between these modes during the year and, even in humid areas, and particularly where cultivated fields are bare for part of the year, extreme rainfalls may generate infiltration excess overland flow. When saturated overland flow occurs, the contributing area commonly expands as saturation builds outward from stream banks and stream-head hollows, driven by concentration of subsurface flow from upslope and the accumulation of rainfall on the nearly saturated ground. Infiltration excess overland flow, when it occurs, tends to be generated more uniformly, so that flows, when they occur, tend to be more flashy and more damaging. However, there remains a very strong variability in local infiltration capacity, so that, particularly at the beginning of a storm, the detailed pattern of overland flow is characterised by patches of flow generation and re-infiltration which persist until flow becomes general (Kirkby, 2014) and is then dominated by local flow convergence steered by the micro-topography (figure 3).

In humid areas, particularly under forest, there is an extensive literature (e.g. Barthold & Woods, 2015) on subsurface flow mechanisms. There appears (Tromp-van Meerveld and McDonnell, 2006) to be strong similarity in many cases between the mechanisms of subsurface flow and those of infiltration excess overland flow. In each case, rainfall fills depressions and/or infiltration storage and flow begins as these progressively spill over to form connections. The surface for which this process is most critical may be the ground surface (for infiltration excess overland flow), or a subsurface level below which there is a sharp decrease in permeability, whether due to soil layering or at the soil-bedrock interface. Experimental (e.g Graham et al, 2010) and modelling data (e.g Kirkby 2014, Penuela et al, 2015) supports percolation theory (Stauffer & Aharony, 1985; Ali et al, 2013) in finding that the response of such a system to increasing rainfall amounts shows a rather sharp threshold, below which there is negligible flow, and above which there is transition to a near-linear increase in connected flow. Since the sharpness of the threshold varies, it may be best to define the storm size at which 50% of rainfall runs off as a theoretical threshold.

Two valuable ways of generalising response at the hillslope scale are through the concepts of connectivity (McGuire & McDonnell, 2010: Bracken et al, 2015) and residence time (e.g. Tetzlaff et al, 2010). At its simplest, connectivity queries the presence or absence of a through connection between two points. However, it has proved more fruitful for describing the totality of connections from points in an an area to an outlet point, and is thereby linked to the runoff coefficient. Connectivity has been widely applied in ecology (McCrae et al, 2008) applying an analogy with electrical conductivity, but the one-way nature of water flow downhill makes this less applicable in hydrology. Instead the application of percolation theory or the concept of a breakthrough volume to establish connections have proved more applicable, and continue to be developed (Larsen at al, 2012; Janzen & McDonnell, 2015). Residence time is, in a way, the inverse of connectivity, long residence times being associated with poor connectivity for a given reservoir size. The great value of residence time is that its mean value and distribution can be quantified using tracer methods. Perhaps these methods may provide the basis for a better understanding of how water interacts with the critical zone, by focussing on the hillslope rather than the soil profile scale.

Within even a relatively simple soil profile, there are a number of inter-connected reservoirs of water (Figure 4) Rainwater infiltrates into the soil matrix and in films along the walls of macropores, filling them completely only when the soil is saturated. Further infiltration into the soil matrix takes place along macropore walls. Mainly during storms, some water is able to reach a perched or regional saturated lavel where it provides most saturated lateral subsurface flow. Water in the matrix provides the main reservoir for extraction by plant roots as transpiration, newly infiltrated water mixing with water that has already resided in the matrix for many months. Saturated subsurface flow also comes from a reservoir in which old and new water are mixed together (McDonnell, 2014; Kirchner et al, 2000). During a storm, therefore, much of the ‘new’ rainwater is replacing local storages, while much of the slope base outflow consists of older water that is being pushed out. In soil profiles and soil catenas more complex than the cartoon of figure 4, and where flood plain deposits abut hillslope catenas, the possible pathways and range of residence times are further increased (Tetzlaff et al, 2010; McGuire & McDonnell, 2010).

Some storm precipitation is not involved in this fill and spill process. Until break-through occurs, all of the rainfall; and after break-through a small fraction, percolates downwards commonly reaching a level of saturation. Where and when precipitation is of the same order as, or exceeds potential evapotranspiration, this downward percolation contributes to lateral subsurface flow that brings the saturation level progressively closer to the surface in response to flow rates that respond to hillslope plan and profile form: in less humid areas this percolation only occurs in the largest storms, and most water is lost to evapotranspiration. Subsurface flow between and during storms, if it occurs, establishes a dynamically varying saturated area, usually along slope-base concavities and plan-convergent stream heads. Rainfall falling on these saturated areas cannot enter the soil, but is immediately diverted as saturation excess overland flow. The fill and spill level and the saturated subsurface flow level are discussed here as being physically separate, but may be vertically adjacent, distinct or combined and/or in multiple layers. In many cases one or other of these mechanisms dominates the hydrological response of a hillslope or headwater area (Beven, 2000; Tarboton, 2003). Both fill and spill mechanisms and saturated contributing area mechanisms share a very strong non-linearity in response to storm size, corresponding to the increasing connectivity of flow. At extremes which are rarely achieved, there is 100% connectivity, but most observations reflect the region of increasing partial connection (e.g. Bracken at al, 2013),although the mechanisms of establishing connected flow differ, with persistent subsurface connection for saturation excess and episodic connection in storms for fill and spill dominated systems.

For infiltration excess overland flow and other fill and spill regimes, connection is typically established dynamically during the course of each individual storm, and decays rapidly afterwards. For saturation excess regimes, initial connections are established by subsurface flow that persists between storms in areas where precipitation exceeds potential evapotranspiration. The saturated area continues to expand during a storm, and connectivity is only slowly lost, often on a seasonal time scale (Reaney et, 2014). Over a period, an area may experience fill and spill runoff when storm rainfall exceeds some threshold; and may, at other times, experience saturation excess runoff when net rainfall over a period exceeds another threshold. The fill and spill threshold depends on the structure of vertical storage within the soil, whereas the saturation excess threshold depends on topographic wetness index and near-surface lateral permeability (Sivaplan et al, 1987, Kirkby et al, 2008). Clearly semi-arid areas, with little net rainfall, rarely experience saturation excess runoff, but both mechanisms can co-exist in an area, often with seasonal switching between the two modes (Kirkby et al, 2011)

3. Water as a transporting medium in the critical zone

As parent material weathers, breaks down into smaller fragments and is eventually removed by erosion at the surface, it passes through the critical zone from bottom to top. Figure 5 sketches the path of grains from the parent material for a steady state in which the critical zone depth remains constant, surface erosion balancing advance of the weathering front. Initially a grain is subjected mainly to chemical weathering, so that it approaches the surface vertically, relative to the downward advancing weathering front. As grains get closer to the surface, they become increasingly influenced by diffusive movements in the soil. These all gradually move material down-slope, at a rate that decreases with depth. Eventually erosion will expose grains at the surface and remove them (Anderson et al, 2002). There is a lateral flux of eroded sediment and weathering products in solution at every point down the length of the hillslope, and, perhaps after intermediate deposition, this material is finally exported at its base, normally to a channel.

Water plays an essential part in these processes, generally percolating less and less with depth where it interacts with rock minerals to release solutes and advance the weathering front (Anderson et al, 2007; Kirkby, 2015). The water is then partly diverted laterally, and partly returned to the surface as evapotranspiration. In semi-arid climates, where potential evapotranspiration exceeds precipitation, there is little lateral movement, and many solutes are re-deposited beneath the surface. In more humid climates, lateral flow carries solutes away, and weathering produces a much greater loss of rock substance.

Within the soil, slow diffusive movement is commonly driven by freeze-thaw, wetting-drying and/or bioturbation, and all of these respond positively to the presence of soil water. Where the slope configuration is suitable, larger and more rapid mass movements can also move critical zone materials downhill, usually under conditions close to saturation. At the surface, raindrop impact and overland flow drive soil erosion, which is most effective where the surface is not protected by vegetation or stone cover. In all of these ways, the action of water is strongly instrumental in shaping the path followed by grains as they migrate through the critical zone (figure 5) and progressively reduce in grain size.

Weathering processes progressively convert strong rock minerals, that have generally been synthesised under high temperatures and pressures in an anoxic environment, to weathering products that are closer to equilibrium with surface conditions and oxygen levels. In this process most minerals lose strength, eventually converted to granular sand or silt and clay minerals. This loss of strength and reduction in grain size facilitates lateral movement of weathered material close to the soil surface. The balance between chemical(C) and mechanical (M) denudation rates determines the degree of weathering of surface soils. The depletion ratio (Riebe et al, 2003), defined as C/(C+M) is a measure of the degree of weathering in the soil, and generally increases in humid climates (with high C) and decreases where slope gradients are high (with high M). Low rates of mechanical denudation reduce stripping of the soil, which then accumulates to greater depth and, in turn, reduces chemical denudation, so that depletion ratios, in any given rock/climate environment, tend towards a stable end-point value.

Water also plays an important role in the carbon and nitrogen cycles that are central to biological activity.
Much of the Nitrogen in circulation comes from the application of artificial fertiliser for agriculture, and in deposition around urban areas. Although essential for the increased yields it promotes, it is also one of many organic and inorganic pollutants that reach the soil through direct application and/or in wet and dry deposition (Keesstra et al, 2012). These pollutants or their metabolites play an increasing role in contaminating stream groundwater, with potentially adverse effects on soil organisms and human health (Davidson, 2009).

Overland flow, however generated, is the key agent of soil erosion. Unprotected soil surfaces are impacted by raindrops that break up and detach surface aggregates, packing some down to crust and seal the surface, and ejecting some either into the air (rainsplash) or, where water is already flowing downslope, into the flow (rainflow). Once flow becomes sufficiently strong, due to topographic convergence and/or at high rainfall intensities, the tractive stress exerted directly by the flowing water becomes sufficient to erode the surface and detach material (rillwash). When this happens, the flow begins to incise channels into the surface, thereby increasing the convergence of flow lines in a positive feedback that leads to rilling or gullying. All of these processes are highly size-selective, transporting the finest material farthest from its detachment point, and rates of movement increase with slope gradient Knapen et al, 2007).

Surfaces may be protected either by vegetation or by stone cover. The crown cover of vegetation breaks the impact of falling raindrops, so that they then strike the ground with low momentum and detach little material (except under high-crowned trees). Stones protect the surface directly, and each stone tends to shield a rim of soil in its immediate shadow, so that it does not become crusted (Poesen et al, 1994; Cerda, 2001). Crusting, particularly in silt-rich soils, is very effective in reducing infiltration and therefore increasing overland flow and, indirectly, erosion. Where the soil is stony, initial erosion tends to winnow out the fine material until the stones, that are less easily carried way, are left behind to armour and partially protect the surface from further erosion. Deep gullying is therefore strongly associated with deep soils that are deficient in stones, either through the action of weathering or as a property of the parent material: thick loess deposits provide an extreme example.

Agricultural fields, at times of year when the surface is almost bare, are generally vulnerable to greater erosion than areas of semi-natural vegetation, particularly so when this period is also one with a high risk of intense rainstorms. During a severe storm, rills generally form with a more or less regular spacing. At the same time as their bed is being incised by the concentrated flow, material is also being delivered to them by rainsplash and rainflow from the intervening areas, so that their downward incision may be self-limiting, often cutting down only to a hardened plough-pan level.

On all but the steepest slopes, slow mass movements, soil erosion by water and chemical denudation are the dominant processes through which hillslopes evolve over time. Under diffusive processes such as soil creep, rainsplash and tillage erosion, hillslope profiles gradually evolve towards a mainly convex form, with a narrower concavity towards the base, as has long been observed (Gilbert, 1877). In steeplands however, rapid mass movements assume the dominant role, and tend to produce almost rectilinear slopes once cliffs have been eliminated. The much higher rates of sediment transport create a critical zone that generally remains thinner, and with lower chemical depletion ratios than on lower-gradient slopes, even though the shallow soil depth promotes a relatively high rate of chemical denudation (Emberson et al, 2015).

Sediment transport, also shapes the three-dimensional landscape geometry, through the interplay of diffusive and advective sediment transport processes. Where advective sediment transport by water is able to evacuate sediment faster than it can be replaced by diffusive processes or mass movement, then channels become progressively incised, defining the drainage density of the landscape, and so the average length of hillslope profiles. This is a dynamic process in which major storms are responsible for headward stream extension, and fresh headcuts are partially infilled between major storms, so that the instantaneous stream head position fluctuates, reflecting recent storm history. Drainage density tends to be higher in more arid climates, reflecting the dominance of surface flow processes where vegetation is sparse. Density also tends to increase with valley gradient, because advective transport generally increases more than diffusive transport as gradient increases (Montgomery & Dietrich, 1992).

The interplay of hillslope and channel processes responds not only to climatic variability but also to land use changes that modify sediment supply, most strikingly following changes in land use. Where land use change exposes more bare soil, as in deforestation and adoption of arable farming, runoff and sediment load tends to increase. Channel runoff is generally less strongly affected by local changes, so that the increased sediment delivered from side slopes is redeposited along channelways because their transporting capacity is not proportionally increased (Rommens et al, 2005). Contrariwise, afforestation can lead to stream incision (Keesstra, 2007, Sanjuan et al, 2010).

