



Review

Temperate Soils Exposed to Drought—Key Processes, Impacts, Indicators, and Unknowns

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Abstract: The summer drought in the United Kingdom (UK) in 2022 produced significant speculation concerning how its termination may impact and interact with the soil resource. Whilst knowledge regarding soils and droughts exists in the scientific literature, a coherent understanding of the wider range of impacts on soil properties and functions has not been compiled for temperate soils. Here, we draw together knowledge from studies in the UK and other temperate countries to understand how soils respond to drought, and importantly what and where our knowledge gaps are. First, we define the different types of droughts and their frequency in the UK and provide a brief overview on the likely societal impacts that droughts place on the soil and related ecosystems. Our focus is on ‘agricultural and ecosystem drought’, as this is when soils experience dry periods affecting crops and ecosystem function, followed by rewetting. The behaviour of moisture in soils and the key processes that contribute to its storage and transport are examined. The principal changes in the physical, chemical, and biological properties of soils resulting from drought, and rewetting (i.e., drought termination) are discussed and their extensive interactions are demonstrated. Processes that are involved in the rewetting of soils are explored for soil and catchment-scale soil responses. Lastly, soils’ recovery after drought is considered, knowledge gaps are identified, and areas to improve understanding are highlighted.

Keywords: meteorological drought; soil moisture; soil water infiltration; rewetting; drought recovery; drought termination; soil microbes; soil fauna; soil water repellency; soil nutrients; soil health



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1. Introduction

This paper reviews the current knowledge regarding soils and droughts with a focus on the UK (temperate climate), but including relevant studies from other temperate countries. Its aim is to aid policymakers by bringing relevant information together after it was found that a knowledge gap existed during the 2022 UK drought [1]. Various definitions of drought exist, with the simplest being the ‘absence of water’ or ‘a prolonged period of abnormally low rainfall, leading to a shortage of water’ (*Oxford English Dictionary*). However, drought is a complex, natural phenomenon, with large variations in extent, duration, intensity, and impact. The National Oceanic and Atmospheric Administration recognises several drought types, including meteorological drought, hydrological drought, agricultural/ecosystem drought, and socio-economic drought. In this review, we largely focus on ‘agricultural and ecosystem’ drought, given its frequency of occurrence and potential impact on temperate soils. Across the temperate climate region, hydrological droughts may occur over several years, often involving dry winters, when precipitation does not fully replenish soil moisture storage, or reservoir and water table levels have

not been recharged. During ‘hydrological droughts’, rainfall occurs, albeit at lower than ‘average’ quantities, thus not impacting soils in the manner that a prolonged rain-free period may. When ‘agricultural’ droughts occur [2], soil moisture may be present, but plants cannot access it, either because the water potential is too low or because the soil is frozen.

Kendon et al. (2013) [3] suggest that whilst major droughts in the UK are infrequent (agricultural droughts occurring in 1921, 1934, 1976, 1984, 2003, 2018, 2022 being examples; and in [4]), in recent decades, there has been a cluster of major rainfall deficiencies (e.g., 2010–2012, 2004–2006, 2003, 1995–1997, 1990–1992, 1988–1989). Similar patterns have been observed across the temperate climate region [5–9]. However, whilst the duration and spatial extent of drought determine the range and severity of impacts, an important aspect is how they terminate. Drought terminations can occur in any season across the temperate climate region, though they are more common during the wetter season, as precipitation is more ‘effective’ at that time and evapotranspiration is likely to be lower [10,11]. In general, drought onset is more predictable than drought termination [12]. For soils, the process of drought termination is particularly important, as the perceived threats of erosion and flooding may be influenced by the intensity of rainfall. The breakdown of drought can be divided into (i) the initial breakdown, (ii) the longer-term weather patterns that lead to more usual weather conditions, and (iii) the return of more typical soil moisture conditions. The initial breakdown of drought is of importance, as this is when soil properties are likely to have been altered significantly by dry conditions. However, initial breakdown is likely to exhibit large-scale spatial variability, and rainfall can be highly variable in intensity.

The impact of drought on soils in the UK that is most widely recognised by the public is that of vegetation dieback. This is often demonstrated in the media by satellite images of the country before and after drought [13]. Along with vegetation dieback, frequent questions are raised relating to crop yields and the impact of drought on food production and likely increases in retail prices [14]. For agricultural production, the impacts of drought on crop yield may partially be driven by antecedent weather conditions. For example, one of the impacts of the 2018 heatwave/drought in the UK was that mean winter wheat yields across the country were reduced by an average of 5.1% [15]. Another example is the 2003 European-wide drought, which caused an overall reduction in plant primary productivity [16]. Specifically, the authors observed a drop in maize production of 36% in Italy, and overall forest net primary productivity was on average reduced by $16 \text{ gC m}^{-2} \text{ month}^{-1}$. A further feature of many droughts is an increase in wildfires after wet periods with increased vegetation growth ([17], e.g., in the northern Mediterranean region [18] and the wildfires in California [19]), which removes vegetation cover, leaving bare soils prone to soil erosion. A further observable impact of droughts in the UK and globally is that of soil cracking due to desiccation ([20], Figure 1). This occurs when expansive clay minerals dehydrate and shrink, leading to the undermining of foundations of houses and infrastructure. The process is of major economic consequence, with damage to infrastructure in the UK estimated to be around GBP 100 million a year, and sometimes reaching GBP 400 million in very dry years [21]. Moreover, at the global scale, during the 20th and early 21st centuries, droughts accounted for more than 50% of all natural hazard deaths [22,23].

Scientists are beginning to understand the role that soil moisture plays in determining the magnitude and persistence of heatwaves through land–atmosphere interactions [24,25]. In addition, the drying out of soils during heatwaves can play a role in mitigating deadly heat stress by reducing humidity [26]. As a result of the importance of soil moisture to earth system processes, droughts or floods that push soil moisture levels beyond their normal operating range are likely to have a cascade of impacts [27].



Figure 1. Visual impacts of drought on soils: (a) field moist and (b) dried and shrunk organic soil, (c) field moist and (d) dried and cracked soil, (e) shrunken topsoil (0–5 cm), (d) compared to the cracked subsoil of the same soil core, (f) soil parent materials in England and Wales, UK, which may exhibit shrink–swell characteristics due to smectitic clay concentrations. Pictures (a–e) were taken by I. Lebron (UKCEH). (f) BGS Geology Data © UKRI and OS data © Crown copyright and database right 2022.

2. Key Soil Moisture Processes and Properties Relating to Soil Moisture Storage and Infiltration

2.1. Soil Moisture Retention

In terms of the global hydrological cycle, the overall quantity of water in soil is only ~0.05% [28]. However, its importance in both the global energy balance and the supply of water to plants far outweighs its physical quantity [27,29]. Soil moisture retained in soils is taken up by plants along with nutrients used in photosynthesis and growth. Moreover, soil moisture is required by the soil microbiome to function, with its activity being closely linked to soil moisture levels [30,31]. In turn, the microbiome is responsible for processing dead organic matter, contributing to the global carbon and nitrogen cycles, and producing materials that are important in developing physical characteristics of soil, such as its strength and structure.

Soil structure is fundamental to how precipitation landing at the earth’s surface is partitioned into infiltration and runoff (Figure 2). To develop an understanding of the impacts of drought on soils, an overview of soil hydrological processes, both at the scale of the soil profile and at the grain scale, where water interacts with the soil matrix, is required. The main processes that determine the storage and movement of water in soils are summarised using a water balance approach (Figure 2). Water arriving at the soil surface as precipitation infiltrates or runs off. The water that infiltrates distributes itself through the soil profile. The moisture stored within the plant root zone is potentially available to plants for uptake and may be transpired back to the atmosphere. Some soil

moisture will be directly evaporated back to the atmosphere and never make it into the biologically transpirable soil moisture pool. Conversely, water moving beyond the root zone moves through the vadose zone and into the saturated zone, providing recharge to ground water. Water may also move laterally, generating interflow through the soil.

