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2. Global distribution and characteristics of black soils

2.1 Definition of black soils

Although "black soils" is a term used in some national soil classifications, which is influenced by the national linguistic specifics, there has been no consistent definition for black soils at the global level. In the WRB classification (IUSS Working Group WRB, 2015), the majority of black soils would correspond to Chernozems, Kastanozems and Phaeozems. Hovewer, other groups such as Vertisols, Fluvisols, Cambisolos and Anthrosols may fit the definition of black soils. In the United States of America and Argentina, black soils correspond to the Mollisols Great Order according to the United States of America Soil Taxonomy (USDA, 2014). Many other regional variants exist, such as in China, where the original name for these soils was "black soils", and they are now classified as "Isohumisols" in Chinese Soil Taxonomy. In Ukraine, these soil types are included in a group characterized a humus-accumulative type of soil formation, which is a great group of the Chernozems, assimilated to Russian Federation black soils or "black earths".

The harmonization of the definition of black soils is required to facilitate their sustainable management and international technical exchanges. In 2019, FAO and its advisory body, the Intergovernmental Technical Panel on Soils (ITPS), endorsed the definition of black soils as "black soils are mineral soils which have a black surface horizon, enriched with organic carbon that is at least 25 cm deep" (FAO, 2019).

Two categories of black soils (1st and 2nd categories) are recognized. The categories are distinguished to recognize the higher value, and thus greater need for protection, of some soils (Category 1), while still including a wider range of soils within the overall black soil definition (Category 2).

The 1st category of black soils (the most vulnerable and endangered, needing the highest rate of protection at a global level) are those having all five properties given below:

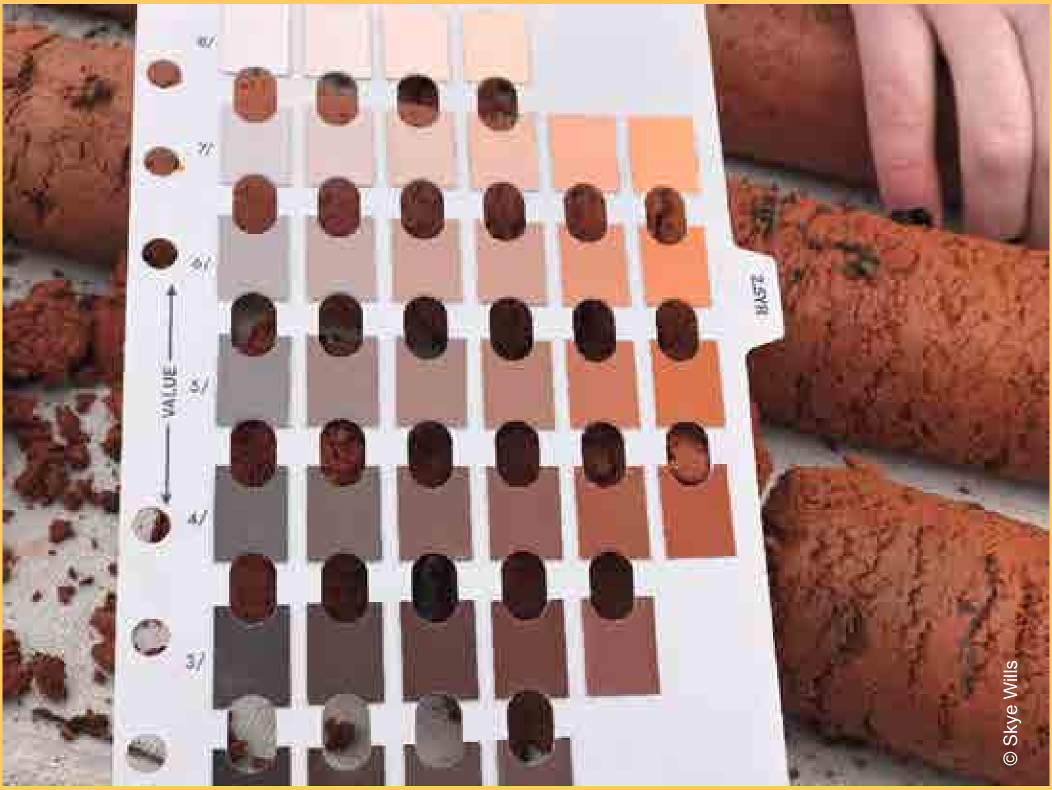
1. The presence of black or very dark surface horizons typically with a chroma of ≤3 moist, a value of ≤3 moist and ≤5 dry (by Munsell colours);
2. The total thickness of black surface horizons ≥25 cm;
3. Organic carbon content in the upper 25 cm of the black horizons of ≥1.2 percent (or ≥ 0.6 percent for tropical regions) and ≤20 percent;
4. Cation-exchange capacity (CEC) in the black surface horizons ≥25 cmol/kg; and
5. A base saturation in the black surface horizons ≥ 50 percent.

Most, but not all, 1st category black soils have a well-developed granular or fine sub-angular structure and high aggregate stability in the black surface horizons that are in a non or slightly degraded state, or in the humus-rich underlying horizon which has not been subjected to degradation.

The 2nd category of black soils (mostly endangered at the national level) are those having all three properties given below:

1. The presence of black or very dark surface horizons typically with a chroma of ≤3 moist, a value of ≤3 moist and ≤5 dry (by Munsell colours);
2. The total thickness of the black surface horizons of ≥25 cm; and
3. Organic carbon content in the upper 25 cm of the black horizons ≥ 1.2 percent (or ≥ 0.6 percent for tropical regions) and ≤ 20 percent.

6 | Global Soil Doctors Programme



Impact of restrictions of food exporters

Adapted figure from Food and Fertilizer Export Restrictions Tracker by David Laborde (2022)

Soil colour is a very useful indicator of soil quality because it can provide an indirect measure of other soil properties, such as organic matter content. Generally, black soils are associated with a high organic matter content which is what gives soils their dark colour. These soils are rich in organic carbon (0.6 to 20 percent) in the upper 25 cm of the black horizons (FAO, 2019). The most commonly used method to determine the colour of soils is through the Munsell Table. It classifies soils based on three attributes: hue (the dominant colour of the soil), value (the lightness or darkness of the soil colour), and chroma (the intensity or saturation of the colour) (Zhang *et al.*, 2021b). For example, the presence of black or very dark surface horizons is typically found with a chroma of ≤3 wet, a value of ≤3 wet and ≤5 dry (according to Munsell colours) (FAO, 2019). Another method for assessing soil colour is found in the FAO Global Soil Doctors Programme's "Methods of Soil Analysis" document (FAO, 2020). This document contains a list of easy-to-use, low-cost soil testing methods that can help assess soil condition directly in the field. The method consists of: 1) sampling: one sample from the field, the second under the nearest fence or similar protected or undisturbed area; and 2) comparison: the relative difference in colour of the soil samples to identify the relative change in soil colour that has occurred.

2.2 Creation of a global map of black soils

Digital soil mapping (DSM) is the computer-assisted production of digital maps of soil type and soil properties by use of mathematical and statistical models that combine information from soil observations with information contained in explanatory environmental variables. DSM has been largely applied to predict the distribution of soil types (Chaney *et al.,* 2016; Holmes *et al.,* 2015; Nauman and Thompson, 2014; Bui and Moran, 2001). The advantages of DSM with respect to alternative methods are that the mapping process can be documented, it can be easily modified and updated if necessary, and the prediction uncertainty can be estimated.

In the process of creating the global map of black soils, every country member was responsible for producing its own black soil map and a bottom-up, country-driven approach was followed to define the global coverage of black soils. A similar experience was successfully implemented for the Global Soil Organic Carbon map (GSOCmap) done by FAO (FAO, 2017), and therefore, a similar approach was implemented in this case.
The goals of this section are to describe the DSM approach implemented for mapping black soils at country level and summarize black soil products of member countries. Some countries could not follow the methodology proposed due to a lack of up-to-date verified soil survey samples to cover the whole country territory, and instead they have presented a first version of what they considered to be the area covered by black soils.

2.2.1 Data collection process

The 2nd category black soils for mapping purposes were used for the global map. In order to map their distribution, a digital soil mapping framework was applied (Figure 2.1).

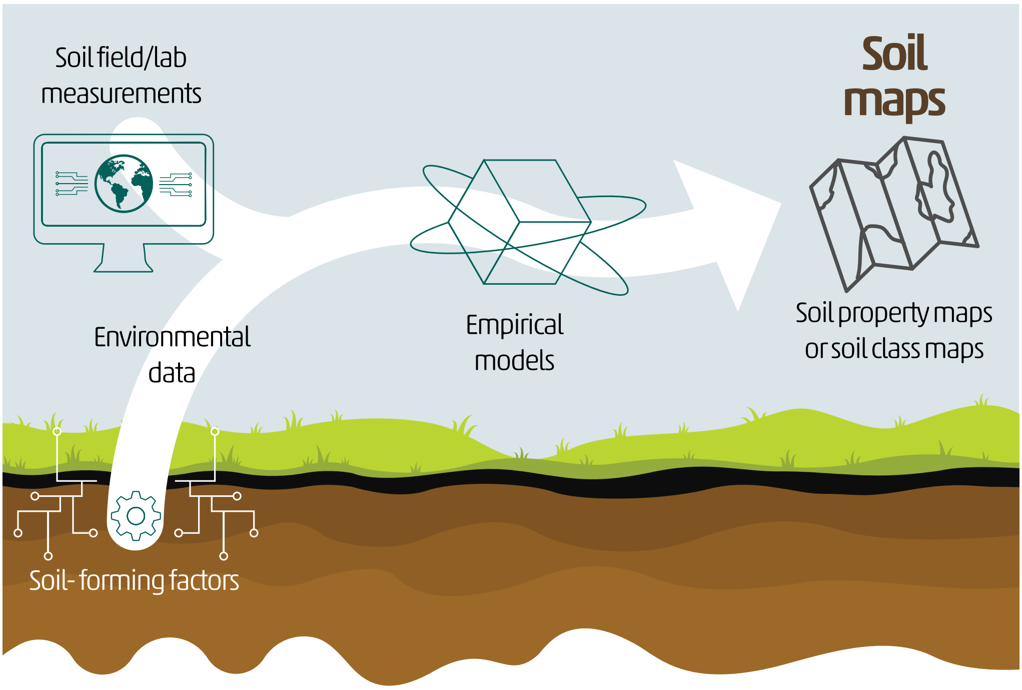


Figure 2.1 General framework of digital soil mapping (DSM)
Source: Authors' own elaboration

In DSM, soil data from lab measurements and field observations were combined with environmental data through empirical predictive models to spatially interpolate target soil properties and soil classes. Ideally, soil data is available at point locations. When this is not the case, classical polygon-based soil maps can be used as an information source. Additional environmental data are also used, which are meant to represent or to be proxies of soil-forming factor, and helping to represent the spatial variation of the target soil property. This additional data usually includes terrain attributes, such as digital elevation models, slope, terrain curvature, etc., remote sensing data from different missions, such as Landsat, Sentinel, MODIS, etc., climate data (locally or globally available), as well as other maps, such as legacy soil maps, geological maps, and land use maps, etc. With regards to empirical models, there are a wide range of options depending on the nature of our target variable(s) (qualitative or quantitative) and the type of product that we want to obtain. Nowadays, one of the most common methods applied in DSM is Random Forest (Breiman, 2001), as well as many other machine learning algorithms (Hothorn, 2022). The resulting soil maps are generally raster maps of the most probable soil property value or soil class together along with an uncertainty map that indicates the level of confidence of the primary product.

2.2.2 National maps

Figure 2.2 shows the workflow for mapping the distribution of black soils at country level using the DSM approach. For this case, we assume that soil profiles with geographical coordinates are available in the study area.

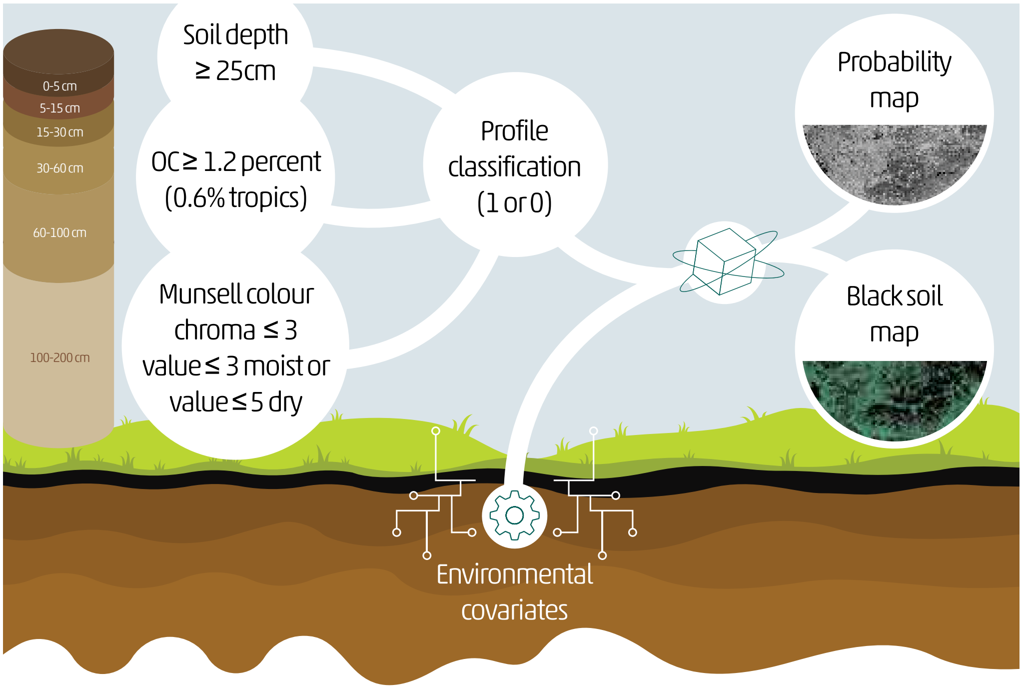


Figure 2.2 Workflow for mapping black soils
Source: Authors' own elaboration

First, we classified the soil profiles into black soils (1) or non-black soils (0) based on the soil horizons/layers to 25 cm depth. Black soils had Munsell colours of these horizons that had chromas ≤ 3 and values ≤ 3 moist or value ≤ 5 dry. These horizons in black soils also had to have concentrations of organic carbon higher or equal to 1.2 percent (0.6 percent OC in tropical soils). If a profile was within these thresholds, then it was classified as a black soil (1), otherwise it was a non-black soil (0). Second, we prepared environmental covariates that covered the whole study area (or country). Environmental covariates included climate data, vegetation data, and terrain attributes. Other covariates, such as national geology maps and soil maps, etc., could be included. A rich source of covariates is the OpenLandMap project (OpenLandMap/global-layers, 2022). Third, we applied a Random Forest model. Random Forests is a regression and classification decision tree approach widely used in DSM. Random forests include hyper parameters that must be optimized before calibration. Accuracy was measured using 20 times 10-fold cross-validation and confusion matrices. Overall accuracy and class-accuracy were reported. Finally, the model was used for prediction at 1 km resolution. Both the probability map and the categorical map of the black soil distribution were generated (OpenLandMap/global-layers, 2022).

Some countries were not able to follow the proposed methodology because of a lack of data, and instead provided polygon-based soil maps where black soils were present, based on the large scale soil survey or expert knowledge. This is the case for Bulgaria, Slovakia and Indonesia. The Russian Federation provided a polygon map with expert knowledge input where they indicated the probability of having black soils at each cartographic unit. Thailand and the Syrian Arab Republic also provided polygon maps, but we did not include them within the global map because the scales were too small.

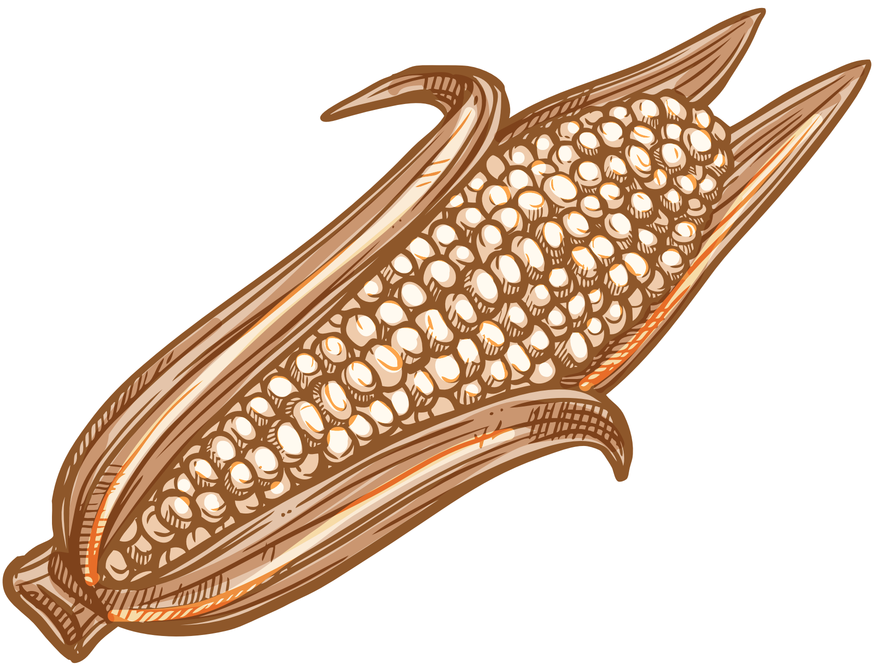
2.3 Global map of black soils

National maps of black soils provided by the country members were used to extrapolate probability values at global scale. A total of 30 000 random locations were allocated spatially based on three main thresholds: 1) 10 000 samples were randomly distributed on pixels with probability less than 0.2; 2) another 10 000 samples were equally distributed along pixels with probability between 0.2 and 07; and 3) and another 10 000 samples were randomly distributed on pixels with probability greater than 0.7. Next, we gathered 41 globally explicit and openly available environmental variables. The majority of them came from OpenLandMap project (OpenLandMap/global-layers, 2022), including the probability of USDA soil orders (Mollisols, Vertisols, and Andosols), clay percentage map at 10 cm depth, pH map at 10 cm depth, snow coverage, monthly maximum temperatures, mean annual precipitation, cropland area, terrain attributes (slope and wetness index, among others), and land cover. Other sources of variables were Google Earth Engine, from which seasonal land surface temperature mean and standard deviation were extracted; the same method was applied to NDVI; and elevation at 1 km resolution was estimated using MERIT DEM.

A random forest model using recursive feature elimination was trained and used for prediction. Among the most important predictors were GSOCmap, terrain wetness index, land surface temperature, NDVI, clay percentage at 10 cm, precipitation, and maximum temperature. Detailed information about the methodology and results will be provided in the forthcoming GBSmap technical report.

The country maps that were used to produce the global map were of two types: probability maps (Argentina, Brazil, China, Colombia, Uruguay, Mexico, United States of America, Canada, Ukraine, and Poland) or detailed polygon maps (Bulgaria, Slovakia, Indonesia, and the Russian Federation)

The global map that resulted from this process is the first to give a global overview of the distribution of black soils (Figure 2.3). Black soils are found mostly in eastern Europe, central and eastern Asia, and the northern and southern hemispheres of the Americas. Table 2.1 depicts the top ten countries in terms of black soil areas, which together account for 93.4 percent of the total black soil area. The overall area of black soils is 725 million hectares, with the Russian Federation, Kazakhstan, and China accounting for more than half of it. The Russian Federation has by far the largest black soil area, with 327 million hectares accounting for 45 percent of the overall black soil area.



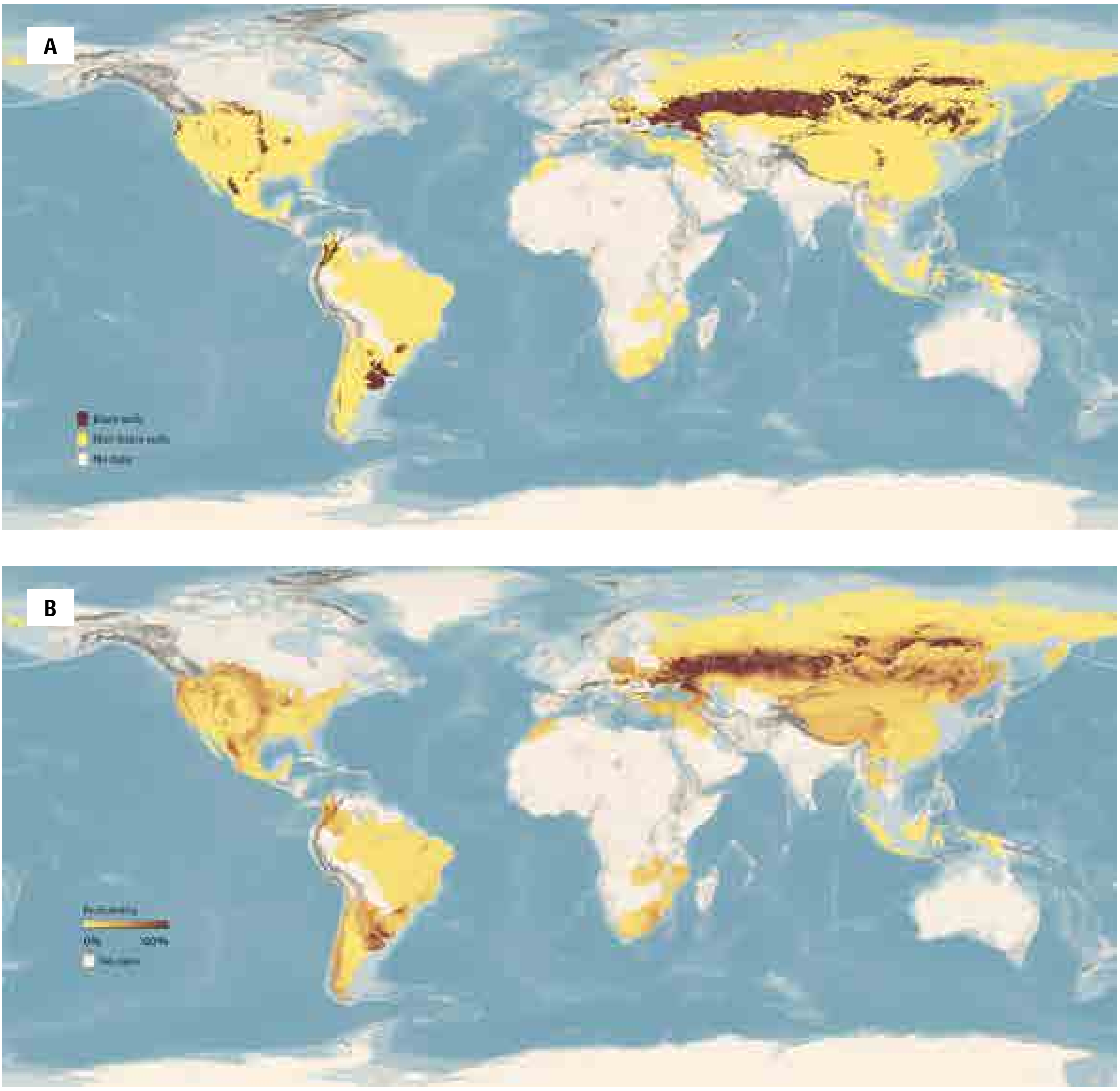


Figure 2.3 Global Black Soil Distribution map (GBSmap)

(A) categorical map showing areas with more than 50 percent probability of being black soils;
(B) continuous map showing the probability distribution of soils being black soils
Source: Authors' own elaboration

Note: The designations employed and the presentation of material in the map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.

