

Chapter 2

Agricultural Adaptation to Climate Change - Limiting Degradation of Soil and Water Resources

Abstract

Climate change is associated with elevated temperatures, more intense rainfalls, and longer and hotter droughts. These changes add stress to soil and water resources, which form the foundation for a productive resilient agriculture. Crop management practices often increase stress to soil and water resources leading to loss of soil organic carbon, increased soil erosion, and degraded water quality. However, selected management systems can improve soil and water quality or limit their degradation, even in light of anticipated climate change stressors. This chapter identifies approaches to increase the adoption of recognized favorable practices in different countries or regions. Three primary approaches seem to exist: 1) incentive-based with no or minor regulatory component; 2) regulatory-dominated with government exercising authority over producer practice options; and 3) long-term planning addressing spatial and temporal land management elements and adoption of those plans with a combination of government support and regulatory authority.

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2.1 Introduction

The most agriculturally productive rain fed areas exist in regions of the world having fertile soils and climate conditions that support relatively high and stable crop productivity (Fisher et al. 2002). Further, these areas exist because unique combinations of soil forming factors and the climate conditions favoring this development have remained stable over millennia. Inherent in both the soil development process and current crop production is the interaction of climate, soil and vegetation; the climate was favorable for plant biomass production during the soil development process and remains favorable for crop production now. Prior to human influence the soil and plant community system that evolved was both resilient and self-sustaining – climate and soil favored nutrient and water uptake through plant growth; plants converted atmospheric carbon into organic matter and furnished it to soil biota that functioned to recycle nutrients in the biosphere, and the plant canopy covered the soil surface protecting it from stresses associated with periodic extreme weather conditions or events.

Current agriculture methods have altered this resilient system by replacing native plant communities with food, feed, and biofuel crops. Crop management practices have altered the soil and soil surface cover reducing soil protection from rain, wind and heat. These practices have also changed the amount and distribution of biomass (above vs. below ground; perennial vs.), which impacts soil organic matter dynamics, nutrient cycling and soil biology. Disrupting such an inherently resilient system carries a risk of degrading system components, especially soil. This is particularly concerning because most areas recognized as favorable for dryland production by Fisher et al. (2002) are also vulnerable to accelerated soil erosion (Borelli et al. 2017) and resulting land degradation.

A stable or stationary climate has been an important component contributing to high and reliable plant production potential in these areas. While modern agriculture has played an important role in disrupting resilient biomass producing systems, a changing climate brings another existential threat to long term productivity (IPCC 2019). Despite the rather ominous evidence projecting continued and even accelerated soil degradation rates, the most important factor impacting soil sustainability, especially for soil erosion, remains land management choices (Olsson et al. in press). How we choose to manage our soil resources will determine the long-term productivity of our global soil resource base. This chapter will identify agricultural practices and approaches being used to adapt to a changing climate for five different agriculturally productive areas of the world – the Northeast Mollisol belt in China, the Loess Plateau in China, Europe, Uruguay, and Central United States.

2.2 Changing Climate and Soil Degradation

The Earth and its atmosphere are warming and extremes in precipitation and drought are more frequent and intense; the scientific confidence that these trends will continue is high (IPCC 2019; USGCRP 2018). Evidence also indicates seasonal rainfall shifts are occurring, at least in selected areas; for example, in the Central US increase spring rainfall and reduced rainfall in late summer and autumn are being recorded, and models suggested this is likely to continue (Feng et al. 2016). These shifts interact with timing of agricultural activities affecting soil degradation as will be explained later. The combination of spatial and temporal climate shifts will likely add stress to soil and water resources beyond that historically experienced.

Climate components, especially precipitation and temperature have major impacts on soils and the capacity of soil to produce agricultural crops. Most productive soils have a favorable surface layer, the A-horizon, with elevated soil organic matter and nutrient contents compared to deeper

horizons. The A-horizon developed favorable properties largely because of elevated biological activity in this layer – maximum plant rooting density and associated macro and micro fauna that rely on root materials deposited in the soil for their life processes. The A-horizon characteristics, especially depth (see FIGURE 2.1), have been repeatedly used as an independent variable when characterizing soil loss (A-horizon thinning) impacts on crop yields (den Biggelaar et al. 2003).

More intense precipitation, longer growing seasons, and elevated temperatures threaten the nature of the A-horizon. Longer growing seasons (longer duration of warmer temperatures) and higher temperatures lead to warmer soils; organic matter oxidation rates and thus soil organic matter loss have a direct positive relationship with temperature (Amundson et al. 2015). The soil organic matter balance, additions vs. losses, could remain positive *if* our changing climate resulted in appreciably greater organic matter deposition below ground than losses associated with temperature rise. This might occur if warmer conditions induced farmers to adopt crops with greater root biomass or if plant genetics were modified such that the current crops increased root biomass, for example. However, current evidence indicates the entrenched markets and infrastructure for current commodity crops will likely preclude major changes in cropping systems. This is especially true for the U.S. However, efforts are underway to modify current cropping systems such that they are more soil organic matter friendly.

Changing precipitation patterns create a different type of challenge for the productive surface layer. Elevated rainfall amounts and rainfall energy increase soil erosion potential (IPCC 2019) resulting in increased translocation of surface soil particles and materials, for example organic matter, attached to them. Movement of soil particles downslope with subsequent deposition where the velocity of overland flowing water slows results in soil removal and A-horizon thinning of more steeply sloping areas with soil accumulation downslope. The combination of

tillage-induced down-slope soil movement and water erosion has resulted in approximately 35% of the farmed US corn belt devoid of topsoil (Thaler et al. 2021). This has occurred during a climate period that has been relatively stable and favorable for farming activities (Takle and Gutowski, 2020). The challenges imposed by elevated rainfall energies in the world's food producing areas must be met with management practices that limit the negative impact of heavier rainstorms while maintaining crop productivity.

Reduction in yields associated with thinning A-horizon has been documented extensively (den Biggelaar et al. 2003). Of arguably greater importance is the impact of thinning topsoil on crop productivity during climate stress conditions. Water infiltration and storage in the soil profile are dependent on favorable soil physical conditions, especially at and near the soil surface.

Removing the most favorable soil materials from the soil surface layer will reduce infiltration rates, leading to more surface runoff, and ultimately less soil water storage. Climate projections are for longer dry periods between increasingly heavy and intense rainfall events or rainfall periods (IPCC 2019). Elevated temperatures will increase evapotranspiration demand and longer times between rainfall events will increase the overall need for soils to store more water for crop use. While improved management and genetics may help increase water use efficiency, it remains a biophysical law that biological productivity for a given plant or crop species is directly related to quantity of water transpired (Ben-Gal et al. 2003).

The impact of degraded soil combined with elevated water demand required for higher crop yields poses challenges for maintaining or increasing existing productivity. FIGURE 2.1 illustrates the corn yield response to thinning topsoil measured on Mollisols in Central Iowa, USA. Maize yield and corresponding A horizon depth were recorded across four years in which growing season rainfall was below normal (personal communication Tom Kaspar, USDA-ARS,

4/19/2021). As horizon depths declined to less than 0.2 m yields rapidly declined. Because a substantial area within the US Corn (Maize) Belt is now missing A-horizon (Thaler et al. 2021) the reduced production potential associated with increased heat and drought stress for degraded soil conditions appears ominous. Specific yield response to soil degradation is crop specific, however negative production impacts of degraded soil is to be expected for virtually all crops produced in rain fed regions, especially under climate stress conditions.