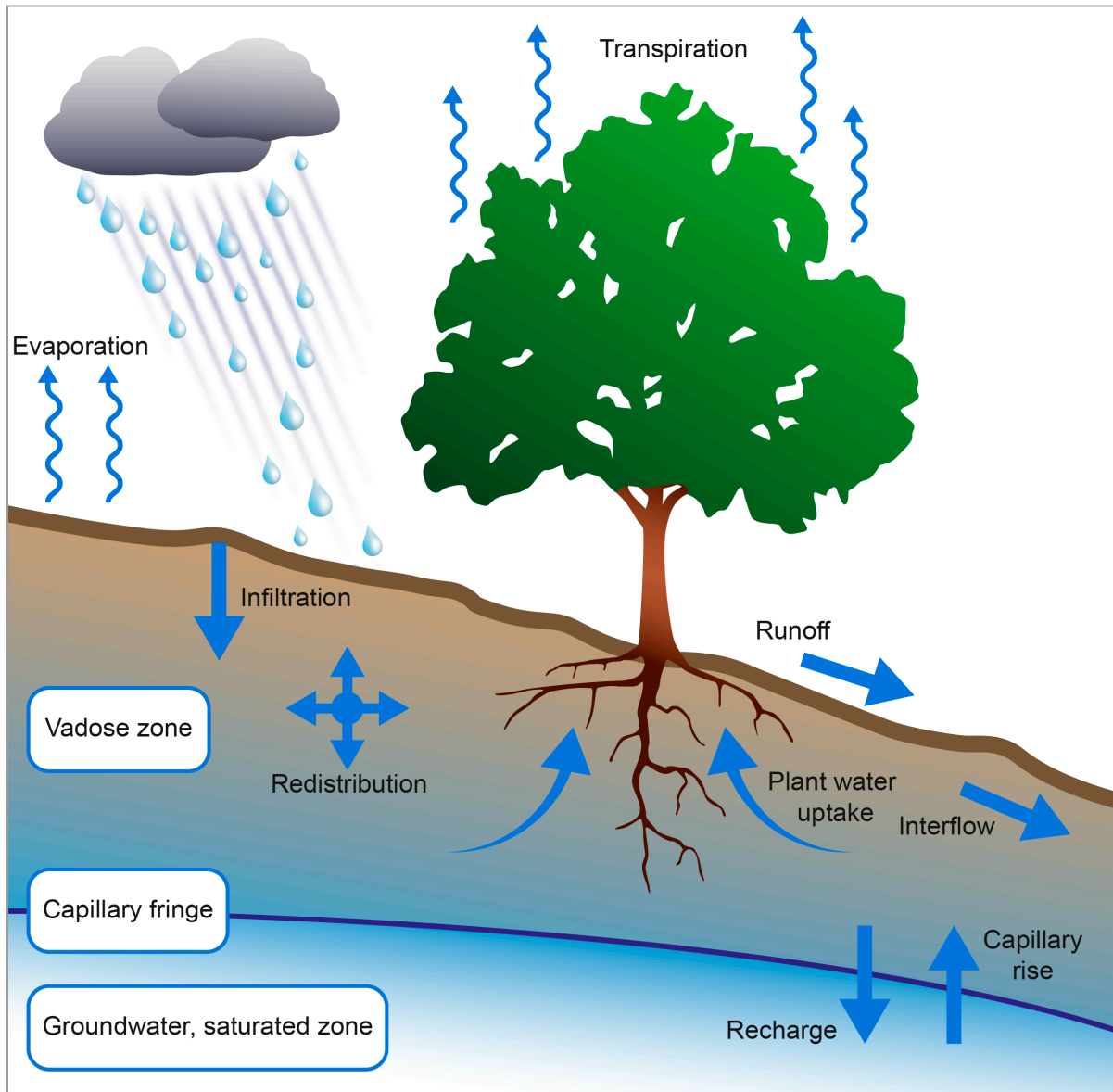


Figure 2. Basic processes in the soil water balance.

Once in the soil, water interacts with the soil matrix at the grain scale. Two important characteristics play fundamental roles: cohesion (water–water attraction) and adhesion (water attraction to other substances). Cohesive forces arise from the intrinsic properties of water, in particular hydrogen bonding, which causes molecules to be attracted to one another. Cohesive forces are responsible for the phenomenon of surface tension. This is the tendency of a liquid surface to resist rupture when placed under tension. It is this phenomenon that causes water to curve or bead in contact with air. Adhesive forces are those that form between the water and other materials, such as clay minerals, in the soil. Adhesion and cohesion lead to the phenomenon of capillarity. Examples of capillarity are (i) when a narrow tube is placed upright in water and the water is seen to climb up the tube against gravity because of the strong attraction between water and glass, and (ii) when a dry paper towel is dipped into water and moisture climbs up the towel. In soils, it is the

balance of these and other forces (e.g., gravity) that controls the storage and movement of water. During droughts, soils dry out and water is held at more negative water potentials. Moreover, when water becomes available as drought terminates, it is these forces that determine the soil's sorptivity, drawing water into the soil matrix.

2.2. Water Infiltration

When a wetting fluid, such as water, has contact with dry soil, it is drawn in. When this process occurs without the influence of gravity, e.g., as horizontal flow, it is considered a 'sorption' process [32] controlled by the characteristics of the soil and matrix forces. When gravity aids the process, it is termed infiltration—the sum of capillarity and gravity [33]. The infiltration capacity, or infiltrability, is the maximum rate at which the soil can absorb water at the surface [34]. In the case of dry soils, this rate is initially higher than in wet soils, but the two reach an equilibrium and steady state, which in theory occurs at the saturated hydraulic conductivity (K_s). Based on theory, soils that have experienced drought and are dry should exhibit the highest infiltration capacity initially, as shown by the solid black line in Figure 3.

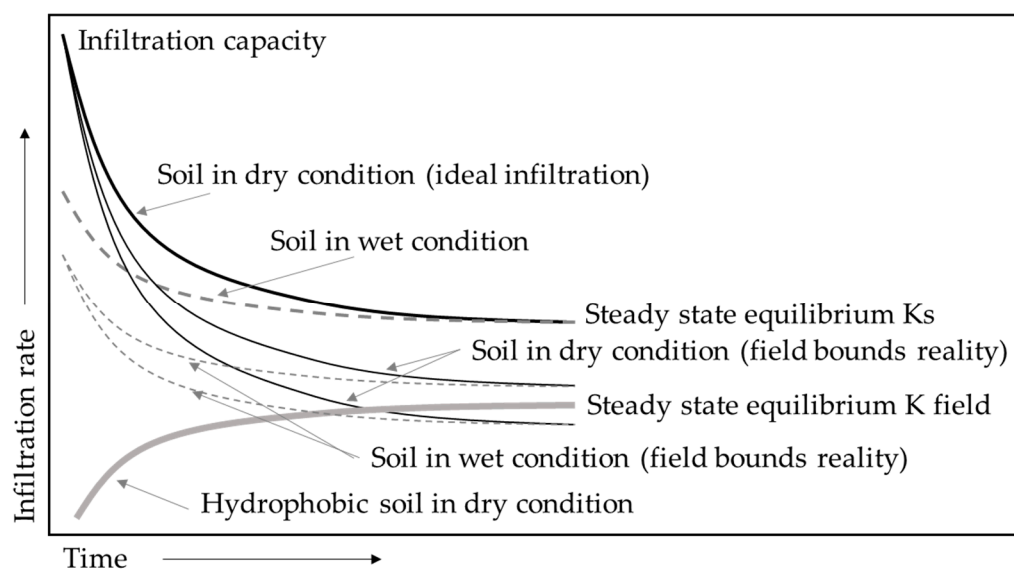


Figure 3. Schematic overview of changes in infiltration rates with time and soil condition. Reprinted from . . ., 2023, Environment Agency.

2.3. Abiotic and Biotic Factors Influencing Soil Water Infiltration

A number of abiotic and biotic factors modify infiltration rates in different soils. These factors are described below.

2.3.1. Abiotic Factors

Air entrapment: When water infiltrates, it rarely fully wets the soil. Air becomes entrapped in the soil and reduces the steady-state infiltration rate. Measurements of steady-state infiltration rates in the field compared to those produced for saturated hydraulic conductivity in the laboratory are typically one-half to two-thirds in magnitude (Figure 3; field bounds reality) [35]. The soil water content that the soil saturates at with air entrapment, which is lower than the true saturated soil water content, is called the satiated water content. This satiated water content is often ~5% lower than the true saturated value. The drying of soil will allow more air into the soil profile, reducing the soil's capacity to infiltrate water.

Thermal effects and frost: Temperature can alter soil hydraulic properties by changing the surface tension and viscosity of liquid or by altering the soil structure due to thermal expansion of minerals. The former is considered the main influence, and differences are

likely to be less than an order of magnitude [36]. During winter droughts, if the soil experiences freezing conditions, ice crystals can form in the soil and have a similar impact to entrapped air, reducing the pore space available for infiltrating water and reducing hydraulic conductivity.

Soil structure change: In soils with smectitic clay content (Figure 1f), there is potential for shrinking and swelling as soils wet and dry, leading to increases and decreases in porosity and infiltration [37]. Soils can develop a ‘wetting front instability’ which may create preferential pathways of infiltration and wetting and may be associated with structural or physico-chemical changes [38–40]. Capillarity and the sorption of water into soils depends on the adhesion between water and particle surface and is described by the contact angle between the water and surface. The electrolyte concentration, especially in the presence of sodium, can exert a strong influence on the contact angle and hence the capillarity [41]. Moreover, low-electrolyte-concentration rainfall can impact soil structure in saline soils, causing structural collapse of aggregates. There are few saline soils in the UK, but areas around the coast may be susceptible. Dry conditions may reduce the cohesion between soil particles, making them vulnerable to being windblown, and potentially settling and clogging pores upon redeposition. This essentially results in a ‘capped’ or ‘sealed’ layer on a soil profile. The seal forms a layer that impedes water flow and hence reduces infiltration [42,43]. Soil structural changes caused by drought are discussed in Section 3.7.

Soil water repellency: Capillarity exerts sorption due to the adhesion between water and soil surfaces. However, infiltration in hydrophobic soils is more complex, such that hydrophobicity may reduce, or conversely increase, infiltration under different circumstances [44]. Soil water repellency and drought is discussed further in Section 3.7.3.

2.3.2. Biotic Factors Influencing Soil Water Infiltration

Biological factors have the potential to impact and alter infiltration rates into soils. The authors of [45] proposed four primary pathways through which soil biology alters infiltration rates: (i) inputs of organic matter changing bulk density, porosity, and/or pore size distribution [46–50], (ii) rooting structure and decreases in porosity through compression induced by new root growth, or macropore generation when roots decay [51–53], (iii) bio-pore characteristics and abundance resulting from the activity of macrofauna, the “ecosystem engineers” [54–56], and (iv) microbial activity, especially in the rhizosphere, which impacts biofilms and hydrophobicity [57].

Meta-analyses indicate the important contribution that plants, particularly woody vegetation, make to infiltration [50,58,59]. Robinson et al. (2022) [50] comparing infiltration under different land uses on the same soil type, found that infiltration rates were 2.2 times higher under woodland compared to cropland. Grasslands were more nuanced, with higher infiltration rates than cropland in general, but likely dependent on levels of compaction due to grazing. Native grasses appeared to have similar infiltration rates to woodland, with rates dropping as grassland soils become more highly managed with grazing pressure increasing. Temporal studies on the impacts of drought on such systems are less common and represent an important knowledge gap. General shrinkage around plant roots may increase porosity for infiltration with drought, but conversely, there might be less root exploration, especially through fine roots. Persistent drought and reduced long-term plant productivity are likely to have the largest impacts.

3. Impacts of Drought on Soil Properties

Interactions between soil biological, chemical, and physical processes cause a wide range of soil properties to be impacted by drought. These impacts may combine and influence soil structure and infiltration capacity. In this section, we review the key components of the soil ecosystem that are impacted by drought.

3.1. Soil Macrofauna

Soil macroinvertebrates are organisms with body widths generally between 2 mm and 30 mm. In temperate systems, they can account for up to 79% of soil animal biomass [60]. These invertebrates drive dynamic changes in soil biophysical properties, with several groups considered soil ecosystem engineers [61]. They include common taxa such as earthworms, woodlice, and millipedes, as well as some insect larvae. The movement of earthworms through soil shapes the architecture of the matrix, particularly the arrangement and size distribution of the pore network [62,63]. Some earthworm taxa engineer biogenic structures such as deep vertical burrows and surface casts. The feeding activities of several soil macroinvertebrate taxa (earthworms, woodlice, millipedes) break down litter and redistribute faeces, thus influencing the incorporation of organic matter into the mineral soil. Engineered changes in soil architecture and biophysical properties by soil macroinvertebrates have significant impacts on soil hydrology and the ability of soils to retain moisture.