Table 2.1 Top ten countries with the largest black soil areas

Country	Black soil area (million hectare)	Country area (million hectare)	Black soil proportion (percentage)
Russian Federation	326.8	1700.2	19.22
Kazakhstan	107.7	283.9	37.93
China	50	934.6	5.35
Argentina	39.7	278.1	14.28
Mongolia	38.6	156.5	24.67
Ukraine	34.2	60	57.01
United States of America	31.2	950.1	3.28
Colombia	24.5	113.8	21.54
Canada	13	997.5	1.30
Mexico	11.9	196.4	6.04

Source: Authors' own elaboration

2.3.1 Human use of black soils

We can assess population distribution in black soil areas using the gridded population of the world map (CIESIN, 2018) (Table 2.2). According to this, the Russian Federation has the largest number of individuals living on black soils (68 million inhabitants). Kazakhstan has the second largest area of black soils in the world, with about 108 million hectares, yet it is modest in terms of its population (8 million people). With about 30 million people, China and Colombia are the countries with the second-largest populations living on black soils. While this is a minor percentage of China's population, 32 million people is an important proportion for Colombia (almost 50 percent of its population).

Table 2.2 Land cover and population in black soils

	Black soils	World	Percentage
Area (million hectare)	725	12 995	5.58
Cropland (million hectare)	227	1 308	17.36
Forest (million hectare)	212	4 496	4.72
Grassland (million hectare)	267	3 129	8.52
Population (million people)	223	7 788	2.86

Source: Authors' own elaboration

According to the land cover distribution, black soils are covered by 227 million hectares of cropland, 267 million hectares of grasslands and 212 million hectares of forests at global level. Black soils cover 5.6 percent of the global land area, are home to 2.86 percent of the global population, and have 17.36 percent of cropland, 8.05 percent of global SOC stock and 30.06 percent SOC stock of global cropland. These proportions, howeve vary between FAO regions (for example, Asia has approximately 50 percent black soils under grasslands, and North America has 54 percent of black soils that are under cropland).

At a global level, approximately one third of the black soil area is used as croplands, which represents 17.4 percent of the global croplands (Zanaga *et al.,* 2021). The distribution varies within each region.

From the total cropland in black soils, Europe and Eurasia account for 70 percent, while North America, Latin America and Caribbean, and Asia share ten percent each. This is of great significance for European and Eurasian agriculture, which represents 160 million hectares.

Despite representing a small portion of the world's soils, black soils feed the global population. They not only sustain people settled on them but also the rest of the world through exports. Key for food security and the global economy, a significant share of oilseed, cereal, and tuber crops is cultivated in black soils. Globally, in 2010, 66 percent of sunflower seeds, 30 percent of wheat and 26 percent of potato outputs were harvested from black soils (Figure 2.4).

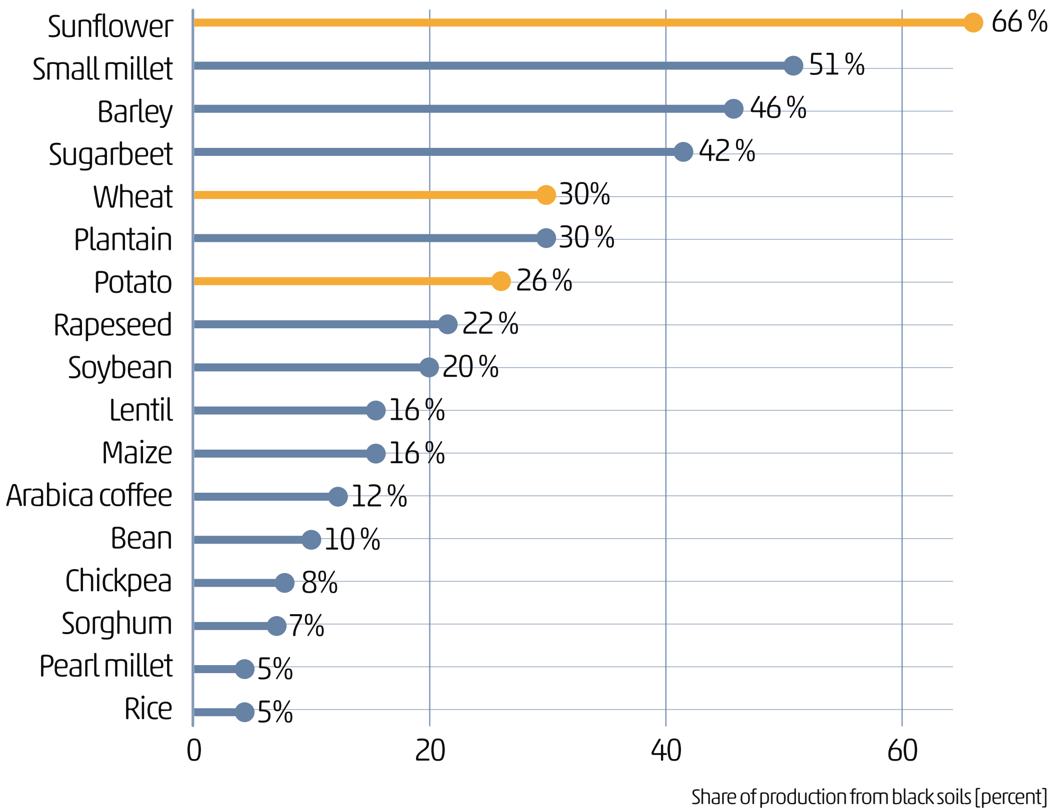


Figure 2.4 Global share of crop production directly attributable to black soils

The shares were derived by intersecting the GBSmap with the "Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0", International Food Policy Research Institute, 2019. Results for crop shares under 5 percent and for aggregated crop types were excluded from the analysis. **Source**: Authors' own elaboration

According to the land cover map of the ESA WorldCover (Zanaga *et al.*, 2021), there are 212.3 million hectares of forested black soils, which is 4.7 percent of the world's forests. The Russian Federation is by a large margin the country with more forests in black soils, with 142.9 millions hectares, which representing 15 percent of the Russian Federation forest lands. Colombia (18.5 million ha), China (12.7 million hectares) and the United States of America (7.1 million hectares) have the next three highest percentages.

The updated version of Hansen Global Forest Change v1.9 (Hansen *et al.*, 2013) reported that the forest loss in black soils has been 27.9 million hectares between 2000 and 2021 (FAO, 2022a). Forest loss has occurred mainly in the Russian Federation (20 million ha), but other countries such as the United States of America, Brazil and Argentina also registered important forest loss. The three countries account for 4.6 million hectares evenly distributed.

2.3.2 Soil organic carbon content of black soils

Soil organic carbon between 0 to 30 cm depth has been estimated at 677 Pg worldwide (Pg = 1 billion tonnes) (Table 2.3) (FAO, 2017). Nine percent of this total is in black soils. Note that about 23.9 percent of SOC stock of Europe is in black soils, 9.7 percent for Latin America and Caribbean, 3.9 percent for North America and 8.7 percent for Asia.

Table 2.3 Total and cropland soil organic carbon stocks and potential carbon sequestration rates associated with black soils

	Black soils	World	Percentage
SOC stock (PgC)*	56.0	677	8.21
Cropland SOC stock (PgC)**	18.89	62.8	30.06
Potential SOC sequestration (PgC/year)	0.029	0.290	10.11

Notes:
*GSOCmap (FAO, 2017)
** Based on WorldCover map (Zanaga *et al.*, 2021)
*** Based on GSOCseq product (FAO, 2022c), scenario of ten percent increase in C inputs
Source: Authors' own elaboration

Potential SOC sequestration differs significantly between countries. In Europe, most of the total SOC potential sequestration remains in black soils. The Russian Federation, Ukraine and Kazakhstan could capture about 14 million TnC/year in black soils.

In Argentina, Colombia and Uruguay, a large proportion of their potential SOC sequestration is in black soils. In Asia, Mongolia accounts for 80 percent of the total potential SOC sequestration in black soils, while the same ratio only reaches 10 percent in China (FAO, 2022a).

7 | Standard operating procedures to determine soil organic carbon

The Global Soil Laboratory Network (GLOSOLAN) was established in 2017 with the aim purpose to strengthen the capacity of laboratories in soil analysis and promote the harmonization of soil analytical data with the goal for soil information to be comparable and interpretable across laboratories, countries and regions (FAO,2022b). GLOSOLAN actually amounts for 700 labs worldwide, distributed in Regional Soil Laboratory Networks (RESOLANs) for Asia (SEALNET), Latin America (LATSOLAN), Africa (AFRILAB), the Pacific (ASPAC), Europe and Eurasia (EUROSOLAN) and the Near East and North Africa (NENALAB). As part of its main activities, GLOSOLAN developed globally harmonized standard operating procedures (SOPs) for known soil analysis methods. For example, the SOP to determine total carbon is the Dumas dry combustion method, and to quantify soil organic carbon (SOC), while the corresponding SOPs are the Walkley-Black method (titration and colourimetric method), and the Tyurin method (spectrophotometric method). Soil carbon is probably the most important component of soils, as it affects almost all soil properties. In black soils, SOC estimation represents a major indicator for their definition and for better understanding their health. Black soils contain 8.2 percent of the world's SOC, and their potential SOC sequestration is 10 percent of the global potential (FAO, 2022a). It is important to have SOPs that help us ensure the replicability of a measurement and the accuracy and traceability of the data.

2.4 The nature of black soils

Black soils are present on all continents. Under its strict definition, black soils have developed preferentially on prairie vegetation with grasses. However, in its expanded definition, black soils appear with other types of vegetation, such as woodland and wetland. They even appear with parent materials with expandable clay minerals, giving rise to Vertisols.

Black soils are named for their colour, organizing in the process of melanization and accumulation of organic matter. This is often due to with a chemical medium rich in bases and with high biological activity. Despite their high original fertility, many black soils have lost it due to the high pressures of agricultural and pasture use.

The degradation suffered is generalized. The most identified processes have been erosion by water and wind, acidification, lack of plant nutrients and worsening of soil physical-hydraulic quality. Most of this degradation is reversible only with the adoption of good management practices. However, soil loss due to erosion is irreversible and affects millions of hectares in South America and China, among others.

The implementation of recovery or restoration practices depends a lot on the good governance of the soil and the availability of resources. This limits recovery practices such that they are not carried out in all the affected countries, but mostly in developed countries. The problem is that as most of the food insecurity occurs in the poorest countries, not in the developed countries with available resources for recovery. This is the main challenge for monitoring and management – not only of the black soils – but of all the productive soils of the world.

2.4.1 Black soils of midlatitude grasslands

The most abundant area of distribution of deep black soils is associated with the midlatitude grasslands, the areas where Chernozems, Phaeozems, and Kastanozems occur (note that throughout this chapter WRB taxonomic classes are used unless otherwise noted). Deep black soils are developed in temperate or subtropical climates where precipitation is distributed more or less equally throughout the year. The black colour is a result of a accumulation of organic matter originating from numerous dying roots of gramineous vegetation in a process known as melanization (Bockheim and Hartemink, 2017; Rubio, Lavado and Pereyra, 2019)

Black soils may also penetrate to more humid and cooler landscapes where grassland is interspersed with forests. These soils of steppes, prairies, and pampas are the most widespread archetype of black soils.

Black soils cross the Eurasian continent from Austria in the west to Manchuria in the east, mostly between the latitudes of 45 and 55 N under temperate steppe vegetation. In North America, due to the specific gradient of temperature and mean annual precipitation, black soils under grass vegetation (prairies) form a broad band crossing the continent diagonally from northeast Mexico to the southwestern part of Canada flatland. In South America, black soils occupy extensive areas in pampa in Argentina and Uruguay, forming under warmer and more humid conditions than in the northern hemisphere, although the biome is close in appearance and functioning to the more temperate steppes and prairies. Currently it is agreed that black soils under grasslands accumulate significant amounts of humified organic matter because of the peculiarity of the biological cycling in these biomes, where a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significant part of biomass is represented by easily decayed fine roots and soil biological activity is high.

Black soils of midlatitude grasslands are the most extensively cultivated soils in the world. In Europe, Asia and North America, a major part of these soils is used as arable land for producing wheat, corn and soybean. In South America, in contrast, the area with black soils is used for pastures and agriculture. In all the continents, practically the entire area is used for agriculture, and only minor nature protection areas have virgin black soils under natural grasslands.

Apart from being highly productive lands, the black soils of midlatitude grasslands are responsible for multiple ecosystem services such as water retention, maintaining biodiversity both of soil organisms of various sizes, and animals inhabiting tall grass ecosystems. Grassland black soils of grasslands are the most important pools of carbon among the soils, although endangered by the processes of organic carbon loss due to the accelerated humus oxidation under cultivation. In many places, the loss of humus and nutrient mining are the most important threats to black soils because these soils are considered as highly fertile "by nature" and thus do not need application of organic and mineral fertilizers. The other common threat is soil compaction due to the use of heavy machinery and consequent water erosion of over-compacted soil. Wind erosion is also a big problem (such as the infamous dust storms in the 1930s that tremendously affected the Midwest of the United States of America and the problem in west Siberia and north Kazakhstan in the USSR during the development of virgin lands in 1950s). Currently, soil salinization is a growing problem, especially in irrigated areas in the most arid parts of the distribution of black soils.

8 | Black soils in Ukraine

Black soils in forest steppe of Ukraine, Solovei Vadym

Black soils distributed on the territory of Ukraine include a group of soils in grassland. They have an important common feature which is a high content of organic matter, which led to the formation of saturated dark (from dark gray to black) topsoil. In the grassland, black soils are represented mainly by Haplic Chernozems, which are found on low-lying plateaus and high loess terraces. In the past, these areas were represented by steppe meadows and meadow steppes. The soil cover of the northern steppe is represented mainly by Haplic Chernozems, which were formed under the herbaceous-fescue-feathergrass steppes. The diversity of soils is associated with an increase in aridity in the subzone from north to south, which led to a decrease in the thickness of the humus layer, carbon content in the topsoil, depth of accumulation of carbonates, gypsum, and water-soluble salts. The southern steppe is dominated by Calcic Chernozems (Tonguic), formed under fescue-feather steppes in arid climates. The main component of the soil cover of the dry steppe are Kastanozems. In the Carpathians and the Crimean Mountains black soils occur sporadically, in the first tier of vertical zonation. Degradation of black soils in grassland is caused by unreasonable economic activity, especially in the context of global warming and under the influence of agrochemical pollution. As a result, most of the territory of black soils especially in grassland should grow environmentally friendly agricultural products (Boroday, 2019), which is of direct importance to society.

2.4.2 Black soils of floodplains and wetlands

Another widespread variety of black soils is represented by soils of floodplains and wetlands. On floodplains, the dark colour is due to excessive soil moisture that hinders mineralization of organic residues and to the continuous input of fine organic particles transported with water. In wetlands, the black colour of the topsoil layer reflects the presence of incompletely decomposed plant material under anoxic conditions. This black material has much in common with dispersed peat or mud. These black soils commonly have excessive moisture content that makes the management of such soils difficult, requiring drainage to be used in agriculture. However, it should be noted that the drainage of these soils threatens key ecosystem services, such as carbon stocks, biodiversity, and water filtering and quality (Wang *et al.,* 2015). These soils are classified mainly as Mollic Gleysols, and those soils formed on the floodplains and tidal marshes also may receive the qualifier Fluvic. If the percentage of organic material is high, such soils may be classified as Histic Gleysols, but the topsoil consists mainly of clayey mud rather than of recognizable plant debris.

The exact area covered by wetland black soils is difficult to estimate, because these soils commonly do not cover extensive areas and thus seldom appear on small scale maps. The specific feature of these soils is that they are practically ubiquitous and may be found practically in every climatic zone, though most of them are typical for humid and subhumid areas. Unlike these difficult-to-map wetland soils, in Argentina these black soils cover 12 million hectares in huge continuous flood plains also affected by salt and sodium excesses (Rubio, Lavado and Pereyra, 2019).

The black soils of floodplains and wetlands can support highly productive meadows. For example, in the northern taiga zone, such soils are the most important land resources for producing forage for livestock. Beyond feed production, wetland black soils are important habitats for maintaining biodiversity. The reduction of the wetland area is responsible for the loss of biodiversity of birds, mammals, insects and fish worldwide. The black soils of the floodplains commonly have good water-holding capacity and thus play an important role in water regulation and prevention of floods.

Carbon stock in wetland black soils vary in a wide range. In some of these soils humus penetrates to a depth of more than 1 metre, and the total carbon reserves may be even higher than in deep Chernozems (O'Donnell *et al.,* 2016). Due to reductive conditions, at least for some period of the year, these hydromorphous soils serve as a sink for atmospheric carbon. However, some of these soils may produce methane which is released into the atmosphere and has a negative impact on atmospheric greenhouse gases concentration. Draining of wetland black soils can provoke a dramatic loss of soil organic carbon and consequent discharge of climatically active gasses to the atmosphere.

9 | Black soils in the Chinese wetlands

Intensive rice cropping system in Sanjiang plain of China, 2011

Rapid and periodic assessment of the impact of land cover changes on ecosystem services at regional level is essential to understanding services and *sustainability* of ecosystems in black soils. For example a quantification and assessment of the changes of multiple ecosystem services was conducted in the black soil wetland in Sanjiang plain of China throughout land cover changes over the period from 1992 to 2012. This region is important for its large area of natural wetlands and intensive agriculture. The result has confirmed trade-offs between ecosystem services and negative consequences to environment in this black soil region. The trade-offs were typically manifested by increased water yield and significantly increased *food production*, which is in contrast with significant losses in ecosystem carbon stocks and suitable waterbird habitats, mainly due to the conversion of land cover from wetland to farmland. This finding implies that *land use planning* and policy making for this economically important black soil region should take ecosystem service losses into account in order to preserve its natural ecosystems in the best interest of society.

Swelling black soils are also an abundant soil group, which is widespread from tropics to temperate areas under alternating dry and wet conditions. Shrinkage of these soils in dry seasons and their swelling in the rainy season is due to their specific mineralogical composition of clays with the predominance of smectites. Most of these clayey soils are black, though the organic carbon content is not very high. Their dark appearance is due to the presence of humus-clay complexes that have grey to black colour. These soils are classified as Vertisols. These soils are well-known over the world and practically every traditional soil classification has a special name for such soils, reflecting their particular physical properties. The list of vernacular classification for compacted black soils includes almost 100 names worldwide (Krasilnikov *et al.,* 2009).

Swelling black soils are widespread in lowlands and valleys under the tropical and subtropical climates with contrasting dry and moist seasons. The most extensive areas may be found in Australia and India, with smaller areas on the plains around the Gulf of Mexico in North America and in Uruguay, Northeast Argentina and south Brazil in South America. Minor areas may be found in temperate areas, including central, eastern and western Europe. Most of these soils form in lacustrine and marine sediments, but also in tropical areas there are Vertisols derived from smectite-rich products of basalt weathering. Also, in places Vertisols may form volcanic glass in toposequences together with Andosols.

Although hardening and cracking of Vertisols in dry seasons may cause problems in their management, these soils are considered to be productive in tropical and subtropical regions compared to strongly weathered Ferralsols and Acrisols. In India, their technical name in the nineteenth century was "black cotton soils" that indicating their importance for producing fibre.

Swelling black soils typically avoid water erosion because of their location in the lowlands. Their packed structure also prevents them from wind erosion. However, by nature these soils are vulnerable to shrinkage and cracking. Specific physical soil properties (swelling and cracking) cause troubles not only for their agricultural management, but also for road and civil engineering (Chen, 2012; Mokhtari and Dehghani, 2012).

10 | Argentinian Vertisols

Native vegetation of the southern Mesopotamian region for low-input livestock production (Entre Ríos province, Argentina), and the corresponding soil profile (Hapludert)

In Argentina, swelling black soils (Vertisols), are found in various regions, but they are particularly relevant in the southern part of the Mesopotamian region, and in the eastern part of the Pampean region. Vertisols can also be found in restricted areas of the Argentine Chaco and the Patagonian region (Moretti *et al.,* 2019). The parent material of Vertisols of this region, as well as of associated vertic Luvisols and Phaeozems, is made up of sediments of silty-clay or clay-loam textures, with a predominance of smectites in its clay fraction and quartz in the coarse fraction, and with a considerable proportion of calcium carbonate, some gypsum and manganese and iron oxides segregations. These soils are mainly devoted to mixed crop-livestock production, though a small proportion is used to grow rice. In recent years, soybean growing has taken over these soils. Because of their low permeability, undulating relief, and summer rainstorms, these soils are prone to erosion. No-till and contour-line cultivation are now widely used to mitigate erosion problems (Cumba, Imbellone and Ligier, 2005; Bedendo, 2019). More information is in Annex I (Section A.4.1)

2.4.4 Volcanic black soils

Volcanic black soils are a less well understood group of soils where black colour does not correspond well with the current climatic conditions. Black soils on volcanic ash may be found both under grassland and forest vegetation. Recent studies disapproved the hypothesis that in the black colour reflects soil development under grasslands in the past (Sedov *et al.*, 2003). The intensive black colour is reflected in the name of these soils, Andosols (in Japanese An- means dark and Do– means soil). These soils are rich in humus, containing mainly humic acids, which are partly complexed with poorly ordered aluminosilicates, allophane and imogolite. Many volcanic soils are dark, except those on recent ash deposits or formed under a arid climate.

The distribution of these soils depends on recent volcanic activity and has little relation to current climates. Only in the coldest regions, where weathering rate is exceptionally low, does volcanic glass not produce amorphous compounds essential for volcanic black soils formation. Most of these soils form in the mountains and in the mountain toeslopes. The most extensive areas of these soils are found in Japan, New Zealand, Iceland and Indonesia. In North America, such soils are found in the Rocky Mountains and Transmexican Volcanic Belt and in South America along the Andes. The productivity of these soils is relatively high, though specific P retention is a common limitation factor for their productivity. Apart from their use in agriculture, these soils contribute a lot to water retention because of their high water-holding capacity. The latter property also protects them from water erosion, though slope processes such as landslides are rather common. Carbon reserves may be high in volcanic soils, especially when pedocomplexes with multiple buried profiles form in the zones of active volcanism.