These considerations show that water plays a crucial role in almost all processes acting within the critical zone, and across the full range of landscape scales (Brantley et al, 2007; Anderson et al, 2015). Although other factors, such as lithology and tectonics, also play a very important role, climate, principally acting through the availability and distribution of water, has a dominant influence on the structure and composition of the soil, on the rates and styles of mechanical and chemical denudation, and on the profile form, plan shape and length of hillslope profiles. Many of the processes involved in shaping three-dimensional hillslope form are now being incorporated into successful landscape evolution models (Tucker et al, 2001; Egholm et al, 2013) including the effects of non-linear diffusion (Roehring et al,2001). However, the incorporation of chemical solution in these models perhaps remains their least satisfactory component (Brantley et al, 2007).

Water for plant growth

Roots grow actively to seek pore water which they require to maintain their turgor against strong capillary tension and to permit photosynthesis. Except where a saturated zone in within reach of their root system, the water that plants use appears to come mainly from the matrix within soil peds, and is substantially separate from the water in cracks and macropores between aggregates that is the main contributor to stream flow (McDonnell 2014). When water flows through macropores, it also infiltrates into the peds beside each macropore, recharging the soil matrix which then provides a longer lasting store of water to supply the plants (Germann and Beven, 1985). Water also supports soil microflora, especially fungi, bacteria and viruses; and fauna from termites and earthworms to nematodes and protozoa that graze, mainly on bacteria and living plant material or their organic matter residues. Bacteria are important in catalysing weathering processes and, with some fungi (mycorrhiza), support plant growth by fixing atmospheric nitrogen. The various soil organisms are essential to a healthy soil, and typically contribute up to 5% of the total organic soil biomass.

It has been argued (Schymanski et al, 2008) that the vegetation cover develops in such a way as to maximise its productivity, and such a principle of optimality may be a way to simplify the complex web of interactions linking vegetation and soil organisms to water use. Most existing models, however, use a more physically based set of constraints to model vegetation and how it may respond to global climate change (e.g. Scheiter et al, 2013).

Matrix water is most frequently available near the soil surface, since macropores are most frequent there, and are commonly active with every rainfall event. Roots require water and oxygen and partly to mirror this distribution, often with a more or less exponential decay in density with depth. Some plants also develop deep tap roots that can reach down to a water table at 10 m or greater depths, a strategy favoured by semi-arid phreatophytes that exploit local water tables below ephemeral streams.

Water is probably the most important agent responsible for the structure and processes within the root zone; its presence and distribution, acting through the vegetation and soil organisms, enabling the processes of decomposition and bioturbation that dominate these surface layers of the critical zone, and these processes profoundly modifying the soil structure and hydrology.

Plant roots and mesofauna (e.g. earthworms and termites) physically break up the soil, allowing the penetration of air and water. Larger burrowing animals, falling trees and freeze-thaw or wetting-drying cycles can also play a part in breaking up and mixing the near-surface soil. The cumulative action of all these processes can be considered as a diffusive mixing, with a net upward drift of soil material towards the free surface, which is counterbalanced by settling under gravity, significantly assisted by the downward percolation of water (Gabet, et al, 2003). Over a few decades, the balance between these processes leads to an equilibrium bulk density profile, in which porosity declines with depth. This bioturbation mixes and homogenizes the upper layers of mineral soil, since it occurs much more rapidly than chemical weathering, and may readily be visually distinguished from weathered saprolite, in which original bedrock morphology is preserved in the weathered material.

Organic matter is released from plants, partly as leaf (and stem) fall to accumulate on the surface and partly as in-situ root decay. Over decades, this material takes part in the vertical mixing and is also decomposed, gradually releasing CO_2 into the soil (Attal et al,2015; Johnson et al, 2014; Herold et al, 2014). Since the processes of mixing and decomposition occur over similar time-spans of decades to centuries, the soil organic matter also develops a vertical distribution within the soil, generally with a smaller scale depth (10s of centimetres) of exponential decay than for bulk density. Plants also modify the chemical environment of the soil, synthesising organic acids that influence water movement and soil pH.

These mixing processes, by modifying the near-surface soil, tend to increase the rate at which water is able to infiltrate, creating a positive feedback in which greater biological activity increases the availability of water in the soil, which in turn encourages biological activity. Eventually, soils are able to absorb the available precipitation so that, over a time span of decades to centuries, there is a feedback tendency for soil structure, and to some extent topography, increasingly to reflect the natural vegetation and to reduce overland flow runoff.

4. Water as an agricultural and food resource

By far the greatest consumptive use of water by mankind is for agriculture. An average of approximately 3,800 litres a day is needed to support each individual (Hoekstra & Mekonnen, 2012), 92% of which grows their food. Other major requirements are for domestic use (3.8%) and for clothing and other industrial products (4.7%). These requirements differ in kind, in that domestic water has to be delivered to the individual, whereas for other uses the water can be more economically provided by transporting the food or clothing. However, most countries are also concerned with food security, so that there is some perceived pressure towards being at least partially self-supporting for food production.

Historically, the development of large scale agriculture has been in semi-arid regions of the Middle East and Meso-America, commonly using irrigation water canalised from rivers (Mazoyer & Roudart, 2006). Semi-arid areas have the advantages of providing ample solar energy for photosynthesis, together with relative ease of weed removal. However, irrigation has, historically, commonly led to salinization of the soil, sometimes irreversible, depending on the quality of the irrigation water and whether sufficient irrigation water has been applied to leach excess salts. Clearance of land in warm humid regions, although providing ample water and solar energy, is hampered by the re-establishment of native weed species and rapid depletion of topsoil nutrients. Long fallow periods (shifting agriculture) were therefore required until modern machinery and fertilisers could be applied. Increasing population pressure may also place pressure on land resources, forcing undesirable reductions in the fallow rotation period. In all areas, seasonal exposure of the bare land surface prior to planting and after harvest, expose the land to increased soil erosion, particularly when rainfall is intense at these critical times of year. In the great majority of cases, arable farming increases the natural rates of soil erosion by water, increasing losses by at least an order of magnitude (Montgomery, 2007) and progressively degrading the land. Water erosion takes some steeper, thin-soil areas out of production and, more widely, removes the most nutritious topsoil and organic material. Cultivation, by exposing the soil surface and allowing it to dry out, can also increase wind erosion in semi-arid areas (e.g. Houyou et al, 2014). In addition, conventional ploughing, whether on the contour or downslope, moves material downslope and generally exposes soil organic matter to more rapid decomposition, reducing the long-term water holding capacity of the soil. However, because significant deterioration of the soil takes many decades and restoration is also slow, farmers may have little short-term incentive to improve conservation practices.

Some of the negative effects of agriculture can be mitigated by appropriate management (e.g. Keesstra et al, 2016), but these often require initial and ongoing investment that is not available to all farmers. Some soil conservation measures such as inter-cropping can be applied at low cost but the majority, including terracing, contour ploughing, residue management, water harvesting, and reduced tillage, require investment and/or some sacrifice of cultivable land area. Management systems that retain a vegetation cover reduce the loss of sediment (Abrahams et al, 1994; Zhao et al, 2016) and organic matter (Gao et al, 2016), even where runoff is not reduced.

As well as on-site management of water resources, there is a global shortage of renewable water resource in the face of increasing populations. There are a number of technical solutions to these problems, for example breeding crops that require less water, irrigating crops as efficiently as possible without incurring the risk of salinization and water harvesting. Others, for example large scale desalinisation of sea water, carry significant costs that cannot readily be accepted by increasing the cost of food to consumers.

.

The broader implications, for global water needs and for food security, are analysed further in figures 6-8 on a country by country basis, using data drawn from FAO reports (2000, 2016). In figure 6, the population that can be supported by renewable water and potential arable land resources is calculated, using two simplified scenarios. In the first, rain-fed cereal cultivation is assumed, utilising the available average annual water supply from rainfall. For efficient agriculture with good agronomic practice and fertiliser application, the grain yield Y in $kg.Ha^{-1}$ is calculated as

$$Y = 16.7 (E-150),$$

Where E is the annual depth of water in millimetres available for plant transpiration, which is assumed equal to precipitation for dry climates (based on Sadras et al, 2011). An upper limit of 8,400 $kg.Ha^{-1}$ is assumed, corresponding to a consumptive use of 600mm in optimal conditions. However yields in the Western Sahel, and elsewhere where soils are poor and fertiliser not widely available are approximately 40% of the above estimate. In figure 6a, estimates of sustainable population are plotted against actual country population. The blue line and left hand vertical scale refer to efficient agriculture with adequate fertiliser inputs: the red line and right hand scale to low efficiency agriculture. In each case the lines indicate countries with or without adequate resources for self-sufficient rain-fed agriculture. It can be seen that there are a few counties without adequate rainfall, even with efficient agriculture, and a number that may fail without efficient farming practices. In addition, 31% of the countries, for which there is data, have less than 150 mm annual rainfall and therefore do not, on average, have enough water to support any rain-fed farming.

In a second scenario, efficient water harvesting, potentially gathering water from the entire area, is used to concentrate water on as much as possible of the potentially arable land, to provide 600mm of water and optimum yields on th farmed area. Figure 6b shows, with a similar key, that many countries are still short of water, and the extent to which efficient farming alleviates this. Figure 6b appears to show many more countries with a water deficit than figure 6a, but this is because all countries have at least some theoretical water harvesting potential. Although these simple analyses make

the optimistic assumption that water is freely transferrable within a country, it can be seen that there is a lack of sufficient water resources, that is made more severe where yields are low due to a lack of fertiliser and good farming practice . Some continuing increase in world population, together with further deterioration of soil resources due to erosion and salinization, therefore presents a major challenge for the future.

Figure 7 shows the actual and potential arable land in each country and the average renewable water in each. The horizontal line is set at 600mm, which is the approximate amount of water required to grow an optimal cereal crop. It can be seen that many countries have not sufficient water to make full use of their presently utilised arable land resources, and that water limitations are a major factor in preventing cultivation of additional potential arable land. Figure 8 shows the renewable water resources per capita for each country, plotted against the population. The upper horizontal line shows the approximate amount of water required to grow food for the population (ca 1200 m^3 per capita per year), and the lower line the amount needed for domestic use (ca 60 m^3). It can be seen that there are many countries that cannot feed themselves, and a smaller number that lack sufficient renewable water to supply domestic needs. Although food needs can be and currently are being partially met by international trade, with implicit water transfers within the food, lack of food security remains a source of potential conflict.

One renewable and low cost means of increasing available water is through water harvesting. Where rainfall is almost adequate for rain-fed farming, conservation measures may be all that is needed to ensure that storm runoff is retained on-site, in mulch layers, in trenches or behind bunds. As water scarcity increases, an area to be cultivated can be supplied with runoff from a collecting area above and around it, which provides water to the cultivated patch. The required ratio of cultivated area to collecting area can be estimated as the ratio of actual to potential evapotranspiration in a given region. Analysis of the climate thus gives some idea of where different styles of water harvesting can be applied most effectively. Figure 9 shows, for Africa, the ratio of actual to potential evapotranspiration for the most suitable 5-month growing season, and for the worst 25% of annual conditions. Water harvesting can benefit crop yields when this ratio lies between about 0.2, where ephemeral stream floods can be diverted into fields up to about 1.5 to maximise crop reliability in areas with high inter-annual variability. The ratios of collecting area to irrigated area are the reciprocals of these values, and are generally somewhat larger due to the inefficiencies of collection and redistribution. Where the collecting area is large, runoff collection can be made more efficient by removing stones from the surface to encourage crusting of the soil, and by channelling runoff into discrete runnels to further reduce infiltration losses.

Where the collecting: cropping area ratio is low (<3), an individual group of plants can be supplied by an immediately adjacent patch of bare soil. This gives a pattern of pits where seeds are planted, each surrounded by a small area that drains towards it (zai). At larger scales, a small planted field of, say 10x10 m, may be supplied with water collected from a small upslope min-catchment (jessour), with perhaps a 20:1ratio of collecting area to irrigated area. At the coarsest scale, these water harvesting practices (Critchley et al, 1991) merge into regional irrigation systems. Increases in the ratio of collecting area to cultivated area lead to increased yields, but this may be offset by the sacrifice of potential yield from the uncropped area where this is also suitable for arable farming. Part of the net advantage is therefore obtained through greater labour efficiency in farming a smaller area, and the reduced likelihood of crop failure. Figure 10 shows the modelled frequency distribution of estimated yields over a run of years, for Mekele (northern Ethiopia), with different ratios of collecting to cropping area (CAR). It can be seen that although most years provide some harvest, the median yield and its reliability are greatly enhanced by water harvesting (Fleskens et al, 2016). Reliability can be further increased by installing ponds that not only collect but also store water, often allowing irrigation in dry spells, but subject to evaporative loss.

It is clear that water is a critical resource for agriculture, and will become more so in the future (Falkenberg et al, 2009) , particularly because global warming is thought to increase aridity in many water stressed areas (e.g. Gao and Giorgi, 2008 for the Mediterranean), and because of the interactions with energy production (Pimentel at al, 2004). Figure 12 sketches some of the interactions that need to be managed in order to maintain affordable food production for a still growing world population. Crop production requires both water and energy, mainly used for the manufacture of nitrogen fertiliser, but also for transportation on the farm and to the market. Widespread use of fertiliser has quadrupled yields since 1900, reducing the dependence of land as a critical resource, but without reducing the need for additional water to support the increased crop yields, so that water has become the most critical resource for further expansion of food production. Nitrogen fertiliser production uses 3-5 % of world natural gas as a source of hydrogen, and only a fraction of the nitrogen is used by crops, so that nitrogen is a major source of pollution both directly in runoff, re-cycled through animal manure, and as a greenhouse gas. Nitrogen in runoff contaminates groundwater and is responsible for eutrophication of lakes and coastal waters.