Earthworms are soft-bodied and reliant on moist conditions to allow oxygen exchange through their skin, which makes them intolerant of dry conditions. To avoid drier summer soil conditions, earthworms migrate down the soil profile, seeking moist conditions to escape desiccation. Some species may enter a semi-dormant or dormant state (quiescence or diapause) to conserve moisture and energy. Laboratory experiments by Holmstrup (2001) [64] exposed an endogeic earthworm species, *Aporrectodea caliginosa*, to a two-week drought. He found diapause to be induced below a water potential of -0.02 MPa, with all earthworms entering diapause at -0.04 MPa. It was noted that these modest water potentials inducing diapause may be linked to the abrupt nature of the change under experimental drought conditions, whereas earlier field studies under progressive drought found diapause occurring from about -0.16 MPa [64]. The increasing number of earthworms entering diapause as drought stress progresses from -0.061 MPa to -0.19 MPa over three weeks [65] supports this.

Drought also has the potential to alter earthworm populations and community composition over time through differential impacts on species and functional groups. Eggleton et al. (2009) [66] studied earthworm populations in a UK pasture woodland over 72 consecutive months, with the sampling period including two dry phases. Seasonal patterns were evident across most of the common species, with maxima in winter and minima in summer, and this was reflected in the total earthworm abundance [66]. However, severe declines were noted for the surface dwelling epigeic *Dendrobaena octaedra* following successive dry summers, and no adult earthworms were found after the two dry phases. A review of climate change effects on earthworms by Singh et al. (2019) [67] suggested that while drought generally had negative impacts on earthworm populations, more evidence is needed on the interaction with other context-dependent factors such as soil type and environmental stresses.

Prolonged drought may increase earthworm mortality. McDaniel et al. (2013) [65] demonstrated that a three-week drought stress, resulting in -0.19 MPa water potential, led to 14% mortality of the endogeic *A. caliginosa*. Evidence also suggests, however, that earthworm populations can recover from severe drought events. In the study of Eggleton et al. (2009) [66], all affected species recovered from successive dry phases after one year. Both behavioural (i.e., diapause) and life-history traits (i.e., cocoon production) likely contributed to this recovery. In another study [64], it took only 74 days for earthworm cocoon production to recover in treatments where earthworms had been induced to diapause. It is not well understood how the impacts of drought on earthworm communities or the transition to recovery feed back to modulate their dynamic impacts on hydrological and biogeochemical processes in soils.

3.2. Soil Bacterial and Fungal Communities

Bacterial and fungal populations are instrumental in the processing of dead organic matter and recycling of nutrients in soils, producing substances that help bind soil par-

ticles together into aggregates and playing a central role in the biogeochemical cycling of nutrients. Understanding how extended periods of drying and heat impact bacterial and fungal functioning and how this contributes to water infiltration and a range of other soil processes is important in understanding the resilience of soil systems to drought. In addition, many bacterial and fungal populations are involved in symbiotic relationships with plants. Thus, drought impacts on soil bacterial and fungal communities and function may impact plants and vice versa.

Soil microbial activity ceases at a nearly constant soil moisture threshold with a water potential of about -13.6 MPa in mineral soils and -36.5 MPa in surface litter [68]. The constraints microbes experience within soils result from limited water diffusion. Or et al. (2007) [69] provides information on activity thresholds for different microbial species (Figure 4, Table 1) with bacteria, but also fungi and soil fauna displaying species-specific declines in activity with decreasing soil water potential; the order of sensitivity being soil fauna > bacteria > actinomycetes > fungi (Table 1; [68]). Manzoni et al. (2012) [68] also found microbial activity thresholds to be much lower in undisturbed soils (compared to experimentally broken up soils), likely due to intact aggregates and restrictions on diffusion occurring naturally. Thus, if soil structure collapses due to drought, the microbial community may become more sensitive to lower soil water potentials. Interestingly, Manzoni et al. (2012) [68] did not find effects of biome, climate, or fungal-to-bacterial ratio on the soil water potential threshold governing activity in the soils.

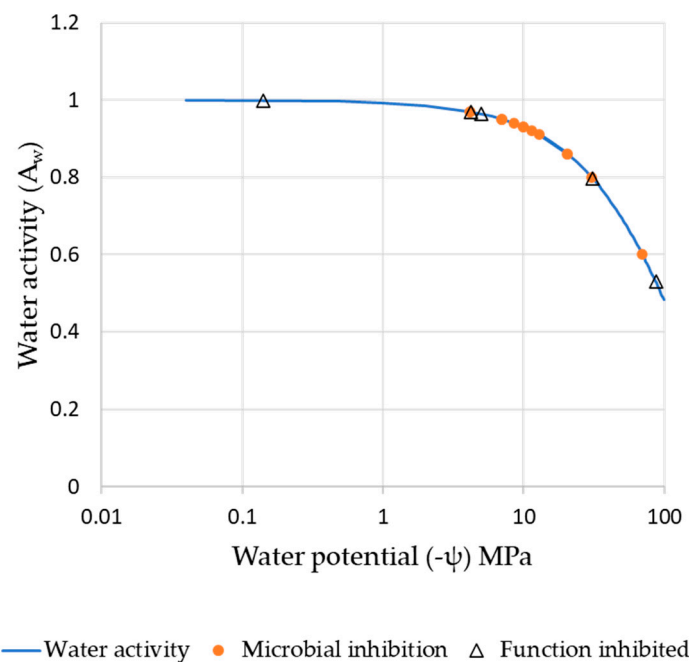


Figure 4. Relationship between water activity and water potential.

Malik and Bouskill (2022) [70] discuss the processes microbes use to maintain a positive intracellular turgor pressure relative to their external environment. This is achieved by the synthesis or transport and subsequent accumulation of solutes within the cytoplasm. If the external solute concentration increases (hyperosmotic shock), water efflux from the cytoplasm into the surrounding soil matrix can result in a drop in turgor pressure. In contrast, a quick decline in external osmolarity (hypoosmotic shock) may lead to a swift influx of water and an elevation in turgor pressure. Turgor pressure is highly important for microbes that have evolved different pathways to maintain their intracellular turgor pressure under fluctuating external osmolality. Three pathways of microbial drought adaptation were described: (i) the production of extracellular polymeric substances, which are the main components of biofilms, (ii) the acquisition of solutes from the surrounding environment, but this may be limited by the constraint of diffusion in dry soils, and

(iii) dormancy via spores. The energetic expenditure decreases from (i) > (ii) > (iii), and will ultimately govern the microbial response to drought [71].

Table 1. Summary of water potential thresholds for soil biological activity from the literature.

Water Potential (MPa)	Soil Ecosystem Components
−0.02 to −0.04	Diapause induced in the earthworm species <i>Aporrectodea caliginosa</i>
−0.06 to −0.19	Diapause induced in most earthworm species
−0.5	Functional inhibition of soft-bodied fauna (e.g., nematodes)
−0.6	Functional inhibition of nitrifying bacteria
−0.7	Critical soil moisture threshold for (European) plants
−1.5	Permanent wilting point of plants
−2	Functional inhibition of hard-bodied fauna (e.g., arthropods)
−2	Functional inhibition of Gram-positive bacteria
−4	Functional inhibition of wood-decaying fungi
−10 to −3	Functional inhibition of fungi
−10	Functional inhibition of Actinomycetes
−10	Threshold where solute diffusion ceases; see Figure 4 where microbial activity drastically declines
−13.9	Start of microbial activity ceasing in mineral soils
−36.5	Start of microbial activity ceasing in surface litter
−60	Functional inhibition of some xerophilic fungi

Soil microbial communities change when exposed to drought, with drought-resistant communities becoming prevalent or changes occurring in soil microbial community functioning [72,73]. Canarini et al. (2021) [73] undertook a drought experiment to test the microbial memory of drought *in-situ*. Plots were subjected to (i) no drought, (ii) a single drought, and (iii) 10 years of reoccurring droughts in a mountain grassland. They studied the microbial community, as well as carbon, nitrogen, and other nutrients. Microbial responses were measured and found to be different after 1-year and 10-year long droughts, with soil nutrient components changing after 1 year. However, although soil nutrient status was not different between controls and drought plots after 10 years, the soil bacterial and fungal communities still differed. This finding suggests that reoccurring drought events can change the soil microbial community to maintain ecosystem functioning. This long-term response may be mediated by the fungal component of the microbial community, which was found to be more stable under drought than the bacterial network [74].

3.3. Plant Responses to Drought

Plants protect soils from erosion [75]. However, droughts can severely reduce the protective effect of plants, leaving soils exposed to erosion processes and degradation. Beyond the physical protective barrier plants create on top of the soil surface, plants are active modulators of the soil chemical environment. For example, Ciais et al. (2005) [16] highlighted the detrimental effect of the European-wide drought in 2003 on continental-scale plant primary productivity, which was associated with a soil carbon loss equivalent to four years of carbon sequestration.

Plants rely on soil water availability to maintain growth. These processes include nutrient absorption, translocation, photosynthesis, respiration, transpiration, and cell division, along with many metabolic reactions within plant cells and the root zone. Water is transported and stored in xylem tissue and moves via evapotranspiration. Water moving through xylem tissue also transports water-soluble nutrients, chemicals, and photosynthetic products. Thus, the most important impact of drought on plants is the reduction in

availability of soil moisture to maintain water connectivity within the plant. Zia et al. (2021) [76] reviewed drought stresses in plants, which include the following. Initially, plants may experience (i) reduced water potential, (ii) changes in ion and nutrient fluxes, (iii) a decrease in turgor pressure, (iv) stomatal closure, and (v) changes in phytohormone abscisic acid concentration in shoots and roots. As drought intensity increases, plants suffer (i) damage to photosynthetic apparatus, (ii) a decline in PSH photochemical efficiency, (iii) partitioning of assimilates in organs, (iv) high abscisic acid concentration in shoots and roots, and (v) a decrease in canopy leaf area. These processes cause a range of morphological, biochemical, molecular, and physiological responses, leading to a reduction in crop quality, stunted growth, senescence, and premature cell death. Besides the good evidence base of drought impacts on plant xylem tissue (for water transport), evidence on drought impacts on plant phloem tissue is less developed. Phloem tissue is used to move carbohydrates, sugars, and amino acids through plants and is in constant exchange with xylem tissue. Drought effects on the phloem tissue may play a role in plant survival time during a drought or revival after a drought event [77].