11 | The Japanese black soils

Andosols in Japan

Black soils in Japan are called “Kurobokudo”, which means black (kuro) and fluffy (boku) soil in Japanese. The black soils are mainly derived from volcanic ejecta or tephra, and the soils have unique properties such as being light, soft and fluffy, having a high humus content, and very high phosphorous-fixing capacity. According to the World Reference Base for Soil Resources, these soils are classified as Andosols, derived from “ando” which denotes black and dark soil in Japanese (Shoji *et al.*, 1993). Andosols have the largest distribution area among the soil great groups in Japan. The total distribution area of Andosols in Japan is estimated at some 0.1 million km^2, which is about 10 percent of the global Andosol distribution area. Andosols are mainly distributed in the southern part of Hokkaido, in the northeastern part of Tohoku, and in the Kanto-Koushinetsu and Kyushu regions (Saigusa, Matsuyama and Abe, 1992; Fujita *et al.*, 2007; Okuda *et al.*, 2007).

2.4.5 Black soils in tropics

Black soils are not very common in the tropics, although some mollic or umbric horizons can be found in few places. These soils are mainly associated with basic rocks and isothermic climates. They belong to many groups such as Ferralsols, Nitisols, Acrisols, Cambisols and Vertisols and especially Lixisols, and the presence of dark topsoil is reflected by the modifiers Mollic, Umbric, or Hyperhumic. In general, these soils are more productive than other tropical soils.

The area covered with tropical black soils is not very extensive. Most of them are associated with the humid savannas and semi-deciduous forests. Their use in agriculture depends on the density of population and the level of agricultural development in the country. Carbon storage is limited in such soils, and organic matter may be easily mineralized when the soils are ploughed. These soils are vulnerable to many degradation processes such as water erosion, compaction, nutrient depletion etc.

12 | Brazilian tropic

Profiles of tropic black soil. Location: Municipally of Corumbá, Mato Grosso do Sul state, Brazil

The dominant group of black soils in Brazil is the tropical black soils, with parent materials derived from basalt, gabbro and diabase (Demattê, Vidal-Torrado and Sparovek, 1992) or calcareous rocks (Maranhão *et al.,* 2020). The dominant climate is tropical (dry, with moderate water deficiency or semi-arid). Soil profiles, in general, occur on flat to strongly undulated slopes, uplands and backslopes, with surface horizons up to 65 cm thick and soil profile depths less than 130 cm. They show high content of Ca and Mg, with a predominant loamy to very clayey texture. When in the lowest part of the slopes, due to the presence of expansive clays (smectites), soils are very hard when dry and very sticky when wet. In some areas with gentle slopes, soils are poorly drained (Pereira *et al.,* 2013). The tropical black soils represent a hotspot, and they occur in small extensions under specific soil-forming conditions. The vegetation in many sites is designated as "dry forest" that includes tropical deciduous forest, with high canopy trees and rich plant undergrowth (Caatinga, tall deciduous and semi-deciduous forests in dry semi-arid climates; and the Cerrado, a mixture of open grasslands, shrub lands, open woodland, and closed canopy woodlands).

2.4.6 Black soils in highlands

In highlands, black soils may be found under several ecosystems at different elevations. Black soils are widespread under alpine meadows in temperate areas and under páramos in tropical mountains. These highland grasslands produce a high amount of root residues, which are responsible for dark humus accumulation. Depending on the precipitation, these soils may be rich in exchangeable bases or strongly leached. In the first case they are classified as Phaeozems, and in the latter case as Umbrisols.

Since multiple mountain ecosystems other than alpine meadows have black soils, the exact area covered with mountainous black soils is not well recorded. Their use varies depending on the ecosystems. In páramos and in alpine meadows they are used mainly as pastures. Water erosion and compaction due to overgrazing are the most common degradation processes in these soils

13 | The Kyrgyz highlands

Tien-Shan Mountains

Kyrgyzstan is very mountainous and black soils develop in the mountains under grasslands. Their distribution is determined by the elevation of the terrain, and also related to the exposure, steepness, shape of slopes and other regional factors. The exposure of slopes has a great influence on the formation of mountain black earth soils. The slopes of the northern and northwestern expositions are more protected from significant insolation, so they create favourable conditions for the diversity and good growth of herbaceous vegetation, made up of bushes of rosehip, stem, barberry and woody vegetation. Under a lush variety of grass and cereal grass, black earth leached from carbonates are formed (Shpedt and Aksenova, 2021). Mountainous conditions determine the unique morphological shape and physico-chemical properties of black soils located on uplifted plains, characterized by a dark brown colour, high content of humus (up to 10 percent) that penetrates deeply down the profile. In the composition of humus, humic to fulvic acids ratio exceeds 1, with deep leaching from carbonates, a neutral reaction of the upper and weakly alkaline of the lower horizons, and high cation exchange capacity (30 to 40 $Cmol_c/kg^1$ of soil). These soils are characterized by relatively high gross content of nutrients (Shpedt and Aksenova, 2021). These soils differ from the mountain-valley ones by a more developed sod layer, sharp differentiation of the soil profile, a dark brown, almost black colour, higher humus content (up to 15 percent), and higher cation exchange capacity (Shpedt and Aksenova, 2021). Annex I, Section A.3.2 for more information.

2.4.7 Anthropogenic black soils

Anthropogenic (or human-made) black soils constitute a specific group where its dark colour depends both on organic matter and the presence of charcoal particles. Ever since humans became sedentary and practiced agriculture, they have been confronted with the need to manage their organic refuse. Refuse was initially just added to the soil where it may have somewhat increased soil organic matter levels. In most cases this addition resulted in only small increases in soil organic carbon, as a new equilibrium developed rapidly. Especially in tropical areas, where high temperatures and abundant moisture are conducive to rapid decomposition, effects were likely small. However, under certain conditions, the addition of organic refuse has modified soil properties, with soil becoming darker and eventually almost blackish and containing (substantially) higher amounts of carbon and nutrients. Under these conditions humans acted as soil-forming agents, resulting in anthropic black soils or Anthrosols (IUSS Working Group WRB, 2015).

Soil taxonomists recognize several types of Anthrosols, based on the diagnostic characters of the anthropic upper horizon. Important types are the Plaggic Anthrosols, which originated by the use of bedding material for livestock, consisting of sods and excrements, on agricultural land (Pape, 1970; Giani, Makowsky and Mueller, 2014); Hortic (from the Latin hortus, meaning garden) Anthrosols, and Pretic (from the Portuguese preto, meaning black) Anthrosols. Pretic Anthrosols are usually dark-coloured, deep (the pretic horizon is at least 20 cm thick, but can be up to 100 to 200 cm due to intense bioturbation by ecosystem engineers such as earthworms), well-drained, sandy to clayey soils, with higher values for pH, organic C, total, extractable and available P, exchangeable divalent cations (Ca and Mg), CEC, and base saturation than the surrounding soils, while the amounts of extractable Fe is lower. The darker colour is both due to the inputs of charcoal and to biological processes (melanisation).

There are several specific threats to anthropic black soils. Intensive agricultural use can result in superficial erosion, nitrate losses, and the resulting lowering of pH and increased levels of extractable Al can also result in animal-species losses (Demetrio *et al.,* 2021). Intensive agricultural use and subsequent erosion is also a cultural loss. More information about Anthropogenic black soils in Annex I.

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14 | Terra Preta do Índio

Terra preta do Índio soil and landscape, Brazil.

The most accepted hypothesis for genesis of these soils, based on pedological and archaeological evidence, is that they were formed unintentionally by pre-Columbian Amerindian societies in the Amazon basin (Kern and Kampf, 1989; Schmidt *et al.,* 2014; Kern *et al.,* 2019). The anthropic A (Au) horizons have a thickness up to 200 cm and colours ranging from very dark to black, with yellow or red colours in the subsurface horizons, marking a clear differentiation in the profile. By definition, the Anthropic horizon is marked by high fertility, when compared to adjacent soils, high contents of P, Ca and Mg, and stable organic matter (usually as charcoal), in addition to the presence of cultural artefacts. In general, they are well drained and have a texture ranging from sandy to very clayey, with a clear differentiation between anthropic A horizon (with loamy sandy, sandy loamy and clay textures) and subsurface horizons (with clay-sandy and clay textures) (Campos *et al.,* 2011). Estimates for the whole Amazon basin range from 0.1 to 0.3 percent (Sombroek *et al.,* 2003) to 3.2 percent (McMichael *et al.,* 2014) or even 10 percent (Erickson, 2008), with areal estimates ranging from 600 to 600 000 km^2. The rate at which such soils develop have not been quantified. However, because of feedback between human activity and soil amelioration, it is likely that incipient Terra Preta do Índio soils did develop within a few decades (Van Hofwegen *et al.,* 2009). Attempts are being undertaken to recreate such soils (Terra Preta Nova), however with incomplete knowledge on the recipe of Terra Preta do Índio formation, such attempts have not yielded large successes (Lehmann, 2009) and the literature on Terra Preta Nova in the last decade is very scant. In the Colombian Amazon region, these soils have been reported along the Caquetá river (Mora, 2003) and along some small tributaries of the Amazon river (Morcote-Ríos and Sicard, 2012). Most of the indigenous inhabitants of the Colombian Amazon basin have access to both natural soils and Terra Preta. For the Middle Caquetá river region, reports show that Indigenous Peoples recognize these soils as the most suitable soils for agriculture (Galán, 2003).

Black soils may form in many other environments, but commonly they occupy minor areas. Of special importance are black soils formed on limestone: these soils are called Rendzinas in many classifications. In WRB (IUSS Working Group WRB, 2015) such soils are called Rendzic Leptosols and Rendzic Phaeozems. In these soils derived from rocks with high content of calcium carbonate, the topsoil is black and thick. These soils form mostly under humid and semi humid climates from tropics to taiga area climatic belts. In places these soils occupy significant areas. Being shallow, these soils have evident limitations for their use in agriculture, though in places they are successfully used both as arable lands and pastures.

In places, black soils also form on lignite shales and other carbon-rich materials. In these cases, the colour of the topsoil horizon depends not only on the content of organic matter, but also on the dark colour of the parent material. Some of these soils are known for high fertility, but others have regular properties similar to those formed on other parent rocks. Of special interest are ornithogenic black soils, which form in bird rookeries in Arctic and Antarctic islands and coastal areas. The main source of organic matter in these places are bird excrements, and these soils are extremely rich in P, which plays an important role in their geochemistry.

2.5 Regional characteristics of black soils

2.5.1 Africa

Africa is an extremely large continent (30.4 x 10^6 km^2), equalling more than the countries of China, United States of America , India, Mexico, and the whole of Europe combined. Africa is generally subdivided into seven geographical regions, each defined by distinct geology and climate and thus unique landscapes and soils (Jones *et al.,* 2013). The Mediterranean has dry, hot (>35 °C) summers and cool (10 °C) winters, and rainfall that occur mainly in the winter. The vegetation is mainly shrubs and agriculture can only be productive if additional water is available. Soils tend to be rich in calcium and magnesium, but low in organic matter. Deserts, encompassing the Sahara, the Namib and Kalahari, and northern Kenya and Somalia are very dry and very hot, and have great daily temperature variability. The vegetation cover is therefore poor or non-existent, soils are shallow and stony, and arable agriculture almost impossible. The Sahel and Savannah cover almost half of Africa. Savannah is a mixed grassland and woodland, occurring next to the forest region. Soils are well-drained, with thin organic matter rich topsoils, and can support limited cultivation. Its fertility degrades quickly. Tropical Forests have rather constant temperature and have either rainy or dry conditions. Forests are thus characterised by high vegetative production with organic matter-rich, nutrient poor, and acidic. Mountains encompass the Atlas Mountains of North Africa, the highlands in the Sahara and southern Africa, the eastern Africa rift valley, and the Ethiopia highlands. The climate is hot and dry and is defined by altitude. Soils are varied and closely related to the geology due to limited development. Rivers and wetlands include the floodplains of major rivers, swamps, and forested wetlands. Soils are characterized by fluvial stratification, good drainage or waterlogged, and are typically fertile with high organic matter content. Lastly, southern Africa is unique due to its very old and stable geology, was as well as warm and dry climate resulting in thin and moderately fertile soils.
Various soil maps, covering the African continent, have been produced. They include the Soil map of the World (FAO-UNESCO, 1981), the Harmonised World Soil Database (FAO, ISRIC and JRC, 2012), and the Soil Atlas of Africa (Jones *et al.,* 2013). Hartemink, Krasilnikov and Bockheim, (2013) reviewed the global soil mapping attempts. For determination of the black soils defined in the Soil map of the World (FAO-UNESCO, 1981), all Rendzinas, Kastanozems, Chernozems, Phaeozems, and Greyzems were included in the search. This yielded 55 polygons (out of 1 635), varying in composition of the selected soils from 5 to 100 percent and covering an area of only 64 666 km^2, or 0.21 percent of the African land surface.
In the Soil Atlas of Africa (Jones *et al.,* 2013), only 367 of 13 693 polygons are defined as Kastanozems, Phaeozems, or Umbrisols; totalling 203 923 km^2 or only 0.67 percent of the African land surface. There are no Chernozems or soils with the mollic horizon in the Soil Atlas of Africa. This 203 923 km^2 comprises of 121 435 km^2 Phaeozems (59.5 percent), 55 746 km^2 Umbrisols (27.3 percent), and 26 742 km^2 Kastanozems (13.1 percent). It should therefore not be surprising that the available research on black soils in Africa is similarly sparse.
Eswaran *et al.*, (1997) state that Mollisols (Chernozems, Phaeozems and Kastanozems) dominate more in areas with a xeric soil moisture regime, covering Morocco and coastal Algeria and Tunisia. In Sub-Saharan Africa, black soils are restricted to isothermic areas, with base-rich parent materials and commonly occur in association with Luvisols and Lixisols.
Kastanozems are very fertile soils and thus favoured by farmers, although these soils may be subject to nutrient imbalances as a result of the increased calcium levels in the soil (Jones *et al.*, 2013). The soils may be droughty and will thus require irrigation in the hot, dry summer seasons to be productive. Kastanozems might be susceptible to wind erosion in the dry season and to water erosion in the wet season, especially if situated on steeper slopes.
Phaeozems are very productive if sufficient rooting depth is available. These soils can also be droughty, because the water-holding capacity is provided by the surface layer only. Phaeozems are also susceptible to wind and water erosion, similar to Kastanozems.
Umbrisols are prone to acidity, since they occur primarily in humid areas, and are thus particularly suited for woodlands. These soils therefore require significant lime application to increase productivity. The wind and water erosion risk of Umbrisols is similar to that of Kastanozems and Phaeozems.
Eswaran *et al.*, (1997) conclude that Mollisols (Chernozems, Phaeozems and Kastanozems) and Vertisols that have high available water holding capacity, mainly associated with the higher 2:1 clay content of

these soils and that only these soils plus Luvisols can be considered as prime agricultural land.

The average organic matter content of 58 black topsoil soils in south Africa was 1.8 percent, varying from 0.5 percent to 4.3 percent (Van der Merwe, Laker and Buhmann, 2002b). The study stated further that the organic matter content was proportional to the kaolinite content and acidity.

Van der Merwe, Laker and Buhmann (2002a) studied the clay mineralogy of 58 black topsoil soils in south Africa and concluded that more than 50 percent of the soils were dominated by smectite, one third by kaolinite, and the rest had an association of mica, kaolinite, and smectite in approximately equal proportions.

Smith (1999) contends that wildlife anthrax in the Kruger National Park of south Africa was more associated with the high calcium and alkaline pH ecology, typically associated with Calcisols and Kastanozems.

In a study on the genesis of black topsoil soils in south Africa, Van der Merwe *et al.*, (2002b) concluded that these soils cover about 23 000 km² and are mainly associated with mafic igneous or sedimentary parent material, but that climate seems to be the dominant soil forming factor, with the soils limited to areas with contrasting seasons, mean annual precipitation of 550 to 800 mm, and an aridity index of 0.2 to 0.5. These soils do not develop in areas with mean annual precipitation <500 mm, probably due to the lack of organic matter addition and/or the lacking preservation thereof. Fey (2010) also gives an excellent overview of the genesis, properties and distribution of black topsoil soils in south Africa.

Black soils cover only about 0.67 percent of the African land surface, and as such do not feature extensively in research literature. These soils are, however, amongst the most productive on the African continent and are therefore in serious need of detailed research investigation.

2.5.2 Asia

Asia is a huge region, and all the varieties of black soils are present there. One of the three largest black earth zones in the world is in China, where they are concentrated in northeast plain (Krasilnikov *et al.,* 2018). Chernozems are also found in Mongolia. In this chapter, two country case studies are presented for China, with extensive areas of black soils under grassland vegetation, and for Japan, with abundant black soils formed in volcanic ash deposits.

China

In the early stage of land reclamation in the northeast region of China, farmers called the black and soft soil with a plough depth (15 to 18 cm) as ''black soils'', including black soil, chernozem, meadow soil, white clay soil, and dark brown soil etc. (Liu *et al.,* 2012). Its administrative regions include Liaoning province, Jilin province, Heilongjiang province and the eastern fourth league of Inner Mongolia Autonomous region (Chifeng city, Tongliao city, Hulunbuir city and Hinggan league), with a land area of 1 244 million km² (Tong *et al.,* 2017). In the northern and eastern region of China, because the growing season is both hot and rainy time, the vegetation grows abundantly in summer and accumulates a large amount of organic matter (Ding, Han and Liang, 2012). Due to the long and cold winter, microbial activities are restricted, which is conducive to the accumulation of organic matter, and soil organic matter accumulation is greater than decomposition, forming a deep black soil layer (Sorokin *et al.,* 2021).

Black soils in northeast China are mainly distributed in the Liaohe plain, Songnen plain and Sanjiang plain (38°43 ' north ~ 53°33' north, 115°31 'east ~ 135°05' east) (Qin *et al.,* 2021). It is one of the three major black soil belts in the world within a range of 1 600 km from east to west and 1 400 km from south to north. The natural black soils have been developed in the Tertiary, Quaternary Pleistocene or Holocene gravel and clay layers. The unique climate, hydrological conditions and vegetation types in the region have laid a foundation for the accumulation of humus in the soil, forming a deep and fertile black soil layer, and black soils has become one of the most fertile soils in the world (Li *et al.,* 2020).

The thickness of the black soil layer (layer A) of natural soils is closely related to regional climatic conditions. Due to the transformation of natural soils into cultivated soils after reclamation, the black humus in the A horizon was rapidly decomposed, the black colour gradually disappeared and changed to a grey leached layer (B horizon). The colour of the A horizon in some soil types gradually changed to the colour of the parent material (Zhang, An and Chi, 2019). The black soil area in northeast China is divided by 45°north, with a thin black soil layer in the south and a medium thick black soil layer in the north. Most of the black soil layer is more than 30 cm thick, and soil organic matter content is more than 35 g/kg. The black soil layer and its organic matter content of meadow soil are similar to those of medium thick black soils (Li *et al.,* 2020).

Before the nineteenth century, the black soil area was an ecosystem with outstanding ecological services and functions, with less interference from human activities, and a large number of animals and soil organisms inhabited and multiplied here (Liu *et al.,* 2019). Those black soils were most important carbon sinks in the global terrestrial ecosystem (Li *et al.,* 2020). Since the twentieth century, with the rapid development of modern agriculture and the continuous increase of the world's population, black soils have been rapidly devoted to farmland, and most of the black soil area was then cultivated land (Wen *et al.,* 2021). The black soil area in northeast China has been converted in an important commodity grain production base of China, thus playing an important role in ensuring national food security (Li *et al.,* 2020).

However, due to the intensive utilization of black soil resources, the natural fertility of black soils have been on a downward trend year by year, mainly in the following aspects decreased: soil organic matter content, the plough layer becoming shallower and harder, and soil air-water-heat transference functions worsening as well as soil fertility. Continuous cropping leads to serious soil degradation such as erosion and acidification processes; the soil erosion of slope farmland is serious, and leads to the serious degradation of black soils (Zhang *et al.,* 2021).

In recent years, the Ministry of Agriculture, the Ministry of Science and Technology, the Ministry of Land and Resources and the four provinces of northeast China have actively implemented high standard farmland construction, soil and water conservation, soil testing and formulated fertilization, soil organic matter increases, conservation tillage and other projects, forming a series of measures suitable for different regions and black soil types, such as subsoiling for soil compaction alleviation and soil preparation, reduced tillage and no tillage, straw returning, and increasing the use of organic fertilizers (Li *et al.,* 2021). The comprehensive technical mode and operation mechanism of black soil protection and utilization are to control the loss of black soils and keep water and fertilizer (Han *et al.,* 2018).

Japan

Andosols account for about 30 percent of the agricultural land in Japan and are widely distributed on volcanic mountains, hills and Pleistocene such as plateaus near active volcanoes. The main parent materials of Andosols are volcanic ejecta such as volcanic ash, pumice, and scoria. Andosols are rich in active Al and Fe as soil formation products such as allophane, imogolite, Al-humus complex, ferrihydrite, etc. The morphological characteristics of the soil profile of Andosols in Japan are as follows: (1) the formation of an organic-rich, black and dark-coloured humic horizon, (2) the formation of an organic-rich, brownish humic horizon, mainly under forest vegetation, (3) the formation of a cumulic humic horizon, and (4) the formation of a buried humic horizon (Takata *et al.,* 2021). Andosols are unique among soil types in terms of their physical and chemical properties (Shoji *et al.,* 1993). That is: (1) fluffy and light texture; (2) high water-holding capacity; (3) high reactivity with fluorine and high phosphate absorption; (4) high cation exchange capacity (CEC) and predominant variable charge (charge depends on pH), and (5) low retention of base cations and acids under humid climate. These unique properties are closely related to the presence of short-range order minerals or humus. Andosols are known as productive soils on a global scale. In contrast, in Japan they had traditionally been regarded as poor productive soils, because low phosphorus contents often limit crop production in Andosols (root crops and potatoes are the most common crops, and paddy fields are rarely used).

In Japan, phosphate adsorption coefficient (PAC) is among the soil properties routinely measured in soil survey. Soil PAC allows farmers to determine the adequate level of phosphorus fertilization. The main factors controlling PAC in Andosols are organo-Al complexes and the Al in allophane and imogolite present at aqueous-mineral interface (Nanzyo, Dahlgren and Shoji, 1993). It has been recommended that the amount of phosphate (molten phosphorus) fertilizer applied should be targeted at 3 percent of PAC, and that Ca and Mg supplementation should also be applied. Matsui *et al.*, (2021a) reported that PAC showed more significant positive correlation with SOC compared to clay and silt–clay contents for Japanese Andosols.

After soil chemical improvement by enrichment of phosphate and bases, the Andosols zone has become a popular production area for root crops and tubers, taking advantage of its large, flat area, favourable physical properties and easy cultivation.