Although water can be desalinated, the cost of irrigation water produced from seawater its cost is very high in relation to other costs of food production. Typical developed world farm-gate current cereal costs of about 200 USD per tonne (Zimmer, 2012) would be increased by about 1000 USD per tonne for the desalinated water needed to grow the cereal (ca 1 USD per cubic metre). These costs may be becoming acceptable for domestic water supply and for some high value crops, but cannot, at present, be accepted for staple foods or animal husbandry. Although desalination might be supported by renewable energy, for example to irrigate the Sahara, it also generates disposal problems for the salt removed, and so is not environmentally neutral.

5. Conclusion

Water is everywhere. Life and mankind would not exist without it. As population continues to grow, fresh water is becoming an increasingly scarce resource. To make the best use of fresh water, most critically for food production, it is vital to share it wisely. One key aspect of this is to progressively improve our knowledge of how water interacts with the critical zone at every time and space scale, and to better recognise, and gradually stretch the limits of what is possible. Water and soil present challenges at every scale, from the grain to the globe, and it is a matter of urgency to engage with these issues as best we can, both as practical problems requiring urgent solution and to enhance scientific understanding.

References

Abrahams, A.D., Parsons, A.J. & Wainwright, J., 1994. Resitstance to overland flow on semiarid grassland and shrubland hillslopes. J. Hydrology, 156, 431-446. DOI: 10.1016/0022-1694(94)90088-4

Ali, G., C.J. Oswald, C. Spence, E.L.H. Cammeraat, K.J. McGuire, T. Meixner & S.M. Reaney, 2013. Towards a unified threshold-based hydrological theory: necessary components and recurring challenges. Hydrological Processes 27, 313-318. DOI: 10.1002/hyp.9560

Anderson, R.S. & Anderson, S.P.,2010. Geomorphology: the mechanics and chemistry of landscapes. Cambridge University Press. 651pp. isbn: 978052151978.

Anderson, S.P., Anderson, R.S. & GE Tucker, G.E.,2012. Landscape scale linkages in critical zone evolution. Comptes Rendus Geoscience 344 (11), 586-596. DOI: 10.1016/j.crte.2012.10.008

Anderson, S.P., RC Bales, R.C., & CJ Duffy, C.J., 2008.Critical Zone Observatories: Building a network to advance interdisciplinary study of Earth surface processes. Mineralogical Magazine 72 (1), 7-10. DOI: 10.1180/minmag.2008.072.1.

Anderson, S.P., von Blanckenburg, F., White,A.F., 2007. Physical and chemical controls on the critical zone. Elements 3 (5), 315-319. DOI: 10.2113/gselements.3.5.315

Anderson,S.P., Dietrich,W.E., Brimhall, G.H., 2002 Weathering profiles, mass-balance analysis, and rates of solute loss: Linkages between weathering and erosion in a small, steep catchment Geological Society of America Bulletin 114 (9), 1143-1158.

Anderson,S.P., Foster, M.A., Anderson, S.W., Dühnforth, M., Anderson, R.S.,2015. Putting weathering into a landscape context: Variations in exhumation rates across the Colorado Front Range. EGU General Assembly Conference Abstracts 17, 7992

Attal, M , S.M. Mudd, , MD. Hurst, , B. Weinman, K. Yoo, & M. Naylor, 2015. Impact of change in erosion rate and landscape steepness on hillslope and fluvial sediments grain size in the Feather River basin (Sierra Nevada, California) Earth Surface Dynamics 3, 201-222.

Banwart, S., Manoj Menon, M, . Bernasconi, S.M., Bloem, J., Blum, W.E.H., Maia de Souza, D. , Davidsdotir, B., Duffy, C., Lair, G.J., Kram, P., Lamacova,A., Lundin, L., . Nikolaidis,N.P., Novak,M., Panagos,P., Vala Ragnarsdottir,K., Robinson, D., Rousseva, S, de Ruiter, P., van Gaans, P., Weng,L., White,T., Zhang, B, 2012. Soil processes and functions across an international network of Critical Zone Observatories: Introduction to experimental methods and initial results Comptes Rendus - Geoscience 344 (11-12). 758-772. DOI: 10.1016/j.crte.2012.10.007

Bardgett, R., Anderson, J., Behan-Pelletier, V., Brussaard, L., Coleman, D., Ettema, C., Moldenke, A., Schimel, J., and Wall, D., 2001: The influence of soil biodiversity on hydrological pathways and the transfer of materials between terrestrial and aquatic ecosystems, Ecosystems, 4, 421–429. DOI: 10.1007/s10021-001-0020-5

Barthold, FK & Woods, RA 2015, 'Stormflow generation: A meta-analysis of field evidence from small, forested catchments' Water Resources Research, 51, 3730–3753., 10.1002/2014WR016221

Beven, K. J., 2000. Rainfall Runoff Modelling: The Primer, John Wiley, Chichester. ISBN 978-0-470-71459-1

Beven, K. & Germann, P., 1982. Macropores and water flow in soils. Water Resources Research, 18(5), 1311-1325. DOI: 10.1029/WR018i005p01311

Beven K. and Germann, P., 2013. Macropores and water flow in soils revisited, Water Resources Research 49 (6), 30171-3092. DOI: 10.1002/wrcr.20156

Bracken, L.J. & Croke, J., 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes*. 21:1749-1763. DOI: 10.1002/hyp.6313Bracken, L.J., Turnbull, L., Wainwright, J. & Bogaart, P., 2015. Sediment connectivity: a framework for understanding sediment transfer at multiple scales. Earth Surface Processes and Landforms. 40:177-188. DOI: 10.1002/esp.3635

Bracken, L.J., Wainwright, J., Ali, G.A., Tetzlaff, D., Smith, M.W., Reaney, S.M. & Roy, A.G., 2013. Concepts of hydrological connectivity: Research approaches, pathways and future agendas. Earth-Science Reviews.119:17-34. DOI: 10.1016/j.earscirev.2013.02.001

Brantley, S.L., Goldhaber, M.B., and Vala Ragnarsdottir,K.,2007, Crossing Disciplines and Scales to Understand the Critical Zone. Elements, 3, 307-314. DOI: 10.2113/gselements.3.5.307

Brevik, E.C., Cerdà, A., Mataix-Solera, J., Pereg, L., Quinton, J.N., Six, J., and K. Van Oost, K., 2015. The interdisciplinary nature of SOIL. SOIL, 1, 117–129, 2015. doi:10.5194/soil-1-117-2015

Buckingham, E, 1907, Studies on the movement of soil moisture, Bureau of Soils, Bulletin 38, Washington, D.C.: U.S. Department of Agriculture, Washington DC

Bullard, J.E. 2013. Contemporary glacigenic contributions to the dust cycle. *Earth Surface Processes and Landforms*. doi:10.1002/esp.3315. DOI: 10.1002/esp.3315

Cammeraat, E.L.H., Cerda, A & Imeson, A.C., 2010. Ecohydrological adaptation of soils following land abandonment in a semi-arid environment. Ecohydrology 3, 421-430.

Cerda, A., 2001. Effects of rock fragment cover on soil infiltration, interrill runoff and erosion. European Journal of Soil Science 52, 59-68. DOI: 10.1002/eco.161

Critchley, W. K. Siegert & C. Chapman, 1991.Water Harvesting: a manual for the design and construction of water harvesting schemes for plant production. FAO, Rome

Darcy, H. ,1856. Les Fontaines Publiques de la Ville de Dijon, Dalmont, Paris. 647pp

Davidson, E.A., 2009. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. Nature Geoscience 2, 659-662. doi 10:1038/NGE0608.

Dere, A., T. White, L. Jin. D. Harbor, M. Townsend, and S. L. Brantley, 2010. Shale weathering rates across a continental-scale climosequence. Geography and Geology Faculty Proceedings & Presentations. Paper 1. http://digitalcommons.unomaha.edu/geoggeolfacproc/1

Dunne, T. and L. B. Leopold, 1978, Water in Environmental Planning, W H Freeman and Co, San Francisco, 818 p. ISBN-10: 0716700794

Egholm, D.L.,, Knudsen, M.F. & Sandiford, M. 2013. Lifespan of mountain ranges scaled by feedbacks between landsliding and erosion by rivers. Nature 498, 475-480. doi:10.1038/nature12218

Emberson R., Hovius N., Galy A., Marc, O,, 2016. Chemical weathering in active mountain belts controlled by stochastic bedrock landsliding. Nature Geoscience 9, 42–45. DOI: 10.1038/NGEO2600

Falkenberg, M., Rockstrom, J. & Karlberg, L.,2009. Present and future water requirements for feeding humanity. Food Security 1, 59-69. DOI: 10.1007/s12571-008-0003-x

FAO, 1961. The Digitized Soil Map of the World. World Soil Resources Report 67., FAO Rome

FAO, IFAD and WFP, 2015. The State of Food Insecurity in the World 2015. Meeting the 2015 international hunger targets: taking stock of uneven progress. Rome, FAO

FAO. 2016. AQUASTAT Main Database, Food and Agriculture Organization of the United Nations (FAO). Website accessed on [03/06/2016 14:44]

FAO, Land and Water Development Division, 2000. Land Resource Potential and Constraints at Regional and Country Levels, based on the work of A. J. Bot, F.O. Nachtergaele and A. Young, 114pp. FAO, Rome

Fleskens, L., Kirkby, M.J. & Irvine, B.J., 2016. The PESERA-DESMICE Modeling Framework for Spatial Assessment of the Physical Impact and Economic Viability of Land Degradation Mitigation Technologies. Frontiers in Environmental Science, http://dx.doi.org/10.3389/fenvs.2016.00031

Gabet, E.J., Reichman, O.J. & Seabloom, E.W., 2003. The Effects of Bioturbation on Soil Processes and Sediment Transport. Annual Review of Earth and Planetary Sciences. Vol. 31: 249-273 . DOI: 10.1146/annurev.earth.31.100901.141314

Gao, X. & Giorgi,F, 2008. Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. Global and Planetary Change 62, 195-209. DOI: 10.1016/j.gloplacha.2008.02.002

Gao, Y., Dang, X., Yu, Y., Li, Y., Liu, Y., and Wang, J., 2016: Effects of Tillage Methods on Soil Carbon and Wind Erosion, Land Degradation and Development, 27, 583-591, 10.1002/ldr.2404.van Genuchten, M.Th., 1980. "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils" (PDF). Soil Science Society of America Journal 44 (5): 892–898.

Germann, P.F. & Keven KJ, 1985. Kinematic Wave Approximation to Infiltration into Soils with Sorbing Macropores. Water Resources Research, 21, 990–996. DOI: 10.1029/WR021i007p00990

Graham, C.B., Woods, R.A., McDonnell, J.J., 2010. Hillslope threshold response to rainfall (1): a field based forensic approach. J. Hydrology 393, 65-76. DOI: 10.1016/j.jhydrol.2009.12.015

Grayson, RB, Western, AW, Chiew, FHS and Bloschl, G. 1997 . Preferred states in spatial soil moisture patterns: Local and nonlocal controls. Water Resources Research , 33(12), 2897-2908. DOI: 10.1029/97WR02174

Green, W.H. and G. Ampt. 1911. Studies of soil physics, part I – the flow of air and water through soils. J. Ag. Sci. 4:1-24

Haber-Pohlmeier, S., Bechtold, M., Stapf, S. & Pohlmeier, A., 2009.Water Flow Monitored by Tracer Transport in Natural Porous Media Using Magnetic Resonance Imaging. Vadose Zone Journal, Vol. 9 No. 4, p. 835-845. DOI: 10.2136/vzj2009.0177

Herold, N., I. Schöning, B. Michalzik & M. Schrumpf, 2014. Controls on soil carbon storage and turnover in German landscapes. Biogeochemistry 119,435–451.ewlett, J. D. and J. R. Hibbert, 1967, "Factors Affecting the Response of Small Watersheds to Precipitation in Humid Areas," in Forest Hydrology, Edited by W. E. Sopper and H. W. Lull, Pergamon Press, New York, p.275-291 reprinted 2009: Progress in Physical Geography doi: 10.1177/0309133309338118.

Hillel, D. 1971. Soil and Water. Academic press. 288pp

Hoekstra, A.Y. & Mekonnen, M.M., 2012. The water footprint of humanity, Procedings, National Academy of Sciences, 109(9), 3232–3237. doi: 10.1073/pnas.1109936109Horton RE. 1933. The role of infiltration in the hydrologic cycle. Transactions, American Geophysical Union 14: 446–460.

Houyou, Z., Bielders, C. L., Benhorma, H. A., Dellal, A., and Boutemdjet, A., 2014: Evidence of strong land degradation by wind erosion as a result of rainfed cropping in the Algerian steppe: A case study at Laghouat, Land Degradation and Development, 10.1002/ldr.2295.

Howell, M.S., 2009. Mineralogy and micromorphology of an Atacama Desert soil, Chile: A model for hyperarid pedogenesis. University of Nevada, Las Vegas Theses, Dissertations, Professional Papers, and Capstones. Paper 52.

Jacobson, M.C., R.J. Charlson, H. Rodhe, G.H., Orians, 2000. Earth System Science: From Biogeochemical Cycles to Global Changes. International Geophysics series 72. Elsevier 526 pp,

Janzen, D. & McDonell, J.J, 2015. A stochastic approach to modelling and understanding hillslope runoff connectivity dynamics. Ecological Modelling 298, 64-74.

