**Introduction Walk-Through (“Treating Soils Like Dirt: The Failure of the European Union to Combat Soil Degradation in Europe, A Meta-Analysis”)**

Question 1 – What is soil degradation? What are the different types of soil degradation? (Physical, chemical, biological, ecological) What is the cause of soil degradation? (Natural and anthropogenic)

*Soil degradation is considered as one of the main causes of stagnating productivity growth (Bindraban et al., 2012).* Soil degradation refers to the loss of the present and/or future ability of the soil to provide functions and services due to a decline in soil quality (Lal, 2015). Soil degradation can be a direct result of natural processes, such as water or wind erosion (Bindraban et al., 2012). However, it most commonly arises from anthropogenic activity caused by socioeconomic pressures and population growth. Examples include deforestation, intensive agricultural practices, and urbanisation. These developments disrupt the natural fortification of a soil and its vegetative cover against climatic hostility (Oldeman, 1992). This is partly due to most human activities being depletive of the natural environment (Abrol et al., 1990). Four types of soil degradation have previously been defined: (i) physical; (ii) chemical; (iii) biological; and (iv) ecological. Soil physical degradation refers to a loss of structural attributes in the soil, which exacerbates crusting, compaction and hardsetting, soil erosion and sedimentation, soil temperature fluctuations, and laterisation. Soil chemical degradation is identified by acidification and salinisation, nutrient depletion, excessive leaching of cations, and contamination by industrial waste leading to a toxicity imbalance that is detrimental to plant growth. Soil biological degradation is characterised by a decline in SOC, activity, density, and diversity of soil fauna, and the capacity for soil C sink retention. Consequently, biological degradation can lead to soils being a net output of GHG emissions, such as CO2 and CH4. Ecological degradation is a consequence of all three soil degradation types and presents itself in the impairment of ecosystem processes, including nutrient and hydrological cycling, and a reduction in net biome productivity.

Question 2 – What agricultural processes lead to soil degradation?

The causes of soil degradation are multifaceted. Agriculture is one of the leading causes of stress to the environment (Seybold et al., 1999), and its effects can be seen long after the period of cultivation has ended. Agriculture can be defined as any crop-plant production system, and has huge ramifications for soils and surrounding ecosystems (McLauchlan, 2006). Soil can be categorised as “resilient” or “resistant” based on how it responds to agricultural perturbation (Seybold et al., 1999). A soil that is particularly vulnerable to change under agricultural management practice but rapidly returns to its original state would be defined as “resilient”. In comparison, a “resistant” soil can withstand greater levels of management intensity without changing, but once changed may lose the ability to return to its initial condition. Biomass amendments, tillage, fertilisation, and altered hydrology are specific agricultural management practices that have the potential to drastically change the quality of the soil. The elimination of naturally competing plant species and introduction of annual crop plants significantly alters plant biomass. Annual harvest diminishes organic C returns to the soil (Imhoff et al., 2004); in an agricultural system soil organic C is a linear function of C loads from crop residues (McLauchlan, 2006). Inversion tillage creates belowground disturbance through the pulverisation of the topsoil that increases SOC decomposition rates (Reicosky et al., 1997; Collins et al., 2000; Six et al., 2000) and enables physical soil erosion due to the lack of vegetation cover. It has been found that after 100 years of maize cultivation, agricultural land contains less than half the amount of topsoil in comparison with perennial grasslands (Gantzer et al., 1991). The full extent of soil degradation caused by inversion tillage can only be realised decades after its use: subsoil begins to appear at the surface, tillage-related landforms such as tillage banks form, and tillage translocation (the movement of the cultivation layer) takes place (Van Oost et al., 2006). Nutrient inputs through fertilisation can cause changes to the microbiome, leading to shifts in soil characteristics (Lin et al., 2019), and whole ecosystems (Wang et al., 2011). Irrigation exacerbates siltation, salinisation and sodicity, and can cause an anaerobic shift in the soil, leading to loss of soil hydroecological functioning (Assouline et al., 2015) and irreversible soil damage (Yin et al., 2021). Additional factors influencing soil degradation include continuous cropping/grazing and the use of heavy machinery. This is due to grazing interrupting the natural cycle of returning mineral-rich, dead plant matter to the soil, and machinery compacting the soil, which in turn prevents water infiltration and accelerates erosion. Soil degradation processes such as these call conventional management practices into question.

Question 3 – Can we stop/slow down soil degradation? Can it be reversed?