Under well drained conditions, Andosols accumulate the highest amount of organic matter of any soil groups in the world (Shoji, 1984). Humus in Andosols forms complexes with Al, which increase its stability against decomposition by soil microbes. Andosols is distributed over only 0.84 percent of the Earth's terrestrial area, but their SOC accounts for about 1.8 percent of the global SOC. Andosols accumulate more than twice as much carbon as other soils, and it covers 30 percent of Japan's total land area. Andosols are an important soil resource from the viewpoint of both Japan's food security and global environmental conservation. According to the national soil carbon monitoring project in Japanese agricultural land from 2015 to 2018, the average of Andosols carbon stocks (0 to 30 cm) is 122 tonnes C/ha in paddy field, 117 tonnes C/ha in upland crop field, 154 tonnes C/ha in pasture fields, and 137 tonnes C/ha in orchard field (Matsui *et al.,* 2021b). Andosols carbon stock are much higher than the other soil groups such as Fluvisols, Cambisols, and Acrisols in Japan. Simulated total SOC stock (1970 to 2006) in agricultural lands in Japan (sum of SOC stock among all land-use types) using the Roth-C model were found to increase its SOC stock in Andosols, whereas decreased SOC stocks in all other soil groups (Yagasaki and Shirato, 2014).

Soil water erosion has been reported as a soil degradation process in volcanic highlands. Subsurface horizons of Andosols generally have a very high phosphate fixation capacity, and if the ploughed layer is lost due to soil erosion, soil fertility will be significantly decreased. Soil water erosion not only reduces soil fertility, but also it may affect the watershed environment because of water pollution through the discharge of eroded sediment into rivers. Rivers flowing through the Andosols zone often turn black after rainfall (Matsumoto, 1992). In general, soil aggregation is not strongly developed in the ploughed layer of Andosols; abrupt changes in soil texture among soil horizons are often observed due to the deposition of different volcanic ashes. These characteristics make Andosols prone to soil water erosion. Fujino and Matsumoto (1992) reported that the thickness of the ploughed layer (adjusted by soil carbon content) was reduced by about 40 cm compared to the surface horizon (adjusted by soil carbon content) of the adjacent semi-natural grassland. Shiono *et al.*, (2004) conducted field measurements of soil erosion under bare and cabbage cultivation in Andosols distributed area in northern Kanto region. They showed that sediment yield from the cabbage plot was much less than that from the bare plot, and they also pointed that sediment yield in the cabbage plot was influenced by the coverage of crop and crop residues on the field (Shiono *et al.,* 2004). Heavy rainfall is common during the rainy season and typhoon season in Japan, and it is important to avoid bare land at those times to control soil water erosion.

Based on these principles, soil water erosion and sediment control should employ appropriate combinations of agronomic measures, soil management, field management and mechanical methods. However, farmers rarely adopt agronomic and field management methods because they receive few direct benefits from their efforts and costs for the control practices. Mechanical methods are difficult to adopt because of the huge budgets they require. However, the Minsitry of Agriculture, Forestry and Fisheries (MAFF) supports these countermeasures. A subsidy system for multi-functionality in agriculture offers a grant under certain conditions to local action groups practicing field management methods. This support is grounded in the following ideas that agriculture plays multiple roles, including conservation of national land, water resources, and natural water discharge during a runoff event (Shiono, 2015).

2.5.3 Europe and Eurasia

In Europe, the zone of black soils (Chernozems, Phaeozems and Kastanozems) partly covers Hungary, Bulgaria, Austria, southern Germany, the Czechia, Slovakia, Romania, and the Balkan Peninsula (Krasilnikov *et al.,* 2018). An extensive area with black soils is reported in Ukraine of 34.2 million hectares. In the Republic of Moldova, black soils cover 86.4 percent of the territory of this small republic equaling 2.92 million hectares. However, the largest area, totaling 326.8 million hectares are found in the Russian Federation, in the central Chernozem region, the Volga region, the Northern Caucasus, the southern Urals and western Siberia. Further to the east, black soils occur in the plains and foothills of the Altai, on the outskirts of the foothills of the eastern Sayan. Black soils are widespread in the northern part of the Republic of Kazakhstan and occupy 107.7 million hectares, or 9.5 percent of the territory of the republic (FAO, 2022a). For Europe and Eurasia, we present three case studies, which represent typical areas of black soil distribution in temperate plain grasslands (Ukraine) and in the mountains (Kyrgyzstan) and one country (Poland) with a minor area of black soils under transitional forest-steppe vegetation. The Ukrainian case study is the most detailed one, as in this country black soils cover a major part of the national territory and there are extensive studies on the productivity, ecosystem services, and degradational status of such soils.

Ukraine

Black soils distributed in the territory of Ukraine include a group of soils with certain differences in their genetic origin and history of development. All of them share a high content of organic matter, leading to the formation of saturated dark topsoil, from dark gray to black. In general, in the WRB system, they are classified as Chernozems, Kastanozems and Phaeozems.

The evolution of Chernozems and other black soils lasted almost the entire Holocene, so it is a polygenic soil. Plant-climatic conditions had a great influence on the genesis of black soils with both steppe and meadow vegetation with strong turf contributing to the accumulation of organic material.

The most favourable conditions for black soil formation are in the southern part of the forest-steppe zone, and in the north of the steppe, where Haplic Chernozems are widespread. To the south of these subzones, the moisture deficit increases and the amount of plant precipitation and the depth of the root system decrease. As a result, the depth of a humus-enriched topsoil and quantity of organic matter decreases. To the north, on the contrary, the amount of moisture and the leaching of exchange cations increase, and the concentration of organic carbon also decreases. From west to east, the continentality of the climate increases, thus increasing the amount of soil organic matter in chernozems and reducing the thickness of the humus horizon with relatively stable total humus reserves in the profile. Biological activity has a similar dynamic, and it is greatly influenced by the unfavourable water regime, which depends on trends in continental climate.

The particle size distribution of these soils is determined by the parent rocks: loess and loess-like loams occupy an area of about 75 percent of black soils in the country. The lithology of parent material varies depending on the geological and geomorphological factors (Polupan, 1988). In general, clay content increases from northwest to southeast. The soil profile depth of black soils, rich in organic matter, varies from 60 to 120 cm and more, especially on the watershed plateau and on north facing slopes. Black soils are characterized by a dark grey colour, which gradually lightens to the parent rock. In Phaeozems with slight vertical clay redistribution, topsoil has a lighter colour of eluviation. Black soils of Ukraine have variable physical and chemical, water-physical and agrochemical properties.

The spatial distribution of the soils of Ukraine on the plain has a well-defined latitudinal zonation, but within these natural zones and subzones local climatic, geological, and topographical factors complicate the situation that also affects the distribution of black soils. Since they are found in all climatic zones, it is worth noting certain features inherent in these localizations.

Luvic Greyzemic Phaeozems in Polissya are confined to loess islands. In the forested steppe, black soils are represented mainly by Haplic Chernozems, which are found on low-lying plateaus and high loess terraces. In the past, these areas were represented by steppe meadows. The second largest area in Polissya is occupied by Phaeozems and Luvic Chernozems. The soil cover of the northern steppe is represented mainly by Haplic Chernozems, which were formed under the herbaceous-fescue-feathergrass steppes. The diversity of soils is associated with an increase in aridity in the subzone from north to south, which led to a decrease in the thickness of the humus layer, carbon content in the topsoil, depth of accumulation of carbonates, gypsum, and water-soluble salts. The southern steppe is dominated by Calcic Chernozems (Tonguic), formed under fescue-feather steppes in arid climates. The main component of the soil cover of the dry steppe are Kastanozems. In the Carpathians and the Crimean Mountains, black soils occur sporadically, in the first tier of vertical zonation.

Unfortunately, soil resources management in Ukraine, is not sufficiently balanced and does not ensure the preservation of soil fertility (Baliuk and Kucher, 2019). The current state of Ukraine's soil resources is characterized by intensification of soil degradation processes, which is due to the contradiction between the national tasks of soil conservation and private interests in obtaining a quick profit from agricultural activities. Therefore, the problem of conservation of soil resources and overcoming soil degradation in Ukraine requires new methodological approaches and comprehensive solutions in the organizational, informational, technological and financial spheres (Balyuk, Medvedev and Miroshnychenko, 2018). The issue is especially relevant in the context of the impact of global and regional climate change on soil resources and agricultural production (Borodina *et al.,* 2016; Kazakova, 2016) and the need to adapt land use to such changes (Kucher, 2017).

The vast majority of black soils are intensively used in agricultural production. Thus, purely chernozemic soils like Luvic Chernozems (6.0 percent), Haplic Chernozem (21.3 percent) and Calcic Chernozem (39.5 percent), together make up 66.8 percent of the area of arable land (Miroshnychenko and Khodakivska, 2018). This area grows almost the entire range of crops, and especially high yields are obtained in cereals, sunflower, sugar beet, canola and more.

However, this high productivity also involves extremely high risks. According to Yatsuk (2015), the ploughed agricultural land is 78 percent with a total ploughed territory of 53.9 percent. Almost 74 percent of agricultural land is privately owned, and 24 percent is state property. Ignoring crop rotations has become a daily practice, which causes soil fertility declines. Growing monocultures, saturation of crop rotation with energy-intensive crops leads to soil nutrient depletion, water-physical functions and chemical properties deterioration, and other negative consequences.

This became especially widespread with the advent of agricultural formations with small land areas, which led to a reduction in crop production and the transition to non-specialized short-rotation to crop rotation. In addition, the current market situation forces farmers to grow primarily energy-intensive crops, such as sunflower, that leads to neglect of crop rotations (Yatsuk, 2015).

The prevalence of black soils determines their high importance for the global environment. According to the data (FAO, 2015), ecosystem services can be characterized as follows (Table 2.5.1).

Table 2.5.1 Generalized ecosystem service rating of specific soil groups (WRB)

Types of soils	Ecosystem services, score points				
	Food, feed and fibre production	Water regulation	Biological diversity	Climate change mitigation and adaptation	Other benefits
Chernozems	5	4	4	4	Erosion control
Phaozems	4	3	4	4	Erosion control
Kastanozems	3	2	3	4	Erosion control

Source: FAO. 2015. *Healthy soils are the basis for healthy food production*. Rome, Italy, FAO. https://www. fao.org/documents/card/en/c/645883cd-ba28-4b16-a7b8-34babbb3c505/

Current management of soil resources consists of the following components: 1) management of soil fertility reaching the maximum possible soil and climatic potential; 2) preservation of ecosystem services and soil functionality as a component of the biosphere; and 3) use of soil opportunities for carbon sequestration and its minimum emission in agricultural use.

Excessive soil ploughing, monoculture, no addition of of organic fertilizers, with an excess of plant protection products and the lack of real monitoring of soil quality are all point towards the need to improve the management of soil resources. These apply to all types of soils, but mostly to black soils, due to their priority in use.

Soil organic carbon in Ukraine has a clear latitudinal-zonal gradient (Plisko *et al.,* 2018; Vyatkin *et al.,* 2018). When analyzing the distribution of values of organic carbon reserves in the layer of 0–30 cm in the soils of Ukraine with a resolution of 1x1 km clearly visible carbon-rich black soils Forest-Steppe and Steppe. The lowest values of soil organic are typical for sandy Podzolic soils of the Ukrainian Polissya zone, which, although not directly related to black soils, are important for evaluative judgments. Organic carbon reserves are markedly declining in the arid zones of the Dry Steppe in the south of the country, which is described in the literature (Polupan *et al.,* 2015).

The distribution of data according to Table 2.5.2 shows that the values of organic carbon reserves for the black soils of Ukraine are very different. The high concentration of SOC in Meadow steppe (dark chernozem-like soils) and Chernozems (podzolic, leached, typical, ordinary, southern, meadow) contrasts sharply with lower concentrations in Gray forest soils (dark-gray forest soils). Thus, in the first mentioned group of soils, the SOC concentration is 83 to 85 tonnes C/ha, which is almost twice as much as Dark-gray forest soils(Luvic Greyic Phaeozems) (45 tonnes/ha). The content of organic carbon in Chestnut soils is intermediate and is 59 tonnes C/ ha. The progression is as follows: Luvic Gleyic Phaeozems (Dark-gray forest soils), Kastanozems (Chestnut soils), Chernozems (podzolic, leached, typical, ordinary, southern, meadow chernozems), Gleyic Phaeozems (Meadow dark chernozem-like soils).

Table 2.5.2 Reserves of organic carbon in the layer of 0–30 cm in the main types of soils of Ukraine
(according to Plisko *et al.*, 2018; Viatkin *et al.*, 2018)
Source: Polupan, N.I. 1988. *Soils of Ukraine and increase of their fertility: Vol. 1. Ecology, regimes and processes, classification and genetic and production aspects* (In Russian). Kiev, Urogaj.

Types of soils	FAO/WRB	Average SOC stocks, tonnes C/ha
Grey forest soils (Dark-grey forest soils)	Luvic Greyic Phaeozems	45
Chernozems (podzolic, leached, typical, ordinary, southern, meadow chernozems)	Chernozems (Greyi-Luvic Phaeozems, Luvic Chernozems, Chernic Chernozems, Chernozems, Calcic Glossic Chernozems)	83
Chestnut soils	Kastanozems	59
Meadow steppe (Meadow dark chernozem-like soils)	Gleyic Phaeozems	85

Note: Soil type specified according to the classification of soils Ukraine (Polupan, 1988)

Some of the main factors of soil degradation in Ukraine, along with the unbalanced land structure with significant overload of agricultural land, is erosion, loss of organic matter and loss of nutrients (Balyuk *et al.,* 2012; Balyuk and Medvedev, 2015; Boroday, 2019; National report on the state of the environment in Ukraine in 2018, 2020).

Thanks to agrochemical certification, which is carried out in Ukraine, the following degradation processes are well detected: loss of organic carbon, denitrification, loss of phosphorus, potassium, sulfur and micronutrients, decalcification, contamination with heavy metals, contamination with persistent pesticides, radionuclide contamination, acidification, salinization and alkalization (Balyuk *et al.,* 2012; Miroshnychenko and Khodakivska, 2018; Yatsuk, 2018; National report on the state of the environment in Ukraine in 2018, 2020). In general, the types, prevalence and degree of various degradations can be traced according to Table 2.5.3, and some of them, according to Medvedev (2012), are irreversible.

Table 2.5.3 Distribution of soil degradation types in Ukraine
Source: Medvedev, V.V. 2012. *Soil monitoring of the Ukraine.* The Concept. Results. Tasks.(2nd rev. and adv. edition).Kharkiv: CE "City printing house.

Type of degradation	Extent, percentage of arable land according to the degree of expression			
	light	medium	strong	sum
Fertility declines and reduced humus content	12	30	1	43
Compaction	10	28	1	39
Sealing and crusting	12	25	1	38
Water erosion, surface wash	3	13	1	17
Soil acidification	5	9	0	14
Waterlogging	6	6	2	14
Soil pollution by radionuclides	5	6	0.1	11.1
Wind erosion: loss of topsoil	1	9	1	11
Soil contamination with pesticides and other organic contaminants	2	7	0.3	9.3
Soil contamination with heavy metals	0.5	7	0.5	8
Salinization / alkalization	1	3	0.1	4.1

Type of degradation	Extent, percentage of arable land according to the degree of expression			
	light	medium	strong	sum
Water erosion: terrain deformation by gullying	0	1	2	3
Off-site effects of water erosion	1	1	1	3
Lowering of the soil surface	0.05	0.15	0.15	0.35
Wind erosion: terrain deformation	0.04	0.23	0.08	0.35
Desertification	0.04	0.18	0	0.21

The degradation of black soils in Ukraine is mainly the result of the use of inappropriate agricultural technology (Balyuk *et al.,* 2010). Application of NPK fertilizers from the average value of 150 kg/ha in 1990 fell to 18 kg/ha in 2000. Recently, some positive dynamics have been observed, and in 2015 the average NPK application reached 50 kg/ha (Miroshnychenko and Khodakivska, 2018). However, these values still cannot provide a positive balance of nutrients.

Due to the degradation of black soils and desertification, biodiversity have been lost, small (and sometimes large) water bodies are drying up, eutrophication of water bodies, groundwater pollution is increasing, the concentration of greenhouse gases in the atmosphere is increasing, and so on. Virtually all soil properties deteriorate as a result of irrational economic activity, especially in the context of global warming and under the influence of agrochemical pollution. As a result, most of the territory of black soils is unsuitable or suitable to a limited extent for growing environmentally friendly agricultural products (Boroday, 2019), which is of direct importance to society.

To minimize anthropogenic pressure on soils, the concept of organization and functioning of soil monitoring was developed (Medvedev, 2012) as well as a version with an emphasis on the experience of leading European countries (Balyuk and Medvedev, 2015). Accordingly, a set of measures was proposed to mitigate the current state and achieve a neutral level of degradation not only of black soils, but also of all soils of Ukraine (Baliuk, Miroshnychenko and Medvedev, 2018). Monitoring the neutral level of degradation, will provide effective approaches to assessing the actual condition of soils according to developed indicators and standards, as well as designing a roadmap for cooperation in the agricultural, climate, ecology, the soil science and other sectors (Dmytruk, 2021).

Kyrgyzstan

Kyrgyzstan is one of the most mountainous countries in the world. Black soils are developed in the mountains under grasslands, and their distribution is determined by the elevation of the terrain, and also related to the exposure, steepness, shape of slopes and other regional factors. Mountain black soils are widespread in the northern Tien Shan, on the mountain slopes of the Tassa-Kemin and Kastek ridges, on the northern slope of the Kungei Ala-Too and relatively less on the northern slopes of the Kyrgyz and Talas ridges. Black soils also occupy a considerable area on the slopes of the ridges that border the intermountain depressions and hollows of the central Tien Shan, in the eastern part of the Kungei and Terskei Ala-Too, Dzhumgal, Suusamyr, Naryn and At-Bashin ridges, on the northeastern slope of the Fergana range. Chernozem soils are also found in the western Tien Shan, on the slopes of the Fergana, Chatkal and Alai ridges and on the mountain slopes of the ridges surrounding the Ketmen-Tiubinskaya depression. Mountain Chernozem soils occupy various height marks, beginning from 1 400 to 2 700 m on shady, wet slopes and terraced ledges. In the Karkyra tract at an altitude of 2 000 – 2 200 m above sea level, there is up to 1 000 mm of precipitation per year. The exposure of slopes has a great influence on the formation of mountain black soils. The slopes of the northern and northwestern expositions are more protected from significant insolation, so they create favourable conditions for the diversity and good growth of herbaceous vegetation, which is replaced by bushes of rosehip, stem, barberry and woody vegetation. Under a lush variety of grass and cereal grass, black soils leached from carbonates are formed (Shpedt and Aksenova, 2021).

Mountainous relief of Kyrgyzstan creates certain conditions for the formation of black soils: mountainous and mountainous-valley soils. Mountainous conditions of soil formation determined the unique morphological shape and physical and chemical properties of these soils. Black soils located on uplifted plains and in the valleys are characterized by a relatively weak differentiation of the soil profile, a dark brown colour, and a relatively high content of humus (up to 10 percent) that penetrates deeply down the profile. In the composition of humus, the ratio of humic to fulvic acids ratio exceeds 1, it has a relatively narrow ratio of C: N = 8 to 9, deep leaching from carbonates, neutral reaction of the upper and weakly alkaline – of the lower horizons, and high cation exchange capacity (30 to 40 $cmol_c$/kg of soil). These soils are characterized by relatively high gross content of nutrients (Shpedt and Aksenova, 2021).

Mountain black soils differ from the mountain-valley ones by a more developed sod layer, sharp differentiation of the soil profile, dark brown, almost black colour, higher humus content (up to 15 percent), wider C: N ratio (9 to 11), and higher cation exchange capacity (Shpedt and Aksenova, 2021).

Root biomass of herbaceous vegetation is of great importance for forming the properties of black soils. According to Mamytov and Bobrov (1977) the number of roots accumulated in the 0 to 50 cm layer for the subgroup of Chernozems of the north Tien Shan mountains is on average 45.55 tonnes /ha, while for the Issyk-Kul Mountain Chernozems on the southern slope of the Kungei Ala-Too, the average is 44.61 tonnes /ha. In the northern Tien Shan mountainous tableland, Chernozems accumulate less root biomass than mountain Chernozems, within 29.60 tonnes/ha. In the Issyk-Kul basin, mountain and longitudinal Chernozems accumulate 34.26 tonnes/ha, while mountain chernozems accumulate 46.35 tonnes/ha. Thus, the annual inflow of root mass in the chernozems of mountain slopes is higher than in the mountain-hillsides.

As many authors note, annual root production represents one third of the total stock of organic matter in soil (Voronov and Mamytova, 1987). Thus, about 15.0 tonnes /ha of organic matter are accumulated annually in black soils of mountain slopes, and in the mountain-horizon soils this indicator is 9.90 to 11.4 tonnes /ha, which indicates the unevenness of biomass intake during their formation.

In the black soils in central Asia there is a correlation between C:N ratio and climatic conditions. The widest C:N ratio is observed in the Chernozems of the Issyk-Kul subgroup, as well as in the most humidified northern Tien Shan, and the lowest (in the western and inner Tien Shan). However, it should be noted that the first two subgroups are characterized by a wide C:N ratio only in the upper sod layers, and from a depth of 15 to 20 cm it sharply narrows, for the latter, there is a narrow C:N ratio throughout the profile. In these soils this ratio is gradually narrowed from high humus to low humus soils, from 11.0 in low humus soils to 13.4 in black soils rich in organic matter. A wide C:N ratio in mountain slope soils is conditioned by the presence of a large amount of resistant residue in these soils.

All black soils of central Asia have a pH between 6.9 and 7.3 in upper humus horizons and 8.5 to 8.6 in lower carbonate ones. Mountainous black soils do not contain easily soluble salts. The cation exchange capacity of alpine black soils exceeds 50 $cmol_c$/kg. Calcium prevails in the sum of absorbed bases. Magnesium content slightly increases and only in some cases reaches 30 to 31 percent of the sum.

Black soils in Kyrgyzstan are characterized by quite good structural condition and high water retention capacity. Over 80% of the topsoil has an aggregate size of less than 10 mm and more than 0.25 mm. Sufficient moistening, dense grass vegetation, and activity of earthworms in these soils are the main structural forming factors. However, if proper agricultural techniques are not followed, mountainous black soils can quickly lose their structure. During ploughing and irrigation, a compacted layer is formed, which should be periodically destroyed by changing the ploughing depth.

Agricultural use of black soils in Kyrgyzstan depends on terrain and climate conditions. Tableland and valley black soils have high fertility and are used for sowing grain, fodder and potatoes under irrigation and rain-fed conditions. Horticulture and beekeeping are widely developed on these soils. Mountain black soils are used as spring and autumn pastures and as hayfields, in some places under rainfed agriculture for grain crops. If proper agricultural techniques are not followed, the mountainous longitudinal chernozem soils quickly lose their structure and easily succumb to erosion processes, especially in irrigated areas (Duulatov *et al.,* 2021).