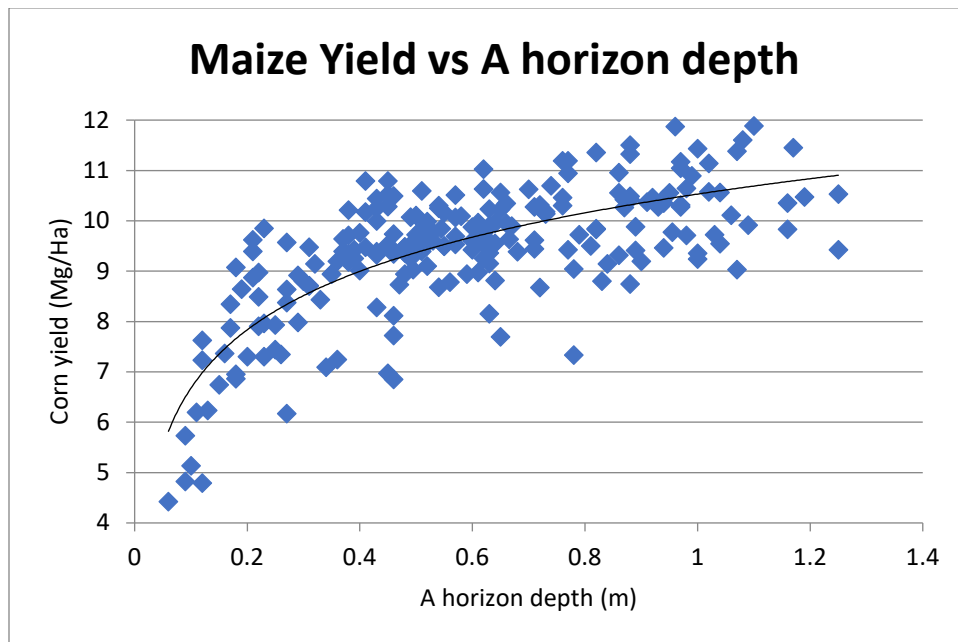


FIGURE 2.1. Relation between maize yield and A-horizon depth in Central USA across four years with growing season precipitation below normal.

Seasonal change in precipitation and its interaction with farming operations impacts soil erosion potential in more subtle ways. In the Central US, increasing spring precipitation associated with a changing climate (Feng et al. 2016) brings with it potential delays in pre-plant tillage and planting of row crops. While our biggest concern is typically delayed planting impacts on crop yield, these delays can also impact soil erosion rates. FIGURES 2.2.A AND 2.2.B illustrate the impact of delayed tillage and planting on soil erosion, estimated using the Daily Erosion Project (Gelder et al. 2017) and observed Iowa rainfall. Spring rainfall becomes more erosive in the

Central US during April to June. The most vulnerable soil erosion condition for most row crops occurs between the time of pre-plant tillage (that reduces surface residue cover) and crop canopy closure. Delaying this vulnerable condition until later in the spring aligns with more erosive late spring rainfall.

2.3 United States Climate Change Adaptation and Mitigation Strategies

Adaptation strategies are based on concepts proven to reduce soil degradation or improve soil health, which is especially important during harsh climatic conditions. Practices that provide continuous surface cover, increased plant root growth and/or root density, diversified crop rotations, and limited or no tillage are the primary in-field tools for directly improving soil health and indirectly adapting to climate change in the Central US. Of these approaches, limiting or eliminating tillage has arguably been the most successful in this era of voluntary compliance and no or limited government regulation (explained later) because tillage reduction has been cost effective, supported by industry, and responsible for improved yields and better economics for many farmers.

A wide variety of state and Federal government programs encourage practices that support climate change mitigation or adaptation. Three examples of Federal government supported programs are given below. In addition, a range of farmer led groups and organizations, for example Practical Farmers of Iowa (Practical Farmers of Iowa, n.d.), demonstrate and promote practices to others that are economically favorable, that are resilient to weather anomalies and that favor soil health maintenance or improvement. A variety of non-profit groups such as The Nature Conservancy (The Nature Conservancy, n.d.) work with researchers and farmers to increase favorable practice adoption and develop new management approaches favoring soil health. Many opportunities exist for interested farmers to engage with experts and/or obtain

A

Tillage/Planting Date	Soil Erosion (Mg/Ha)
10-Apr	4.0
20-Apr	4.3
30-Apr	4.5
10-May	4.9
20-May	5.4
30-May	5.6

B

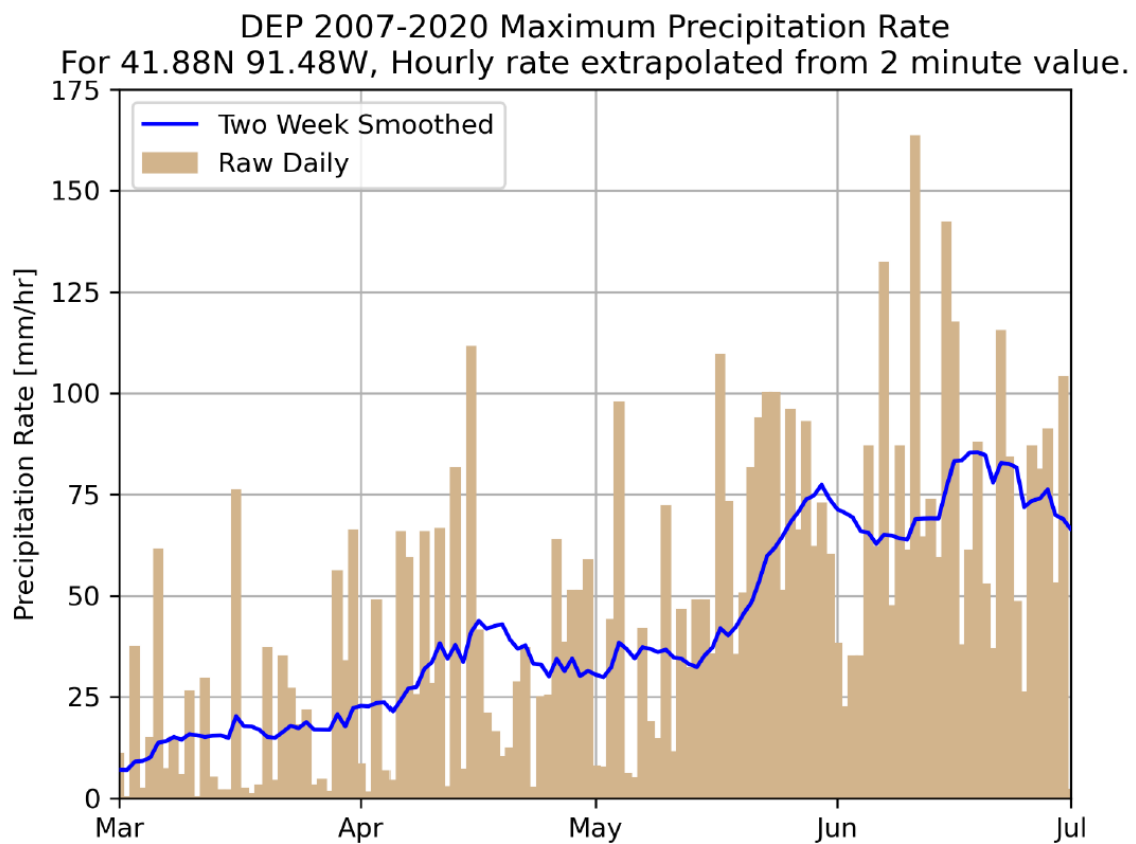


Figure 2. A. Annual sheet and rill erosion estimates associated with progressively later spring-time tillage and planting dates in Iowa, USA.
B. Maximum daily observed precipitation rate occurring from March 1 to July 1 for 41.88N 91.48W (East-central Iowa) across the time period 2007-2020. Courtesy of Daryl Herzmann.

government financial support for adoption of practices that are perceived to adapt to and mitigate against climate change.