Traditionally, the permanent wilting point is considered the lower limit of soil moisture at which the cohesion and adhesion of processes that maintain moisture in soil exceeds the energy that plants can exert to extract water from the soil. At this point, wilting is irreversible. This is typically considered to occur at -1.5 MPa, but is likely to vary according to the soil's hydraulic characteristics and the morphological and physiological properties of individual plant species [78]. A further parameter to consider when understanding the impact of drought on soil moisture and plant relations is the critical soil moisture threshold (θ_{crit}). This is the point at which, due to water stress, evapotranspiration starts to decrease due to the soil moisture deficit. Fu et al. (2022) [79] suggest that for European ecosystems, θ_{crit} may start at thresholds of 16.5% and -0.7 MPa. Beyond these detrimental soil water thresholds where plants cannot survive, some plants have developed isohydric behaviour, which is the ability to maintain water potential by reducing stomatal conductance when soil water potentials decrease [80]. However, either isohydric or anisohydric behaviour can be beneficial under different scenarios of droughts [80].

The overall impact of drought on individual plants and vegetation types depends on their local environment, their usual climatic conditions, the duration and timing of drought, associated weather effects such as temperature and wind, and the distribution of precipitation that terminates the drought. Additionally, plant-specific characteristics such as plant phenology and species adaptability, including their ability to alter their form and physiology, will determine the response of vegetation to droughts [81].

Compared to plant responses to drought, soils modulated by drought can directly affect plants. Examples include the cracking of soils, which can cause physical damage to plant roots and expose roots to dry air. Cracking also alters water infiltration patterns and evaporation rates from deeper soil layers. Additionally, without precipitation, there is no evaporative cooling, with dry soils reaching higher temperatures [82], which can directly kill plant roots and disrupt fungal connections.

3.4. Interactions Between Microbes and Plants in Response to Drought

A meta-analysis summarised the findings of drought impacts on biological soil responses [83]. Within the soil environment, microbes are intimately connected with plant roots through the rhizosphere, which is the area of highest microbial activity [76]. There is microbial activity in the bulk soil that is not directly associated with plants, but this activity is much lower and may still contribute to soil moisture retention by creating biofilms. Plant-soil feedback occurs as a result of drought [84]. For example, in a grassland mesocosm study [74], the soil bacterial community was found to be less resilient to drought-induced changes in plant community composition (compared to the fungal community), leading to a change in the bacterial community.

It has been shown that the soil microbial community can improve the drought tolerance of plants [85–87]. Plant growth-promoting bacteria secrete compounds such as

osmolytes, antioxidants, and phytohormones, enhancing root osmotic potential under drought stress [88,89]. These also regulate plant growth under drought, either directly by enhancing phytohormone production or indirectly by increasing nutrient availability. Inoculating plant growth-promoting bacteria into crops can increase their drought tolerance [90]. However, plant–microbe responses to drought are numerous and are likely associated with plant traits and the ability of plant and microbes to adapt to past droughts, as well as the drought frequency and severity [84].

Arbuscular mycorrhizal fungi are symbionts with plant roots (Brundrett and Tedersoo, 2018) [91]. They promote host plant growth by enhancing water uptake and nutrient absorption, helping control abiotic stresses like drought [92,93]. During droughts, plant root physiology may change to alleviate stress by enhancing arbuscular mycorrhizal fungi colonisation [94] and increasing nutrient (N, P, K) uptake. Soil potassium drives changes in root morphology, assisting in alleviating drought stress [95]. The soil microbial community can also create a legacy effect of drought on plant performance, as shown by [96] on the grass species *Lolium perenne*, *Bromus hordeaceus*, and *Alopecurus pratensis* and the forb species *Centaurea jacea*, *Diploaxis tenuifolia*, and *Prunella vulgaris*. The interplay between plants, microbes, and soil fauna determines the ecosystem’s drought stress magnitude [70].

Belowground interactions and responses to drought in the physical soil environment influence how plants and microbes (and fauna) experience reductions in soil moisture availability, the mechanisms they have as a community to deal with reduced hydrological connectivity, and which changes they may induce (Figure 5). All adaptive mechanisms in response to drought will affect the soil environment and cause changes in other properties (e.g., soil carbon content). However, studies into the effects of drought on plant–soil feedback are in their infancy [84].

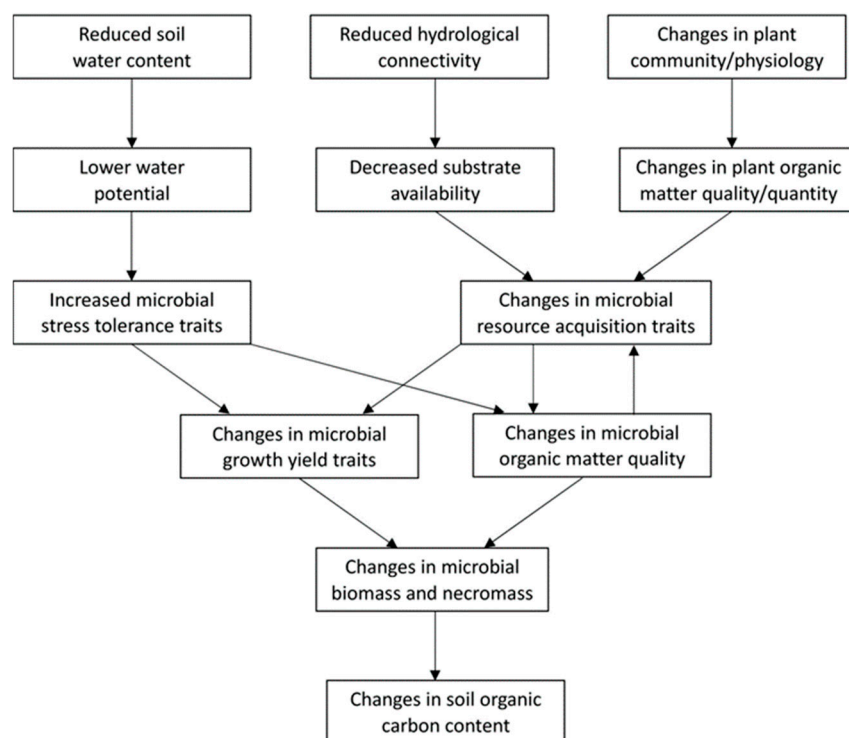


Figure 5. Theoretical framework of how drought affects soil microbes, and how these link to the soil carbon pool (Reprinted from Malik and Bouskill (2022) [70] under the CC BY 4.0 license).

3.5. Wildfires

Wildfires often occur during droughts, impacting vegetation and soils in many ways post-fire. The impact of fire on soil depends on the temperature reached and the duration of heating. Direct effects include reductions in soil organic matter content, porosity, saturated

conductivity, water retention, and infiltration capacity, and increases in dry bulk density and fire-induced soil water repellency [97]. Plant responses to fire are linked to seasonal phenological cycles of growth, dormancy, flowering, and reproduction, meaning fire during vulnerable stages can negatively impact post-fire recovery. Some plants allocate more biomass to roots to compensate for nitrogen limitation after fire, changing the root-to-shoot ratio and increasing soil respiration [98]. Conversely, vegetation restoration can be rapid if rhizome buds of perennial herbaceous plants remain unharmed [99]. Lastly, the amount and chemical properties of ash depend on the vegetation burnt and fire intensity [100], which is likely to affect the soil's micro- and macronutrient status.

3.6. Drought Impacts on Macronutrient Cycling in Soils

Changes in soil macronutrient cycles caused by drought have been identified. Many changes are linked to microbial responses, such as the production of extracellular polymeric substances. For example, the diversion of resources away from microbial growth during drought is proposed to change soil organic matter chemistry and its persistence, depending on the microbial compounds produced [70]. Patel et al. (2021) [101] recognised that soil texture and porosity were important factors in the response to drought (and flooding), as they control microbial communities' access to organic substrates. Whilst a major impact of drought may be a decrease in microbial activity and the recycling of nutrients, He and Dijkstra (2014) [102] suggest that the availability of water is the main driver of reduced plant growth [102–104], rather than the availability of nitrogen and phosphorus. Studies have shown that changes in nitrogen and phosphorus availability occur during drought, although specific reasons cited vary. For example, soil inorganic nitrogen (NH_4^+ and NO_3^-) was found to increase during drought [83,105], whilst NH_4^+ and NO_3^- were observed to be more abundant during drought in soils with grass, but not in forests [105,106]. This is likely due to differences in rooting systems between herbaceous and woody plants, and their overall life strategies. Additionally, labile carbon in the form of dissolved organic carbon was found to increase under drought in forest, grassland, and shrublands [106], making soil carbon loss more likely when droughts terminate.

It was suggested that decreased plant phosphorus uptake may be associated with the death of surface roots, the reduced soil hydraulic conductivity increasing root soil air distance and increased root tortuosity reducing flow transmission [107]. Bi et al. (2023) [108] reviewed the impacts of drought on soil phosphorus in soil–plant systems and found that in some studies, soil phosphorus availability increased. A possible explanation is that during droughts, microorganisms die and release phosphorus, whilst the uptake of phosphorus by plants decreases [104]. It was also suggested that the activities of plant phosphorus-acquisition enzymes decrease in the mid- to late period of drought [109].

Turner and Haygarth (2003) [110] examined the response of phosphorus in drying soils from permanent lowland pastures in England and Wales. They suggested that increases in soil available phosphorus after drying were linked to (i) enhanced physical weathering and the disruption of organic matter coatings on clay and mineral surfaces, revealing previously protected surfaces where phosphorus sorbs, (ii) the release of soluble phosphorus due to the lysing of microbial cells, and (iii) large soil aggregates breaking down, reducing soil organic matter protection and increasing soil surface area for phosphorus desorption. Increases in nitrogen availability may also occur for similar reasons. Due to these processes, an enhanced pool of nutrient concentrations is often available at the termination of drought. These may be susceptible to transport to watercourses through leaching (nitrogen) or associated with eroded sediment (phosphorus). Some soil systems may be more susceptible to enhanced transport processes. Increased leaching may occur in cracked soils, leading to greater conductivity upon rewetting and increased nitrogen concentrations reaching the water table [111]. Many clay soils that crack also have under-field drainage systems, and the combination of soil cracking and drainage systems may act as a rapid transport system of macronutrients to surface waters.