In the zone of irrigated black soils, scientifically grounded crop rotations are of great importance. On rich Chernozem soils it is possible to introduce crop rotations without perennial grasses but with obligatory steam for winter crops, annual legumes and cereals for grain and hay (Mamytov and Mamytova, 1988). It is recommended to practice activities that contribute to snow retention (such as ridges, wing plants, etc.), to fight weeds (such as oats, mussels, etc.) and apply organic and mineral fertilizers. Mountainous chernozem soils are used as autumn to spring pasture lands and are under great pressure. Herbs from year to year, productivity decreases, and the land is overgrown with prickly bushes and inedible weed vegetation. Farmers are insufficiently informed about special soil-protecting crop rotations, agrotechnical methods of zero tillage, there is practically no contour treatment, so they sow across slopes on lands with significant escarpment.

Improvement of pastures is possible only on relatively large and levelled areas – is the ploughing and sowing of legumes and cereals grass mixture. Good results are given by superficial improvement by harrowing, discarding with sowing of legumes and cereals grasses. The livestock load should be property distributed on rangelands, providing individual slops or areas of rest, which will contribute to individual slopes or areas of rest, contributing to a good growth of natural herbs. Studies of many research institutes (Yusufbekov, 1968; Mamytov, 1973) show that a one-year rest of cereals and grass meadow-steppe pastures increases yield by 40 to 50 percent.

Ecosystem services of mountain regions preserve the aesthetic and recreational potential of nature, secondly, the production of oxygen and carbon dioxide assimilation, supply of products and materials. Mountain forests and meadows have the highest potential to create a favorable climate for life in the field of humidification. Sequestration (content) of organic C in mountainous longitudinal dark chestnut soils is 2.33 to 2.91 percent (humus 4.0 to 5.0 percent), in mountainous longitudinal low humus chernozems is 2.33 to 3.49 percent (humus 4.0 to 6.0 percent), and in mountainous longitudinal medium humus chernozems is 3.49 to 5.81 percent (humus 6.0 to 10.0 percent). In mountain black soils, the content of organic C ranges from 2.33 to 11.62 percent. Gross organic C stocks in the upper 0 to 25 cm layer of black soils are 50.54 to 92.47 tonnes /ha.

Poland

1st category of the black soils: Arable use for over 100 years. Black soils in the Silesian Lowland (SW Poland) have the highest agricultural productivity in Poland. They were described by Bieganowski *et al.*, (2013). The black soils genesis is connected with climate fluctuation during the whole Holocene period as well as human impact, differentiating their morphology and properties depending on their position in the landscape. Soils in higher positions are well drained, but those situated in lower positions can be excessively moist in early spring. Draining of these soils guaranties proper soil moisture and water supply for plants during the vegetation season. Soil profile with SiL texture fulfill the criteria to Chernozems (IUSS Working Group WRB, 2015) with the sequence of soil horizons: Ap (0 to 26 cm); A (26 to 47 cm); ACg (47 to 60 cm); Cg (60 to 85 cm); Ckg (+85 cm). Very dark gray colour (2.5Y 3/1) humus horizons reached 47 cm. The soil indicates granular fine structure in the humus horizon and visible stagnic properties starting from ACg horizon. Earthworm channels and crotovinas are visible in the whole profile. The content of Total Organic Carbon (TOC) in the Ap horizon reach 2.13 percent and the stock of TOC achieving 120 tonnes/ha. Despite the carbonate absence in the surface horizon, soil pH is alkaline in whole profile and base saturation is in range of 90 to 100 percent (Table 2.7).

2nd category black soils: Meadow use for over 100 years. The profile is located on the Holocene floodplain (1.5–3 m above the river level) with varying degrees of drainage. The soil, despite the SL texture reached 33 cm thick humus horizon. The sequence of soil horizons as follows: Ap (0 to 33 cm); Cg1 (33 to 50 cm); Cg2 (+50 cm) and the redoxymorphic features appeared directly below the humus horizon. The morphology of the soil profile can presume that the humus horizon was created by the conditions of agricultural use. The evidence of deep ploughing is visible as an abrupt humus horizon boundary and as a granular fine structure of the humus horizon. Due to high humidity, the soil has a reduced biological activity. The content of TOC in Ap horizon reaches 3.18 percent and the stock of TOC achieve 142 tonnes /ha. Due to the carbonate absence, soil pH is acid in the whole soil profile with base saturation is in range of 25 to 41 percent (Bieganowski *et al.,* 2013) (Table 2.5.4).

Table 2.5.4 Selected properties of different types of black soils

Source: Bieganowski, A., Witkowska-Walczak, B., Glinski, J., Sokolowska, Z., Slawinski, C., Brzezinska, M. & Wlodarczyk, T. 2013. *Database of Polish arable mineral soils: a review.* International Agrophysics, 27(3).

Properties	Explanation (short, referenced)	
	1st Category black soils	2nd Category black soils
Soil texture	silt loam (SiL)	sandy loam (SL)
Soil structure	granular, fine	granular, fine
Soil porosity	47 percent	40 percent
Soil colour	2.5Y 3/1	10YR 2/1
Soil chemistry	2.13 percent TOC, 0.18 percent TN, pHH2O 7.23, ECEC 30.0, BS 97 percent	3.18 percent TOC, 0.18 percent TN, pHH2O 4.8, ECEC 11, BS 25 percent

In Polish conditions, the majority of soils meeting the criteria of black soils are developed on carbonate-bearing thick loess deposits, alluvial and colluvial (humus-rich) materials, limestones and other carbonatic rocks. Black soils developed from loess poses islands in the loess belt in southern part of Poland. Black soils may also occur in flat positions in the river valleys and other depressions or footslopes. Some of them are present in the fine slopes and in the hilly areas where limestones have occurred.

Due to their high productivity potential, some of black soils were being intensively used as arable land already in the Neolithic period which is confirmed by archeological findings. Some areas covered by "wet" black soils were drained, which enabled their agricultural use as arable land but part of them remained unchanged, as grassland.

The black soils in Poland are primarily used for food and fibre production due to their high fertility. They were characterized in terms of their susceptibility to compaction and aeration constraints by Domzal, Glinski and Lipiec, (1991), as well as other authors. Most black soils are located far from contamination sources, therefore they are referred to as non-contaminated. This assumption was partly confirmed by a country-wide monitoring programme. Black soils under grasslands and forests are used for walking and contemplation. They may also provide cultural experiences due to archeological findings.

Black soils are important for climate change mitigation and adaptation. This part of ecosystem services is not widely implemented by agriculture because black soils are intensively used for food production. They undergo the degradation processes accelerated by a lowering pH and reduction in organic carbon content. The degradation processes of black soils in Poland are indicated by soil acidification and the water erosion, which influence the loss of organic matter. The erosion process is usually accelerated by the tillage preferred by farmers. Due to their texture, black soils with higher content of clay are threatened by soil compaction.

2.5.4 Latin America and the Caribbean

Argentina

Black soils of midlatitude grasslands. In Argentina, most of the black soils are found as zonal soils in the grasslands of the eastern part of Pampa region, in the center-east of the country, within the limits of the temperate zone, roughly between the latitudes 31° south and 39° south (Figure 2.5-A). The Pampa is an extensive plain, in which totally flat areas alternate with gently undulating plains and with rolling landscapes, and several sub-regions are identified based on environmental features (Figure 2.5-B) (Durán *et al.,* 2011). In the eastern part of the Pampa, the mean annual temperature varies from 16 °C in the south to 19 °C in the north, and the mean annual rainfall varies from 750 mm in the southwest to 1 100 mm in the northeast. Spring and autumn receive the most rainfall, while winter has the least. According to Soil Taxonomy, the soil moisture regime is udic while flat and low-lying lands have an aquic moisture regime. The natural vegetation includes large grasslands and steppes with medium height perennial and annual grasses. (such as *Andropogon, Bothriochloa, Stipa, Poa, Panicum, Paspalum*). The landscape has been greatly modified by agriculture and livestock activities, and the original vegetation only remains in some areas of lower agricultural aptitude.

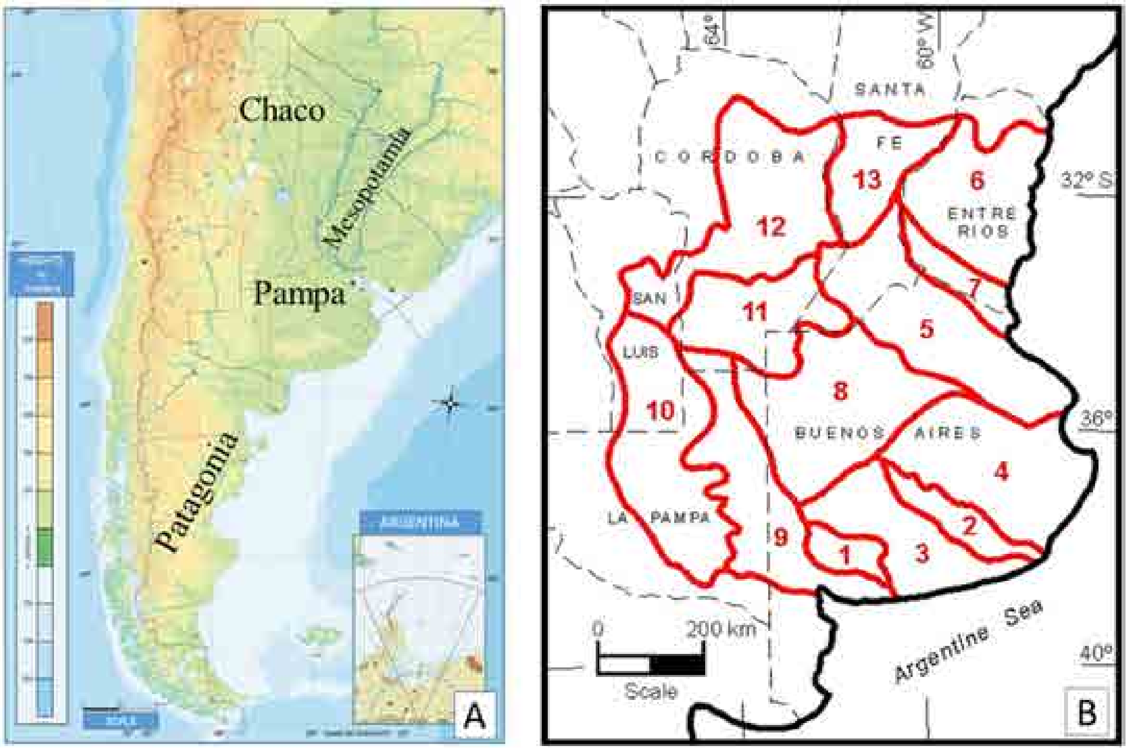

Figure 2.5 Distribution of main ecological regions in Argentina

A, Map of Argentina with the main ecological regions mentioned in this text. B, Sub-regions of the Pampa: 1- Hill range and piedmont of Ventania; 2- Hill range and piedmont of Tandilia; 3- Interrange Pampa; 4- Depressed or Flooding Pampa; 5- Undulating Pampa; 6- Mesopotamian Pampa; 7- Delta of the Parana river; 8- Sandy Pampa; 9- Polygenetic Pampean plains; 10- western or Dry Pampa; 11- Endorreic Pampa; 12- Piedmont Pampa (piedmont of the Cordoba and San Luis hill ranges); 13- Flat Pampa of Santa Fe

Source: Durán, A, Morrás, H., Studdert, G. & Liu, X. 2011. *Distribution, properties, land use and management of Mollisols in South America*. Chinese Geographical. Science, 21 (5): 511–530.

Note: The designations employed and the presentation of material in the map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.

The Pampa region is a large and deep sedimentary basin. Rocky hills occur only in the south of Buenos Aires province (Tandilia and Ventania hills) (Figure 2.5-B). The most recent Quaternary deposits lying on the surface, and therefore the parent material of Pampean soils, are loess and loessoid sediments to the east and aeolian sands to the west. The bulk of these sediments of Late Pleistocene-Holocene age came from andesitic and basaltic rocks and tuffs deposits from the Andes piedmont and northern Patagonia, as well as direct falls of volcanic ash from different sources in the Andes cordillera, to which are added contributions from a diversity of igneous, metamorphic and sedimentary rocks from other sources located around the region. As a consequence of aeolian transport by the predominant southwestern winds, a granulometric sorting of sediments took place, this being in the origin of the differentiation between the coarser sediments to the west and the finer to the east. Unlike the typical loess of the northern hemisphere, where quartz predominates, in the Pampean loess the set of light minerals is characterized by the abundance of volcanic glass, while pyroxenes and amphiboles are usually abundant in the heavy fraction (Zárate, 2003; Morrás, 2020). With regard to the clay fraction, illite is the dominant mineral in most of the region accompanied by traces of kaolinite, while interstratified illite-smectite and smectite increase and become predominant to the east, close to the Parana river and the Atlantic Ocean (Durán *et al.,* 2011). A petrocalcic layer, considered Plio-Pleistocene in age and covered by a thin mantle (less than 1.5 m thick) of Holocene loess, is widespread in the southern part of the Pampa region. In the northern Pampa the calcrete, usually discontinuous, occurs at higher depth and is covered by a thicker mantle of Pleistocene and Holocene loess.

Pampean black soils are mainly Mollisols, and among them, Argiudolls and Hapludolls are the most representative (Durán *et al.,* 2011; Rubio, Pereyra and Taboada, 2019). Two sectors are characterized by a larger proportion of black soils: the Undulating Pampa to the northeast, and the hill ranges and the interrange area to the south. In the northern part of Undulating Pampa (5-Figure 2.5-B) the drainage network is well defined, and the relief is gently undulating (slopes of about 2 percent and up to 5 percent). Typic Argiudolls are the most extensive; the mollic epipedon has at present about 2 percent of organic carbon, the argillic horizon is deep with a clay content that ranges between 30 percent to the west and 50 percent to the east, and the solum easily reaches 120 cm depth; calcium carbonate nodules frequently occur in the BC and C horizons. Also Vertic Argiudolls are common in the margins of the Parana-de la Plata fluvial axis, due to the higher content of expanding clay minerals in the soil parent material (Morrás and Moretti, 2016). In the southern part of the Undulating Pampa Vertic Argiudolls are very extensive and Vertisols are frequent, with Aquic Argiudolls and Argialbolls occurring in concave micro depressions.

On the other hand, in the Tandilia and Ventania mountain systems, loessic sediments have covered the igneous and metamorphic rocks with different thicknesses, from a few centimetres to almost to 2 m. All the soils belong to the Mollisol order, and their properties depend on the thickness of the loess cover and the contact with the underlying material. In the hill range of Tandilia (2-Figure2.5-B) and in the Interrange Pampa (3-Figure 2.5-B), with a thicker sedimentary cover, the main soils are Argiudolls and Petrocalcic Paleudolls, with some Hapludolls. These black soils from the southern Pampa have higher contents of organic matter than the black soils from other areas of the Pampa (around 3 to 4 percent SOC). In the piedmont of Ventania (1-Figure 2.5-B), the moisture regime is transitional to ustic and the sedimentary veneer overlying hard rocks is thinner; dominant soils are Petrocalcic Paleustolls and Haplustolls, with some Calciustolls.

Other Pampa sub-regions have a lower proportion of black soils than the precedent. In the Sandy Pampa (8-Figure 2.5-B) the most extensive black soils are Hapludolls. They consist of a recent superficial loamy sedimentary layer of about 30 to 50 cm depth where an A-C or A-AC sequence overlies the buried argillic horizon of a paleosol developed in a silty loam sediment. Depressed Pampa (4-Figure 2.5-B) has udic to acuic regime, and soils are characterized by an excess of exchangeable sodium. Most black soils are represented by Natrudolls and Petrocalcic Paleudolls. The Flat Pampa of Santa Fe (13-Figure 2.5-B), north of the Undulating Pampa, is flat to gently undulating, with long slopes of less than 1 percent. The representative soils here are Typic Argiudolls, with a deep and highly clayey Bt horizon. In the western sector of the Mesopotamian Pampa (6-Figure 2.5-B) close to the Parana river, Typic Argiudolls and Vertic Argiudolls are developed in a mantle of loess covering lacustrine smectitic sediments. Pampean black soils, originally high in organic matter and of very high natural chemical fertility, have been cropped without fertilization from the end of nineteenth century until recently (Viglizzo *et al.,* 2010; Durán *et al.,* 2011). The main crops are wheat, corn, soybeans, sorghum, barley and sunflower. Soybean is the only crop that has steadily increased its acreage in the last thirty years, while the area under the other crops remained relatively stable or has decreased slightly. Extensive livestock production is also another important activity in the humid Pampa. It was only in the early 1990s that acute depletion of nutrients, particularly phosphorus, became apparent and that the use of fertilizers began to spread in the region. This depletion is linked not only to the extraction of nutrients by crops but also to erosion.

Swelling black soils (Vertisols). In Argentina, Swelling black soils (Vertisols), are found in various regions, but they are particularly relevant in the southern part of the Mesopotamian region (which includes de Mesopotamian Pampa), and other sub-regions in the eastern part of the Pampean region. Vertisols can also be found in restricted areas of the Argentine Chaco and the Patagonian region, although they are not mentioned in this section due to their limited geographical distribution. Instead, the works of Moretti *et al.,* (2019) and Pereyra and Bouza (2019) can offer further information on these black soils.

The Mesopotamian region is an extensive area framed by the great Paraná and Uruguay rivers (Figure 2.5-A). The landscape is characterized by numerous streams dissecting the Plio-Pleistocene fluvial-lacustrine sediments, resulting in a gently undulating relief. The climate is humid subtropical, with annual rainfall ranging from about 1 100 mm in the south to about 1 400 mm in the northern part of the area. The hydric regime is udic, or eventually aquic. The vegetation is a mix of open savannas, wooded grasslands and semidry forests. In this geographical context Vertisols are the main soils, occupying about 3 million hectares.

The parent material of Vertisols of this region, as well as of associated vertic Alfisols and Mollisols, is made up of sediments of silty-clay or clay-loam textures, with a predominance of smectites in its clay fraction and quartz in the coarse one, and with a considerable proportion of calcium carbonate, some gypsum and manganese and iron oxides segregations. Unlike most of the Vertisols in the world, a large part of the Vertisols in the Mesopotamian region present horizons that are described as argillic Bt, taking into account the notable increase in the amount of clay and the existence of clay coatings in the B and especially in the lower BC or C horizons (Cumba, Imbellone and Ligier, 2005; Bedendo, 2019). Many of these Vertisols have a linear "gilgai" micro-relief. Almost all Vertisols correspond to the Hapluderts taxonomic great group. In most Swelling black soils the A horizon has a silty-clay loam texture and a high content of SOC (2 to 3.5 percent). In turn, the B horizon is silty-clayey to clayey, very dark up to 70 cm depth (10YR2/1 – 10YR3/1, moist), very dense and with poor drainage. The transitional BC horizon has always some fine $CaCO_3$ in the groundmass and abundant calcareous nodules (gley features and small gypsum crystals can be occasionally found). The CEC in the epipedon is around 35 cmol/kg and in the Bt is around 45 cmol/kg, and they are highly saturated. These soils are mainly devoted to mixed crop-livestock production, a small proportion are used to grow rice. In recent years, soybean growing, has taken over these soils. Because of their low permeability, undulating relief, and summer rainstorms, these soils are prone to erosion. No-till and contour-line cultivation are now widely used to mitigate erosion problems.

In the rest of the Pampean region, Vertisols occur in the east of the province of Buenos Aires, in two clearly differentiated sectors: that of the Undulating Pampa and the coast of the Río de la Plata and in the littoral area of the Depressed Pampa (Figure 2.5-B).

Swelling black soils are present in moderate proportion in the southeastern part of the Undulating Pampa (5-Figure 2.5-B), developed in loessic Upper Pleistocene sediments with a silty-clay loam texture and about 50 percent smectite in the clay fraction. The Hapluderts in this region, similarly to those in the Mesopotamian region, also present illuvial Btss horizons; the clay content is about 35 percent in the surface horizon, reaching between 55 to 60 percent in the Btss. In this region, the diapiric structures and the "gilgai" micro-relief are poorly expressed. The O.C. content is around 2 to 2.5 percent in the A horizon. The CEC oscillates around 24 cmol/kg in the A horizon and 37 cmol/kg in the B horizons. Unlike Mesopotamiam soils, these Vertisols have lower $CaCO_3$ content in the Bt and do not present gypsum at the base of the profiles. Towards the north of the Undulating Pampa, along a strip of about 60 km wide that borders the Paraná-de la Plata fluvial axis, some Vertisols appear on relief tops and slope heads, associated to Vertic Argiudolls (Morrás and Moretti, 2016). These vertic soils are developed in sediments with a moderate to high proportion of smectite; they have diapiric structures, although no "gilgai" micro-relief is observed in the field, maybe as a consequence of the intense agricultural and urban intervention in the area. Their A horizon is brownish black (7.5YR3/2), with a SOC content about 2 percent and a 30 percent clay. In turn, the Btss horizon has more than 50 percent clay and is darker than the topsoil (7.5YR2/2) though the SOC is about 0.7 percent at 45 cm depth. Due to their close association in the landscape with Vertic Argiudolls, these Vertisols are used both for agriculture and for urban development.

The coastal plain of the Río de la Plata constitutes a long strip of about 5 to 10 km wide and about 110 km long from the city of Buenos Aires to the south. These sediments correspond to a middle Holocene marine ingression. Most of the Vertisols are Natracuerts, although Hapluderts are also present (Imbellone and Mormeneo, 2011). The clay fraction ranges between 50 and 70 percent in the solum, decreasing towards the base of the soils. The colour of the surface horizons is dark (10YR2/2 in some cases, 2.5Y3/2 in others) and the SOC content is around 2 percent. In the A or Ag horizon the CEC and the base saturation are high, with the pH oscilatting around 8 and increasing to pH 9 in the Bssg horizon.

On the other hand, Swelling black soils cover a large and extremely flat area in the easternmost sector of the Depressed Pampa, in a strip about 30 km wide from the coast (4-Figure 2.5-B). Vertisols are developed in muddy sediments deposited in the plain during Upper Pleistocene and Holocene marine transgressions. They are very clayey from the surface, with high levels of salinity and alkalinity. Swelling black soils here are Natracuerts and Hapluderts. The SOC content is very high, ranging between 2 and 15 percent. The clay content oscillates between 40 and 50 percent in the A horizon and amounts to 55 to 65 percent in the Btss horizon. Both the CEC and the base saturation are high, while the exchangeable sodium ranges between 15 and 25 percent in the Btss horizons. Due to the limitations imposed by the environment, these soils are used exclusively for livestock production.