Land degradation must not only be reduced, but reversed to ensure long-term productivity. As intensive land management practices are largely responsible for soil degradation, it would be logical to conclude the implementation of less intensive practices is key to rehabilitating degraded land. Conservation Agriculture (CA) has the ability to reduce soil degradation and increase soil productivity (Pereira et al., 2019). Conservation Agriculture, also known as no-till farming, is based on three principles: i) no-till seed drilling; ii) continuous vegetation cover with organic mulch e.g. crop residue, green manure, cover crops; and iii) maintaining plant diversity by creating polycultures of crops. In contrast to conventional agricultural practices, CA wields the natural diversity of the ecosystem as a tool to propagate soil health and productive capacity (FAO, 2011). CA has the ability to encourage infiltration and storage of water in the soil, and indirectly improve interactions in the rhizosphere between plant roots and soil microbes, as well as the uptake of nutrients (Kassam et al., 2014). This builds resilience in the soil to environmental stressors. There is ample documentation surrounding the benefits of CA practices in long term studies, including: positive responses of soil biota to the removal of mineral fertilisers and pesticides (Henneron et al., 2015), increased soil fertility as a result of crop diversification (DiFalco et al., 2017), and boosted soil productivity under wide crop rotations and cover crops (Ranaivoson et al., 2017; Garcia-Gonzalez et al., 2018). There is enough evidence to imply that the implementation of CA, in conjunction with other defensive management practices to combat erosion and enhance SOC, has the potential to conserve our soils (Lal et al., 2013). For this reason, CA is at the forefront of approaches proposed in the FAO sustainable agricultural intensification strategy (FAO, 2011). Additionally, among the 17 sustainable development goals (SDG’s) proposed by the United Nations (UN) in their agenda for 2030, there is mention of achieving Land Degradation Neutrality (LDN), which cannot be achieved without CA (Kust et al., 2017; Pereira et al., 2019) as agriculture is a primary cause of degradation.

Question 4 – What are the implications if soil degradation is not prevented/slowed down? (Ecological, economical, social?)

Three quarters of terrestrial ecosystems are impacted by soil degradation, with no intervention this number could rise to 90% by 2050 (Pereira et al., 2019). Soil degradation affects more than half of the global agricultural systems, adding a huge strain to approximately 54% of global ecosystem services (Nkonya et al., 2016). More recently, there has been significant interest in the increasing interactions of the pedosphere, biosphere, and atmosphere as a result of soil degradation. The pedosphere is the second largest carbon reservoir on the planet (Stolte et al., 2016). An estimated 2400 Pg of soil organic carbon (SOC) is locked in the upper 2 metres of the soil (Kirschbaum, 2000). However, soil degradation processes such as soil erosion is able to relocate and unlock this soil organic carbon. Currently, there is an active debate in the scientific community regarding whether soil degradation and associated ecosystem changes translates into a net C sink or source for atmospheric CO2. It is widely known that soil degradation has huge influence over the global carbon budget. Berhe (2007) estimated that over time the volume of CO2 unlocked from the soil and released into the atmosphere would be equal to three quarters of all fossil fuel carbon emissions. Within the last two centuries, 200 Pg C has entered the atmosphere as a direct result of land conversion and soil degradation (DeFries et al., 1999). The work of Lal (Lal 1995, 2001, 2003a, 2003b, 2003c, 2004) lends huge support to this debate, having found that soil degradation process, such as soil erosion, are a source term as opposed to sink, in the global carbon budget. They predict that annually 1.14Pg C is being released into the atmosphere from the soil due to aggregate breakdown. There is significant support for these finding in the literature (Schlesinger et al., 1995; Starr et al., 2000). A scientifically-backed conclusion of this debate would have huge implications for the future of soil science, ecology and environmental policy. Soil degradation also has important economical consequences. At the going rate, the cost of no intervention is significantly higher than the cost of intervention (Mirzabaev et al., 2015). Estimations of the global revenue lost as a result of soil degradation processes range from 300 billion US dollars (Nkonya et al., 2016; Pancheco et al., 2018) to 6.3 trillion (Sutton et al., 2016), on account of impaired ecosystem function. In Europe, it is thought that the European Union suffers losses of 1.25 billion Euros annually, due to a reduction in agricultural productivity, as a result of 12 million ha of European soils being degraded (Panagos et al., 2018). Similarly, the United Kingdom bears the brunt of a heavy 1.4 billion pound deficit as a consequence of the aforementioned soil degradation (Graves et al., 2015).