2.3.1 Government Approaches

The United States Department of Agriculture (USDA) Climate Hubs have often endorsed a concept developed by the Food and Agriculture Organization of the United Nations (Food and Agriculture Organization of the United Nations 2010) termed Climate Smart Agriculture. While there are 10 building blocks associated with Climate Smart Agriculture, today's US Climate Smart Agriculture has three primary goals (Buda, 2021): increased productivity, enhanced resilience, and reduced greenhouse gas emissions.

The USDA has shaped various agricultural programs to induce farmers to conserve soil and water with in-field practices, and as a result these programs are aligned with Climate Smart Agriculture principles and goals. Encouraged practices have typically existed for years – they are not new. Recognition that we have been operating for decades in a relatively favorable climate for agriculture (Takle and Gutowski 2020) and that with this favorable climate substantial soil degradation has occurred is adding a new level of seriousness to agriculture resilience discussions considering projected challenging climate change trends. Concerns over increased rainfall intensity and longer periods of drought and extreme heat have prompted multiple programs with increased focus on soil health.

The USDA approach to changing or influencing farmer decisions has been and continues to be volunteer-based with little effort to modify agricultural practices through regulatory means.

Volunteer in this sense means farmers choose to adopt a practice with few or no government mandates imposed regarding practices to be used. In many situations a government agency encourages farmers to change practices through offering a government subsidy payment and/or

technical assistance from sources such as county based Natural Resource Conservation Offices (NRCS). University Extension service and farm cooperative agronomists likewise play critical roles in educating farmers regarding alternative practices. This is a sharp contrast to approaches used in some countries such as Uruguay (explained later in this chapter) that rely heavily on regulatory approaches to ensure practices are used that favor soil and water resources and climate change adaption and mitigation.

2.3.1.1 Selected US Government Program Examples

The NRCS administers through its county offices multiple conservation programs of potential interest to a wide range of producers. One of the more popular programs is the Environmental Quality Incentives Program (EQIP) (USDA, Natural Resources Conservation Service, n.d).

Producers are offered financial support and technical assistance to adopt practices new to their farming operations, practices such as cover crops, extended crop rotations, forest stand improvement, prescribed grazing, and new irrigation. The farmer and agency sign a binding contract regarding practice implementation and support payments for specific conservation practice implementation on targeted farmland area(s).

The Conservation Stewardship Program (CSP) administered through the local NRCS office supports farmers financially and with technical assistance for improving existing conservation efforts on their farms' working lands, that is on land being used for crop production, grazing or production of forests. CSP is the largest agricultural conservation program in the United States (USDA Natural Resources Conservation Service, n.d.)

The Conservation Reserve Program is administered by the Federal Farm Service Agency (FSA) and is designed to remove farmland sensitive to soil erosion from crop production while enhancing environmental benefits and mitigating climate change through carbon sequestration.

Farmers sign a 10- or 15-year contract with the agency and for removing erosion sensitive lands from production and growing environmentally favorable plant species they receive an annual land rental payment from the Federal government (USDA Farm Service Agency, n.d.).

2.3.2. Do these approaches work?

The NRCS periodically estimates sheet and rill soil erosion rates for each state in the U.S. using Revised Universal Soil Loss Equation technology. This allows an evaluation of soil erosion rates through time as influenced primarily by crop and soil management practices. Nationally, soil erosion rate estimates decreased from 1982 to 1997 after which soil erosion rates have remained stable (U.S. Department of Agriculture, 2020). The major corn producing states in the Central U.S. have seen similar estimated soil erosion rate declines from 1982 until 1997 however erosion rate increases after the 1997 – 2002 period (U.S. Department of Agriculture, 2020), which coincides with the time that important soil conservation programs were implemented. Continued soil erosion rates greater than renewal rates and acceleration of these rates brings into question the capacity of existing volunteer programs to foster adoption of practices necessary to maintain resilient soil resources, resources that will be necessary in a more hostile climate.

2.3.3 Carbon Markets

The capacity of soils to sequester carbon is well known (Lal 2012). However, means to estimate the effect of cropping systems or selected management practices on quantity of carbon sequestered has been elusive. Nonetheless, the concept of carbon markets based on carbon offsets is gaining popularity. Farmers who use practices that, based on peer-reviewed science, are effective at sequestering carbon receive payment for an estimated mass of carbon sequestered by a given practice over a given time. Carbon markets are designed to link industries that exceed established minimum levels or carbon release to farmers who are ‘capturing’ the industries

carbon release excess. Payments made to farmers for carbon capture originate from industry and are managed through a 'carbon exchange' or business that manages such exchange activities.

2.4 Uruguay: Introduction

The Uruguayan continental area is 169,000 km² located between 30-35° S and 53-58° W. Annual average precipitation is 1100 mm (\pm 200 mm); mean annual temperature is 24°C in summer and 12°C in winter. No frozen soils nor snow cover exists. The country belongs to the Río de la Plata Grasslands Physiographic Unit (Paruelo et al. 2001) that occupies 65% of the territory.

Topography is gently rolling; dominant slopes are 3-6%, with some flat plains and some areas with more than 8% slope; mean altitude is 140 m above sea level. In Soil Taxonomy, the most important soils are Mollisols and Vertisols, but there are significant areas of Alfisols, Ultisols, Inceptisols, Entisols and Histosols.

Durán (1998) estimated the Uruguayan soils organic carbon (SOC) content using the national general soil map (1:1 million scale, 99 mapping units). Values came from sampling and analyzing 200 profiles, mostly from undisturbed soils. Therefore, his information represents the country's potential SOC content assuming other country soils could match the SOC of the sampled profiles. Durán's results indicate that to a 1 m depth, the country's soils can hold 2.3 Pg of SOC, with a mean value of 13.4 kg.m⁻³. This is 17% above the world average of 11.5 kg.m⁻³ (Eswaran et al. 1993 and 1995, cit. by Durán 1998). The area occupied by the mapping units dominated by Mollisols and Vertisols, representing 30.6% of the country, have SOC content from 15 kg.m⁻³ to 20 kg.m⁻³ and more. Also, 40-45% of these soil's SOC is in the upper 20 cm of the profile.

Until the mid-20th Century, agriculture was dominated by continuous cropping (CC) with conventional tillage (CT); wheat was the main crop managed with several tillage operations

leaving low amounts of surface crop residues. This generated unacceptably high soil erosion rates, having significant negative effects on approximately 30% of the country's surface by the mid-60s, impacting the most productive soils in the country (Cayssials et al. 1978, cit. by Durán and García Préchac 2007). A complimentary study (Sganga et al. 2005, cit. by Durán and García Préchac 2007), identified the same proportion of the territory had been negatively affected (30.1%), separating the degradation into the following categories: Slight 18.3%, Moderate 9.9%, Severe 1.3% and Very Severe 0.6%.

By the mid-60s, there was a general adoption of crop-pasture rotations (CPR), cropping 3-4 years followed by another 3-4 years of seeded grass and legume pastures for direct grazing. This change, even with CT, resulted in an important erosion rate reduction and SOC content recovery during the pasture CPRs phase (Garcia Préchac et al. 2004). During the 90s mostly no-till (NT) and some reduced till (RT) replaced CT; this, together with the CPRs, improved soil conservation further (García Préchac et al. 2004).

New cropping intensification began early in the 21st century, resulting in shorter pasture duration in the CPRs or even its elimination, resulting in a much greater CC area. This dramatic change was due to the relatively low price of Uruguayan land compared to other land in the region, excessive taxing to grain exports in Argentina, and the great international increase of soybean price. Large scale Argentina agricultural enterprises came to Uruguay, generating structural changes in land size, tenure, and operational management (Arbeletche et al. 2010). Soybean became the new leading crop, increasing its area from almost nothing, around 10 kilo hectares (kha) in 1999, to 14,000 km² in 2014.