Volcanic black soils. Andisols in Argentina are found in the Andean-Patagonian region (Figure 2.5-A) (Pereyra and Bouza, 2019). This is a belt of mountains extending from 37° south to 54° south in the southwestern part of the country. The average altitude is around 2 000 metres above sea level and the valleys are aligned N-S according to the Andean structure. Great lakes associated with moraine landforms are found along the region. The climate is cold humid and shows great spatial variability. Precipitation decreases markedly from about 3 000 mm at higher altitudes to the west, to about 700 mm in the piedmont to the east. The vegetation is a cold-temperate humid forest called the Subantarctic phytogreographic province characterized by Nothofagus, also including Araucaria araucana among other tree species.

Surface sediments have great spatial variability, predominating colluvial deposits, tephra and volcanic ash, till, gravel and fluvial sands. Andisols are very frequent in glacial valleys, glaciofluvial plains, lower slopes screes and morenic arcs. These soils can occupy any position in the landscape and can occur at any elevation. Their parent materials are volcanic ash or lapilli of mesosilicic to acidic composition, mixed in varying proportions with colluvial material and glacier materials. The soil temperature regime is cryic, and the soil moisture regime is udic, ustic, xeric or aquic. The most common profiles are O-A-Bw-C or O-A-AC-C. The surface mineral horizons are mollic, melanic or umbric; their colour is 10YR 2/1–2/2 (dry), the organic carbon is around 5 percent, the pH is around 5, the texture is sandy loam and the bulk density is below 1. They are characterized by a high content of allophanic materials and a strong phosphate retention. In general, these soils exhibit an incipient Bw horizon with a high CEC due to the presence of allophane and high organic matter content. According to the Soil Taxonomy the most frequent Andisols are Hapludands and Udivitrands. In the lower and humid areas of the landscape, usually on the floor of the glacial valleys, Andisols are hydromorphic and rich in organic matter (Endoacuands). The Andisols of Argentine Patagonia largely comprise protected natural areas and a small proportion are dedicated to afforestation with foreign species.

Black soils of subtropical regions. The Argentine Chaco is a large sedimentary plain in the center-north of the country that presents a variety of climatic and vegetation environments (Figure 2.5-A) (Moretti *et al.,* 2019). Rainfall is highest to the east, in the areas surrounding the Parana and Paraguay rivers (about 1 300 mm per year), gradually decreasing to 450 mm in the southwestern boundary of the region. Mean annual temperatures rise from 19 °C in the limit with the Pampean region to 24 °C in the northern border of Argentina. Unlike the Pampean grasslands, the vegetation in the Chaco is mainly characterized by forests and savannas, although herbaceous communities are typical in the extensive alluvial plains and wetlands of the eastern part. The geology of the Chaco is equivalent to the one described for the Pampa, although the surface sediments differ somewhat in their composition, origin and distribution. Generally speaking, late Pleistocene loessoid sediments cover large areas in the central and western Chaco while Holocene fluvial silty and clayey sediments are widespread in the eastern alluvial floodplains. The scarce information available on the mineralogy of the Chaco soils shows compositional differences between different sectors of the region in relation to the existence of sedimentary contributions from different sources. Thus, the geochemical composition of the materials differs and consequently the fertility of the soils is varied. In the central and the western sectors, the soils are characterized by high phosphorus and potassium contents, related to the sediments contributed by Pampean Hills and Andes cordillera. Conversely, the eastern sector presents lower contents of those elements due to predominance of sediments from the Paraná basin.

Black soils are found in three distinct sub-regions: in the Mountain Chaco, in the Xerophytic Woody Chaco and in the Chaco´s Grasslands and Savannas. The Mountain Chaco integrates the eco-region of Yungas, a subtropical forest which characterizes the mountain system of northwestern Argentina and within which the climate becomes more humid with the altitude. Black soils develop on gentle slopes, in the lower parts of the eastern piedmont. Argiudolls and Hapludolls are found in the most humid sectors, and Argiustolls and Haplustolls in sub-humid sectors. The texture of the parent material is varied but many are silt loam, the SOC content ranges from 1.5 to 2.5 percent, they are deep and are the most developed in the western Chaco. Rainfed agriculture is practiced on these soils, the main crops being beans, soybeans, corn and wheat. In the southernmost part of the Xerophytic Woody Chaco, in the limit with the Pampa, black soils appear in the eastern foothills of northern Pampean Hills. The soil parent material is constituted by loamy fluvio-aeolian deposits, and the dominant soils are Haplustolls. The pH of the epipedon is around 7, the SOC is about 1.8 percent and the content of soluble phosphorous is high (40 to 60 ppm P). These soils are used for extensive rainfed agriculture. Finally, the Chaco's grasslands and Savannas sub-region (also known as Sub-meridional lowlands) is an extremely flat and monotonous herbaceous plain that stretches north-south for roughly 300 kilometres and is bordered to the east and west by higher regions with forest vegetation. The edaphoclimatic regime is hyperthermic udic, and most soils exhibit hydromorphic and halomorphic features, with a wide variety of salty, saline-alkaline, and alkaline soils observed in connection to meso and microrelief changes (Morrás, 2017). The majority of the territory is covered with Natracuolls with highly salinized Bt horizons (E.C. about 12 ds/m at 60 cm depth). The epipedon of most of these soils is composed of an A horizon that is only about 10 cm deep, dark (10YR 2/1, moist), with 20 percent clay and 2 to 4 percent organic carbon, and a Bt1 horizon that is dark (10YR 2/2, moist), with 30 to 40 percent clay and 1 percent organic carbon. Although the salty content in the subsurface horizons is substantial, the textural and structural difference between the A and Bt horizons acts as a barrier to the capillary rise of saline water, which is why the A horizon is non-saline (EC <4 ds/m). When this barrier is breached by conventional tillage, salt levels rise and salty efflorescence forms on the surface. Because of the significant danger of deterioration, the only use for these black soils is grazing.

Brazil

Genetic groups and geographical distribution. Three groups of soils fit the definition of black soils in Brazil. The first and dominant group is the Tropical black soils, with parent materials derived from basalt, gabbro and diabase (Dematê, Vidal-Torrado and Sparovek, 1992) or calcareous rocks (Pereira *et al.,* 2013; Melo *et al.,* 2017; Maranhão *et al.,* 2020). The dominant climate is tropical dry, with moderate water deficiency or semi-arid. Soil profiles, in general, occur on flat to strongly undulated slopes, uplands and backslopes, with surface horizons up to 65 cm of thickness and soil profile depths less than 130 cm. They show high content of Ca and Mg, with a predominant loamy to very clayey texture. When in the lowest part of the slopes, due to the presence of expansive clays (smectites), soils are very hard when dry and very sticky when wet. In some areas with gentle slopes, soils are poorly drained (Dematê, Vidal-Torrado and Sparovek, 1992; Pereira *et al.,* 2013; Melo *et al.,* 2017; Maranhão *et al.,* 2020).

The second group, the Midlatitude black soils, represent a relict in the landscape, formed in much cooler and drier conditions in the mid-Holocene, according to Behling (2002). Today, the climate is warm and moist. The parent material is mainly basalt and diabase, and siltstone and argillite. The soils are generally shallow, with the surface horizon thickness reaching 60 cm and the soil profile depth is less than 100 cm. They have high content of Ca and Mg, and a loamy to very clay texture. When poorly drained and with expansive clays, the consistency is very hard when dry and very sticky when wet (Almeida, 2017).

The third group is the Anthropic black soils, represented by the Amazon Dark Earths (ADEs), also called locally "*Terra Preta de Indio*". The most accepted hypothesis for the genesis of these soils, based on pedological and archaeological evidence, is that they were formed unintentionally by pre-Columbian Amerindian societies in the Amazon basin (Kern and Kampf, 1989; Schmidt *et al.,* 2014; Kern *et al.,* 2019). The anthropic A (Au) horizons have a thickness up to 200 cm and colours ranging from very dark to black, with yellow or red colours in the subsurface horizons, marking a clear differentiation in the profile. By definition, the Anthropic horizon is marked by high fertility, when compared to adjacent soils, high contents of P, Ca and Mg, and stable organic matter (usually as charcoal), in addition to the presence of cultural artefacts. In general, they are well drained and have a texture ranging from sandy to very clayey, with a clear differentiation between anthropic A horizon (with loamy sandy, sandy loamy and clay textures) and subsurface horizons (with clay-sandy and clay textures) (Campos *et al.,* 2011).

In Brazil, the Tropical black soils represent a hotspot and they occur in small extensions under specific soil forming conditions. The vegetation in many sites is designated as "dry forest" including: Tropical deciduous forest, with high canopy trees and rich plant undergrowth (Caatinga, tall deciduous and semi-deciduous forests in dry semi-arid climates) and the Cerrado (a mixture of open grasslands, shrub lands, open woodland, and closed canopy woodlands). In the Midlatitude black soils, there is a uniqueness of grasslands in a plain to slightly undulated landscape referred to as "campos" or "pradarias" (Overbeck *et al.,* 2007). The vegetation is dominated by grasslands, from plain to a slight shrubs and occasional small trees within the grass matrix (Cabrera and Willink, 1980). In other regions, trees form gallery forests and shrub forests (Overbeck *et al.,* 2006).

The Anthropic black soils (ADEs) occur in discontinuous patches, and they have varying sizes, from less than a hectare up to ten times this area, usually near to watercourses and floodplains, in adjoining higher elevations (*Terra Firme*). Their locations are associated with availability of food and other resources from different environments (land and rivers); and the topographic position allowing the control of access routes and visibility for defence (German, 2003).

Land use and management. Regarding land use of Tropical black soils in Brazil, the dry climate, high slopes and the shallow soils with presence of rocks limit intensive agriculture. However, in small farms they represent an important asset, and are cultivated with annual crops, horticulture or used as native pastures. In the "*campos or pampas*" region, the native grassland of the Midlatitude black soils has been used for extensive livestock (beef and dairy cattle, and sheep) (Overbeck *et al.,* 2005), since the seventeenth century. Recently annual crops such as corn, rice and soybeans, and managed pasture with exotic species, are replacing the traditional systems (Pillar, Tornquist and Bayer, 2012; Roesch *et al.,* 2009; Almeida, 2017). Animal overgrazing on the native grass fields, can be considered a soil management threat (Overbeck *et al.,* 2007). Andrade *et al.*, (2015) showed that a large area of native grassland was lost, mostly due to the conversion to arable fields (mainly soybeans) or tree plantations. In some areas, they were nearly completely transformed into croplands, and a considerable part of the remaining grasslands, although mapped as conserved environments, have been degraded by the introduction of exotic forage species, deliberately seeded in some areas and colonized by different means of dispersion in others.

Across the Amazon region, Anthropic black soils are largely used with crops in small farms, where the management is based on the high natural fertility. In some sites, the surface soil is removed and sold as substrate for pot plants, which represents a threat for the farmers and loss of a cultural heritage.

Ecosystem services. The areas of Tropical black soils are recognized by their beautiful and diverse landscapes and the valuable underground water reserves. Some of the karst areas served as a shelter and source of food since the dawn of mankind in the Americas, as proven by cave paintings and archaeological remains. Besides the scientific, cultural, tourism, and environmental value, these areas are also important for small farmers, due to the high fertility of the soils, allowing for high production of many crops and forage for animals. In the Midlatitude black soils, the forage production for livestock was dominant. By the end of the twentieth and early twenty-first centuries, this usage changed to intensive crop cultivation in the summer, with corn, wheat, and, in smaller size farms, irrigated rice (Pillar, Tornquist and Bayer, 2012; Roesch *et al.,* 2009; Almeida, 2017). The areas of ADEs are widely used in food production, in the so-called subsistence agriculture with the cultivation of crops such as cassava, corn, beans, vegetables, cocoa, coffee, fruit trees and pastures, in small and medium farms (Santos *et al.,* 2013; Cunha *et al.,* 2017; Santos *et al.,* 2018a).

The natural coverage in protected areas of tropical and midlatitudes black soils favor infiltration and conservation of water, and the hydrological fluxes are restricted by presence of underground bedrocks or by the shallow soil profiles. The grassland ecosystems of "*campos*" ensures the conservation of surface water resources and groundwater and offers scenic services with a major tourism potential. ADEs are associated with watercourses, supporting, in many cases, riparian forests. They play an important role in maintaining and conserving water resources. Their higher water holding capacity and better soil physical properties ensure adequate flow and storage of water in the soil profile.

The black soils in Brazil occur in small areas but with different biomes, such as Amazon, Cerrado and Caatinga. Even in the least known "*campos*" environment of the south region, with the Midlatitude black soils, a high biodiversity is observed with about 2 200 plant species, and at least nine grassland species are endemic (Overbeck *et al.,* 2007). In ADE areas, Lins *et al.*, (2015) found traces of exotic and native species, evidence of pre-Colombian human occupation.

In addition to the accumulation of organic carbon, the Tropical black soils of semi-arid regions have high stocks of inorganic carbon in the form of carbonates. Studies show the potential to mitigate greenhouse gas emissions in areas converted to agriculture by using systems with legume-based crop rotations combined with no-till (Pillar, Tornquist and Bayer, 2012). In the "*campos*" environment, Conceição *et al.*, (2007) observed an increase in the C stocks (0 to 40 cm) under the lowest grazing pressure management, where the values for high grazing pressure were of 103 tonnes C/ha and 140 tonnes C/ha for lower grazing. The ADE soils present, on average, up to six times more stable organic matter than adjacent soils without an anthropic horizon, appearing as a large reservoir of SOC. Studies show variations in the evolution of greenhouse gas emission in crop systems. Cunha *et al.,* (2018) found efflux values for forest environments of 1.91 μmol/m^2/s, for pigeon pea of 2.29 μmol/m^2/s and for pasture of 2.26 μmol/m^2/s, showing that forested environments emit less carbon into the atmosphere than cultivated ones. Campos *et al.*, (2016), studying the CO_2 efflux in the same region, found, in ADE areas cultivated with cocoa, an efflux of 5.49 μmol/m^2/s, while when with coffee, CO_2 efflux was 3.99 μmol/m^2/s.

Carbon stock and stability. The C content for Tropical black soils varies from 4.9 to 111.7 g/kg (Demattê, Vidal-Torrado and Sparovek, 1992;

Pereira *et al.,* 2013; Melo *et al.,* 2017; Maranhão *et al.,* 2020). The Cseq potential of representative soil profiles shows values from 72.8 to 188.5 tonnes C/ha, for superficial horizons, and from 72.8 to 422.9 tonnes C/ha for the soil profile. The Midlatitude black soils have C content from 7.6 to 50.4 g/kg (Pinto and Kämpf, 1996; Almeida, 2017). The Cseq potential of representative soil profiles shows values from 59.9 to 269.5 tonnes C/ha, for superficial horizons, and from 112.7 to 278.1 tonnes C/ha, for the soil profile. About stability, the high aggregation in natural conditions is a positive factor on both groups of black soils, especially under grasslands, but it is significantly modified when intensively cultivated. The ADEs show C contents from 0.9 to 98.9 g/kg in the anthropic A horizons. In representative profiles of Brazil, the Cseq varied from 26.1 to 348.1 tonnes C/ha for superficial horizons (Cordeiro, 2020).

Major threats and degradation processes. In Tropical black soil salinization, in semi-arid climates, and nutrient leaching are major threats. Another threat is soil erosion, mainly due to location in higher slopes and the incidence of high intensity rains, mostly concentrated in a short period of time. For Midlatitude black soils, overgrazing in the native pastures, erosion and the invasion of exotic species, grasses and shrubs or trees are the most important threats. When intensively cultivated for agriculture, soil compaction and sealing increase (Overbeck *et al.,* 2007; Roesch *et al.,* 2009; Andrade *et al.,* 2015; Modernel *et al.,* 2016). According to Silveira *et al.,* (2017), in the "*campos*" (Pampas biome), the usage with summer croplands increased 57 percent in 15 years, with a strong impact due to drainage (except for rice paddies), accelerating organic matter decomposition, thus reducing SOC. The ADEs have also undergone changes, with the natural forest substituted by agricultural systems (Aquino *et al.,* 2014). In the short term and in small farms, these changes have not severely affected the soil fertility (Oliveira *et al.,* 2015a; 2015b; Santos *et al.,* 2018b). However, it is expected that practices such as burning for area cleaning, animal overgrazing and the non-replacement of soil fertility, will certainly lead to acidification, erosion, compaction, and loss of soil biodiversity and cultural heritage.

In the Tropical and Midlatitude black soils, the presence of expansive clays (smectites) limits mechanization and influences the water permeability and infiltration. The increased pressure by livestock systems is leading to overgrazing, thereby reducing the potential of the native grassland fields. Crops systems are implemented in these lands without proper evaluation of potential and limitations. In the last decades, the advance of the agricultural frontier over forested areas in the Amazon has been a major threat to the ADEs, especially in the region called "Deforestation Arc", a Cerrado-Amazon Ecotone that extends from Maranhão to Rondônia States (Cohen *et al.,* 2007), which major expansion of planted forestry, agriculture, pastures and the extraction of non-timber products. The status of black soils degradation has still to be evaluated and much research is needed. Emphasis should go on losses of SOC and water erosion, when intensively mechanized and after changes in land cover, as well as loss of biodiversity due to competition with exotic species in the grasslands. Fewer studies are available for ADEs, and they are contradictory. Some indicate that agricultural usages (pastures, banana, forest, beans, cocoa and coffee) negatively influence physical attributes (density, porosity, macro and microporosity) in layers up to 20 cm deep. However, Cunha *et al.*, (2017) showed that ADEs cultivated with pigeon pea or with planted forest improved the soil physical quality, with increase in SOC, carbon stock and dominance of aggregates > 2 mm. The Midlatitude black soils played a central role in the cultural and economic history of Brazil. The residents of the South American Pampas (*Gaúchos*) developed a strong tradition based on the livestock in crop rotation with rice, soybeans, corn and wheat, which is still is reflected in their customs and daily practices. In the last decades, large farms have became dominant with major investments in crop production. The evaluation and zoning of areas suitable for grazing, crops, forest and preservation, can help to conserve the soils, and give ecological alternatives such as tourism (Roesch *et al.*, 2009). The ADEs are defined by cultural markers and their anthropological value. They are considered a National Heritage, according to the National Historical and Artistic Heritage Institute (IPHAN) and thus they should be protected. The highly fertile soils are essential for supporting Amazonian Indigenous Peoples and "*caboclos*", with a rich diversity of foods being produced in small plots and family farms. Over the years, the expansion of agriculture and pastures for livestock in the Amazon changed landscapes and vegetation cover, promoting changes on ADEs and adjacent soils. Thus, one way of reducing degradation of the ADEs would be by intensifying the mapping of these areas, and to restrict their usage to family farmers and traditional communities, while promoting sustainable practices.

Peculiarities in genesis and properties. The vast majority of the soils of the southern Patagonia of Chile are of glacial origin, derived from the retreat of large masses of ice and subsequent entry of the sea through channels at the end of the Quaternary. This phenomenon modified the landscape creating undulating sectors that are locally called "vegas" or wetlands meadows. There is great variability in the type of soils associated with these wetlands where Histosol, Fluvisol, Gleysols, Regosols, Solonchak, Solonetz and Verstisols can be found (Filipova *et al.,* 2010). The vast majority of these soil types contain large amounts of SOC; but, they also differ in pH level (related to the absence/presence of carbonates) and the electrical conductivity. The mineral soils associated with wetlands have thick textures in the first horizons, however, as one goes deeper, finer textures are found, reaching semi-impermeable layers, giving them the ability to store and conduct large amounts of water. They are not well-structured soils. The structure is associated with a large number of fine and thick roots in the first horizons. They have dark colours ranging from black, dark gray, and dark brown in the first horizons. However, the colour is highly dependent on the mineralization rate of the large amounts of organic matter associated with these soils (Filipova *et al.,* 2010; Valle *et al.,* 2015).

Coverage and geographical regularities in the distribution. The geographical distribution of this wetlands meadows throughout all of Chilean Patagonia covers an area of around 2 600 ha of meadows in the province of Aysén, 8 500 ha in the province of Coyhaique, 3 800 ha in the province of Capitán Prat, and 1 700 ha in the province of General Carrera, in the Aysén region (CONAF, 2006). In the Magallanes region, according to the Servicio Agrícola y Ganadero, the area of wetlands is 81 500 ha in the province of Tierra del Fuego, 105 700 ha in the Magallanes province and 51 800 ha in the Ultima Esperanza province, occupying 6.9 percent of the sector (SAG, 2003; SAG, 2004a; SAG, 2004b).

Land use and management. The wetlands described here are associated with livestock production in the Magallanes region. This activity was established in the second half of the nineteenth century, through large land grants by the State and an important bet of private companies (Strauch and Lira, 2012). In the Magallanes region, more than 56 ha of the sheep mass of the country and around 141 759 cattle (INE, 2007). The type of livestock is characterized by being extensive and continuous. This means that a large amount of land area is required to support few animals, with the average stocking rate being one sheep per hectare.

Ecosystem services

- **Food, feed, and fibre production, these soils are mainly sustaining prairies destined for sheep and cattle.**
- **Water regulation, this type of ecosystem allows to solve the evaporimetric demands thanks to the large amount of water they accumulate (Ivelic-Sáez *et al.*, 2021).**
- **Biological diversity**
- **Climate change mitigation and adaptation**

Carbon stock and stability. Here, we summarize data published by Filipova (2011) and Valle *et al.*, (2015). See table 2.5.5.

Table 2.5.5 Carbon stock of different types of soils

Source: Filipová L. 2011. *Soil and vegetation of meadow wetlands (Vegas) in the South of the Chilean Patagonia*. Faculty of Science Department of Botany, University Olomouc. PhD dissertation and Valle, S., Radic, S. & Casanova, M. 2015. *Soils associated to three important grazing vegetal communities in South Patagonia*. Agrosur, 43(2): 89–99.