*In 2017, 25% of European land (411,000 km2), particularly in southern Europe, was identified as being at high or very high risk of desertification, a 14% increase*

*since 2008 (Pravalie et al., 2017).*

*There is a growing realisation that soil needs to be treated and managed as a scarce and fragile non-renewable resource, including the constituents that make up soil. Yet, estimates of the rate at which soils are degrading, the extent to what areas are affected, the costs incurred due to productivity decline and other economic losses, and how these impact on food security, are extremely variable and uncertain.*

Question 5 – Who has influence to stop soil degradation? (Farmers, policymakers etc.)

*Land degradation is strongly linked to the three pillars of sustainable development, since it depends on social development (e.g. population increase), economical status (e.g. political instability) and climate change (e.g. drought). Land degradation is directly and indirectly related to several of SDGs, however, is especially connected with the goal !5, Life on Land. Goal 15 is especially focused on four key areas: 1) loss of biological diversity, and degradation in 2) land, 3) forests and 4) mountains. This goal demands the governments to stop biodiversity loss and land degradation, and restore, protect and promote a sustainable use of the land. (Pereira, 2019)*

*With one-fifth of the world’s soils currently degraded, and continuing to degrade at a rate of 5-10 billion hectares annually, the burden and responsibility of addressing soil conservation and management falls on every individual; farmer, land owner, indigenous community, politician, scientist, worldleader and the general public.* [To whom the burden of **soil degradation** and management concerns](https://www.sciencedirect.com/science/article/pii/S2468928919300012)

*The global and regional assessments highlight the considerable impact of land degradation on crop production. Even though policies can deal with regional interventions to improve agricultural systems, local farmer’s experience will need to play a critical role in devising locally applicable management strategies. Generally, global and continental scale studies guide policy decision making while studies at landscape or field scale provide detailed information on what to do where.*

Question 6 – Is there a difference in levels of soil degradation with different agricultural management practices? (Conventional, intermediate, organic, conservation)\*\*\*

Question 7 – What proportions of European land are under each different management intensity?

Question 8 – Will transitioning to organic farming practices stop soil degradation? Do we have enough land to feed our population with 100% organic farming practices?

*Biological mobilisation of soil nutrients for crop nutrition is more important in organic than conventional farming, meaning that soil quality needs to be maintained at a high level. Yet there are management practices and trends in organic farming that may jeopardise soil quality and hence require rethinking and improvement.*

Question 9 – Is there a trade-off between crop management and ecological protection?

*SLM is defined as “the use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions”.*

Question 10 – What is the spatial extent and rate of soil degradation in Europe?

Question 11 – What is the significance of soil biology to sustaining agriculture?

*SOC is an important component of soil quality, and it regulates soil moisture and structure, nutrient supply rates, and microbial activity. Soil organic C emissions have contributed approximately 55 Pg to anthropogenic increases in atmospheric CO2 and changes in the global C balance (Post et al., 2004). According to the dominant paradigm, cultivation causes an immediate and rapid loss of SOC (Davidson et al., 1993). The loss of SOC continues for several decades after the implementation of cultivation, reducing SOC pools on agricultural soils to 70% of their original levels on average (Mann., 1986). Generally, the rate of loss slows as SOC levels reach a new equilibrium that depends on tillage practice (West et al., 2002) and the level of C inputs returned to the soil as crop residue or animal manures (Kirchmann et al., 2004). There are several mechanisms of agricultural reduction in SOC due to alteration of C inputs to and output from soil. Soil erosion is one of the largest environmental problems caused by agriculture (Owens et al., 2002).*

*Soil microbial properties are more sensitive than physical and chemical properties in detecting changes in soil quality (Doran et al., 1996; Nanniperi et al., 2003). Soil biota, a small, labile but crucial fraction of soil organic matter (SOM), is the driving force behind energy transfers and nutrient transformations in soils, thus playing a major role in soil fertility and resiliency (Elliott et al., 1996).*

*The enormous contrasts in regional food production systems reflect disparities in economic development, soil nutrient supply, market access, and risk-avoidance strategies by farmers and land managers. But they also highlight the potential to enhance agricultural production by closing yield gaps, that is, the difference in actual yield and yield that can be obtained when crops are optimally managed. Farmers in North America and Western Europe are estimated to produce yields at 80% of yield potential.*

Question 12 – What strategies are there to mitigate soil degradation?