The temperature response of soil CO₂ emissions was largely unaltered with (experimental) warming across most ecosystems [112]. This follows the normal temperature sensitivity of soil processes, where on average, with every 10 °C increase in temperature, soil respiration increases 2.6–3.3 times [113,114]. Temperature-induced increases in soil CO₂ emissions require soil activity (plants and roots) as well as available carbon. Available carbon will partly derive from plant root exudates, but also from increased mineralisation of soil organic matter, and thus the reduction of the soil carbon pool [114]. The highest loss of soil carbon with warming is observed from high-carbon soils [115].

3.7. Physical Changes in Soil Structure in Response to Drought and Rewetting

3.7.1. Aggregate Breakdown

Experiments have demonstrated that soil aggregation may be impacted by drought, but UK studies have yet to be undertaken. Results have suggested that a reduction in mucilage and polysaccharide production by roots and soil fauna in dry soils is likely to decrease aggregate stability [116,117]. Other studies have examined the manipulation of climate on soil aggregate stability, providing an indication of how aggregates may respond to dry periods in the UK. Zhang et al. (2019) [118] examined aggregate stability in afforested areas on loess soil in China where precipitation was excluded and the understory removed. Results showed that the removal of understory and the exclusion of precipitation and throughfall resulted in decreased soil aggregate stability and aggregate-associated organic carbon pools, whilst having no influence on total soil organic carbon content.

The strength of soil aggregates will determine their stability in response to drought and rewetting. Aggregate disruption may occur through (i) slaking, (ii) the differential swelling of clays, (iii) mechanical disruption through kinetic energy (e.g., more intense rainfall), and (iv) physiochemical disruption. Slaking is probably the most important and widespread mechanism, and is caused by the trapping of air through rapid wetting. The trapped air then pushes soil particles apart, collapsing the aggregates [119]. This may lead to a decline in porosity as soil matrix pores are blocked by the released particles. Splash detachment results in aggregate breakdown and is affected directly by the physical properties of rain such as raindrop size, terminal velocity, rain intensity, kinetic energy, and momentum, along with soil properties such as organic matter content, calcium carbonate content, particle size, and soil structure [120]. Xiao et al. (2017) [119] examined rainfall intensity (60 mm h⁻¹) from different heights (0 m, 1 m, 1.5 m, 2 m, and 2.5 m) to achieve different quantities of kinetic energy. The rates of splash erosion followed the order of loamy clay soil < clay loam soil < sandy loam soil, but the mean weight diameter of disintegrated aggregates followed the reverse order. Overall, slaking and splash detachment of aggregates increases unattached fine particles that can be transported by splash erosion downslope. Assuming drought reduces the strength of organic matter binding of particles, then it is likely that drought will lead to a reduction in aggregate stability, with implied consequences for processes such as infiltration and erosion.

3.7.2. Surface Crusting

Surface roughness is a key control of overland flow, with greater variation in surface roughness influencing the depression storage of water, infiltration, overland flow velocity, and overland flow pathways [121]. A further consequence of aggregate disruption, especially via intense precipitation and splash detachment, is the formation of layers of fine soil particles that when dry create a layer of ‘surface sealing’. When hardened by the sun, this layer has the potential for (i) reducing infiltration, (ii) increasing surface flow and erosion, and (iii) impeding the shoots of plants breaking through the surface [42,43].

3.7.3. Soil Water Repellency

An increasingly documented phenomenon is the development of soil water repellency (Figure 6), which may influence infiltration rates during drought. Whereas soot from fires may block pores, it is the presence of hydrophobic compounds that helps develop soil

water repellency. Initially, soil water repellency was linked indirectly to drought due to its occurrence after wildfire [122], when multiple organic compounds are generated that may coat the soil, leaving it water-repellent. Evidence suggests that the magnitude of soil water repellency depends on the temperature of the wildfire burn. Compounds formed at low temperatures may melt and coat soil grains, whilst at higher temperatures compounds may be completely oxidised. Several linked processes occur following drought-induced wildfire, soil water repellency being one and soil erosion often another [123].



Figure 6. Picture showing water drops on the soil surface visualising soil water repellency. Picture taken by D.A. Robinson (UKCEH).

With global change, it is likely that the UK will experience more drying events leading to wildfire, soil water repellency, and erosion. However, an increasing body of research suggests that soil water repellency is not simply a phenomenon associated with wildfire. Doerr et al. (2009) [124] indicated that background levels of soil water repellency in soils are often high, so the relationship with wildfire is complex. Other sources of soil water repellency may come from fungus [125] and organic compounds, especially waxes and long-chain fatty acids [126]. There is also now a growing literature on different organisms or groups of organisms that under different circumstances become water-repellent. While commonly associated with drought, biological soil water repellency can also occur in response to flood [127].

Soil water repellency may also occur due to organic compounds being produced in response to stresses [128], such as too much or too little water. Plants, bacteria, and fungi all exude water-repellent compounds [129]. Their impact on infiltration will depend on the soil structure. Soils with a uniform pore size distribution will often experience reduced infiltration initially. Moreover, the repellency may also lead to enhanced air entrapment. However, in soils with large macropores, water ponded on the hydrophobic surrounding soil may infiltrate preferentially in macropores. It has been proposed that soil water repellency-enhanced infiltration may result in a competitive advantage for some plants in water-limited environments [130].

For the desert in Utah, Robinson et al. (2010) [130] proposed that stress through extreme drying led to soil water repellency that provided a soil moisture maintenance pool feedback process for woody vegetation. Further, Seaton et al. (2019) [129] found that 92% of soils sampled in Wales showed signs of soil water repellency, indicating that its occurrence is the norm and not the exception and one that drought conditions in soil may promote. The advantages of soil water repellency to microorganisms involve water regulation and management. This may involve keeping water away under saturated conditions and creating air pockets, as observed with fungi. Conversely, it may involve keeping water in the organism, as with fungal hyphae during drought [127]. Moreover, water-repellent films

have been shown to develop as biofilms protecting organisms [131], including from rapid rewetting following drought. These factors and potential benefits to plants under drought conditions indicate nature's adaptations, which to date have not been fully explored.

3.7.4. Soil Structure, Shrink–Swell, and Cracking

The process of shrink–swell and soil cracking is a common feature in many clay soils (Figure 1a–e), particularly across southern UK, and is known to potentially cause significant damage to infrastructure [21]. It occurs in soils that contain expandable clay minerals that demonstrate a change in volume in response to drying. Soils susceptible to shrink–swell behaviour are shown in Figure 1f. Smectitic or expandable clay minerals have an interlayer space in their structure and may swell up to 10% when wet by adsorbing water into the interlayer space. This structure will collapse, causing shrinking when drying out. Whilst soils are likely to crack to some extent (depending on the smectitic clay content) in most summers, prolonged drying in periods of drought enables large, deep cracks to form to depths of 3 m [20,21,132]. Infiltration has been examined in these soils using cores and lysimeter blocks [133–135]. When not cracked, hydraulic conductivity in an Evesham clay soil was found to be as low as 0.26 mm h^{-1} to 4.38 mm h^{-1} [133], whilst hydraulic conductivity at 0.5 m depth was as low as 0.4 mm h^{-1} [136]. However, in a small, replicated field experiment on Denchworth soils where cracking had appeared, over 90% of the runoff was found to move rapidly via preferential flow through the subsoil into drain flow within about 2 h of peak rainfall [135]. Rewetting of the soils in autumn is likely to cause some swelling and 'annealing' of cracks, although there is still debate regarding the importance of hysteresis in shrinkage and subsequent swelling processes in clay [137]. The cracking of these soils in the context of water availability can be considered an important 'resilience' factor during a typical spring and summer, as it allows rapid recharge and rewetting. This process is widely recognised [138].

Another feature of soil cracking is that it may increase evaporation from soils. Poulsen (2022) [139] suggested that in moist cracked soils, soil cracking increased evaporation by 60–65% compared to uncracked soil for wind speeds ranging between $0\text{--}5 \text{ m s}^{-1}$ and a range of cracking densities. Hatano et al. (1988) [140], working in cracked clay soils, suggested that evaporation from the soil surface accounted for 2–12% of the evapotranspiration budget, but evaporation from the cracks alone accounted for 10–50% of the evaporation, although the cracks accounted for only 6.7% of the soil surface area. Thus, in cracking clay soils, drought may enlarge soil macropores and increase evaporation surfaces, accelerating the loss of pore water, lowering the water-retention capacity of soil, and degrading physical and mechanical properties [141]. A final impact of soil cracking was reported by Robinson et al. (2016) [142]. They noted that slowly permeable layers resulting in perched water tables may become cracked and breached under drought, resulting in dewatering. This mechanism was proposed to have induced an alternative soil moisture state where infiltration was increased to such an extent that the soil did not fully rewet in the winter.

3.8. Drought Impacts on Wetland Soils

The drying of wetland (organo-mineral, peat) soils caused by extended dry periods and drought can lead to potential changes in soil chemistry and vulnerability [143]. An associated example is the drainage of peatland soils, where permanently lower water tables resulted in lower soil organic matter content and higher bulk densities, causing these soils to degrade [144]. A key mechanism underlying this degradation process is the ingress of oxygen into the soil profile, producing an increase in the oxidation of organic matter and reduced inorganic species, particularly sulphides. Drying of many wetland soils results in cracking, which aids the ingress of O_2 to greater depths, enhancing changes to biogeochemical cycles [145,146]. Oxidation of sulphides can cause soil acidification and metal mobilisation, which may impact surface water quality. Increased oxygen can also impact greenhouse gas production, with decreases in the production of CH_4 through oxygenation, although the degassing of the profile may increase emissions [147]. Increases

in N₂O production may occur through increased O₂ availability and an increase in nitrate production caused by ammonium oxidation (nitrification) and subsequent leaching into reduced zones [148]. Drought typically increases CO₂ production in previously wet soils due to increased decomposition of organic matter under aerobic conditions. Increasing wetland soil temperature during drought while soils maintain moisture and substrate availability can also increase organic matter decomposition due to the decreased energy required to reach activation energy for chemical reactions [149].