Soil Type (WRB)	Local Name	UTM coordinates	Deep (cm)	tonnes C /ha
Haplic fluvisol	Cabeza de Mar 1	19F0071016;4160004	27	353
Parahístic gleysol	Campo El Monte-1	19F0067913;4162976	31	167
Haplic gleysol	El Álamo	19F0515511;4066613	53	108
Humic fluvisol	Quinta Esperanza	19F0401676;4147744	40	395
Haplic vertisol	Cerro Castillo		100	399
Gleyic solonetz	Laguna Blanca-1	19F0353128;4202000	41	89
Gipsyc solonchak	Laguna Blanca-2	19F0352595;4204986	38	104
Histic fluvisol	Domaike-2	19F0352157;4173300	20	239
Histic fluvisol	Estancia Springhill	19F0477297;4165874	64	149
Calcaric-Humic fluvisol	Parque-Josefina	19F0370477;4165476	90	963
Folic gleysol	Entrevientos	19F350365S;4170106	90	272

Major threats and degradation processes. In Patagonia, the wetlands meadows, are degraded by overgrazing, with signs of strong compaction due to trampling, reduction of plant richness, and invasion of exotic species. Overgrazing changes the structure of vegetation communities, allowing the dominance of indicator species such as *Caltha sagitata* in salty wetlands and *Azorella trifurcata* (Díaz Barradas *et al.*, 2001). This can be corroborated based on studies in Vegas prior to the introduction of sheep, where a low presence of the two species is mentioned (Dusén, 1905). Having prostrate growth, sclerophyllous leaves, the presence rhizomes, and other types of vegetative growth, allow *Caltha* and *Azorrella* to resist grazing, as they can better compete for light versus other taller species, but not very tolerant of continuous grazing (Díaz Barradas *et al.,* 2001). In oil exploitation areas, there is threat of contamination by hydrocarbons (Collantes and Faggi 1999). In Tierra del Fuego, overgrazing sheep and trampling interact with the strong winds of the Fuegian steppe, constituting the main agent of degradation of the wetland's soils (Iturraspe and Urciuolo, 2000). Furthermore, in many cases, drainage has caused the formation of deep cracks that then prevent the ue of paddocks as pastures, with the exclusion of sheep then promoting the growth of competitively strong grass species (Filipova, 2011). The progressive degradation of these types of soils has resulted in the reduction of animals by 16 percent (INE, 2014) since 2007.

Colombia

Black soils in highlands. The parental material has played a very important role in the formation and evolution of moorland soils, despite being considered a passive factor in the edaphogenetic process. In the central and western Cordilleras, and in some areas of the eastern Cordillera, soils have been developed from the weathering of volcanic ash. In the highest part, above 3 800 metres, the volcanic glass is not altered (Vitric Andosols), while between 3 200 and 3 800 metres they are more differentiated (Aluandic and Silandic Andosols, some of them Gleyic). In the definition of these characteristics, low temperatures and relatively young soils play a fundamental role (Morales *et al.,* 2007). In the eastern Cordillera (within the Sumapaz area), partly on calcareous and ashless rocks, there are soils of the reference groups Leptosols and Cambisols, and organic skeletal and, locally, very organic soils (Histosols). Above 3 800 metres above sea level, where low temperatures are a dominant factor, there are Cryosols. In the Sierra Nevada de Santa Marta, Gleysols are found on igneous rocks above 3 800 m and at least up to 4 100 m. When the climate is very humid, peaty soils with very high organic matter content develop in the paramos depressions, in part related to swamp or peatland vegetation types (Sapric, Hemic and Fibric Histosols) (Morales *et al.,* 2007).

Two main factors determine the soil type and properties: 1) the climate; and 2) the existence of a homogeneous layer of volcanic ashes from quaternary volcanic eruptions (Winckell, Zebrowski and Delaune, 1991). A cold and wet climate low atmospheric pressure favor organic matter accumulation in the soil. This accumulation is further enhanced by the formation of organometallic complexes strongly resisting microbial breakdown (Nanzyo, Dahlgren and Shoji, 1993). The resulting soils are dark and humic with an open and porous structure.

The higher values of SOC under natural vegetation are due to the greater protection of the soil surface provided by the type of vegetation cover (Castañeda-Martin and Montes-Pulido, 2017). For example, sites with dense cover such as bryophytes and shrub species that isolate soil from factors such as precipitation and direct incidence of solar radiation, may present greater amounts of SOC because there is less decomposition of organic matter. Also, the higher root density characteristic of these plants can influence the high SOC values. While soils under more dispersed cover, such as natural grasses of the *Asteraceae* and *Poaceae* families and *Pteridophyta*, may contribute less subsurface biomass to the soil and facilitate greater organic matter decomposition (Zimmermann *et al.,* 2010).

Over time there has been an interaction between the moorland ecosystem and the inhabitants of these territories, but at present, this interaction has changed dramatically (Cárdenas, 2013; Sarmiento and Frolich, 2002). In ancient times, the moors were sacred regions for pre-Columbian cultures, who only used them for rituals of worship and offering to their gods, since they were conceived as the place where the ancestors rested. During the time of the conquest and the colony, the arrival of new animal species, like cattle, altered the ecological dynamics in the places where this type of grazing was consolidated, such as the lower regions with better climatic conditions. Due mainly to the lack of land in local communities, the high population growth, and the inequity in land tenure, in the last century the slopes of the mountain ranges were colonized discovering the agricultural possibilities of the moors (Hofstede, 1995; Hofstede, 2001). To all this, we must add the increase in pine plantations, the increasingly evident effects of climate change, and the conflict with armed groups (Cárdenas, 2013). The fresh herbs of moors provide ideal locations for grazing (Hofstede, 1995) and to encourage the growth of fresh grasses, native vegetation including xerophytic shrubs are often burned before being used for grazing. As a result, the combination of grazing and regular vegetation burning activities has become a common management practice to support the growth of appetizing young grasses used for livestock feed (Hofstede and Rossenaar, 1995). At the same time, the most favourable areas related to the presence of black and deep soils are cultivated and used for potato and bean cultivation (Horn and Kappelle, 2009).

In natural moorlands hillslopes, little surface water erosion occurs on Andosols, but this behaviour changes when the natural vegetation is converted to agriculture due to intense mechanized tillage or conversion to pastures where trampling occurs (Dörner *et al.,* 2016). Cuervo-Barahona, Cely-Reyes and Moreno-Pérez (2016) found that native vegetation in the Cortadera moorland, Boyacá (Colombia) had a higher SOC content in relation to the cover crops of *Solanum tuberosum* and *Avena sativa*, and *Pennisetum clandestinum* grasses, possibly due to the low level of resilience of moorland soils, which when subjected to planting and grazing activities, tend to release a proportion of the carbon into the atmosphere through oxidation. Likewise, among the covers established for anthropogenic activities, grassland areas presented the lowest carbon content, which is probably because this activity has deep effects on the structure and functioning of the moorlands, where cattle trampling generates soil compaction and loss of physical, chemical, and biological properties that retain water and carbon (FAO, 2002).

The velocity of land use changes has been quantified at several locations. Van der Hammen *et al.,* (2002) quantified the land use changes in the paramo of Laguna Verde in Cundinamarca, Colombia. From 1970 to 1990, cultivation increased by 106 percent, grasslands by 164 percent. High altitudinal forests decreased by 32 percent. For the whole country, the increase in cultivated area in moorlands was estimated at 24.9 percent (Hincapié *et al.,* 2002). Land use changes in adjacent regions may also affect moorlands climate. Cloud formation in downslope montane cloud forests is assumed to sustain air humidity in upper mountain regions (Foster, 2001). Massive deforestation of the Andean slopes occurred during the last century and as a result, it may have altered the paramo climate (Buytaert *et al.,* 2006b).

Burning, intensive grazing, tilling, and replacement of the natural grassland with more nutritive grass species significantly affect the water balance of the moorland's areas (Sarmiento and Frolich, 2002). Effects typically accompanying pasture farming and tillage, such as soil compaction and soil crusting, additionally alter the infiltration rates, water storage, and regulation capacity of moorlands. This seriously compromises its water supply function. Some scientists also state the effects of human activities in terms of accelerated soil erosion given the properties in moorlands (Poulenard *et al.,* 2001). Very few studies have been conducted to quantify the impact of these land management changes on the hydrodynamic properties of moorlands (Buytaert *et al.,* 2006a), their floristic composition, the vegetation structure (Morales *et al.,* 2007), the morphological evolution of soils (Poulenard *et al.,* 2001) or on carbon storage in soils (Zúñiga-Escobar *et al.,* 2013).

Currently, there is an extension of potato, pea, and bean farming and cattle raising in almost all of the moors, even within some natural national parks. There are sufficient studies on the effects of these activities on vegetation, biodiversity, soils, and water (Van der Hammen *et al.,* 2002). In terms of agriculture, mainly potato cultivation is reaching higher and higher altitudes, approaching 4 000 metres above sea level (Morales *et al.,* 2007). Part of this corresponds to rotation crops, which originally could be left after a harvest to fallow for up to 20 years, but now, with agrochemicals, this period has been greatly reduced, which does not allow for proper regeneration of the vegetation (Morales *et al.,* 2007). In addition, the planting of introduced grasses has been extended, converting the moorland vegetation, little by little, into pastures. Every day there are fewer frailejones, which need between 50 and 100 years to reach a height of several metres again. At present, the moor is occupied by potato farmers, who buy or rent large areas and destroy the original vegetation completely with heavy machinery. The displacement of agriculture to higher altitudes is related to the development of potato varieties that are more resistant to frost and to the increase in temperature (Morales *et al.,* 2007).

Anthropic black soils. The Amazonian Dark Earths (ADEs) are anthropogenic soils created by inhabitants of the Amazon region between 2 000 and 500 years ago (Neves *et al.,* 2004), easily distinguished from natural soils by their chemical properties and other features observable to the naked eye such as their dark colour and their deep A horizon with the presence in most cases of potsherds, lithics, and charcoal pieces left by ancient anthropogenic activities (Kämpf *et al.,* 2003). Therefore, ADEs are classified as Pretic Anthrosols or as anthropogenic soils (Peña-Venegas *et al.,* 2016). These soils have a structure similar to organic soils, which can be created naturally by fluctuations in aerobic levels in areas with high accumulation of organic matter or human-made (Teixeira and Martins, 2003). They are black to dark gray-brown soils, have a high content of available phosphorus, variable calcium and magnesium, and presence of ceramics. The greatest number of studies on ADEs have been of the anthropological type and little is known about their genesis (Woods and Mann, 2000).

About 70 percent of the Amazon basin is composed of mainly very acid, highly weathered natural soils with poor availability of the most important plant nutrients (Richter and Babbar, 1991). There are, however, small patches of anthropogenic soils known as ADEs with completely different characteristics: ADEs are usually less acid with better cation exchange capacity and base saturation than natural soils (Glaser *et al.,* 2001). ADEs also contain more nitrogen, calcium, available phosphorus (Lima *et al.,* 2002) and organic matter; the higher organic matter content results in ADEs having better moisture-holding capacity and lower rates of nutrient leaching than natural soils (Glaser and Birk, 2012). In the Colombian Amazon region, ADEs have been reported along the Caquetá river (Mora, 2003), along some small tributaries of the Amazon river (Morcote-Ríos and Sicard, 2012). Most of the indigenous inhabitants of the Colombian Amazon basin have access to both natural soils and ADEs. For the Middle Caquetá river region where most ADE studies have been conducted, reports show that Indigenous Peoples recognize ADEs as the most suitable soils for agriculture (Galán, 2003).

The characteristics of the Antrosols in the Amazon have led several experts to suggest that these soils were made on purpose more than 1 000 years ago by Amazonian indigenous communities, to have the possibility of maintaining intensive crops for their sustenance. It is now known that these soils maintained permanent crops of *Manihot esculenta*, *Zea mays*, *Bactris gasipaes*, and *Mauritia flexuosa* (Peña-Venegas and Vanegas-Cardona, 2010).

2.5.5 Pacific

In the Pacific region, black soils occur in three main soils. The first group is swelling black soils (Vertisols) present mainly in Australia, where such soils cover about 15 percent of the national territory. It is important to note that Vertisols in Australia are not necessarily black: the national classification indicates also the presence of gray, brown, red and yellow suborders of compacted soils (Isbell, 1991). However, the black colour is the most common one. These soils are widely used in agriculture both for producing grain crops, tropical cultures, and cotton. They have a good potential due to their richness in nutrients and good water-holding capacity. However, their physical properties, such as swelling and shrinking and their strong compaction in a dry state, are limiting factors for their use. Volcanic black soils are especially widespread in New Zealand but are also common in Oceania on the islands of volcanic origin. Papua New Guinea, the biggest island in Oceania, also has some mountainous slopes with volcanic black soils (Neall, 2009). These soils are intensively used in agriculture, though high P retention limits their productivity. On many small islands of Oceania on coral reefs Rendzina-like black soils on calcium-carbonate-rich material form. Though these soils are mostly shallow, local farmers use them for cultivating taro and yams. Cultivation of these soils, unfortunately, increases the mineralization of organic matter and the emission of greenhouse gasses to the atmosphere.

2.5.6 Near East and North Africa

In the Near East and North Africa (NENA) region, black soils are uncommon because of the arid and semi-arid conditions almost everywhere in this region. However, some of the places with Mediterranean climate can lead place to the formation of dark-coloured soil, mainly on limestone material. The Syrian Arab Republic is one of the countries where black soils have been described in the NENA region (FAO and ITPS, 2015).

Syrian Arab Republic

The importance of black soils in the Mediterranean regions comes from its rare occurrence in semi-arid environments (Tarzi and Paeth, 1975). Reifenberg (1947) suggested that the immaturity of these black soils derived from soft limestone due to erosion of disintegration products of soft limestone. Durand and Dutil (1971) showed the importance of the texture of soft and hard limestone in the development of both types of soils. Tarzi and Paeth (1975) found white Rendzina soils derived from soft Miocene and Senonien limestone, developed on the foothills of the Lebanon and Anti Lebanon Mountains. These soils usually have high available P, and $CaCO_3$ contents (Sayegh and Salib, 1969). Soils of the Syrian Arab Republic were mapped by Ilaiwi (2001). Two forming factors- parent material and relief- shape soil characteristics (colour, depth). The impact of parent material is reflected in the emergence of different organic soils such as Rendzina on limestone, chalk, sandstone, conglomerates, and claystone. Reddish Rendzina on Dolomite and hard limestone. Grayish Rendzina on Serpentine. Calcic Kastanozems occur on calcic marl and lacustrine deposits. The impact of relief is clear on soil depth Rendzic Phaeozems occur on toe slopes and foot slopes, Rendzic Leptosols on shoulders, and deep Chernozems occur on a flat plains.

In some areas on the coastal plain as well as in Al Ghab plain, with 600 mm annual rainfall and xeric moisture and thermic temperature regime, soils have high SOC content as well as high carbonate content (Rendzic Phaeozems). These soils were developed from Calcaric Leptosols by humification. On shoulders and slopes, the mollic horizon is shallow (eroded), giving way to the formation of Rendzic Leptosol. This soil is relatively immature, not deep with one unique diagnostic mollic epipedon of 5 to 30 cm depth. The soil shows a strong reaction with dilute hydrochloric acid, which indicates the high content of calcium carbonate.

In the Al Ghab plain, black soils are associated with the extension of the great African faults along the eastern coast of the Mediterranean. Before their recent artificial drainage, most of these areas were annually flooded; ponding of plains last two months (January to February). These soils were developed over marl, freshwater organic, woody materials conglomerates of lacustrine deposits and lacustrine deposits (El Ghab, Amuq), marl, freshwater organic of lacustrine deposits, and basalt (Hola Homs, Hola Galilea). These soils are mollic with or without cambic horizon below the epipedons or of a calcic horizon within 1.5 m of the soil surface are the main reasons for the soil complexity.

There is no special use of these soils, but they are rather similar to other lands. In the coastal plains, they are devoted to cultivating citrus trees and protected crops, and in the Al-Ghab plain are cultivated with field crops (wheat, cotton, sugar beet, tobacco). Because of the availability of water, a part of the land is also devoted to agro-fishery.

Soils from the Syrian Arab Republic suffer degradation and depletion because of wrong practices and the lack of suitable laws to preserve them. The most important factors of deterioration and depletion include salinization because of irrigation with agricultural drainage water, pollution resulting from irrigation directly with untreated water sewage, decline of fertility due to using exhausting crops without using rational agricultural rotation, rapidly decaying of organic matter due to the wrong agricultural practice (organic matter has decayed from average 10 to less than 2 percent during five decades), and urban encroachment on these exclusive lands because of the increase in population and lack of urban planning (FAO and ITPS, 2015).

2.5.7 North America

Canada

In Canada, black soils develop under a Cool Temperate Dry climate. In the Canadian soil taxonomy, these soils are named Ortic Black Chernozem, which corresponds to Udic Haplocryolls in the US Soil Taxonomy and Haplic Chernozems in the WRB. In the Black Chernozem zones, grasses become taller and denser, producing more biomass and hence more organic matter accumulates of about 5 to 6 percent, but it can go up to 8.5 percent. This would be equal to 210.2 Mg C/ha. Stable isotope of carbon is -25.3 $\delta^{13}C$ (‰) for which about 90 percent is C_3 and 10 percent is C_4 plants. C_3 plants such as *Stipa comata* ($\delta^{13}C$ of –25‰), *Agropyron smithti* ($\delta^{13}C$ of –28‰), *Agropyron trachycaulum* ($\delta^{13}C$ of –28‰), *Stipa viridula* ($\delta^{13}C$ of –27‰) (Waller and Lewis, 1979), *Artemisia sp.* ($\delta^{13}C$ of –28‰) (Bender, 1971), *Populus tremuloides* ($\delta^{13}C$ of –27.2‰), *Pinus banksiana* ($\delta^{13}C$ of –26.6‰), *Rosa acicularis* ($\delta^{13}C$ of –27.9‰), *Fragaria virginana* ($\delta^{13}C$ of –31.7‰) (Brooks *et al.,* 1997), and C_4 plants such as *Bouteloua gracilis* ($\delta^{13}C$ of –13‰). The amount of organic C to 120 cm depth on average is about 14.88 g/m. Colour 10YR Chroma is darker than 1.5 and value is less than 3.5. Lower temperature causes a slower decomposition of residue, and there is a possibility of leaching of organic matter from the soil system. Chernozems are dominant in the grassland regions of Canada including the great expanse of the Canadian Prairies. Soils presented here contains carbonates, especially accumulation of secondary carbonates. The pH values for the Ah horizons of the Chernozemic soils are neutral to mildly acidic. Black Chernozems contain high amount of soluble salts. They develop in parent materials ranging from coarse sands through to fine textured silts and clay loams. Parent materials that include significant amounts of marine shales are often higher in sodium. The major soluble cations are Ca^{2+} with Mg^{2+}, and Mg^{2+} increasing with depth. Major soluble anions are SO_4^{2-} and HCO_3^-. Major exchangeable cations are Ca^{2+} and Mg^{2+}. The time for soil formation since deglaciation, estimated to be 12 000 years before present, based on the deglaciation history of the prairies (Landi *et al.,* 2003a, b; 2004). A description of a typical profile of such soils is presented in Table 2.5.6.

Table 2.5.6 A description of a typical profile of such soils

Source: Landi, A., Mermut, A. R., & Anderson, D. W. 2003a. *Origin and Rate of Pedogenic Carbonate Accumulation in Saskatchewan Soils, Canada.* Geoderma. 117:143–156.
Landi, A., Anderson D. W. & Mermut A. R. 2003b. *Organic carbon storage and stable isotope composition of soils along a grassland to forest environmental gradient in Saskatchewan.* Can. J. Soil Sci, 83: 405– 414.
Landi, A., Mermut A. R. & Anderson, D. W. 2004. *Carbon Dynamics in a Hummocky Landscape from Saskatchewan.* SSSAJ, 68: 175–184.

Thickness of A horizon	12 cm
Soil texture	Mainly loamy
Soil structure	Granular and friable in the A and prismaticin B horizons
Soil porosity	All types of tillage provide a good soil porosity to soil at the time of seedlings
Soil colour	10 years < 3.5

As one can see from the description, the thickness of the topsoil A horizon is not sufficient for the criteria for mollic horizon in Soil Taxonomy and WRB. However, in Canada these soils are recognized for their high productivity and thus we include them in the concept of black soils.

Distribution of Black Chernozems in Canada is shown in the Global Black Soil Distribution map (FAO, 2022a). Based on organic matter content and also precipitation, very clearly identifiable zones exist from north to south following the precipitation line and organic matter content in the soil. Soil colour changes from absolute black to dark brown and brown. Anyone working in the field can see the soil colour change when travelling, from north to south in Saskatchewan. This is similar to Dokuchaev's zonality in the Russian Federation. The main controlling characteristic of the climate is, however, the substantial water deficit that occurs in the region. In central and western Europe, the distribution of soils equivalent to Canadian Black Chernozems is commonly found in areas dominated by forest vegetation (Eckmeier *et al.,* 2007).

The Canadian grassland regions have undergone an almost complete conversion to agricultural production since European settlement began in the 1870s. The water deficit limits agricultural production to small grains, oilseeds, pulse, and forage crops, and livestock production. The optimal soil density values were under different-depth cultivation to 25 to 27 cm with periodical loosening of soil to 50 cm (1.16 to 1.28 g/cm^3). The effects of land use on soil physical and chemical properties varied with the intensity and frequency of disturbance. A reduction in soil C is one of the most widely reported effects of land use change and is thought to result from the removal of above- and below-ground biomass during the harvest of crops and from the increased oxidation of C_{Org} during tillage (Dodds *et al.,* 1996). If the cultivated toposequence as a whole is considered, the largest C losses were due to mineralization in lower slope areas and were more than double the amounts lost by erosion at upper slope areas. In upper slope segments mineralization accounted for the largest portion of total C lost in the early years of cultivation, whereas erosion accounted for the largest portion in later years.

Conservation tillage has been a tremendous success story in Canada. However, decades of tilling have severely eroded the soil, removing topsoil from the knolls and slopes of hills. One option is adding cover crops and perennial forages to the rotation to build up organic matter in the soil. A more impactful solution is dragging soil from the bottom to the top of the hill.

Microbial abundance and diversity can be used to assess the relative impact of management on the long-term sustainability of cropping systems. Studies showed that tillage disturbance was not an overriding factor in determining microbial community composition in the long-term no-till (NT) and conventional till (CT) soils. Enhanced microbial activity in organically managed soils may make P more available. Livestock manures are rich sources of available phosphorus, but a majority of organic farmers in Canada do not keep livestock. Increasing management intensity of grasslands through planting more productive species or increasing fertilizer inputs generally increases SOC accumulation. Increasing the number of plant species or functional groups, especially when legumes are added, often increases SOC accumulation. Grazed grasslands generally accumulate SOC more rapidly than undefoliated grasslands. Grazed grasslands generally accumulate SOC more rapidly than undefoliated grasslands (Sollenberger *et al.,* 2019).

The prairies account for about 85 percent of Canada's arable land, making it the most important agricultural region of the country. Historically this region has been dominated by cereal grain production, especially hard red spring wheat. Crop production in the Canadian prairies is based on simplified monoculture input driven production of ecological annual crop production concept, considering the loss of organic matter and natural and agricultural biodiversity to provide a level of economic stability for the farmers (Martens *et al.,* 2013). For example, after the big harvest of 2013 in the Canadian Prairies, a significant drop in nutrients resulted in increased fertilization in 2014.

Continuous crop and animal removal gradually reduces the availability of essential macro and micronutrients in the soil. Prairie soils do not have inexhaustible levels of any nutrient. The bigger the crop yields, the more plant essential nutrient are extracted from the soil. Soil depletion of the macronutrients such as N, P, K and S is more or less fully understood. Soil depreciation of plant essential micronutrients such as Cu, Zn and B are less well understood as we harvest crop after crop (Evans and Halliwell, 2001).