This created major challenges for Uruguay soils as little experimental data existed addressing soybean effects on soil degradation; soybean was not previously grown in Uruguay. Thus,

models (USLE/RUSLE to estimate erosion, and CENTURY to estimate SOC) were used to estimate management effects on SOC (Clérico et al. 2004, cit. by García Préchac et al. 2004; Morón 2009). Their predictions indicated that CC with NT soybean monoculture is not sustainable due to its erosion rate and loss of SOC. Including winter cover crops or double annual cropping of soybeans and wheat could reduce erosion close to tolerance (typically 7 Mg.ha⁻¹.year⁻¹), but could not totally balance the loss of SOC. Sustainability could be achieved with CPR-NT systems, producing erosion rates similar to the ones under natural grasses and maintaining or modestly increasing SOC content. The first modeled prediction was confirmed empirically with the mean of more than one thousand soil samples analyzed yearly in the soil test lab of INIA (Exp. Station La Estanzuela) between 2002 and 2014 (Beretta et al. 2019); the majority of these samples came from continuously cropped fields with soybean. An approximately 20% relative drop in SOC, along with lower content of exchangeable bases and lower soil pH were observed. When SOC falls, the cation-exchange capacity falls, which causes the loss of bases and, consequently, the acidification of the soils.

The political reaction to the new agricultural reality, considering that conserving soil is required to maintain soil quality and productivity, was to update and effectively apply the country's soil conservation legislation. This chapter component's objective is to describe this policy and its consequences in terms of soil and SOC conservation. The conservation or even recovery (sequestration) of SOC is the main contribution that the country can make to mitigate climate change, in addition to reducing fossil fuel consumption. In terms of adaptation, evidence indicates that SOC conservation is reached with more diverse production systems that are more resilient to climate change and world market variations.

The present chapter component is mainly composed of presentations in the Global Symposium on Soil Organic Carbon, March 2017, Food AO-Rome Italy (García Préchac et al. 2017), and in the Global Symposium on Soil Erosion, May 2019, Food and Agriculture Organization of the United Nations (FAO), Rome Italy (García Préchac et al. 2019), and an invited conference in the 2019 Latinoamerican Conference of Soil Science. The first two events were organized by the FAO Global Soil Partnership Organization and its Intergovernmental Technical Panel on Soils (ITPS), and the last by the Latinoamerican Society of Soil Science.

2.4.1 The Uruguayan Official Soil Conservation Policy

The Uruguayan law is based on the principle that soil conservation is of general interest, and according to the country's constitution, is dominant over any other particular interest. Therefore, regulation can limit what private landowners and land tenants do with soils over which they have control. The law determines that the Ministry of Agriculture is the authority that dictates the Technical Normative on soil conservation and prosecutes its fulfillment. The Technical Normative must be applied by the land tenants, independent of the contract type or form of land tenancy giving the tenant's right of land use. This Technical Normative is established by executive resolutions of the authority. The last law modification in 2009, added that when the land tenant is not the landowner, the landowner is jointly liable with the tenant in case of regulatory violation. This provision incentivized the landowners to be the first stewards of soil conservation and was triggered by the majority of the country cropping being conducted by land renters and not owners. The violation fines can range from \$US 300 to \$US 300000, depending on their gravity.

Several general technical norms define “bad” soil use and management practices, like the generation of oriented roughness parallel to the main slopes, performing tillage operations or

herbicides applications in areas of surface runoff concentration leading to gully erosion, etc.

However, the main technical norm from 2009 is that each unit of soil management (lot or parcel) should file a Soil Use and Management Plan (SUMP) for the immediate future and duration of the planned rotation. The SUMP information contains: 1) precise geographic location, 2) description of the rotation to be used, including all soil management details, 3) projected yields of the different crops, and eventually, pastures in the rotation, 4) dominant soil in the polygon, identifying to which Official Soil Map (1:1M) unit the parcel belongs, and 5) topographic characteristics defining L and S in the USLE/RUSLE. This model was validated in the country in long-term experiments (Pérez-Bidegain et al., 2018). Using the identified information, an annual average soil erosion rate is estimated with USLE/RUSLE, using EROSION 6.0.20 (García Préchac et al., 2016), and must be presented to the authority demonstrating that it is below the tolerance officially established for the particular soil.

A certified Agronomist, contracted by the land tenant, prepares the technical report. To be certified, the Agronomist must pass a specific exam taken by the Faculty of Agronomy of the public University of Uruguay, working in agreement with the Ministry of Agriculture. The professional work of the certified Agronomists is reviewed by an ethical and technical board. Once the SUMP is presented, the General Direction of Natural Resources of the Ministry of Agriculture studies and verifies their implementation, using satellite images and other forms of remote sensing, visiting the field when irregularities are suspected, and contacting the responsible agronomists and farmers. If technical irregularities are found in a SUMP, the authority suspends the responsible agronomist certification. If irregularities are detected in the implementation, the land tenants (and eventually the land owners) can be fined, as previously mentioned.

Some key points to be highlighted are the following. A general law identifies the executive authority and the ones subject to prosecution. The authority can change the Technical Normative of soil conservation when needed via executive action. The procedure is based on punishment for the violations (regulations) and does not use monetary incentives. This system adapts to a variety of changes the country might experience including a climate more degrading to soils. A regional climate change study (Giménez et al. 2009), comparing trends and means of the period 1931-1960 vs. 1971-2000, found a 15 – 20% increase in precipitation, mainly during the summer. The countries of the La Plata River Basin, through its coordinator committee, developed a program for the strategic planning of the water resources management considering climate change; one of the studies focused on estimating future precipitation impact on the rainfall erosivity R factor of USLE/RUSLE (Soares 2015). Even though this modelling exercise was based on one regional scale model and only one RCP scenario (4.5), a 10% increase in rainfall erosivity is to be expected over the next 20 years. This change can be incorporated in the modeling systems used to evaluate farm management conservation performance.

Before requiring SUMP in 2013, there were three years of extension work and training for Farmers and Agronomists. It consisted of short courses, workshops, and field work on selected cases, including the study of antecedent information prior to visiting the field and evaluating the SUMP. This was a critical stage in the process, contributing to the results that are presented below.

2.4.1.1 Policy Results: Erosion Reduction

By February 2019 around 96% (14,000 km²) of the Uruguayan cropland for which a SUMP presentation and implementation was required had been filed with the official authority. In February 2019, 16840 SUMP were filed; 1625 of them had field visits. In 941 cases (5,6%)

normative violations were found. This is considered very successful relative to mitigating soil erosion and collateral environmental impacts caused by runoff.

Finally, the most important issue is that the required SUMPs are evaluated before use in the field, meaning that the policy has capacity to prevent use of soil degrading practices. As discussed, this approach ensures acceptable soil use and management practices based on available science and is adaptable to a changing climate. This science based proactive approach ensures Uruguay's soil resource will be preserved in the future. This approach was implemented two years before publication of the UN Sustainable Development Goals and the Voluntary Guidelines for Sustainable Soil Management (FAO 2017); the Uruguayan soil conservation approach resulted in the application of "best management practices" (see Pérez Bidegain et al. 2018), which are the foundation of achieving neutral land degradation and sustainable soil management.