Wetland responses to drought vary across different organo-mineral and peat soils because of their properties [143]. Hughes et al. (1997) [150] investigated summer drought in a small area of flush wetland in a three-year experiment in Wales that included summer drought–rewetting cycles. Drought impacts on peat water chemistry included: (i) a decrease in the summer peaks of dissolved organic carbon and iron concentrations in soil solution, (ii) a decrease in acidity, and (iii) an increase in the natural autumn–summer peaks in sulphate and acidity concentrations in the peat water. Similar increases in sulphate concentrations were later found after a natural drought ([150]) and also in drained peatlands across the East Anglian Fenlands [151]. The increase in sulphate is due to the oxidation of reduced sulphur compounds in the peat. This has implications for contaminated wetland and peat soils in old mining areas of the UK, as the decrease in pH due to sulphide oxidation can mobilize many metals (e.g., Cd, Pb, Zn).

4. Responses of Soils and Catchments to Drought Termination

4.1. Impacts on Soil Moisture Infiltration upon Rewetting

A key theoretical point is that dry soils should have the greatest potential for infiltration. However, many soil processes associated with drought and rewetting will influence this process. Thus, infiltration in the field and its steady-state hydraulic conductivity (K) can vary substantially from the ideal steady-state infiltration rate represented by the saturated hydraulic conductivity determined from laboratory measurements (Figure 3). When the precipitation rate does not exceed the infiltration capacity, soils will wet, but not necessarily as expected, making it difficult to predict the time when ponding and runoff may start.

The responses of soils and catchments to drought termination in the short term will be firstly determined by the nature of the precipitation. Intense storms may generate rainfall that exceeds infiltration capacity, leading to runoff. However, if the infiltration capacity is not exceeded, the same rainfall event can induce drainage and redistribution to occur simultaneously in the same soil profile (Figure 1) [33]. As a result, hysteresis in the relationship between suction and water content can affect the infiltration process.

4.2. Enhanced Runoff and Erosion After Drought Termination

Two of the key concerns regarding a soil's response to drought termination and linked to infiltration rates are runoff leading to flooding and runoff causing soil erosion and the loss of the soil resource. These events are more likely if intense precipitation falls onto hard soils and precipitation exceeds infiltration. Beyond individual soil types' susceptibility to drought, vegetation coverage is key to both these processes, as it is primarily responsible for (i) reducing the impact of rainfall intensity on processes such as splash erosion and the destruction of soil aggregates, (ii) providing a means of reducing moisture reaching the soil surface by acting as a surface for evaporation and providing a physical barrier to encourage slower overland water movement, and (iii) providing a root system that holds the soil together.

In areas of the world where drought is more common and greater long-term datasets exist, the Universal Soil Loss Equation, which combines information on soil texture, slope length and angle, vegetation, and precipitation, has been combined with vegetation health indices to assess the potential effect of drought on erosion [152]. In the UK, Fullen (1992) [153] demonstrated the importance of vegetation cover in decreasing erosion in plot experiments on sandy soil in Shropshire. Using a variety of slope angles and lengths, erosion reached 67.4 t ha⁻¹ on bare soils, whilst being negligible on grassed soils with

similar slope characteristics. Fullen and Harrison (1986) [154] demonstrated the impact of rainfall intensity on bare sandy soils in Shropshire. On raindrop-compacted (capped) soils, erosion rates were found to be up to 42.7 t ha^{-1} during individual storms and increased markedly with slope angle. Where slope exceeded 13° , erosion was largely in the form of rill erosion. Whereas prolonged rainfall duration of low-intensity events were found to cause relatively small amounts of erosion, it was found that high-intensity events where precipitation was $>10 \text{ mm h}^{-1}$ were the drivers of major soil erosion.

The role of extreme drought and high-intensity rainfall can be seen in the landscapes of places such as the Badlands in southern Spain [155]. In these environments, prolonged drought has destroyed vegetation, leading to landscapes dominated by deep gully erosion. However, UK agricultural droughts are unlikely to lead to this degree of vegetation destruction. Vegetation will generally dieback but will leave root systems in place, offering some maintenance of the stability of the soil surface. Soils on which arable crops are grown prior to harvest will be protected by vegetation cover and after harvest will likely maintain root systems until cultivation. Maize and root crops where bare soil exists in between rows and the risks of erosion occurring during normal growing seasons are already appreciated [156].

There are numerous studies from around the world linking wind erosion of soils and drought. In many regions of the world, this may be combined with overgrazing and cropping, leaving soils bare [157]. In England, there was a history of wind erosion, particularly with the removal of hedgerows in the post-war years, but conservation measures have reduced these occurrences. Chappell and Warren (2003) [158] undertook a quantitative study of wind erosion in England. They examined wind erosion flux in eastern England using ^{137}Cs and found that net soil loss amounted to $\sim 0.6 \text{ t ha}^{-1} \text{ year}^{-1}$ with a range of -32.6 to $+37.5 \text{ t ha}^{-1} \text{ year}^{-1}$.

Whilst silty and sandy soils may be at greatest risk of erosion, clay soils are likely to behave differently and to varying degrees. Clay soils are more likely to initially have higher soil moisture retention abilities, but upon severe drying may produce hard surfaces, enhancing runoff. Smectitic clay soils that are prone to cracking in dry periods may demonstrate rapid recharge of soil moisture after storm events, reducing the pressure on runoff and on potential soil erosion. However, because of poor drainage, many clay soils have had some form of under-field drainage installed. Combined with soil cracking, these drainage systems can act as a fast-flow conduit to streams and rivers, thus increasing the flashiness of the storm hydrograph and potentially contributing to increased river flow. However, the greatest contribution to flooding after droughts is the degree of soil sealing and urbanisation within a catchment. A common image of UK summers is of urban flooding after heavy convective rainfall, but rapid runoff via the surface or via drainage systems will likely increase the pressure on flooding.

4.3. Linking Soil, Geology, and Land Cover to Catchment Response upon Rewetting

It is the spatial distribution of soil types and their physical, chemical, and biological interactions, the underlying geology, and land cover that determine the underlying hydrological response to precipitation or lack thereof. In relation to catchment moisture transport, the combined behaviour of the catchment properties is ultimately expressed in hydrographs of the streams draining individual catchments. Typical end-member behaviour of catchments can be primarily base flow-driven or demonstrate flashy response due to rapid overland runoff components. Catchments with high baseflow are often those with high proportions of limestone/chalk or sandstone geology and may typically act as groundwater aquifers. High-runoff catchments are typically those where infiltration is slow due to a high proportion of clay soils, leading to greater overland flow.

The importance of the spatial distribution of different soil types within catchments is due to each acting as a fundamental component in the hydrological and groundwater cycles. Thus, soils are often considered hydro-pedological units [159]. Within a typical catchment, some of these will act as recharge zones, discharge areas, and areas of important dynamic storage change [160,161]. Geris et al. (2015) [162] examined the hydro-pedological controls

on catchment water storage during the very dry and warm summer of 2014 in Scotland. They found that soil moisture storage changes in histosols were small (<40 mm), whilst moorland (~100 mm) and forest (~200 mm) podzols showed greater water storage losses. However, soil water stores were quickly replenished once the drought had terminated, with forest soils taking the longest time (3–4 months). Their results also suggested that for long periods during the summer, large areas of catchment soils were disconnected from the river network, with runoff generated mainly from the histosols. In another study in Scotland, Soulsby et al. (2021) [163] examined the soil moisture response and impacts on groundwater and stream-flow in relation to the 2018 summer drought. This was a drought that followed two previous dry winters that had failed to replenish the soil moisture and groundwater stores. Whilst summer precipitation was 63% of the long-term average in 2018, they found soil moisture storage was only half of the summer average, with shallow-groundwater levels being ~50 cm lower. However, recovery of soil moisture and groundwater stores returned rapidly to their normal winter levels during the autumn and winter of 2018.

Whilst the soil parent material and geology of a catchment will influence the abiotic infiltration within the catchment, biological processes, particularly through catchment land cover, will further influence the catchment hydrograph. Under normal weather conditions, land cover, particularly the area of forest/wood, grassland, and arable agriculture, along with urban area (soil sealing), is key in determining the catchment storm hydrographs. Work on a small catchment in Germany demonstrated that during a drought period (2018–2020), soil moisture recharge was much lower and occurred during a shorter period in winter under forest compared to grassland [164,165]. Soulsby et al. (2021) [163] also suggest that drought-induced soil and groundwater storage deficits may be enhanced by land-use policies such as reforestation. Whilst trees may reduce short-wave radiation from reaching the ground, they also increase ‘green water fluxes’, such as interception losses and transpiration, thereby reducing soil moisture storage.

4.4. Biogeochemical Responses to Drought Termination

When drought terminates and soils rewet, soil biological activity can accelerate, often overshooting normal root and microbial activity until an equilibrium between the microbial community and the exchange with plant roots is reached. This initial rewetting causes a peak in soil respiration losses and increased nutrient mineralisation [68,166]: if there are frequent drying and rewetting cycles, soil carbon and nutrient contents may decrease. This was explored by Barnard et al. (2020) [166], who suggested that besides climate, soil type, and prevailing nutrient and carbon sources, the magnitude of change in soil water potential with the termination of a drought determines the soil carbon loss. The highest soil carbon loss was found in soils containing high soil organic carbon content during drying and rewetting cycles [167].