Jenny, H., 1941. Factors of soil formation: a system of quantitative pedology . McGraw Hill, 281pp.

Johnson, J.O., S. M. Mudd, B. Pillans, N. A. Spooner, L.K. Fifield, M. J. Kirkby and M. Gloor, 2014. Quantifying the rate and depth dependence of bioturbation based on optically-stimulated luminescence (OSL) dates and meteoric ^{10}Be. Earth Surface Processes and Landforms, 39(9), 1188-1196.

Keesstra, S.D., 2007. Impact of natural reforestation on floodplain sedimentation in the Dragonja valley, Slovenia. Earth Surface Processes & Landforms, 32, 49-65. DOI: 10.1002/esp.1360

Keesstra, S.D., Bouma,J., Wallinga, J., Jansen, B., Mol, G., Munoz-Rojas, M., Nunes, J.P. & Montanarealla, L., 2016. Soil Science in a changing world:contributions of soil science for solving global challenges of our time. Soil, Special Issue.

Keesstra, S.D., Geissen, V., Mosse, K., Piiranen, S., Scudiero, E., Leistra, M. & van Schaik, L., 2012. Current Opinion on Environmental Sustainability 4, 507-516.

Kirchner, J.W., X. Feng & C. Neal, 2000. Fractal stream chemistry and its implications for contaminant transport in catchments. Nature 403, 524-527 (3 February 2000) | doi:10.1038/35000537

Kirkby, M. J.(ed.), 1978, Hillslope Hydrology. John Wiley, Chichester. 389pp. ISBN: 978-0-471-99510-4

Kirkby, M.J.. 1985. The basis for soil profile modelling in a geomorphic context. J. Soil Science 36, 97-121.

Kirkby, M.J., 2014. Do not only connect: a model of infiltration-excess overland flow based on simulation. Earth Surface Processes and Landforms 39(7), 952-963. DOI: 10.1002/esp.3556

Kirkby, M.J., 2015. Modelling Soil Profiles In Their Landscape Context. Oral presentation & Abstract at AGU fall conference, San Francisco, Dec2015.

Kirkby, M.J., F. Gallart, T. R. Kjeldsen, B. J. Irvine, J. Froebrich, A. Lo Porto, A. De Girolamo, and the MIRAGE team, 2011. Classifying low flow hydrological regimes at a regional scale. Hydrology and Earth System Science, 15, 1–10. DOI: 10.5194/hess-15-3741-2011

Kirkby, M.J., Irvine, B.J., Jones, R.J.A., Govers, G., & the PESERA team, 2008.The PESERA coarse scale erosion model for Europe: I – Model rationale and implementation . European Journal of Soil Science. 59(6), 1293-1306. DOI: 10.1111/j.1365-2389.2008.01072.x

Knapen, A., J. Poesen , G. Govers , G. Gyssels and J. Nachtergaele, 2007. Resistance of soils to concentrated flow erosion: A review. Earth Science Reviews 80, 75-109.

Larsen LG, J. Choi, M.K.,Nungesser & J.W. Harvey, 2012. Directional connectivity in hydrology and ecology Ecol. Appl 22, 2204-2220.

Lavee, H., Imeson, A.C., & Sarah, P., 1998. The impact of climate change on geomorphology and desertification along a mediterranean-arid transect. Land Degradation and Development 9, 407-422. DOI: 10.1002/(SICI)1099-145X(199809/10)9:5<407::AID-LDR302>3.0.CO;2-6

Lin, H. 2010. Earth's Critical Zone and hydropedology: concepts, characteristics, and advances Hydrol. Earth Syst. Sci., 14, 25–4

McRae BH, Dickson BG, Keitt TH, Shah VB 2008.. Using circuit theory to model connectivity in ecology, evolution, and conservation. Ecology 89: 2712-2724. DOI: 10.1890/07-1861.1

McDonnell, J.J., 2014. The two water worlds hypothesis: ecohydrological separation of water between streams and trees? Wiley Interdiciplinary reviews: Water. 1(4), 323-329.

McGuire, K.J & McDonnell, J.J., 2010. Hydrological connectivity of hillslopes and streams: Characteristic time scales and nonlinearities. Water Resources research 26 (10) DOI 10.1029/2010WR009341. DOI: 10.1029/2010WR009341

Mazoyer, M & Roudart, L..2006 (English Translation). A History of World Agriculture: From the Neolithic Age to the Current Crisis. Monthly Review Press.496pp ISBN-13: 978-1583671214

Martin, P. , Hunen, J., Parman, S. and Davidson, J., 2008. Why does plate tectonics occur only on Earth? Physics education, 43(2), 141-150. DOI: 10.1088/0031-9120/43/2/002

Montgomery, D.R., 2007. Soil erosion and agricultural sustainability. Proceedings National Academy of Sciences. vol. 104 , 13268–13272, doi: 10.1073/pnas.0611508104

Montgomery, D.R. and Dietrich, W.E., 1992.Channel initiation and the problme ofl andscape scale. Science 255, 826-830. DOI: 10.1126/science.255.5046.826

Mooney, S.J., Holden, N., Ward, S and Collins, J.F., 1999. Morphological observations of dye tracer infiltration and by-pass flow in milled peat . Plant and Soil 208(2):167-178. DOI: 10.1023/A:1004538207229

Van Oost, K., G. Govers, T. A. Quine, G. Heckrath, J. E. Olesen, S. De Gryze, and R. Merckx (2005), Landscape-scale modeling of carbon cycling under the impact of soil redistribution: The role of tillage erosion, Global Biogeochem. Cycles, 19, GB4014, doi:10.1029/2005GB002471.

Penuela F.A., Javaux, M & Bielders, C. 2015. How do slope and surface roughness affect plot-scale overland flow connectivity?. Journal of Hydrology, Vol. 528, p. 192-205. doi:10.1016/j.jhydrol.2015.06.031. http://hdl.handle.net/2078.1/164926

Philip, J. R., 1957. The Theory of Infiltration: Sorptivity and Algebraic Infiltration Equation, Soil Sci., 84, 257-264

Philip, J.R., 1969. Theory of infiltration. *Advances in Hydroscience*. v. 5, p. 215-296.

Pimentel, D., Berger, B., Filiberto, D., Newton, M., Wolfe, B.,Karabinakis, E., Clark, S., Poon, E., Abbett, E. & Nandagopal, S., 2004. Water resources: Agricultural and environmental issues Bioscience 54, 909-918. DOI: 10.1641/0006-3568(2004)054[0909:WRAAEI]2.0.CO;2

Poesen, J.W., Torri, D., & Bunte, K.,1994.Effects of rock fragments on soil erosion by water at different spatial scales: a review. Catena 23, 141-166. DOI: 10.1016/0341-8162(94)90058-

Prentice, I.C., Cramer, W. Harrison, S.P., Leemans, R.,. Monserud, R.A. and. Solomon, A.M. 1992. A Global Biome Model Based on Plant Physiology and Dominance, Soil Properties and Climate. *Journal of Biogeography,* 19 (2),117-134. DOI: 10.2307/2845499

Reaney, S. M.; Bracken, L. J.; Kirkby, M. J., 2014.The importance of surface controls on overland flow connectivity in semi-arid environments: results from a numerical experimental approach. Hydrological Processes   28,: 2116-2128 . DOI: 10.1002/hyp.9769

Richards, L.A.,1931. Capillary conduction of liquids through porous mediums. Physics 1 (5): 318–333

Riebe, C.S, Kirchner, J.W. and Finkel, R.C, 2003. Long-term rates of chemical weathering and physical erosion from cosmogenic nuclides and geochemical mass balance. Geochimica et Cosmochimica Acta, 67, 4411–4427. DOI: 10.1016/S0016-7037(03)00382-X

Roering, J.J., J.W. Kirchner, and W.E. Dietrich, 2001. Hillslope evolution by nonlinear slope-dependent transport: Steady-state morphology and equilibrium adjustment timescales, Journal of Geophysical Research, v. 106, p. 16,499-16,513. DOI: 10.1029/2002JB001822

Rommens, T.,Verstraeten G, Poesen, J., Govers, G.,van Rompaey, A.,Peeters, I. & Lang, A., 2005. Soil erosion and sediment deposition in the Belgian loess belt during the Holocene: establishing a sediment budget for a small agicultural catchment. The Holocene 15, 1032-1043. DOI: 10.1191/0959683605hl876ra

Sadras, Grassini & Steduto, 2011: Status of water use efficiency of main crops. In: The state of world's land and water resources for food and agriculture (SOLAW). FAO, Rome and Earthscan, London

Sanjuan, Y., Gomez-Vilar, A., Nadal-Romero, E.,Alvarez-Martinez, J.,Arnaez, J.,Serrano-Muela, M.P.,Rubiales, J.M.,Gonzalez-Samperiz, P. & Garcia-Ruiz,J.M., 2014.Linking land cover changes in the Sub_Alpins and Montane belts to changes in a torrential river. Land Degradation and development 27, 179-189. DOI: 10.1002/ldr.2294

Scheiter, S., Langan, L. and Higgins, S.I., 2013. Next-generation dynamic global vegetation models: learning from community ecology. New Phytologist, 198 (3), 957–969. DOI: 10.1111/nph.12210

Schymanski, S.J., Sivapalan, M., Roderick,M.L., Beringer,J. & Hutley,L.B., 2008.An optimality-based model of the coupled soil moisture and root dynamics Hydrology and Earth System Sciences Discussions, 12(3), 913-932. DOI: 10.1029/2008WR006841

Sivapalan, M. Beven, K. & Wood, E.F>. 1987. On hydrologic similarity: 2. A scaled model of storm runoff production.Water Resources Research 23, 2266-2278. DOI: 10.1029/WR023i012p02266

Stauffer, D. and A. Aharony, 1985. Introduction to percolation theory. Taylor and Francis, London. 193pp.

Steffen, W., K. Richardson, J. Rockstrom, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. de Vries, C.A.de Wit, C. Folke, D. Gertem, J. Heinke, G.M. Mace, L.M. Persson, V. Ramanathan, B. Reyers & S. Sorlin.2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347, Issue 6223, DOI: 10.1126/science.1259855

Tarboton, D.G., 2003. Rainfall-runoff processes. Technical report. Utah State University

Tetzlaff, D., Soulsby, C.,& Birkel, C., 2010.Hydrological connectivity and microbiological fluxes in montane catchments: the role of seasonality and climatic variability. Hydrological Processes 24(9), 1231-1235. DOI: 10.1002/hyp.7680

Tromp-van Meerveld, H.J. and J.J. McDonnell. 2006. Threshold relations in subsurface stormflow 2: The fill and spill hypothesis: an explanation for observed threshold behavior in subsurface stormflow. Water Resources Research, doi:10.1029/2004WR003800

Tucker, G.E., Lancaster, S., Gasparini, N. & Bras, R., 2001. Landscape erosion and evolution modelling, (ed Harmon & Doe) Kluwer Academic/ Plenum, NY. pp 349-388. ISBN 0-306-46718-6

Vitousek, P., Dixon, J.L. & Chadwick, O.A. Biogeochemistry (2016) 130: 147. doi:10.1007/s10533-016-0249-x

Weiler, M. and F. Naef, 2003. An Experimental Tracer Study of the Role of Macropores in Infiltration in Grassland Soils, Hydrological Processes, 17: 477-493. . DOI: 10.1002/hyp.1136

Wright, R.J., Boyer, D.G., Winant, W.M., and Perry, H.D.. 1990. The influence of soil factors on yield differences among landscape positions in an Appalachian cornfield. Soil Sci. 149:375–382. DOI: 10.1097/00010694-199006000-00009.

Youngs, E.G., 1957. Moisture profiles during vertical infiltration. Soil Science, 84 (4), 283-290.

Zhao, C., Gao, J., Huang, Y., Wang, G., and Zhang, M., 2016: Effects of Vegetation Stems on Hydraulics of Overland Flow Under Varying Water Discharges, Land Degradation and Development, 27, 748-757, 10.1002/ldr.2423.

Zimmer, Y, 2012. Production Cost in the EU and in Third Countries: past Trends, Structures and Levels. Workshop on the Outlook for EU Agriculture by COPA, COGECA, European Crop Protection & Fertilizers Europe. Brussels

Figure Captions

1. Inter-relationships between soil forming factors, ultimately controlled by parent material and climate, mediated by water, life and topography over a range of time and space scales
2. Broad typology of soil types, controlled by net atmospheric inputs (e.g. salt and dust) and net water balance (precipitation minus evapotranspiration)
3. Modelled evolution of runoff patterns on randomly rough slope of 160x160m. Individual hydrographs are shown for points on the lower boundary with different catchment areas, parts of the total area of 4096 (64x64). Square shows intensity (on log scale) of local overland flow at a time indicated by the heavy arrows on the hydrographs below.

(a) Early in a 30 mm, 30 minute storm, runoff generated in patches of lowest infiltration capacity.