2.4.1.2 Policy Results: Soils Organic Carbon (SOC) Content

Three long-term experiments in Uruguayan Argiudols, comparing soil use and management alternatives have been used to verify modeling predictions of different management systems impact on SOC. Their results indicate the practices that reduce soil erosion also favorably affect SOC. The oldest experiment started in 1962 in the Experimental Station INIA-La Estanzuela (34°20'12.31'' S and 57°41'08.14'' W). Soil is a Typic Argiudol, Silty Clay Loam, with an original SOC of 2.2 % in the 0-20 cm depth; site slope is 3.5%. Results during the period of CT soil management were reviewed by García Préchac et al. (2004), and after by García Préchac et al. (2017). The second experiment started in 1994 in the Experimental Station EEMAC, Faculty of Agronomy-Univ. of Uruguay (32° 23'40.13'' S and, 58° 03' 26.48'' W). The soil is a Typic Argiudol, clay loam, with an original 3% gravimetric SOC. The site differs from La Estanzuela in that its slope is less than 1%. Treatments are CC or CPR (3 yrs. crops-3 yrs. pasture),

combined with CT or NT. SOC content was determined at 0-15 cm depth after one rotation cycle of the CPR and discussed in two reviews (García Préchac et al. 2004, and García Préchac et al. 2017). The third experiment is in the Experimental Unit INIA-Palo a Pique (33°20'12.31'' S and 54°29'34.43'' W), in an Abruptic Argiudol, silty loam, with an original SOC of 1.7 % in 1995. The experimental area is 72 ha, with 6 ha experimental units (Terra and García Préchac, 2001). All soil is managed with NT. Soil uses contrasted are: 1) CC: annual winter oats and ryegrass directly grazed, and sorghum or moha in summer for silage or hay; 2) SR (short rotation): two years idem CC and two years pasture; 3) LR (long rotation): two years idem CC and 4 years pasture; and 4) PP (permanent pasture): regenerated natural pasture over seeded with perennial legumes. After 8 years, SOC and particulate organic carbon (C-POM, 53-2000 μm) were determined at the 0-15 cm depth (Terra et al. 2006). Results from these long-term experimental results confirmed modeled predictions for most management trials across locations thus providing a tool for determining cropping management system impacts on the soil carbon component of soil sustainability.

2.4.2 Crop-pasture Rotations - Resilient Agro Ecological Production Systems for Uruguay

According to Food and Agricultural Organization of the United Nations (n.d.) here are several definitions of *agroecology*, but all of them share the following elements: diversity, synergy, efficiency, recycling, resilience, co-innovation, human and social values, food culture and traditions, responsible governance, and solidarity and circular economy. Rotations of crops and pastures comply with most elements of agroecology, in addition to minimizing soil erosion and maintaining or increasing SOC. Crop-pasture rotations include plant and animal production, with variants for each, making them *diverse*. Symbiotic nitrogen fixation by pasture legumes increases nitrogen availability for the following crops, which is a *synergistic* element, as well as breaking

weed, pest, and disease cycles during the pasture period. These factors coupled with recycling management of nutrients such as phosphorous, provide *efficiency*. Grazed pastures *recycle* potassium; this nutrient is absorbed by roots of perennial pastures, generally deeper rooted than those of row crops, and during grazing, it is returned to the surface in animal droppings, and therefore not exported in the animal product. The greater SOC content in rotations, apart from improving soil physical properties and nitrogen availability, also favorably affects sulfur availability, a major nutrient provided by soil organic matter and a nutrient that has begun to show a response in continuous cropping systems. Because of their diversity, rotation systems are more *resilient* to changes due to climate or economic conditions associated with input prices or product prices. Crop-pasture rotations have been the product of research, transfer, and adoption by producers since mid-1960s. They had been the predominant production systems before the extraordinary soybean production increase at the beginning of the present century; that is, they are the product of *co-innovation*.

Commercial inputs in CPRs compared to CC are much lower (Ernst and Siri-Prieto 2009). No-till rotations, where pastures occupied 40% of the time and area, reduced use of nitrogen fertilizer, phosphate fertilizers, glyphosate, other herbicides, fuel and machinery field time by 44%, 46%, 42%, 50%, 48% and 48% respectively. Essentially no inputs are needed during the time pastures are present in the rotations. The combination of resiliency and reduced inputs further clarify the importance of this system in the face of a changing climate.

2.5 Loess Plateau region of China: Climate Challenge(s) and Adoption Strategies

The Loess Plateau region is located at the midpoint of the Yellow River in China (lat.34°-40°N and long. 110°-115°), covers an area of 640,000 km², and is globally unique because of its large area and depth of loess. It is a semiarid area with annual precipitation ranging from about 150

mm to 750 mm with an average of approximately 400 mm. The distinct seasonality of precipitation results in most of the rainfall occurring from June to September. Erosion in this region is one of the most significant environmental problems in China; it contributes 90% of the Yellow River sediment making the Yellow River one of the world's most sediment-laden river. In the last century, the Loess Plateau has been losing an average of 1 cm of soil each year. The environment here is fragile.

Agriculture in the Loess Plateau region developed early in its history beginning about 6,000 years ago. This area is one of the world's birthplaces of agricultural civilization. Soil erosion severity has increased in this region in the last half of the 20th century because of rapid population growth and the need for agricultural land; unfortunately, this increase has occurred with lack of proper management. Climate change, heat and drought covering this region, and increasing intensive precipitation events in some locations are the two most important future challenges (Sun et al. 2019; Zhao et al. 2018). These conditions threaten agriculture development and elevate the risk for intensive soil erosion events.

The Chinese government has prioritized soil and water conservation and agriculture in this region. A series of practices have been implemented and resulted in significant improvements in both environment and agriculture since late last century. The sediment load of the Yellow River decreased by about 90% in the past 60 years (Wang et al., 2016) and grain self-sufficiency increased to 105.25% (Shi et al., 2020). In the following paragraphs, we describe three of the most useful practices in this area including the "Grain for Green" program, terrace and check dam construction, and the integrated management of small watersheds.

2.5.1 "Grain for Green" Program

Aimed at both preventing land degradation and controlling Yellow River sediment, a series of afforestation programs in the Loess Plateau region and neighboring areas of China were implemented beginning in the middle of the 20th century, e.g., the "Three North" Shelterbelt Development Program (TNSDP), the Natural Forest Conservation Program (NFCP) and The "Grain for Green" program (GGP) (Zhang et al. 2016). Among these programs, GGP is recognized as the largest ecological restoration and rural development program in the world (Delang and Yuan, 2016) which involves 16 million farmers in 20 provinces (Wang et al., 2014). Farming steep slopes and overgrazing were two of the most important causes of land degradation in the Loess Plateau region. By GGP, steep sloping croplands (slopes of 25° or greater) were converted to native vegetation (trees or grassland, based on the water balance), thus minimizing or eliminating soil erosion and protecting the land and environment. The government compensated farmers for their loss of agricultural land.

The GGP has been very successful since being implemented in 1999 by the Chinese government. From 1999 to 2008, 33.3 million ha of land in the region was returned to forest and grasslands (including hills closed for afforestation) and the average vegetation coverage increased from 31.6% to 63.6% (Shan and Xu 2019). The greatest increase in vegetation coverage was found in the northern, central, and western Loess Plateau (Li et al. 2019), where soil erosion is most severe. Vegetation restoration driven by this land-use change significantly improved the ecological environment, which helped reduce floods and sediment transport. Soil carbon loss on the Loess Plateau was also reduced since it is mainly attributed to sediment transfer (99.6%) (Deng et al. 2019).

At the beginning of the GGP, people worried whether the large areas of cropland converted to native vegetation would threaten the food supply. Indeed, grain production fell in the first three

years of the GGP from 1999 to 2001. In the subsequent years, GGP was combined with improving comprehensive agricultural production capacity and developing high-quality farmland. Taking Wuqi county in the Loess Plateau as an example, 15,200 ha of new basic farmland was developed since 2003 resulting in crop yield increases from 870 to 2,820 kg ha⁻¹ from 1998 to 2014 (Wang et al. 2014). This agriculture success was gained with increased agricultural material input and construction of terraces and check dams to ensure food supply in this area is sustained (Shi et al. 2020), which is discussed in detail in the following paragraph.