The adoption of crop diversification in the Canadian prairie agriculture for the period from 1994 to 2002, reflect its strengths and limitations for managing a variety of risks, including climate change. Based upon data from over 15 000 operations, it was determined that individual farms have become more specialized in their cropping patterns since 1994, and this trend is unlikely to change in the immediate future, notwithstanding anticipated climate change and the known risk-reducing benefits of crop diversification (Bradshaw *et al.,* 2004).

Major threats are the effect of cultivation and erosion on soils. Cultivated and virgin grassland soils were compared on adjacent landscape segments in order to quantify losses or gains of organic C, N, P, and total P. Losses were generally greatest from the upper landscape segments where erosion resulted in significant reductions in solum thickness. Sediment accumulation through erosional processes and redistribution during tillage operations resulted in accretion on selected landscape segments along the cultivated fields. Soils derived from sandstone and siltstone appear to have lost larger proportions of organic C, N, and P through mineralization than the soils formed in shale. Mineralization losses of organic constituents were countered by accretion on depositional segments. Substantial reductions in N, in excess of the amount removed by grain and straw, occurred with continuing cultivation. Regression analyses indicated that losses of organic C, N, and P were more closely linked to erosion in the finer-textured soils formed in shale. Changes in total P were closely linked to redistribution and sorting of soil particles because the total quantity of P in soils is independent of mineralization transformation (Gregorich and Anderson, 1985). In 2011, the majority of farmland (74 percent) in Canada was considered to be at low risk from soil erosion. The risk of soil erosion has been decreasing on agricultural lands in Canada (Agriculture and Agri-Food Canada, 2011).


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United States of America

Geographical distribution. Climatically, the black soils of the United States of America are most abundant in the IPCC climate zone Cool Temperate Dry, followed by Cool Temperate Moist, Warm Temperate Dry, Warm Temperate Moist, Tropical Moist, and least abundant in Boreal Moist (Figure 2.6).

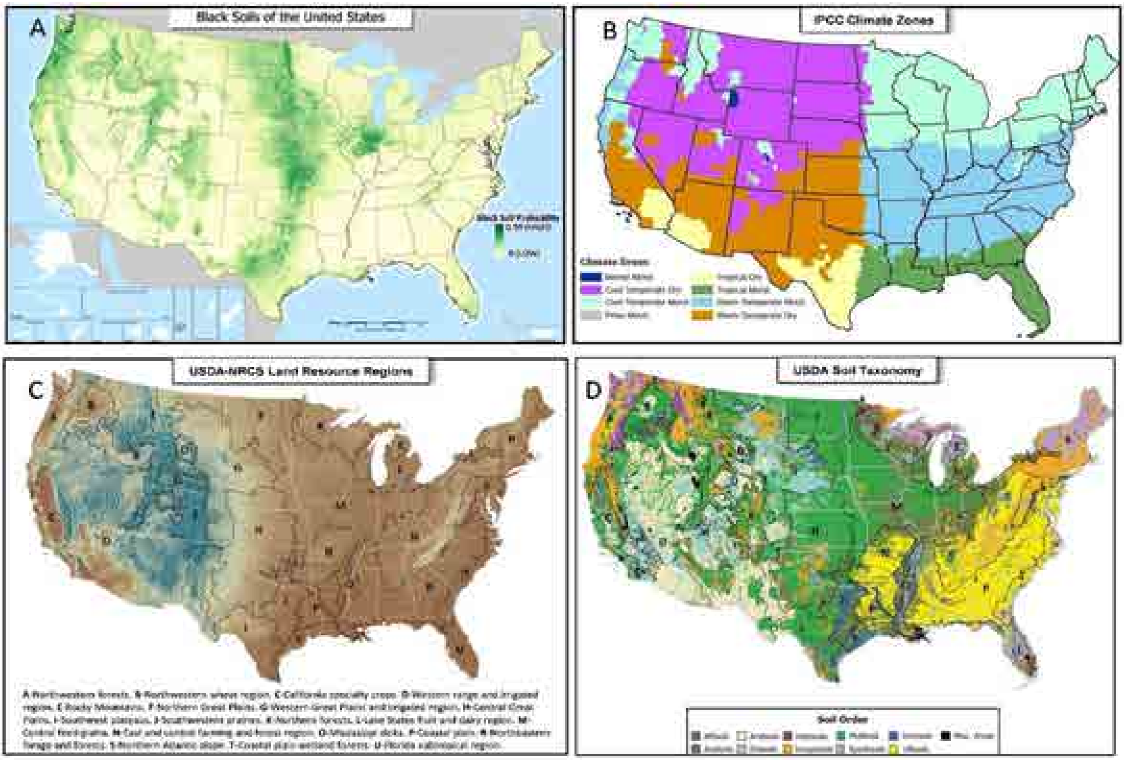

Figure 2.6 Comparison of black soils of the United States of America (A) with the IPCC Climate zones (B), USDA-NRCS Land Resource Regions (C), and USDA-Soil Taxonomy (D)

Source: Soil Survey Staff. 2014. *Keys to Soil Taxonomy*, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Note: The designations employed and the presentation of material in the map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.

Classification of black soils using the World Reference Base for Soil Resources (IUSS Working Group 2015) and Soil Taxonomy (ST) (Soil Survey Staff, 2014) are listed in Table 2.5.7. The table is organized to show each USDA-NRCS Land Resource region (LRR) in which the black soils occur. (Compare Figures 2.6-A and C). Also listed in Table 2.5.7 are the subsection topics that pertain to the type of black soils: 1) black soils of midlatitude grasslands; 2) black soils of floodplains and wetlands; 3) Compact black soils; 4) Volcanic black soils; 5) black soils in tropics, and 6) Anthropic black soils.

Black soils in the United States of America are Mollisols formed under grassland vegetation in the High plains and Midwestern United States of America. The easternmost Mollisols formed under tallgrass prairie with a udic (i.e, humid climate) soil moisture regime and have less calcium carbonate in the subsoil than the Mollisols to the west that gain progressively more calcium carbonate in progressively drier climates. The eastern tallgrass prairie Mollisols are Phaeozems in the WRB system and Udolls or Aquolls (if periodically saturated with water) at the suborder level in the ST system.

Westward across the Great plains, the tall grass prairie transitions into semi-arid steppes while simultaneously the udic moisture regime transitions into the ustic moisture regime. In this transition the Udolls transition into Ustolls and the Phaeozems transition into Chernozems then Kastanozems in progressively drier climates where black soils cease to be present.

Further westward, the black soils reappear in the mountains. With increased elevation, precipitation increases and the climate transitions from arid in the lowest elevations upward through grasslands, savannas, woodlands, and into evergreen forests. Black soils in the western mountains occur as Ustolls (Kastanozems and Chernozems) upward into the higher elevations until the forest canopy closes. In the colder, higher elevations, black soils occur as Cryolls. Continuing west, the semiarid soil moisture regime shifts from Ustolls to Xerolls signifying that the seasonal distribution of precipitation has changed from spring and summer precipitation (ustic) to winter precipitation (xeric). Black soils also occur as volcanic ash soils (Andosols in WRB and Udands in ST) and Inceptisols (Cambisols in WRM and Xerepts in ST) in the westernmost states. These black soil orders are minor in area compared to the Mollisols.

In the eastern United States of America, relatively minor areas of black soils occur as Histosols (Saprists and Hemists in ST), Podzols (Aquods in ST), and Vertisols (Usterts and Uderts in ST). In the southern Appalachian Mountains under temperate rainforest conditions, black soils occur as Cambisols (Udepts in ST).

Table 2.5.7 Soil classification of black soils as they occur in the Land Resource Regions (LRRs) of the conterminous United States of America

Source: Soil Survey Staff. 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.
Note the absence or very minor occurrence of black soils in Alaska, Hawaii, and The United States of America Territories (Figure 2.6A).

Land Resource Region	Black Soil Classification WRB Reference Soil Groups	Black Soil Classification Soil Taxonomy Suborders	Subsection Topic Category
A	Andosols > Cambisols > Chernozems	Udands>Udepts>Xerolls	Volcanic
B	Kastanozems	Xerolls	Midlat. Grasslands
C	Kastanozems	Xerolls	Midlat. Grasslands
D	Kastanozems > Cambisols	Xerolls, Xerepts, Ustolls	Highlands
E	Kastanozems>Chernozems>Cambisols	Ustolls, Ustepts,	Highlands
F	Chernozems, Kastanozems	Ustolls	Midlat. Grasslands
G	Kastanozems	Ustolls	Midlat. Grasslands
H	Chernozems, Kastanozems	Ustolls	Midlat. Grasslands
I	Kastanozems	Ustolls	Midlat. Grasslands
J	Vertisols, Chernozems	Usterts, Ustolls	Midlat. Grasslands
K	Histosols	Hemists, Saprists	Wetlands
L	Chernozems	Udolls	Midlat. Grasslands
M	Phaeozems	Udolls, Aquolls	Midlat. Grasslands
N	Cambisols	Udepts,	Highlands
O	Histosols	Saprists	Wetlands
P	(Very minor occurrence)	(Very minor occurrence)	NA
R	Podzols	Humods	Highlands
S	(Very minor occurrence)	(Very minor occurrence)	Highlands
T	Vertisols, Histosols	Usterts, Saprists	Wetlands
U	Histosols, Podzols	Saprists, Aquods	Wetlands

Peculiarities in genesis and properties. Major factors controlling the soil genesis for black soils in each LRR is listed in Table 2.5.8. Also shown is the predominant land use, the geogenic layers and pedogenic horizons in the soil that impart restrictions to roots, and the carbon stocks, both organic and inorganic ($CaCO_3$). The carbon stocks are given for the whole area of the LRR in which the black soils occur. Thus, carbon concentrations in the black soils themselves will be higher than the values shown.

Table 2.5.8 Major factors controlling black soil genesis, land use of black soils, root-restrictive layers and soil horizons, and carbon stocks for the Land Resource Regions in which the black soils occur. Items in the table are listed in order of abundance if more than one item pertains

Source: Guo, Y., Amundson, R., Gong, P. & Yu, Q. 2006. Quantity and Spatial Variability of Soil Carbon in the Conterminous United States. Soil Sci. Soc. Am. J, 70: 590–600.

Land Resource Region	Black Soil Genesis	Black Soil Land Use	Black Soil Geogenic Restrictions	Black Soil Pedogenic Restrictions	LRR† Organic C Stocks tonnes C/ha	LRR† CaCO3-C Stocks tonnes C/ha
A	Temperate rain forest	Evergreen forest	Paralithic, lithic	Cemented hrz, ortstein	142	0
B	Mountain forest soils	Evergreen forest	Paralithic, lithic	Duripan	78	79
C	Mountain forest soils	Evergreen forest	Paralithic, lithic	Duripan	101	4
D	Mountain forest soils	Evergreen forest	Lithic, paralithic	Duripan	44	91
E	Mountain forest soils	Evergreen forest	Lithic, paralithic	-	79	37
F	Tall grass prairie steppe	Soybeans, corn, wheat	Paralithic	Natric	137	119
G	Steppe, mountain soil	Grassland, Evergreen Forest	Paralithic, lithic	Natric	60	71
H	Steppe and prairie soils	Corn, cotton, grassland/pasture	Densic bk, lithic, Abrupt	Natric, petrocalcic	110	166
I	Savana and steppe soil	Shrubland, cotton	Lithic, densic bk	Petrocalcic	100	348
J	Tall grass prairie	Grassland/pasture, corn	Densic bk, lithic	Petrocalcic	118	296
K	(Very minor), bog soils	(Very minor), wetland	(Very minor) densic	(Very minor), fragipan	252	66
L	(Very minor), Bog soils	(Very minor), corn, wetland	(Very minor) densic	(Very minor), ortstein	209	117
M	Tall grass prairie on till	Corn, soybeans	Densic mtl, abrupt tex.	-	163	92
N	Temperate rain forest	High-elevation mixed forests	Paralithic	-	60	1
O	Flood plain deltaic soils	Wetland	-	-	109	21
P	(Very minor) marl prairie	(Very minor)	(Very minor), paralithic	-	91	1
R	Boreal forest soils	Mixed forest	Densic mtl, lithic	Ortsein	139	3
S	(Very minor) Mountain soil	(Very minor), mixed forest	(Very minor), lithic	(Very minor)	75	0

Land Resource Region	Black Soil Genesis	Black Soil Land Use	Black Soil Geogenic Restrictions	Black Soil Pedogenic Restrictions	LRR† Organic C Stocks tonnes C/ha	LRR† CaCO3-C Stocks tonnes C/ha
T	Marl and bog soil	Wetland	–	Natric	353	24
U	Bog soils	Wetland	Lithic, paralithic	Ortstein	396	10

Note: † Midpoint estimate for the entire LRR from Guo *et al.*, 2006.

Black soil genesis follows three pathways. Most abundant is the addition of organic matter via decomposition of fibrous grass roots. This process (melanization) is responsible for most of the black soils in the United States of America. Second is the organomineral complexes between organic matter and minerals in Andisols and Vertisols. In Andisols, the complexes occur between organic matter and the short-range-order minerals like allophane and imogolite that weathered from volcanic ash (Soil Survey Staff, 1999). This process occurs in the northern regions of LRR A and E. In Vertisols, the complexes occur between organic matter and highly charged 2:1 clay minerals, primarily smectite. This occurs in the Blackland Prairies of LRR J. The third pathway is the concentration of organic matter resulting from curtailed fungal decomposition under anaerobic conditions when soils are submerged in water. This occurs in the wetlands of LRR T, U, and K.

Soil textures vary widely in the black soils of the The United States of America primarily because the mollic epipedon, which is responsible for most of the black soils, is superimposed on numerous parent materials, including loess, glacial till, lacustrine sediments, alluvium from floodplains and fans, volcanic ash, and residuum from a multitude of sedimentary, metamorphic, and igneous bedrock. The structure of the mollic epipedon is typically "granular." The subsoil structure, however, varies as a function of parent material and the degree of soil formation, ranging from "structureless" to "strong angular blocky." The dark colour requirements are those of the mollic epipedon (Soil Survey Staff, 2014). The melanic and histic epipedons of the other black soils are similarly dark.

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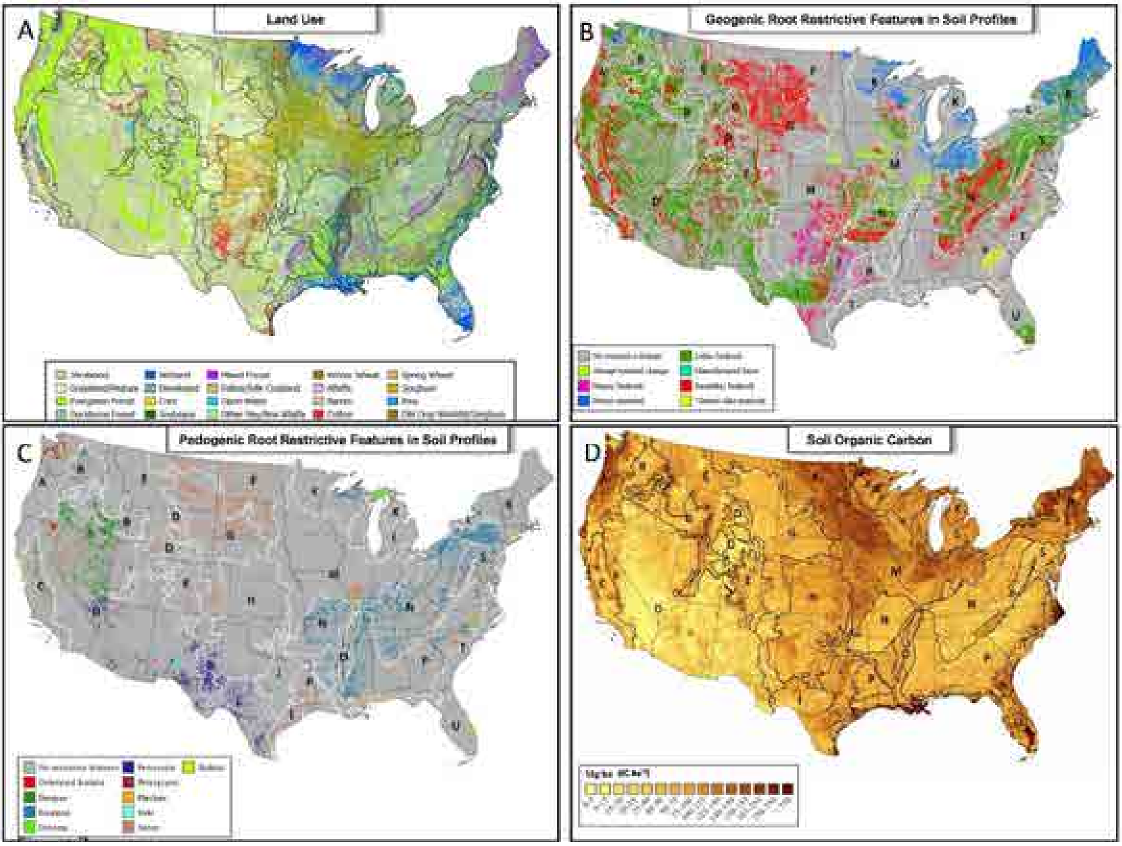

Figure 2.7 Land use, the distribution of root-restrictive layers and horizons, and SOC in the conterminous of the United States of America

Maps courtesy of Chad Ferguson, Natural Resources Conservation Service

Source: Soil Survey Staff. 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Note: The designations employed and the presentation of material in the map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.

Regarding soil depth, Figure 2.7-B shows the distribution of geogenic layers that are restrictive to roots within 2 metres. Those impacting black soils include bedrock (lithic), weathered bedrock (paralithic, such as saprolite), abrupt texture changes, densic bedrock (such as soil fabric from weathered sedimentary rocks that prohibits the entrance of roots), densic material (such as compact glacial till) (Table 2.11). In addition to geogenic layers, pedogenic horizons that impose chemical and physical restrictions to roots are shown in Figure 2.7-C. Those impacting black soils include duripans, natric horizons, petrocalcic horizons, fragipans, ortstein, and cemented horizons (Table 2.11).

Coverage and geographical regularities in the distribution. Black soil distribution within the Land Resource Regions (LRRs) of the United States of America can be seen by comparing Figure 2.6-A and Figure 2.6-C. LRR-M contains the greatest amount of black soils followed by the other LRRs with native prairie soils: (F, H, J, and I). The western LRRs with mountains (E, D, and A) follow with an abundance of black soils. Conversely, the LRRs with few or no black soils are LRRs P, K, and S. Similarly, Alaska, Hawaii, and the United States of America have few or no black soils (Figure 2.6-A).

Land use and management. Land use in the conterminous United States of America is shown in Figure 2.7-A. The land use of black soils is listed in Table 2.11. In LRR M, row crops, mainly corn (maize) and soybeans, occupy almost all black soils. Similarly, the black soils of LRR F and H are predominately used for corn and soybeans. Cotton and wheat are common crops grown on black soils of LRR H. The other black soils are used as grassland/pasture, forest, and wetlands.

Ecosystem services. Food, feed and fibre production is the primary use of black soils in the United States of

America. This occurs primarily in the midwestern and Great plain states of LRR M, F, and H.

Water regulation is a major ecosystem service of the black soils in LRR-R which is the location of several major cities (such as New York city). Likewise, water regulation is a very important ecosystem service for the black soils in the western mountains of LRRs A, B, C, D, and E which supply irrigation water and municipal water to the agricultural lands and cities in the drier lowlands.

Biological diversity is less important for the black soils of the croplands, although protection and restoration of native prairies does exist in a few areas, but it is of major importance for the black soils of the wetlands and mountains.

Climate change mitigation and adaptation pertains primarily to carbon sequestration, both organic soil and inorganic carbon. Essentially all the black soils used for cropland have lost substantial amounts of SOC. Consequently, these soils now have a high potential for sequestering carbon as a negative emissions technique while simultaneously improving soil health (Lal *et al.,* 2021). Carbon sequestration as inorganic carbon ($CaCO_3$) in black soils also holds high potential as a negative emission technique for the black soils of drier regions (Monger *et al.,* 2015a).

Other benefits of black soils include ecotourism for those in wetland, aesthetic and recreational benefits for black soils in western mountains, and scientific discovery for all black soils.

Carbon stock and stability. The distribution of SOC concentrations is shown in Figure 2.7-D and listed in Table 2.11. The values in Table 2.11, however, are mean values for the LRR as a whole, not just the black soils themselves which will have higher values. The highest concentrations are for those LRRs that have black soils occurring as Histosols in bogs (LRRs U, T, L, and K). The lowest concentrations are for those LRRs that have no to very few black soils (LRRs P, S, and N) or that have black soils in mountains surrounded by large deserts and semiarid steppes (LRRs D, B, and G). The black soils of the croplands (LRRs M, F, and H) have intermediate carbon concentrations.

Stability of carbon ranges from being stable in the wetlands (assuming they remain wetlands) but less stable in the western mountains and cropland.

The western mountains are experiencing catastrophic fires and concomitant erosion as well as desertification involving the loss of grassland to invading woody shrubs. Croplands, which have lost much carbon since the beginning of industrial agriculture in the mid-twentieth century, may continue to lose carbon as long as yields remain high, owing to commercial fertilizers. The loss of carbon, however, may be ending, given the recent emphasis on soil health, carbon sequestration, and water pollution, especially algal blooms and high-visibility hypoxia zones in oceans.

Major threats and degradation processes. Black soils of the cropland regions are threatened by surface compaction, loss of soil organic matter and tilth, accumulation of salts, pollution by overuse of fertilizers and pesticides, soil wetness, flooding, water erosion, wind erosion in the drier climates with soils having lighter textures, and loss to urban development (USDA Ag Handbook, in press). Black soils of the mountains are threatened with water erosion on the steeper slopes, overgrazing, the spread of invasive plants, especially noxious weeds, forest fires, soil sealing, loss of biodiversity, and desertification (Wang *et al.,* 2016; Monger *et al.*, 2015b).

The main drivers and pressures of soil degradation are improper land use and population growth. Climate change involving warmer and drier conditions is especially problematic for the black soils of the western mountains.

The status of soil degradation has been monitored by the USDA-Soil Conservation Service (now Natural Resources Conservation Service) since the 1930s. This agency is actively documenting indicators of soil degradation and health and promoting conservation efforts by working with farmers across the country.

Like soil degradation worldwide, the impact of soil degradation and human response in the United States of America are negative consequences for the farmers and the society on the whole, and the loss in natural capital. The efforts to mitigate soil degradation and restore degraded lands is urgently needed, especially with regard to food security, a broad range of environmental issues, and loss of biodiversity, and sustainable development goals of the United Nations (Lal *et al.*, 2021).

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