(b) As storm rainfall ends, downslope accumulation defines connectivity along strongest flow paths

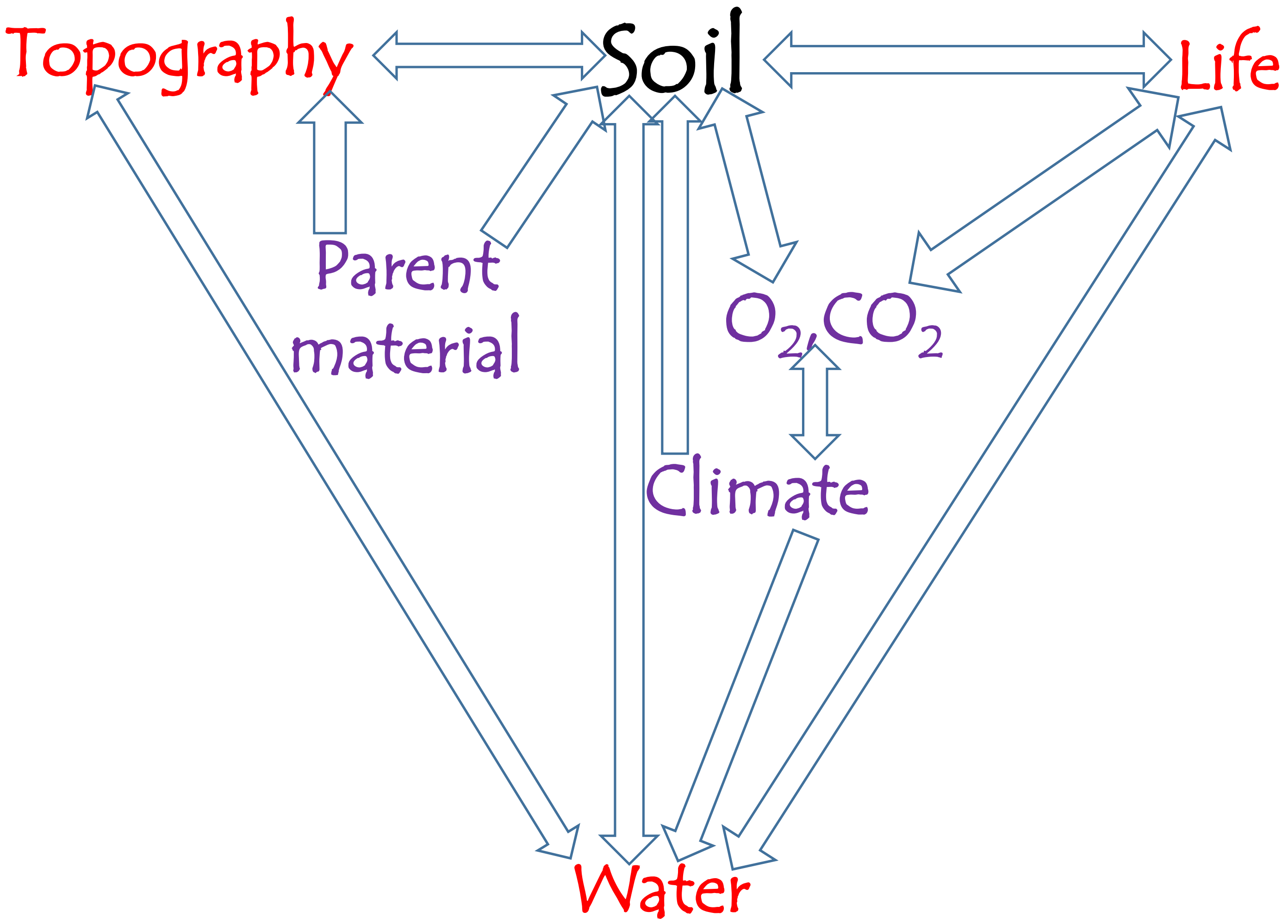
4. Perceptual model of water flow pathways in the critical zone
5. Paths of parent material as it progressively weathers and is carried away as sediment et and near the soil surface. If a steady state develops over time, the rate of surface lowering will be equal to the rate at which the weathering front penetrates into bedrock.

6a. Sustainable population assuming rain-fed agriculture. Left hand axis is for efficient agriculture; right hand axis for low efficiency. Lines show self-sufficiency levels with high (blue) and low efficiency (red) farming.

6b: Sustainable population if available rainfall is effectively concentrated by water harvesting. Note that some of the countries that appear here had insufficient rainfall for any rain-fed farming.

Lines represent levels of full sustainability. The 31% of countries not shown cannot support any rain-fed agriculture based on their average rainfall

7. Renewable water resources (mm of water per year) and arable land available by country. Diamonds show actual arable land and circles show potential arable land. The horizontal line divides countries with and without enough water to fully utilise their arable land.
8. Renewable water per capita against population size by country. The lines the annual water resources needed to grow food (ca 1200 m^3 per capita) and for domestic water supply (a 80 m^3 per capita). Many countries do not have enough water to be food secure, and a some lack enough water for domestic use.
9. Water harvesting potential in Africa, based on climatic data. The map shows the ratio of precipitation to potential evapotranspiration for a 5-month growing season, for the worst 25% of years. At values less than 0.2, water harvesting is only practicable in very favourable situations. Above 1.5, rain-fed farming generally provides an adequate crop without water harvesting.
10. The modelled frequency distribution of crop yields for Mekele, northern Ethiopia, for a range of ratios of collecting: cropping area (CAR), illustrating the greater reliability of crop yields with effective water harvesting.
11. Factors influencing the relationships between water use and the cost of food, taking account of energy needs for fertiliser and possible water desalination, loss of cultivable land and greenhouse gas emissions.



Soil

Topography

Life

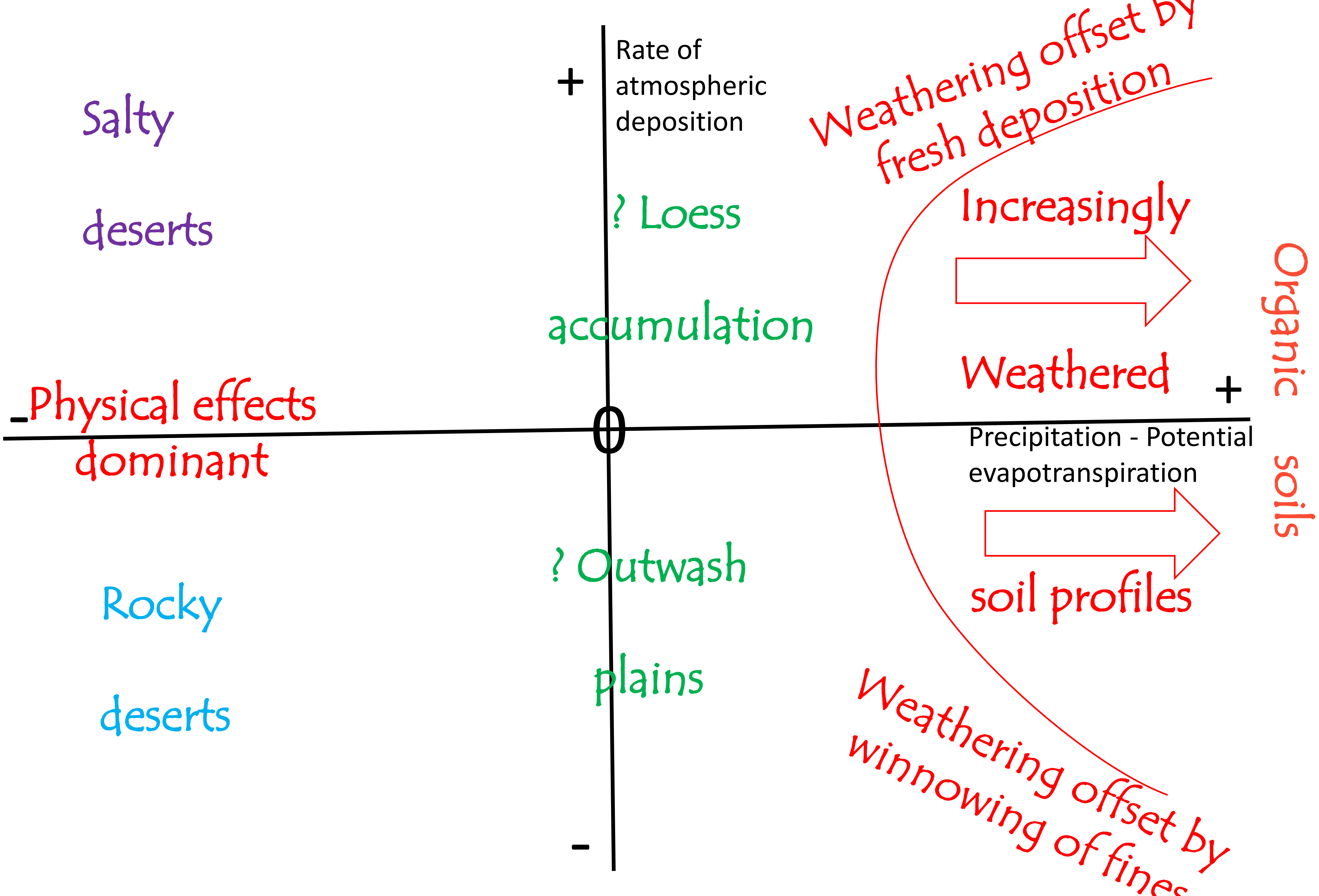
Parent material

O_2,CO_2

Climate

Water

Figure1



\+

Rate of atmospheric deposition

Salty deserts

? Loess accumulation

Weathering offset by fresh deposition

Increasingly Weathered soil profiles

Organic soils

_ Physical effects dominant

0

\+

Precipitation - Potential evapotranspiration

Rocky deserts

? Outwash plains

Weathering offset by winnowing of fines

\-

Figure 2

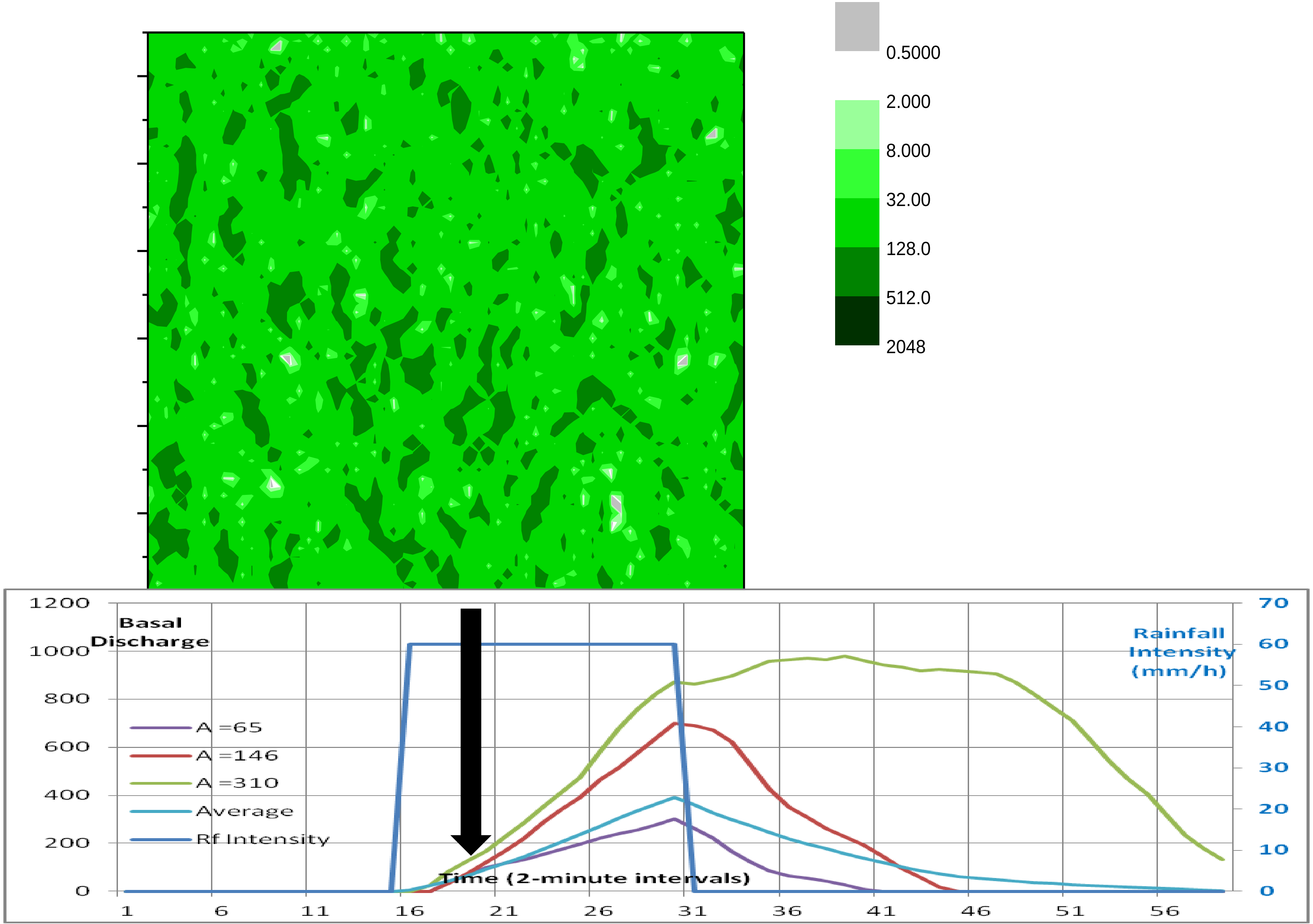

0.5000
2.000
8.000
32.00
128.0
512.0
2048
Basal Discharge
1200
1000
800
600
400
200
0
A =65
A =146
A =310
Average
Rf Intensity
Time (2-minute intervals)
1
6
11
16
21
26
31
36
41
46
51
56
Rainfall Intensity (mm/h)
70
60
50
40
30
20
10
0