2.5.2 Terrace and Check Dam Construction

The construction of terraces and check dams is primarily responsible for the sediment load reduction of the Yellow River (Wang et al. 2016). This practice also improves food security through creating fertile flat agricultural land (Shi et al. 2020) in the Loess Plateau Region. By 2018, 3.36 million ha of terraces had been built in the Loess Plateau region (Gao et al. 2020). Terraces increase rainfall infiltration, reduce surface runoff and soil loss, thus increasing crop yield and ultimately productivity. Check dam use in the Loess Plateau region began at least 400 years ago. In the past century, the most important two periods for check dam construction were 1968 to 1976 and 2004 to 2008. Prior to 2015, 56,422 check dams above the Tongguan station were constructed (Liu et al. 2018). Check dams, temporary structures designed across drainage channels, are effective measures for stopping coarse sediment transport to the Yellow River and was reported to be the dominant approach for sediment control in sub-catchments of this region (Da-Chuan et al. 2008). The agricultural landscape has been changed from sloping cropland to terraced and check dam-dominated farmland in many areas of the Loess Plateau region.

With climate change and more intense precipitation, management of terrace and check dams is becoming a daunting challenge in some areas of the Loess Plateau region. Terraces and check

dams can be seriously damaged by extreme rainstorms if not well managed, causing huge sediment loads from the damaged terrace and check dam farmlands. The efficiency of terraces and check dams in controlling soil loss was greatly reduced under extreme rainstorms. For example, in an extreme rainstorm of July 26, 2017, the sediment interception efficiency of the check dams was only 26.36% in one of the watersheds in the Loess Plateau, and most of the sediment was transported to downstream channels (Bai et al. 2020). The Chinese government is now paying more attention to improving the management and increasing the construction technology standards of terraces and check dams for both sediment control and flood safety. Experience indicates that it is important to combine these practices with other kinds of conservation measures to obtain satisfactory results, an approach called integrated management of small watersheds.

2.5.3 Integrated Management of Small Watersheds

Comprehensive prevention and control systems that combine engineering, vegetation, and agriculture technology measures in a watershed are proving to be more effective in soil loss control than single measures in many areas of the world. Management models for watersheds vary with different geographical factors and human activities. In the Loess Plateau region, this integrated management in small watersheds began in the 1950s with the establishment of five management modes based on experiments in 11 typical small watersheds. The five models include the eco-agriculture model, wood and grass model, traditional agriculture model, economic forest model, and agroforestry model. These models conserve soil; soil loss reductions of 50% - 90% were observed after 10 years of the practice (Liu et al. 2004; Wang et al. 2003). After more than 20 years, this approach developed into a more comprehensive and systematic model and began to be applied in regional-scale management. In the 1980s, the concept of "small

watershed integrated management" was introduced by Chinese scientists, taking a small watershed with a drainage area from 4 to 50 km² as a unit, and combining soil conservation measures inside the watershed. By 2012, more than 50,000 watersheds were enrolled in this integrated management practice in China and this became the primary approach for both environment and farmer income improvement in the Loess Plateau region and across China. A scientist named Zhu, Xianmo, who is one of the most famous and important soil conservation scientists in China, summarized the integrated management of small watersheds in the Loess Plateau region in 28 Chinese characters "全部降水就地入渗拦蓄，米粮下川上塬、林果下沟上岔、草罐上坡下坨" (Zhu 1991), which means "in the Loess Plateau we should try our best to have the precipitation infiltrate and stored, crops could be down at the bottom of the river valleys or go up to the plain plateau area, orchard should be planted in gully areas where water is not so limited, while on steep slopes especially without much water storage, grass and shrub should be the right choice."

After nearly 70 years, integrated management is playing a more and complete role in soil loss prevention. Even in extreme rainstorms, watersheds with well-integrated management schemes have avoided serious soil loss-related disasters. For example, for the 100-year return rainstorm of July 26, 2017, most of the check dams were undamaged and continue playing important roles in stopping sediment transport into the Yellow River from the Jiuyuan watershed, which is located in the most serious erosion area of the Loess Plateau. This success is attributed to grassland conversion across most of the steeply sloping croplands, terrace construction on many gentle slopes, and check dam construction the entire length of streams (Liu et al. 2017).

2.6 NE China Mollisol (Black Soil Region): Climate Challenge(s) and Adoption Strategies

2.6.1 Brief Introduction

Black Soils of Northeast China, located between lat.38°43'-53°33 'N and long. 115°31'-135°05'E, are considered the most fertile soil resource of China - perhaps the world (Liu et al., 2012). Black soils are of global importance because of their role in food security. Nearly one third of China's commercial grains are provided by the Black Soil region. However, interactions of geography, climate, and intensive farming have made the Black Soil region one of the most seriously degraded areas in China, threatening national food security and regional development. Black soil is described as China's giant panda of cultivated land, on one hand, it is scarce and valuable and on the other hand, it is vulnerable to human activity and climate change. For example, the geographic centroid of rice production shifted over 320 km northeastward during the past 30 years due to climate change (Hu et al. 2019). Crop yields may benefit from global warming due to effective accumulated temperature increases (Zhou et al. 2013); however, soil erosion rate has also accelerated due to more intense precipitation (Han et al. 2019; Liu et al. 2020). Additionally, the high soil organic carbon (SOC) content of black soils makes them a potentially large sources of greenhouse gases elevated temperatures and an increase soil organic matter oxidation.

With production pressure associated with increasing food demand and concurrent global warming stresses, black soils must be managed appropriately to maintain their productivity and mitigate climate change. Undoubtedly soil and water conservation measures are the top priority for adapting to a climate with more erosive rainfall events. Conservation tillage approaches, vegetation (e.g., shelterbelt, agroforestry), and engineering practices have been separately or jointly adopted to prevent soil degradation at different landscape scales in this area (Zhang and Li 2014; Deng et al. 2015). The combination of agricultural and forestry practices (e.g., Mountain-River-Forest-Farmland-Lake-Grass Protection and Restoration) are the leading

approaches for effectively retaining soil/soil associated carbon and concurrently capturing carbon in this landscape. As a consequence, climate-friendly agricultural practices in Northeast China will likely transition farmland from a greenhouse gas source to a carbon sink, which is an important component for China to achieve carbon neutrality by 2060.

2.6.2 Conservation Tillage

In China, the adoption of conservation tillage (CT) practices has been actively encouraged since 2002 following the recognition of increased soil degradation rates due to water erosion in Northeast China (Wang et al. 2007). After years of systematic research and demonstration, the CT farming system has been trusted as a sustainable approach to reduce soil erosion, increase water , increase resilience to drought, reduce soil carbon loss, and mitigate climate change. CT, which varies in its practice among regions in China, has been defined by the Conservation Technology Information Center (CTIC) in China as a tillage system that leaves a crop residue cover of at least 30% after crop planting (Kuhwald et al., 2018). According to the CTIC, in China, there are four main categories or types of CT practice (no-tillage, mulch tillage, reduced or minimum tillage, and ridge tillage). Ridge tillage and no-tillage are commonly adopted in Northeast China, sometimes combined with changing ridge orientation and/or size. Compared with the traditional narrow longitudinal ridge tillage, the relative soil conservation associated with wide longitudinal ridge tillage decreases with increased precipitation. For example, when $PI30$ (product of event precipitation P and maximum 30 min intensity $I30$) was around 500, the reduction of soil loss associated with wide longitudinal ridge tillage, compared to the narrow longitudinal ridge tillage, was as much as 90% and when $PI30$ was around 1,600, the reduction of soil loss by the wide longitudinal ridge tillage was as high as about 65%. While the relative effect varied with precipitation erosivity wide longitudinal ridge tillage maintains better soil

conservation effects than the narrow longitudinal ridge tillage system in the Black Soil region of China (Wang et al. 2019).