Related to this increased soil biological activity, greenhouse gas emissions will increase. This is typical of wetting and drying cycles in soils, and is often called the ‘Birch effect’ [168]. Whilst drought causes a decrease in microbial activity and soil respiration, rewetting will stimulate microbial activity, leading to an enhanced pulse of CO₂, CH₄, and N₂O from soils. The processes driving this are (i) a decrease in the physical protection of soil organic matter caused by the disruption of aggregates, creating a pool of nutrients to be exploited, and (ii) a physiological effect where compatible solutes produced by microorganisms and accumulated in cells to maintain the balance of osmotic pressure under drought conditions will be disposed of through the rupture of cell membranes. Organic matter from dead plant material originating from a drought is available for decomposition too. Again, this provides a food source for soil microbes and fauna. These effects are variable between land-cover types. However, despite a greenhouse gas pulse being produced on rewetting, studies have suggested that the amounts of greenhouse gases being released may decrease overall because of the impacts of drought over its duration. Jin et al. (2023) [169] carried out a meta-analysis and found that (i) drying–rewetting cycles decreased CO₂ emissions by an average of 9.7% and did not affect emissions or uptake of soil CH₄ or N₂O, and (ii) the impacts

of drought and rewetting were different between ecosystem types. They suggested that the impacts of drying–rewetting were positively regulated by organic carbon and nitrogen concentrations, pH, clay concentration, and soil depth for CO₂ emissions, and negatively controlled by C:N ratio and silt concentration. For N₂O emissions, negative controls were C:N ratios, silt concentrations, and soil depth. Their overall results suggested that CO₂ emissions were significantly decreased by drying and wetting cycles, while the fluxes of CH₄ and N₂O were not affected. The results, especially for CO₂, suggested that the pulse created on rewetting could not compensate for the deficiency in CO₂ emissions during the drought period, and that the substrate created on rewetting is quickly utilised. Obviously, with shorter drying–rewetting cycles, greenhouse gas emissions have the potential to deplete soil organic carbon and nutrient stores, although this so-called priming effect is not indefinite and depends on the initial nutrient concentrations of the soil and the soil moisture content upon rewetting [170].

5. Soil Recovery After Drought

The nature of the rainfall will often determine how soils respond to drought termination. It is likely that physical, biological, and chemical recovery from drought will operate over a variety of timescales, and some parts of the system may reflect an altered state. These impacts are further complicated by soil type and specific climatic conditions, environmental factors, and management practices they are exposed to. For example, Bardgett and Caruso (2020) [171] reviewed knowledge on soil microbial responses to drought. They identified soil organic matter and soil texture as components of the soil that help the microbial community to resist or recover from drought. Soil texture shapes the environment of the microbial community, and organic matter facilitates soil moisture storage [30,171]. Schimel (2018) [30] also suggests that perturbation history (for example tillage) that changes soil organic matter dynamics determines soil responses to drought, rewetting, and recovery. Beyond soil organic matter, regional characteristics of soil depth and type can impact vegetation recovery post-drought [172]. Xu et al. (2021) [172] showed quicker recovery of vegetation post-drought in soils with deeper bedrock compared to shallow bedrock. In the same study, they compared vegetation recovery after drought in karst and non-karst regions in south-west China and found that soil moisture plays a more critical role in the karst region, likely due to differences in water-holding capacity.

In the ideal case that rainfall infiltrates into soils, soils simply rewet. As indicated above, infiltration is not a straightforward process, and multiple factors may alter behaviour from the expected norm. The speed of rewetting will impact soil processes and infiltration, especially in regard to the entrapment of air and time to ponding. For soils that may have altered structurally during drought, for example, through shrink–swell processes, the cracking is unlikely to change back, but remain as structural weaknesses, which will promote future cracking. It will also impact biological processes such as plant roots and soil fauna, as well as bacteria and fungi. Unprotected cells subject to rapid rewetting may simply burst without time to adjust. This is why many soil organisms produce biofilms that can provide a protective environment. Kaisermann et al. (2017) [173] investigated the legacy effects of drought on bacterial and fungal communities. They described how drought has a lasting impact on belowground communities with consequences on plant–soil feedback [84,174] and plant–plant interactions [175], which may change soil functioning and plant community composition. These studies are in their infancy, but demonstrate the more complex legacies of drought.

Multiple drought indices exist [176–179]; however, these are focused on identifying drought rather than identifying the impacts on soils per se. There are a couple of issues regarding the link between drought and soil health indicators. The first is what the most useful soil metrics for determining the impact of drought on soil health are. The second is how drought in itself might impact monitoring of soil health. Regarding the first, this article has identified and highlighted a range of processes that occur through drought and impact soil health. Key questions often posed by decision makers include “Will the soil

simply spring back and recover from a drought, or might it shift to an alternative, more degraded state?" and "How do we make soils more resilient to drought, so they recover and continue to supply the functions and services of importance; what measures might be needed?" Key indicators that may help to address this include regular metrics, such as changes to soil water storage behaviour, soil organic matter content, nutrient balance, and microbial respiration. However, metrics such as soil water repellency and its magnitude and persistence may also provide novel ways of assessing both vulnerability to and the impact of droughts [180]. Regarding the second issue, there is increased emphasis on soil health monitoring of soils across Europe, for example, through LUCAS [181]. The return time of monitoring on these surveys is often ~5 years. Hence, given the impact of drought on key soil metrics, drought years might skew the time series collected for monitoring soil health. This very real impact might make interpretation of results harder. Hence adopting a rolling program of sampling where a proportion of sites are monitored every year might dampen the effects of intermittent drought or other climate extremes such as floods on the monitoring time series [182]. Countryside Survey [183] has adopted this approach since 2019, aiding interpretation in a changeable environment with the hope that signals will be more easily interpretable.

The recovery of soil functions with the termination of drought has been studied across ecosystems and for different components of the soil system (see above, e.g., bacteria, fungi, soil organic carbon, nutrients). Different intensities of drought have been experimentally imposed to ecosystems and soil types for decadal periods [142,184,185]. However, these experiments are not commonly used to test the effect of additional disturbances (e.g., wildfire) on the recovery of soil function. A major review on environmental droughts considered temporary and permanent impacts of drought on freshwater, fauna, vegetation, and soil by adopting an ecosystem approach [186]. For soils, it was summarised that biochemistry and activity of the soil community recovers once climate conditions return to normal, unless multiple pressures occur simultaneously. These include, but are not limited to, wildfires [17,187,188], land-use pressures [187,189], and warming [190]. From geographic regions where wildfires are common (e.g., southern Europe), the combination of drought and fire showed effects on soil chemistry and biology [191]. In addition, forest windthrows (or felling of mature forests for timber production) and pest outbreaks are relevant examples where recovery of soils may fail when paired with (severe or reoccurring) droughts and there is a knowledge gap that exists concerning these issues.

Given that drought severity and frequency are increasing, soils may not recover from drought disturbance in time before the next occurrence of drought. Recent experimental evidence has been provided on soil microbial communities exposed to pulse drought events entering an alternative state of community size and composition [192]. The effects of changes in, e.g., soil microbial communities induced by reoccurring droughts on soil function may not be immediately visible and create uncertainties in the plant–soil feedback and the recovery of soils after frequent and/or severe droughts. However, recent research suggests that an ecological memory of the soil is developing in response to drought [73,193]. This ecological memory is mediated by the adaptation of the soil microbial community linked to nutrient cycles. Müller and Bahn (2022) [194] discuss the concept of ecological memory, or legacy, from the community to the ecosystem scale. They explain that drought timing, severity, and frequency all modulate drought legacy effects across scales, but that our understanding of these is still limited to a small number of studies. One example of a drought legacy effect is provided from a climate change experiment where a change in soil moisture movement was induced by a natural drought, causing a seasonally water-logged soil to be freely draining [142]. The authors suggested that preferential soil moisture flow was created by the cracking of the underlying (shallow) mineral layer, removing the perched water table.

Ecosystem recovery time post-drought was estimated to be on average 3.3 months globally, with the tendency to be longer considering future climatic conditions [195]. In that study, soil moisture was identified as the most important driver of post-drought recovery. A

study by Yao et al. (2023) [195], agrees with an experimental observation where chronically dry soil exposed to a natural heatwave was not able to facilitate shrub survival [196]. Shrub mortality was linked to soils with higher surface runoff rates when soils were saturated from extreme rainfall events, reducing the amount of soil moisture available to plants compared to annual precipitation. It is also suggested that the speed of recovery is faster in more humid compared to drier regions, likely due to increased drought pressure on soils [186].

Lastly, research on microbial community responses to peatland rewetting (after drainage) suggests some recovery of soil function after long-term drought events. Emsens et al. (2020) [197] observed that microbial communities in 13 fens recovered with rewetting, but only if the soil organic matter content was above 72% of the initial content. This finding suggests that soil biological functions can recover if the physical and chemical environment is still favourable. Further, Gao et al. (2020) [109] performed a meta-analysis of the effects of wetting and drying cycles on soil carbon and phosphorus. The data showed that the soil microbial communities recovered from drought after rewetting across soil and land-use types. Drying and rewetting was found to have different effects on the magnitude of components in the soil nitrogen and phosphorus cycles, potentially slowly changing the chemical environment for soil biota. Once a better understanding of the frequency and magnitude of future drying and rewetting cycles is gained, research should be targeted to explore how soil biological components respond to these new pressures given a change in the soil physical and chemical environment. This knowledge is required across a range of soil types and associated land uses.

6. Soil Resilience to Drought

The UK's landscapes and its soils are highly managed, and management practices may influence how soils and catchments will respond to drought and rewetting [59,198,199]. In recent years, one focus of soil research has been to examine its resilience to perturbations, particularly those of cultivation and climate. Corstanje et al. (2015) [200] defined soil resilience as resistance (degree of change) coupled with recovery (rate and extent of subsequent recovery) from a disturbance. Examination of factors that contributed to physical (void ratio), and biological (respiration) function revealed soil taxonomic class, parent material, and soil texture were dominant in producing resilience, whilst soil organic matter content and land use were ranked lower in the significant factors for 38 soil types from England and Wales. However, Griffiths et al. (2015) [201] cited bulk density, water-retention characteristics, soil carbon, and bacterial community as key properties in soil resilience, whilst [202] again cited soil organic matter being of great importance, but also suggested that grassland soils with higher soil organic matter content may have greater resilience than arable soils. Thus, soils that are well managed, particularly for soil organic carbon, may be more resilient to drought due to the influence of soil organic carbon on properties such as water retention and aggregate stability. In this respect, soil organic carbon may delay the impact of drought on soil function, but if the drought is prolonged, the resilience may continue to fade. Droste et al. (2020) [203] suggested that soil carbon insured crop production against increasing adverse weather occurring more frequently due to global change.

Bearing this in mind, land cover and the management of agricultural soils prior to drought will have an impact on topsoil infiltration rates. This was demonstrated in a global meta-analysis by Basche and DeLonge (2019) [59], who examined a range of soil conservation practices and infiltration rates. The results presented in Figure 7 show that the use of perennials and cover crops led to the largest increases in infiltration. The presence of livestock tended to lead to lower values of infiltration, most likely due to compaction.