Figure3a

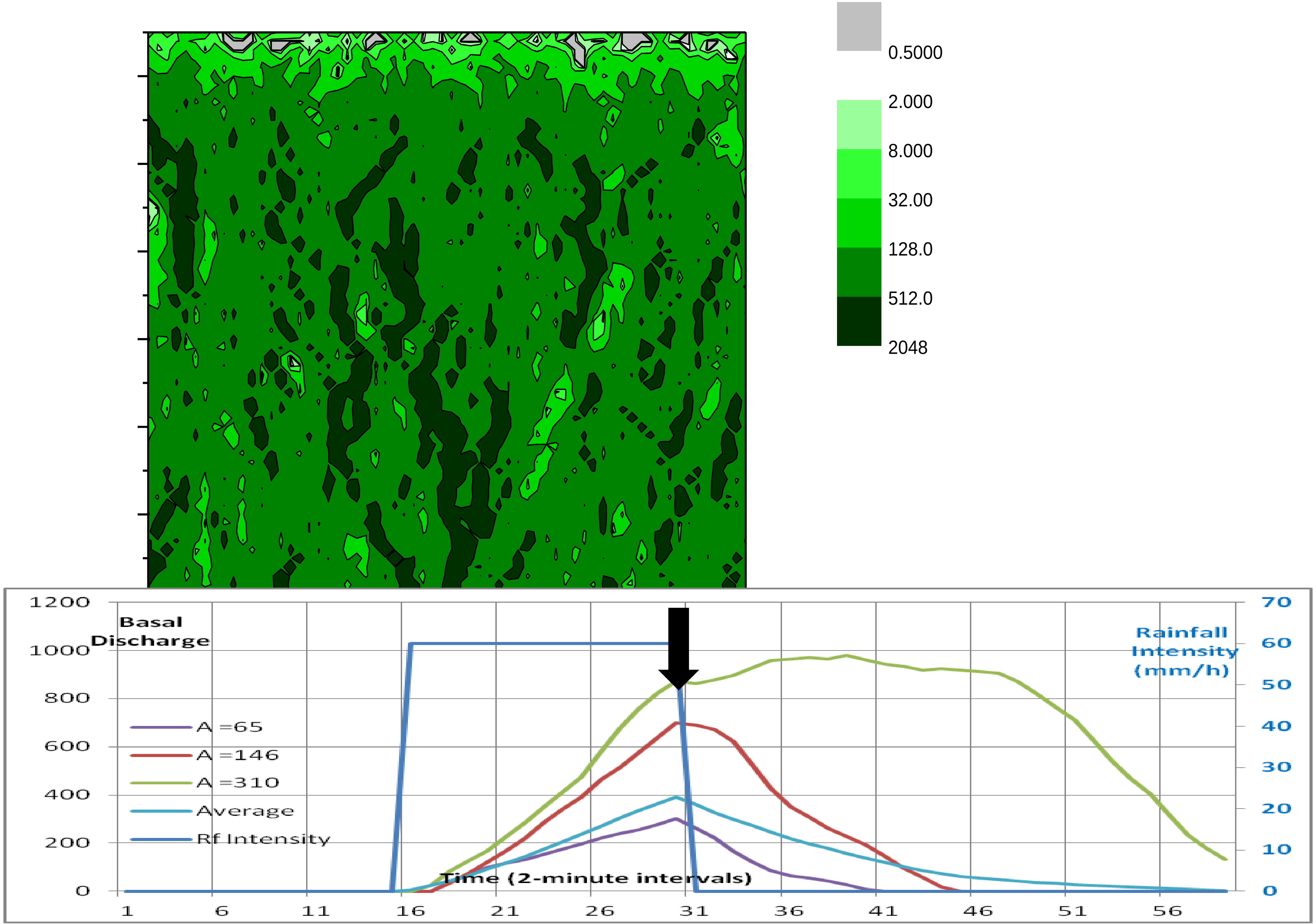

0.5000
2.000
8.000
32.00
128.0
512.0
2048
Basal Discharge
1200
1000
800
600
400
200
0
A =65
A =146
A =310
Average
Rf Intensity
Time (2-minute intervals)
1
6
11
16
21
26
31
36
41
46
51
56
Rainfall Intensity (mm/h)
70
60
50
40
30
20
10
0

Figure 3b

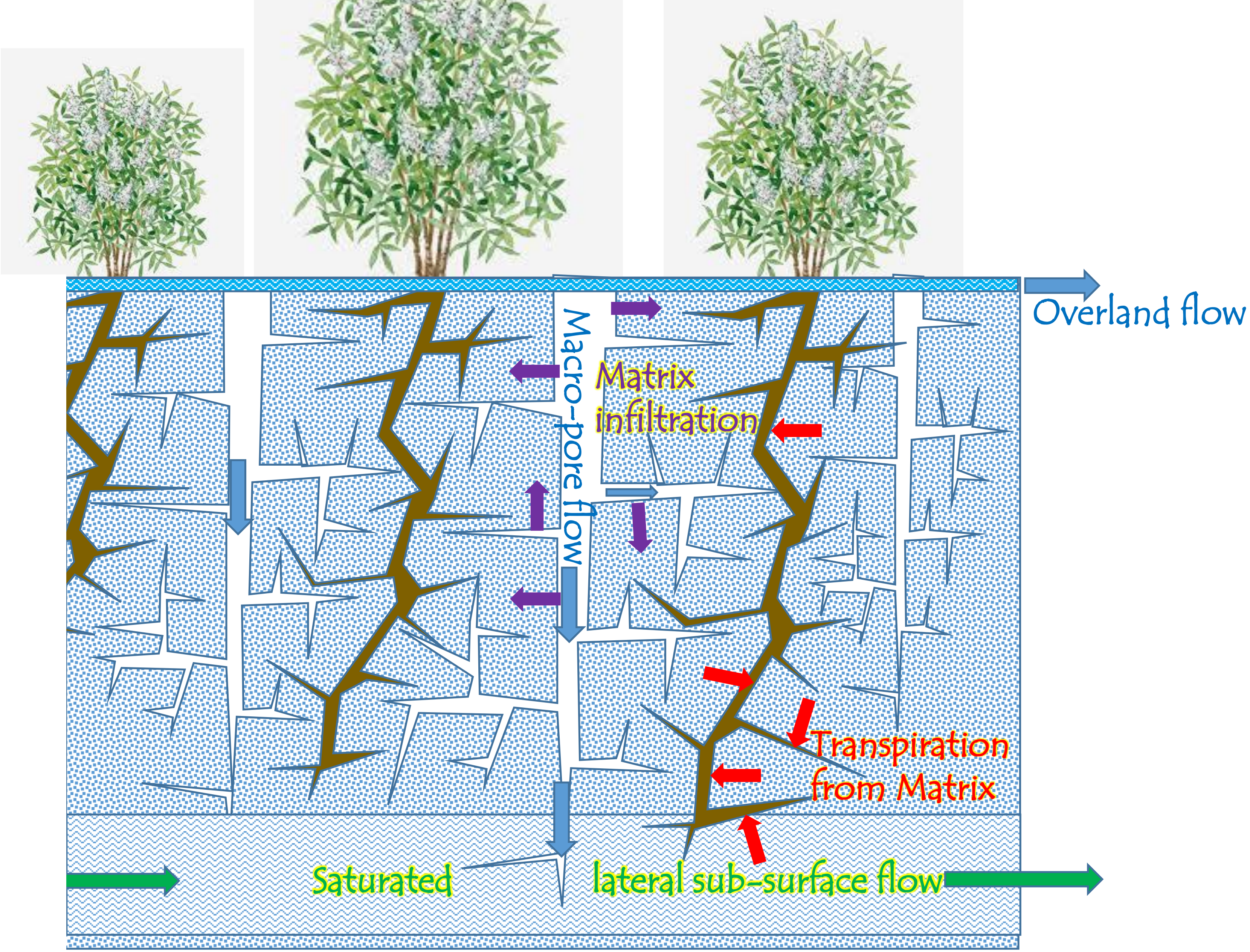
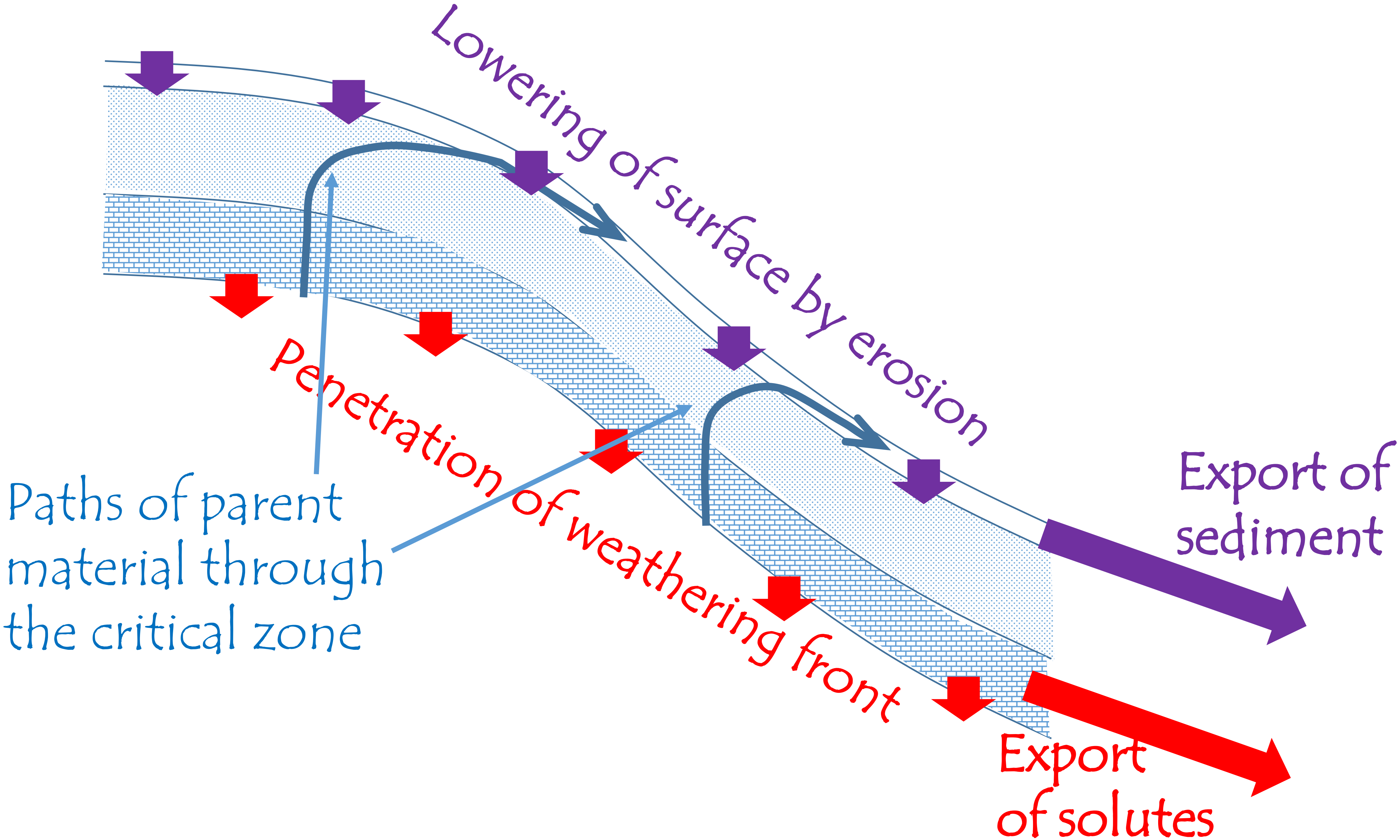

Overland flow
Macro-pore flow
Matrix infiltration
Transpiration from Matrix
Saturated
lateral sub-surface flow