Compared with conventional tillage that leaves the field surface bare after harvest, chopping and returning 100% of the crop residue to the field surface can reduce soil loss more than 90% (Liu et al. 2020). Their field experiment found that subsoiling and returning crop residue and furrow damming worked more effectively than conventional tillage at reducing runoff and sediment losses - about 95% and 90%, respectively; meanwhile, the yield and the water use efficiency can be increased by about 25% and 30%, respectively, compared to conventional tillage (Wei et al. 2013). CT coupled with longer crop rotations could also positively affect crop yield and profitability. For instance, corn-soybean under NT produced better yield and profitability, particularly in dry years, than the three continuous years of corn or corn-corn-soybean rotations with conventional tillage (Wang and Zhang 2008).

Lishu County in the Black Soil region of Northeast China, one of the top five national grain production counties, is an eye-catching example of recent CT implementation and its soil conservation effects. During August and September of 2020, a series of three typhoons: Bavi, Maysak, and Haishen, brought heavy rain and strong wind to the Soil region within half a month, lodging crops and flooding fields. The average rainfall was as high as 170 mm, three times higher than the normal for the same period based on data since 1961. However, a 130,000 ha CT demonstration field of corn in this area still produced $13,500 \text{ kg ha}^{-1}$, with a 10% yield increase compared to conventional tillage. Over 14 years of CT, the soil organic matter content increased 1.68%, the corn rooting depth increased to 1.2 m, and more than 100 earthworms per m^2 were found in the plow layer, with earth worm tunnels extending half a meter deeper than observed for conventional tillage (Reporting Center of the Central Cyberspace Administration of China, n.d.).

Additionally, no-tillage promoted C accumulation within microaggregates which then form macroaggregates. The shift of SOC within microaggregates is beneficial for long-term C sequestration in the soil managed with CT (Zheng et al., 2018).

Given CT's noticeable ecological and economic contributions, many policies for CT have been launched by the Chinese government for the rapid expansion of CT, such as the latest Central Document issued in March of 2020 by the Ministry of Finance and Ministry of Agriculture, "Conservation Tillage Action Plan for Black Soils of Northeast China (2020-2025)". A clear goal was put forward that CT systems will be extensively implemented in the Black Soil region with an area reaching as much as 933,300 km² by the end of 2025, accounting for 70% of the arable farmland of Northeast China (Ministry of Agriculture and Rural Affairs of the People's Republic of China, n.d.).

2.63 Soil and Water Conservation Forests

Limited forest resources and a fragile environment make China's natural resources susceptible to soil erosion, water runoff, wind and sandstorms, floods, and droughts. To address these problems, China has implemented an afforestation program as a national policy and has made it one of the major components of ecological conservation and environmental restoration along with economic development (Zhang 2002). Several national forestry eco-engineering projects oriented towards soil and water conservation, environmental protection, and forest resource expansion have been conducted since 1978. Of which, the Three-North Afforestation Program (TNAP), scheduled to be completed in 2050, is the world's largest afforestation project and covers 4.07 x 10⁶ km² (42.4%) including Northeast, Northwest, and North Central China (Zhu et al. 2017). As one part of the TNAP, dense farmland shelterbelt networks in northeastern China have reduced water and sediment flows. For insistance, at the Keshan Farm, the mean soil

erosion rate and specific sediment yield (defined as the ratio of soil sediment to catchment area ($\text{t km}^{-2} \text{ yr}^{-1}$)) of the 25 reservoir catchments decreased from 351.6 and $93.9 \text{ t km}^{-2} \text{ yr}^{-1}$ under the modeled scenario without shelterbelts to $331.1 \text{ t km}^{-2} \text{ yr}^{-1}$ and $86.3 \text{ t km}^{-2} \text{ yr}^{-1}$ with the current shelterbelts. The sediment trapping efficiencies varied from 0.01% to 23.6% with an average value of 7.6% (Fang 2021).

The two shelterbelts (upper and lower) in the catchment reduced soil loss to a certain degree; sediment deposition usually occurred both above and below the shelterbelts, leading to less sediment delivery compared to that which existed before the shelterbelts were installed.

Conversely, erosion became severe below the shelterbelts as filtered water flowing through the shelterbelt exited on the lower side. In comparison to the lower shelterbelt, the upper shelterbelt with more gentle topography and lower slope gradient between the shelterbelt had higher sediment trapping efficiency. Impacted by the two lines of shelterbelts and the earth bank at the catchment outlet, the catchment resulted in an erosion-deposition-erosion-deposition pattern. In the recent 50 and 100 years based on model predictions, the sediment amounts annually deposited along the shelterbelts at distances of 30 m and 60 m contained 18.8% and 7 % of the total deposited sediment in the catchment, respectively. The sediment delivery ratios derived by ^{137}Cs and ^{210}Pb methods were 53% and 78%, respectively (Fang and Wu, 2018).

The shelterbelt system also plays an important role in the control of gully erosion directly or indirectly in rolling hills of the Black Soil region (Heshan Farm). With increasing slope gradient there was an inverse trend between gully density and shelterbelt density, indicating that farmland shelterbelts can prevent gully erosion. The positive effect of farmland shelterbelts against gully erosion varied with distance: for distances $<120 \text{ m}$ from the shelterbelt, the effect was consistent and very strong; for distances of 120–240 m, a weak linear decrease was found in the gully-

avoidance effect; and for distances >240 m, the effect of the shelterbelts was significantly weaker. A recommended optimal planting density of farmland shelterbelts for the prevention of gully erosion is 1100-1300 m km⁻² (Deng et al. 2015).

Shelterbelts increased maize yields 4.7 %, 4.3 %, and 9.5 % in the high, middle, and low climatic potential productivity zones, respectively (Zhu et al. 2017). In Northeast China, on average 18.3% of the farmland is protected by shelterbelts, which is obviously lower than the optimal level of protection (i.e., approximately 80 %), thus, many shelterbelts remain to be planted in the future (Zheng et al. 2016). It is important to note that some poorly designed windbreaks have accelerated soil loss.

Effective shelterbelts are mainly located in two geomorphology units: the convex position of the hill and the conjunction of two hill slopes. In the typical convex area, the new plan estimates that soil loss can be reduced 32.3 %, while in the typical conjunction area of two hill slopes, an estimated 48.4 % reduction in soil loss is expected (Su et al. 2013). The proposed scheme for optimizing the distribution of existing shelterbelts includes the adjustment of shelterbelt orientation such that they are perpendicular to the slope gradient, improved maintenance, planting of trees in shelterbelts to reduce open gaps, increase in shelterbelt number, and decrease distances between shelterbelts (Zhu et al. 2017).

2.6.4 Integrated Small Watershed Management

Soil and water conservation practices are one of the most important components of an integrated watershed program particularly for the rolling hill area in the Black Soil region. A Three Defense Lines control pattern is most commonly used in this area. The first defense line is the protection system established on the upper portion of the slope. An interception ditch and farmland shelter forest are arranged along the hilltop and road, which retain water from the slope thus avoiding

inundation of farmland below. The second defense line is the protection system set-up on the slope. Based on farmland slope gradient and length, appropriate methods are applied to conserve soil and water and to increase land productivity. If the slope $< 3^\circ$, level ridge tillage is used on the farmland; if the slope is $3-5^\circ$, a vegetation belt is planted on the slope; if the slope is $5-7^\circ$, a level terrace is constructed on the slope; and if the slope $> 7^\circ$, returning farmland to forest and grassland is preferred. The third defense line involves a protection system in the gully position. The recommended measures for preventing gully expansion from devouring farmland include constructing flow cascades on the gully head, building check-dams on the gully bed, reducing the slope of the gully wall and increasing gully vegetation, as well as terminating crop production on hillsides to facilitate afforestation (Sun et al. 2012).