A wide variety of management practices are considered to aid moisture infiltration in soils. These include (i) the addition of organic matter to soils, (ii) controlled traffic systems to reduce soil disturbance, (iii) limiting the number of times equipment is used on a field, particularly if wet, (iv) subsoiling to break up compacted layers, (v) switching cultivation practice to minimum till or zero till, (vi) applying solid manure or other organic material,

(vii) using rotations that include high-residue crops, such as corn (maize) and small grain, and perennial crops, such as grass and alfalfa, (viii) using cover crops, and (ix) farm on the contour (NRCS, 2011, September 19). However, the extent to which activities such as green manuring affect infiltration is not entirely understood. For example, the practice might lead to the development of water repellency in certain soils and cropping systems, which may be exacerbated by drought. Potato fields in Suffolk were found to be strongly water-repellent following green manuring [204].

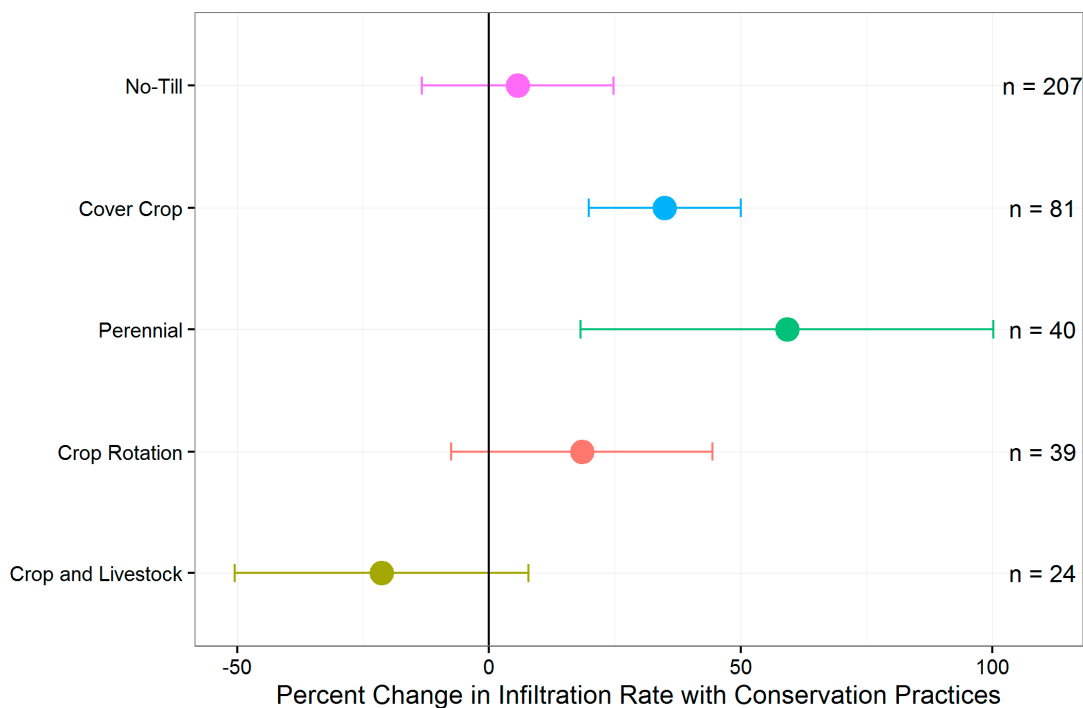


Figure 7. Impact of different agricultural management practices on infiltration rates of cropland soils (Reprinted from Basche and DeLonge (2019) [59] under the CC BY 4.0 license).

A major concern regarding the termination of droughts is that high-intensity rainfall will fall on hard or water-repellent soils, causing runoff and erosion. However, it is likely that some agricultural practices, especially in arable systems, may reduce these effects. Firstly, the chopping of straw by combine harvesters will leave a mulch that will reduce raindrop impact intensity. Secondly, many fields are subjected to post-harvest tillage to produce a ‘stale seedbed’ to help germinate weed seeds before autumn planting. This cultivation is likely to increase soil surface roughness, thereby decreasing overland flow. Govers et al. (2000) [121] demonstrated that soil surface roughness affects depression storage, water infiltration, overland flow velocity, and overland flow organisation. Cultivations are likely to increase all these factors, thereby decreasing the rate of water movement overland and increasing infiltration. However, these post-harvest cultivations may be considered less attractive until rain has fallen, due to the hardness of soil increasing machinery wear and increasing fuel use. These practices on soils vulnerable to erosion or catchments where flooding may occur should be considered in drought years.

7. Key Questions and Unknowns

Considerable information is available regarding the effects of drying on soils [2,24,30,73,101,177]. However, this information is often gained from experiments based on wetting and drying cycles, lab studies, or climate manipulation experiments. Few studies have been specifically designed to examine responses of soils to severe periods of drought. Whilst a couple of long-term monitoring experiments have been run when periods of drought and rewetting occurred, thus providing evidence [205] of the recovery of soils,

these experiments are rare. This means that relatively little is known about how soils respond and recover from extended drought periods. This contrasts greatly with our knowledge of groundwater [206–208] and surface water [3,206] responses to drought, which are captured by long-term monitoring programs that are required to understand flooding and the planning of groundwater resources.

To understand the impact and recovery from drought in soil systems it is required that data are collected prior to, during, and after drought. As UK droughts are unpredictable, it is harder to establish meaningful experiments. Thus, questions remain with specific regard to extended periods of heat and dry soil for both individual soil types and how these may contribute to catchment responses as drought terminates. Therefore, in order to better understand droughts and their impacts on soils (and ecosystems), dedicated monitoring infrastructure investment is required.

This review has identified knowledge gaps that would provide a sounder basis in understanding the impacts of droughts on soils and how they contribute to the overall catchment response. These knowledge gaps, to a substantial degree, are linked with soil organic carbon. Currently, efforts are being made at increasing carbon in soils through agricultural policy, so this may help improve soil resilience to drought. Infiltration itself is known to be influenced by soil organic carbon concentration [46–49], but will also be influenced by management practice [50]. Firstly, in arable soils, a large transition to minimum or zero till has been made in the last 30 years [209]. This creates a very different soil structure to that produced through conventional ploughing. Thus, infiltration rates have been found to become more reliant on preferential flow through engineered macrofauna-derived porosity [62,63]. Secondly, infiltration needs to be better understood where compaction has occurred on intensively managed grassland. Thus, a much greater understanding of infiltration rates on similar soil types, but with differing management practices or land cover, needs to be undertaken to assess how drought impacts the different soil structures. Lastly, infiltration changes with land cover or management are key to understanding the dynamics between soil moisture and shallow groundwater. Increasing interest has been placed on the ability of shallow groundwater as a buffer of soil moisture in drought years and its role in maintaining crop yield (e.g., [210]). If shallow groundwater is acting as a moisture reservoir, how this recovers after drought is also important.

Management aimed at increasing soil organic carbon also suggests that a greater understanding of macronutrient cycling during drought periods is required, especially as changes in soil structure and soil microbiology are likely to have developed as a result. This relates to both nutrient loss through leaching and changes in the concentrations of soluble nutrients present in the soil, in addition to greenhouse gas production. Work has demonstrated changes in greenhouse gas production using different tillage methods [211] and so the influence of drought-induced structural changes in soil needs to be better understood. By linking soil structure, soil organic carbon, and management practice, a question develops as to whether an increased frequency of droughts may expose subsoils to greater drying. If so, an understanding of the biological adaptation of subsoils to droughts and the potential consequences for soil organic carbon and nutrient mineralisation is required. A key area is in the potential for nutrient ‘priming’ of soil organic matter [170] and how this might impact (sub)soil structure and functioning.

This review identifies the susceptibility of soil bacterial and fungal communities and soil fauna to drought, which may impact nutrient cycling and their role in maintaining soil structure and infiltration. Key questions need to focus on whether tipping points exist where soil biological functions do not recover after drought or drying–rewetting cycles and the subsequent impacts on soil function of these new soil states.

A further key area that this review has identified is that of soil water repellency. Relatively little is still known about the spatial extent of soil water repellency with regard to soil type, management, and climate. Thus, in addition to increasing our basic knowledge and understanding of how soil water repellency develops, greater understanding is required of how it develops in response to extended periods of dry weather or drought. Further work

relating soil water repellency to drought-induced wildfire and the recovery of biological systems is also required.

The increased focus on soil organic carbon management in soils also links to the concepts of resistance, resilience, and recovery. Geris et al. (2015) [162] described ‘resistance’ as the strength of a system’s state to remain unchanged under stress, ‘resilience’ as the system’s ability to respond to stress by repelling damage and recovering quickly, and ‘recovery’ as the systems’ ability to restore prestress conditions. Thus, knowledge is required on how different drought-exposed soil ecosystems can resist the initial impacts of drought, respond to drought impacts, and recover after the drought (also after a major perturbation such as drought-induced wildfire). This is key in both agricultural and natural ecosystems, as a change in ecosystem structure and functioning will impact carbon and nutrient cycling. In an agricultural context, this may also have financial implications.

8. Concluding Remarks

Much of the information relating to potential impacts of drought on soils is derived from experiments where wetting and drying cycles are instigated or climate manipulations are used. This is likely, as droughts have been relatively infrequent (e.g., in the UK) and experiments would need to be established to capture the impact of drought on soils. We report on the large number of interactions present between soil physical, chemical, and biological properties in explaining soil response to drought. In particular, soil physical structure (essential for the infiltration of precipitation) is strongly linked to soil biological functioning. Changes in soil biogeochemical cycles are often linked to the changes in soil physical structure, such as aggregate breakdown.

Key gaps in our understanding are related to the resilience, response, and recovery of soil systems. In particular, information is required regarding soil biological communities, soil water repellency, and how shallow groundwater may buffer the soil moisture system. In addition, further gaps in our knowledge exist regarding multiple stressors (heat, moisture) and the impacts of successive extreme events on soil systems (e.g., drought, flood, wildfires). On a planet that is experiencing more extreme climate events, addressing such questions will help to identify actions that can be undertaken to build more resilient ecosystems and help future-proof them to changes to come.

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