Figure 4



Lowering of surface by erosion

Export of sediment

Penetration of weathering front

Export of solutes

Paths of parent material through the critical zone

Figure 5

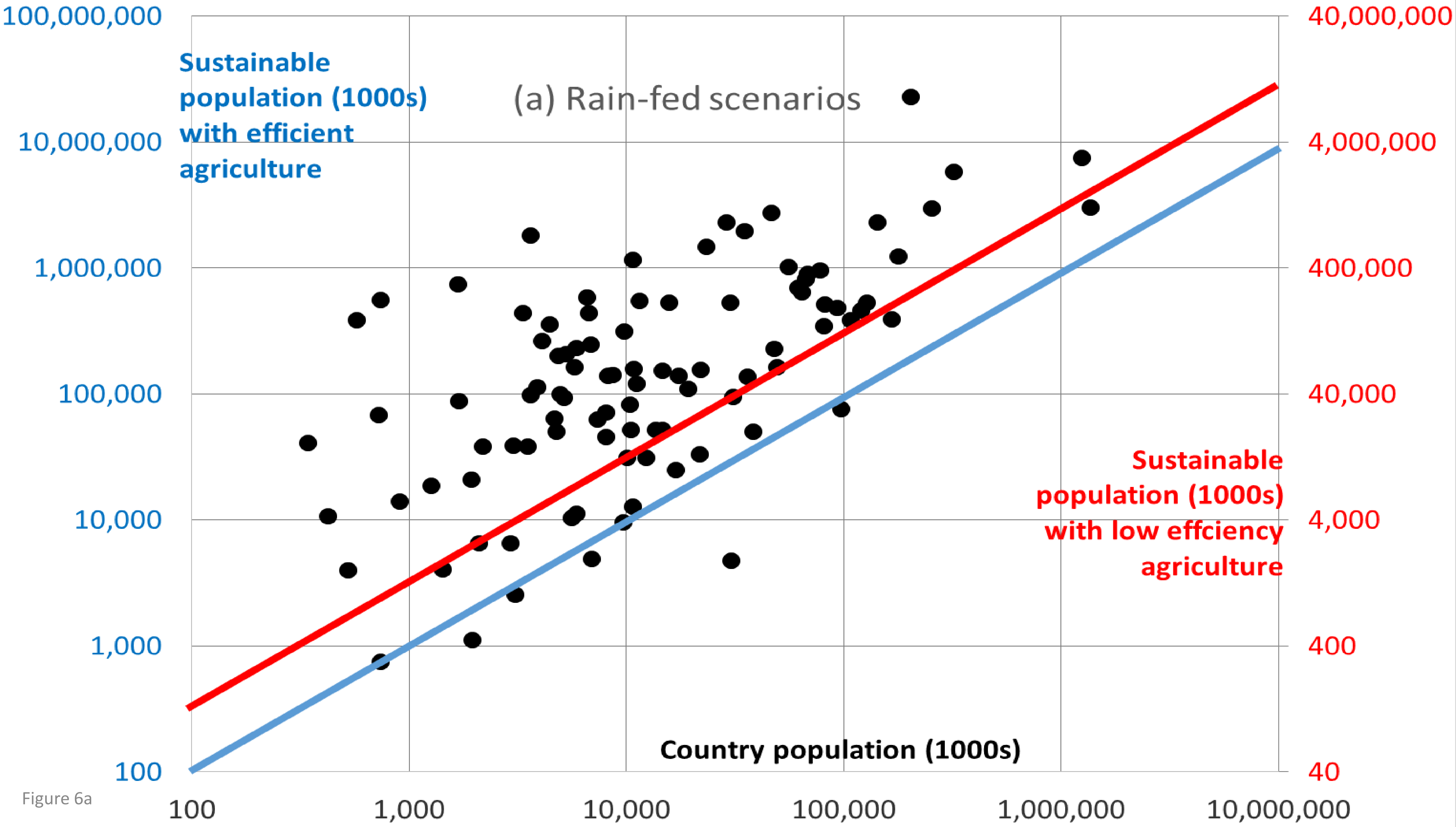
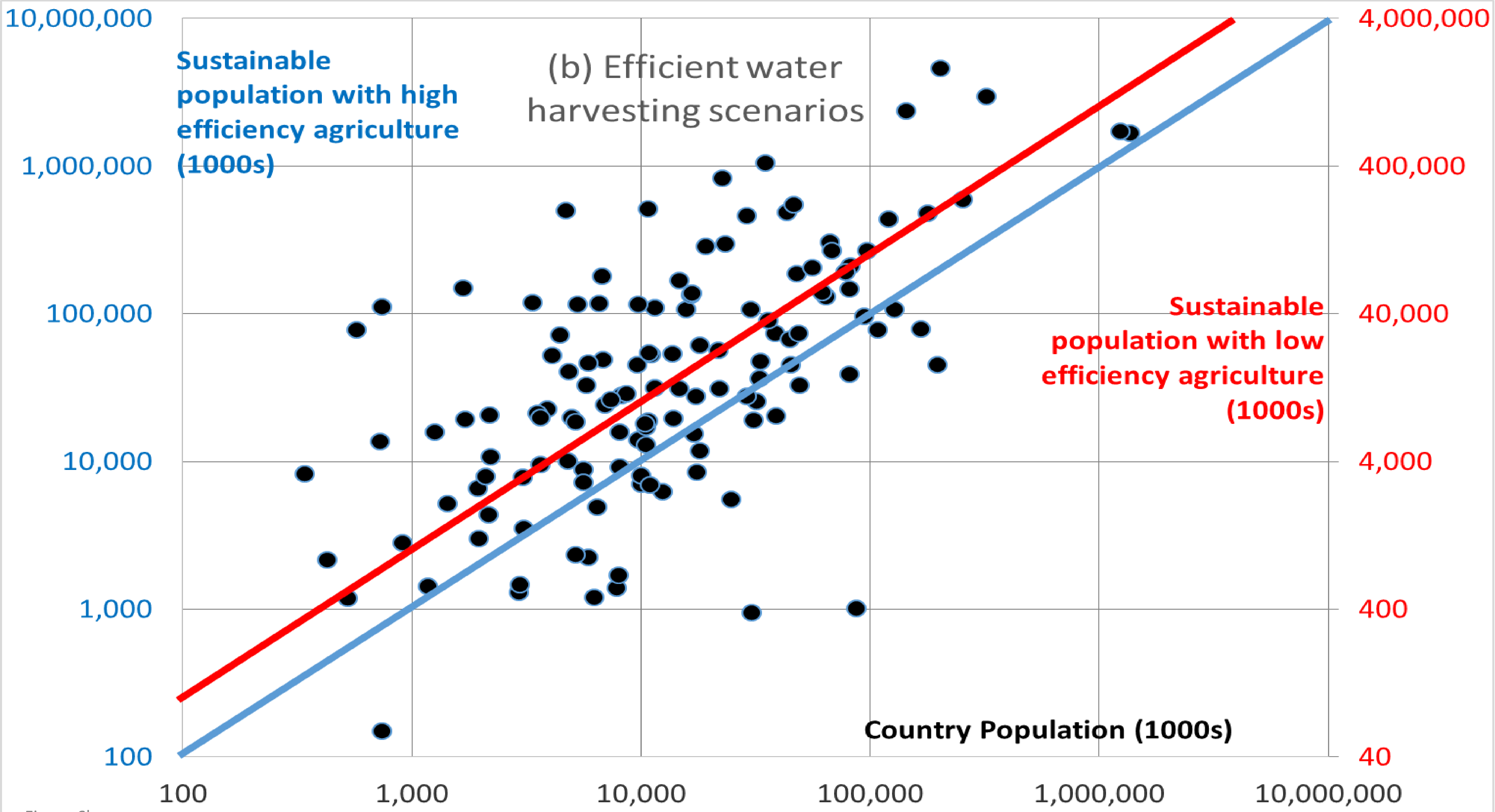

100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
Sustainable population (1000s) with efficient agriculture
(a) Rain-fed scenarios
40,000,000
4,000,000
400,000
40,000
4,000
400
40
Sustainable population (1000s) with low effciency agriculture
Country population (1000s)
100
1,000
10,000
100,000
1,000,000
10,000,000

Figure 6a



(b) Efficient water harvesting scenarios
Sustainable population with high efficiency agriculture (1000s)
Sustainable population with low efficiency agriculture (1000s)
Country Population (1000s)
10,000,000
1,000,000
100,000
10,000
1,000
100
4,000,000
400,000
40,000
4,000
400
40
100
1,000
10,000
100,000
1,000,000
10,000,000

Figure 6b

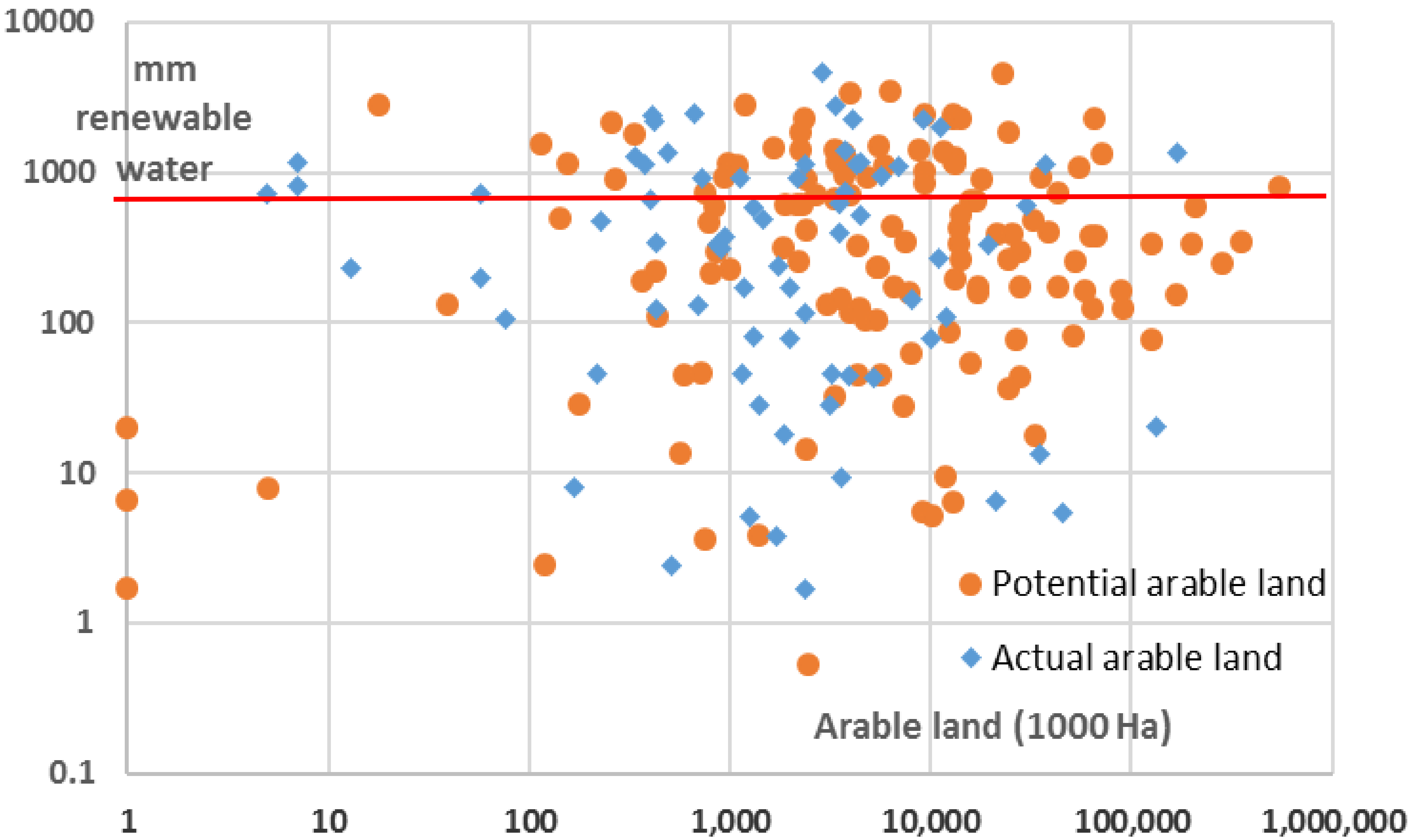

10000
1000
100
10
1
0.1
mm
renewable
water
Potential arable land
Actual arable land
Arable land (1000 Ha)
1
10
100
1,000
10,000
100,000
1,000,000