*Soil degradation is detrimental to livelihoods of poor farmers and results from agricultural practices that deplete the organic matter and nutrient content of the soil. A wide range of techniques can be applied, such as reduced tillage, residue management, mulching, crop rotation, crop mixtures, cover crops, manure application, agroforestry with soil improvement through nitrogen-fixing trees, terrace building, pitting systems, water harvesting techniques, drainage ditches, small dams in valley floors, drip irrigation, and so on to conserve soil and water, and to prevent soil degradation and increase crop yields. Interventions should be specifically targeted to farming systems as well. Interventions that aim at increasing productivity and the nutrient use efficiency at farm level, should take the predominant farm-type and nutrient management strategy into account to target the main loss pathways. Proper management of crop residues and integration of crop and livestock farming along with N fixing crops, and SLM techniques like stone rows and grass strips are necessary to ensure nutrient cycling, reduce erosion and gradually increase soil organic matter content. Evergreen agriculture or ‘fertiliser trees’, that is, the intercropping of particular tree species into annua food crop systems to sustain a green cover on the soil throughout the year, can bolsters nutrient supply through nitrogen fixation and nutrient cycling. It also generates greater quantities of organic matter at the soil surface thereby improving soil* *structure and water infiltration, at rates of 2-4 t C ha-1 compares to 0.2-0.4 t C ha-1 under conventional farming systems. Terracing and straw mulching have been widely adopted and found effective in increasing soil water storage (e.g. by an additional 26mm over 1m soil depth under straw mulching) and yield (e.g. 15% higher spring wheat yield under mulching), while reducing erosion.*

*Conservation agriculture (CA) is often claimed to offer great potential to address land degradation and improve livelihood; including improvement in soil fertility, reduction in soil erosion, carbon accumulation, savings in time and energy (fuel), and increased biodiversity obtained from reduced or eliminated tillage, soil cover and crop rotation. Yet, differences in both agro-ecological as well as socio-economic conditions show that CA is not generally applicable to combat degradation and enhance crop production and needs to be tailored to specific conditions. The success of CA is challenged in environments where soils are inherently poor; have physically hardening properties, have low chemical nutrient and C levels, and have very little biological soil fauna activity. More intensive weed control also demands more labour for which there is neither interest nor incentive as yields may drop after conversion to CA. Poor access to inputs jeopardise the needed increased dependency on herbicides, while continuous cover crop is not possible because of climate, and crop rotation is limited by market mechanisms.*

Question 13 – What are the primary knowledge gaps limiting mitigation of degraded soils?

Question 14 – What are the highest priority research needs to improve soil health and reverse soil degradation?

Question 15 – Soil resilience to combat soil degradation

*Soil resilience has recently been introduced into soil science to address sustainability of the soil resource and to combat soil degradation. The term “resilience” has been used in the ecological literature since the late 1960s and early 1970s. Resilience has been defined in two ways in the ecological literature. The first definition, referred to as “equilibrium resilience” concentrates on stability near an equilibrium steady-state. Speed or rate of return to an equilibrium after a disturbance are used to measure resilience. The second definition, referred to as “ecosystem resilience” is the magnitude of disturbance that can be absorbed or accommodated before the system changes its structure. The term “soil resilience” has been introduced into soil science only recently, mainly to address soil ecology and sustainable land use issues. It was introduced to create a common theory that describes the reaction of soil to a range of impacts or disturbances. Information about the ability of a soil to recover from degradation is essential for the maintenance and sustainability of the soil resource base. Sustainability deals with performance at certain acceptable levels over a given time frame and refers to the productivity and economic, social, and environmental aspects of a land use system, i.e., agriculture. Soil quality is a key component of sustainability. The direction in soil quality with time is a primary indicator of sustainable management. Soil resilience has been defined as the capacity of a soil to recover its functional and structural integrity after a disturbance. However, others have defined soil resilience as the capacity of a soil to resist change caused by a disturbance.*

*The soil’s capacity to recover has two components, the rate of recovery and the degree of recovery. The rate of recovery is the amount of time it takes soil to recover to its original potential or to some stabilised lower potential after a disturbance. The magnitude of recovery to some stabilised potential relative to its predisturbance state defines the degree of recovery. If the disturbance is too drastic or if the soil is inherently fragile, the soil can undergo irreversible degradation in which its capacity to function will not recover within any reasonable time frame. In this case, the soils resilience capacity has been exceeded, resulting in permanent damage or the need for very costly restoration. The greater the rate and/or degree of recovery, the more resilient the soil system is to a specific disturbance. Soil resistance, which is distinguished from soil resilience, has been defined as the capacity of a soil to continue to function without change throughout a disturbance.*

*Characterising the resilience capacity allows a differentiation of resistant, resilient, fragile and marginal soils, and a delineation of their response to stress (Lal et al., 1989). It is essential to identify areas of resistant soils, where high productivity can easily be maintained, and of resilient soils where management practices can be developed and implemented to minimise and reverse degradation.*