Integrated small watershed management adheres to the principles of the Mountain-River-Forest-Farmland-Lake-Grass System of Ecological Protection and Rehabilitation Program, issued by the Ministry of Natural Resources, Ministry of Finance, and Ministry of Ecological Environment in 2020. This is the first program to emphasize the Community of Shared Life in ecological protection. It is a guiding principle for soil conservation, ecological restoration, and regional economic development. The concept of meta-ecosystem has been widely acknowledged by the farmers from Baiquan County of the Black Soil region, which was removed from the national-level poverty-counties list in 2020. A household doggerel “Shi Zi Deng Ke” is used to vividly summarize the measures and achievements of integrated small watershed management, “*Pinus Sylvestris* is planted on the slope top like a hat, *Lespedeza bicolor* is planted on the terraced ridge like a scarf, farmland is converted to grassland like a blanket, fish are raised in the ditch, ducks are raised within the dam, rice is cultivated outside the dam, fruit trees are planted in

the swales, shelterbelts are planted on the flat, making a united effort to open factories, and earn more money by comprehensive ecological management (Shuqing Wang and Jichang Su.1995).

2.7 Europe: Climate change and soil erosion

Globally, climate change is projected to increase severe storm intensity (Brooks, 2013), increasing runoff and decreasing infiltration in arable crops (Basche and DeLonge, 2017) which may cause even greater soil losses than that which occurred in the beginning of the 21st century (Borrelli et al., 2017). Therefore climate change has been addressed in the last decade in relation to increased soil erosion losses. The recent devastating catastrophic floods in Germany, Belgium and Luxembourg (8 July 2021) show that climate is changing faster than expected and is affecting mostly the northern part of Europe with higher intensity rainfalls. However, the excessive heatwave over Greece and South Italy with temperatures exceeding 45 Celsius degrees for more than 10 days (27 July – 6 August 2021) is another example of accelerated climate change on the European continent. In Europe, selected studies have addressed, and others are addressing, the impact of climate change driven intense rainfall on increased erosion. Among others, we reference certain studies in Belgium (Mullan et al., 2019), Greece (Grillakis et al., 2020), Austria (Luetzenburg et al., 2020).

Recently, important developments in climate change data addressing rainfall projections for the 2041-2060 period at highest requested spatial resolution (30 second) became available in the WorldClim database (Fick and Hijmans, 2017). This data were developed based on a large variety of 19 Global Climate Models (GCMs) across three Representative Concentration Pathways (RCPs) In addition, the Rainfall Erosivity Database at the European Scale (REDES) includes high temporal (hourly, sub-hourly) precipitation data and long-term erosivity values (Panagos et al., 2015) and it allows for the development of Gaussian Process Regression (GPR) models (Williams

and Rasmussen, 2006). The GPR model establishes a statistical relationship between the actual erosivity values of REDES and the rainfall records in WorldClim.

Compared to the first decade of the 21st Century, the rainfall erosivity is expected to increase in the range of 22-37% depending on the RCP scenario. Those are average values of the 19 climate model application for the whole European Union (EU) and United Kingdom (UK). In the most aggressive mitigation pathway scenario RCP2.6, the 22% increase of erosivity will result in a mean soil loss increase of 13% in the EU and UK with $\frac{3}{4}$ of the continent showing increasing trends while the rest a slight decrease (Panagos et al., 2021). Similar to the RCP2.6, the RCP4.5 will have the same trends and mean increases but somehow some different spatial patterns. Finally, the RCP8.5 projects a mean increase of rainfall erosivity of about 37% resulting in increase of soil losses close to 26% (Fig. 2.3). Therefore the mean soil loss in the agricultural lands of the baseline (2016) is about $3.07 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Panagos et al., 2020) and it is expected to increase to $3.76 \text{ t ha}^{-1} \text{ yr}^{-1}$ in the business as usual or least mitigation pathway scenario RCP8.5 in 2050. The results are in line with global projections of soil erosion developed by Borrelli et al. (2020).

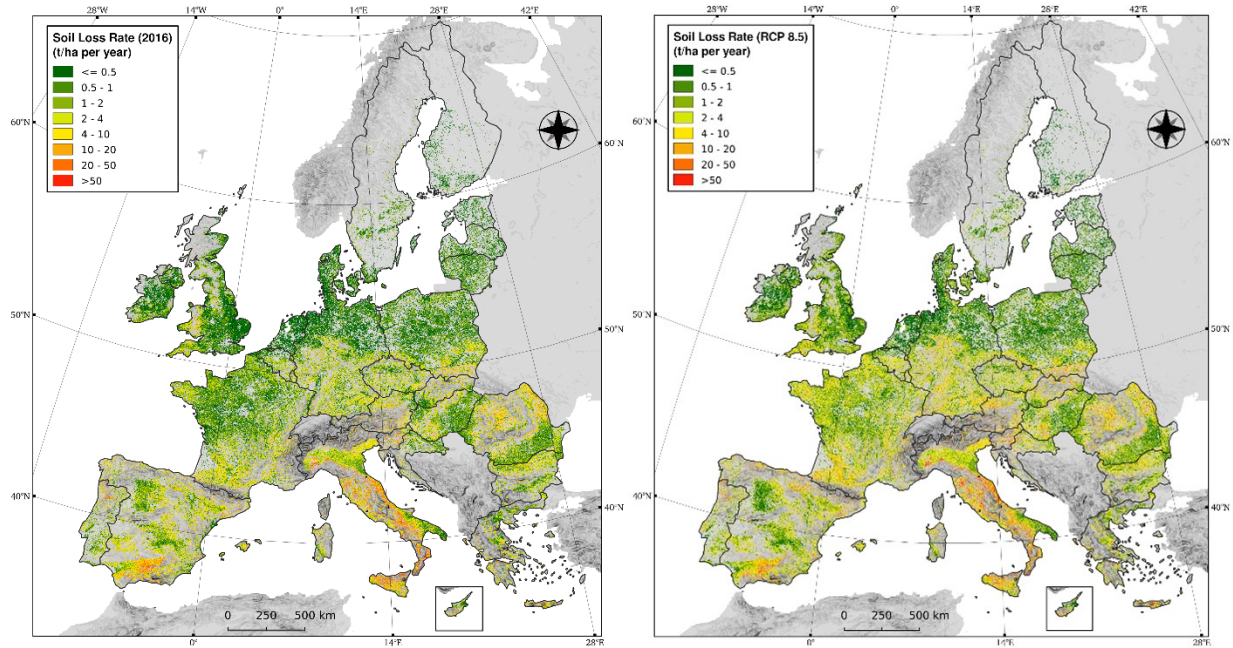


Figure 2.3 Soil loss by water erosion in agricultural lands of EU and UK for the baseline period (2016) and the future projections for 2050 (RCP8.5 scenario). Created by Panos Panagos.

2.7.1 Mitigation measures

Projected land use changes (conversion of arable lands to pastures) mitigate a small part of the climate change impacts on soil erosion. As the share of pastures will increase by 2% by 2050 and the share of arable lands will decrease by 2.1%, this may have a mitigation effect of decreasing soil losses up to 3% in the EU. This small portion needs to be reinforced with mitigation measures applied through agro-environmental policies in the EU. The most effective policy instrument is to link Common Agricultural Policy incentives to farmers with their environmental performance in a targeted way (Panagos and Katsoyiannis, 2019). However, the application of soil conservation measures such as cover crops and reduced tillage should focus in hotspots and should include at least 50% of the area with soil loss rates higher than $5 \text{ t ha}^{-1} \text{ yr}^{-1}$. Such an aggressive soil conservation policy may neutralize the future impact of climate change on water erosion.

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