Figure78

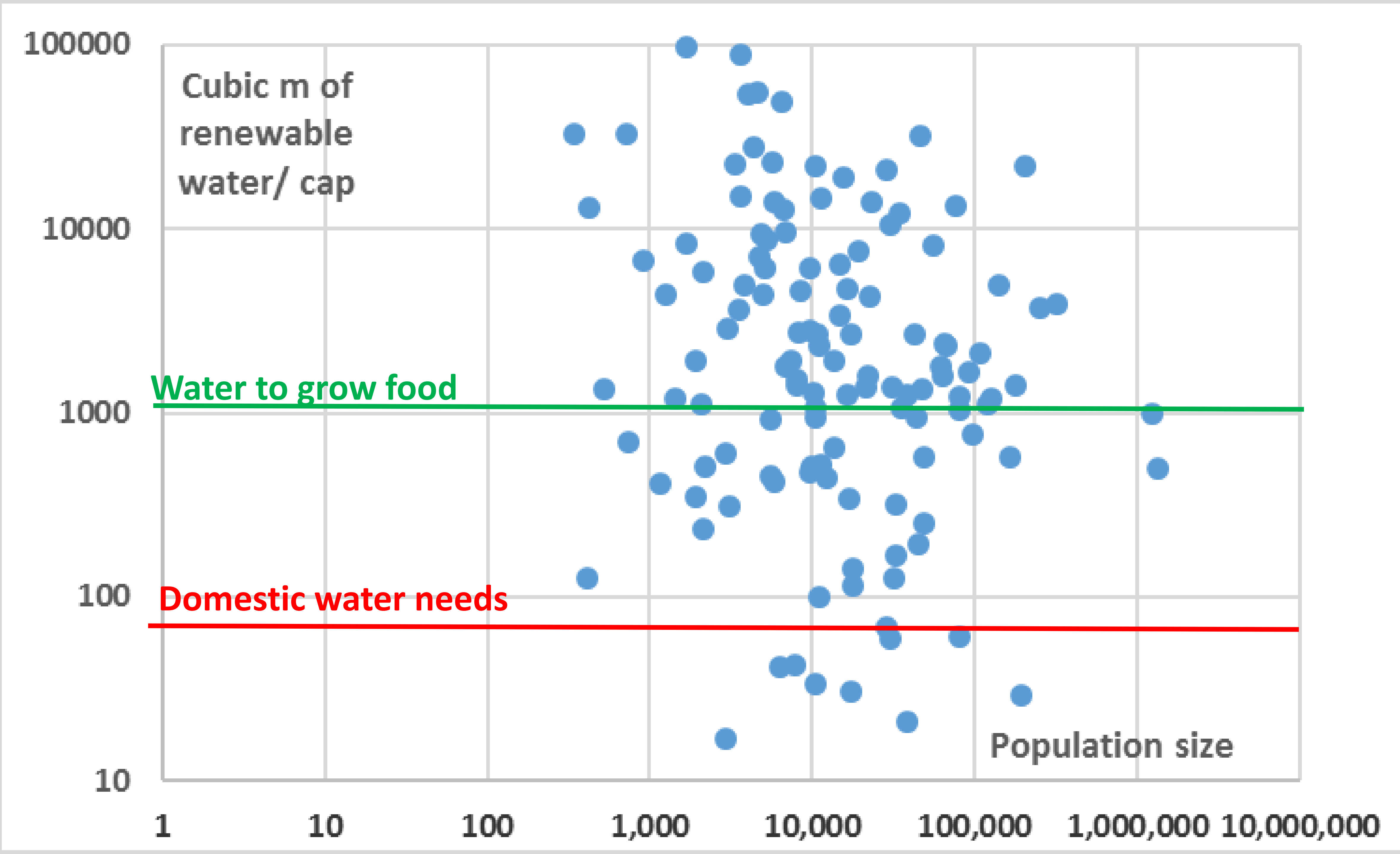
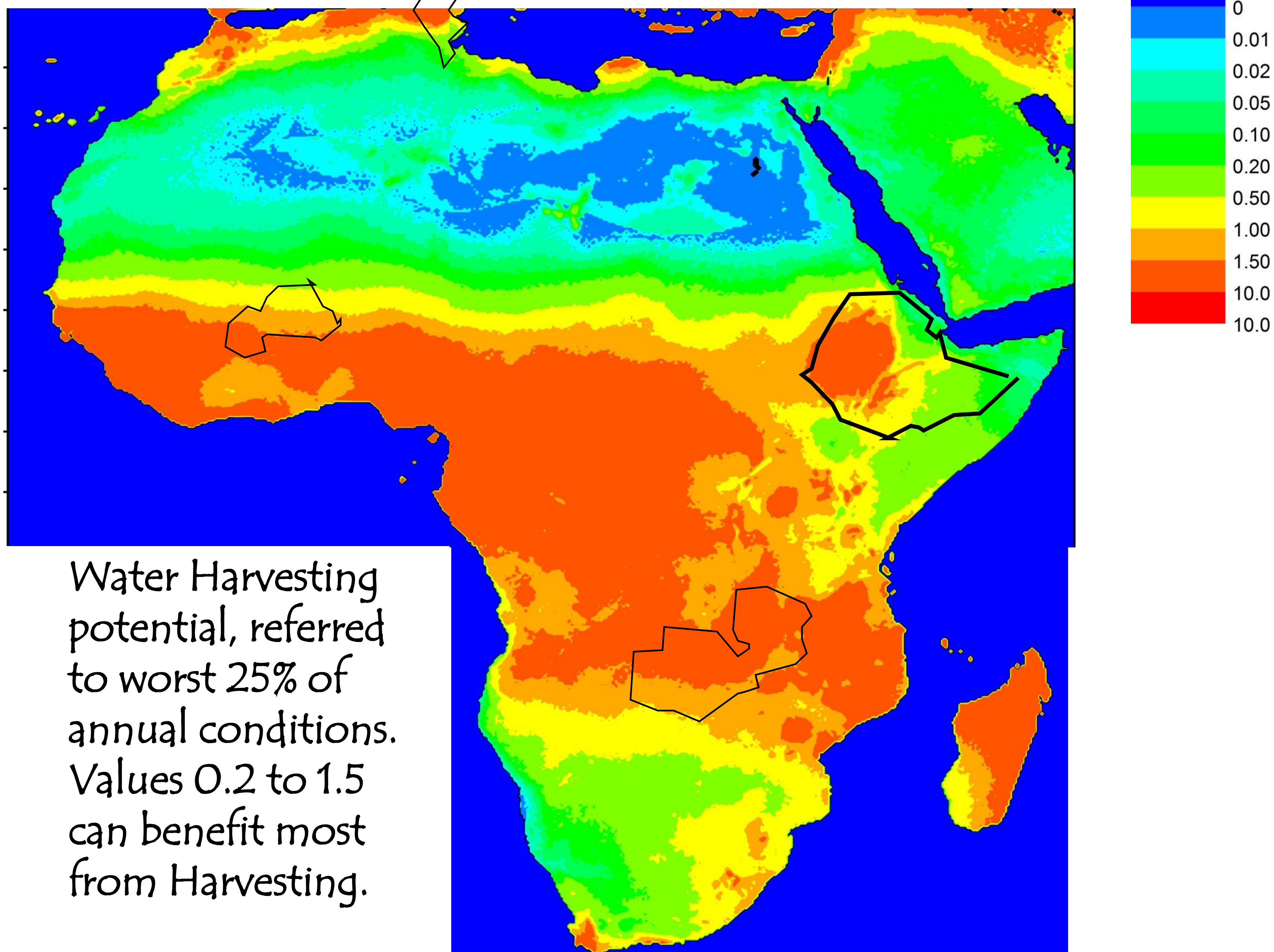

Cubic m of renewable water/ cap
100000
10000
1000
100
10
Water to grow food
Domestic water needs
Population size
1
10
100
1,000
10,000
100,000
1,000,000
10,000,000

Figure 8



Water Harvesting potential, referred to worst 25% of annual conditions. Values 0.2 to 1.5 can benefit most from Harvesting.

Figure 9

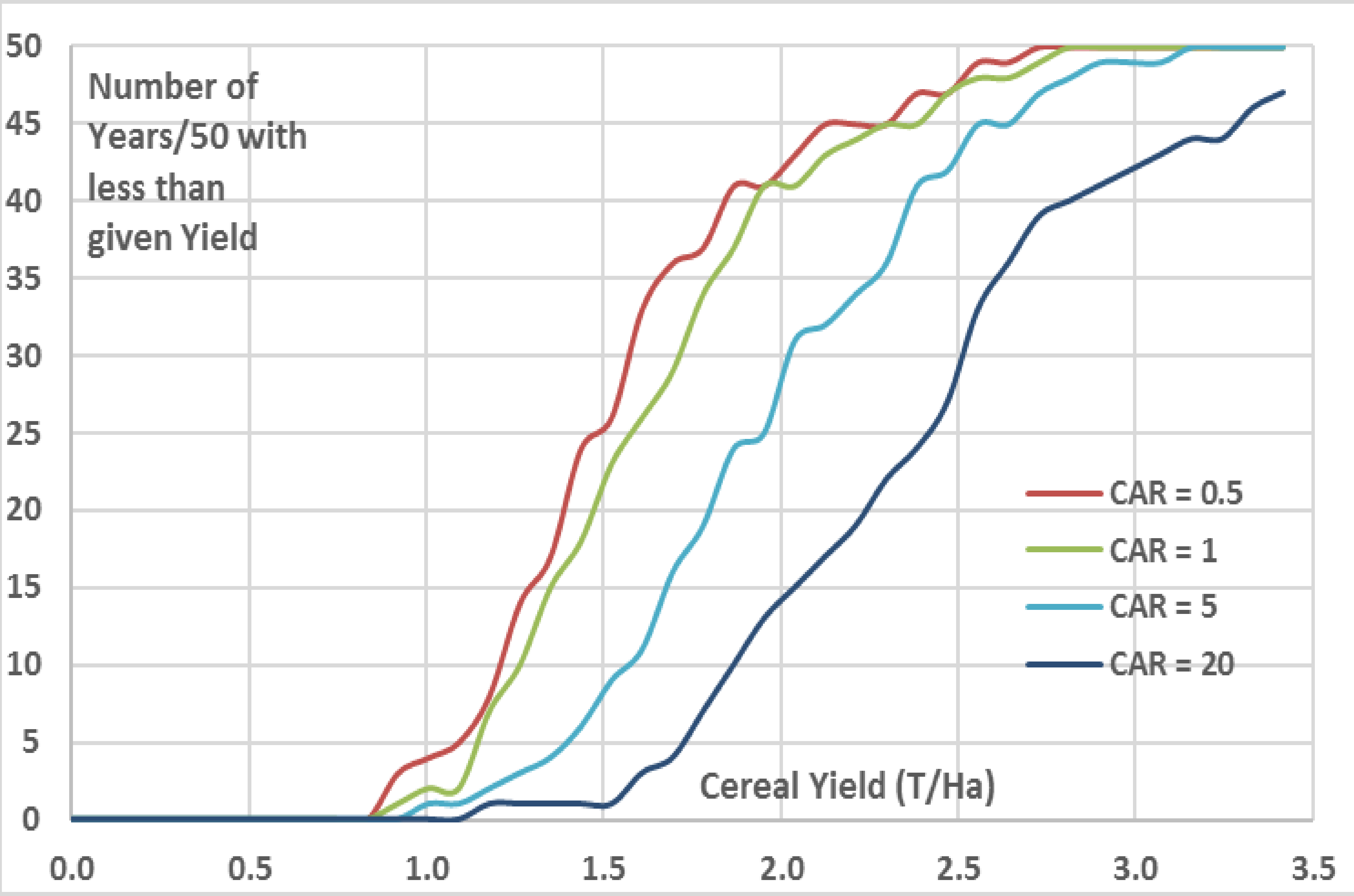

Number of
Years/50 with
less than
given Yield
Cereal Yield (T/Ha)
CAR = 0.5
CAR = 1
CAR = 5
CAR = 20
0
5
10
15
20
25
30
35
40
45
50
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

Figure 10

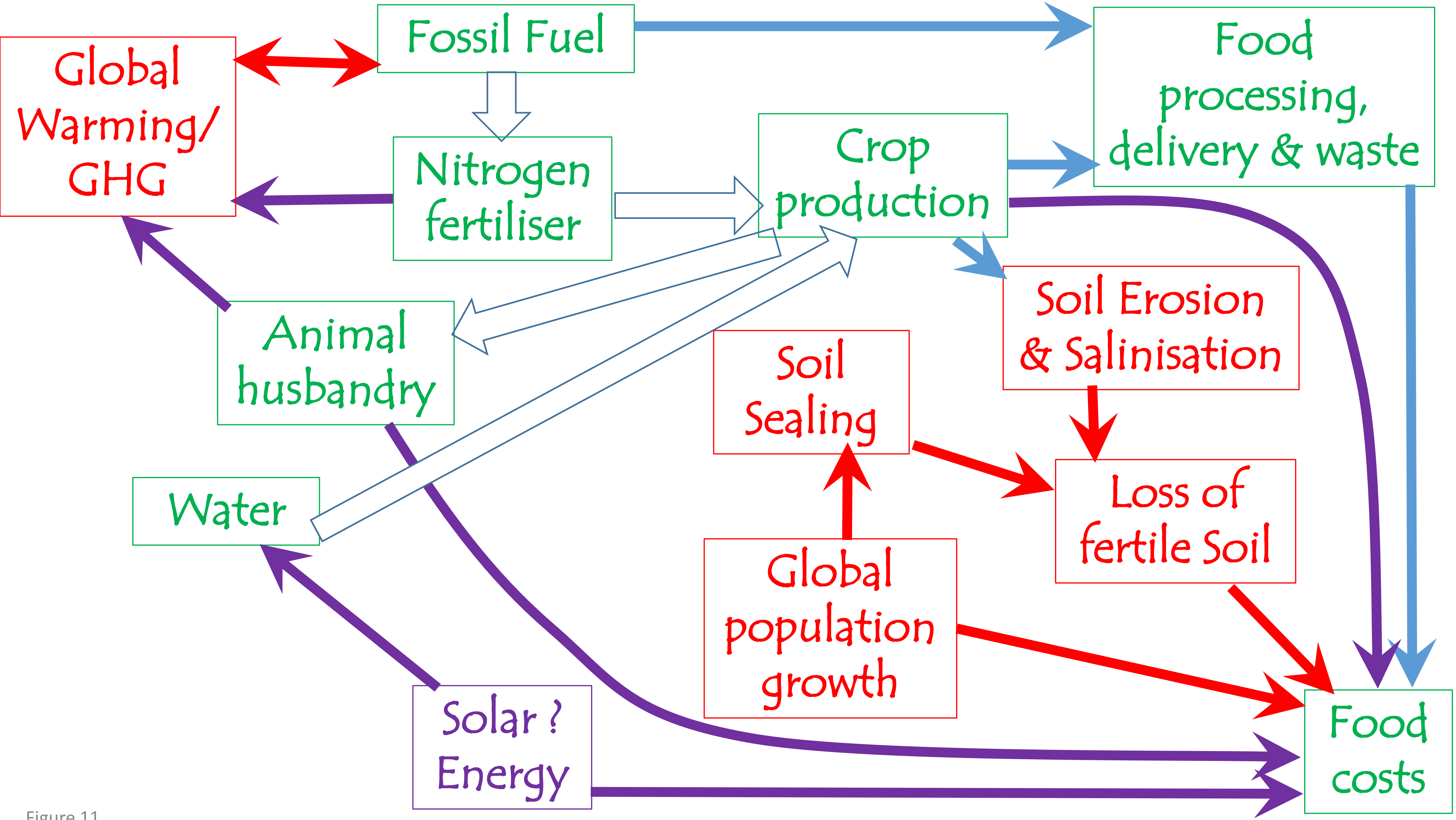

Fossil Fuel
Global Warming/ GHG
Food processing, delivery & waste
Nitrogen fertiliser
Crop production
Animal husbandry
Soil Erosion & Salinisation
Soil Sealing
Water
Loss of fertile Soil
Global population growth
Solar ? Energy
Food costs

Figure 11