Soil Degradation and Climate Change in Serbia

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KEY MESSAGE

- Healthy soil is a service provider to the natural environment, economy, and health, and represents a stabilising factor for the functionality of natural and managed ecosystems.
- Risk of soil degradation in Serbia is continually increasing under changing climate conditions.
- By mid-twenty-first century, Serbia will, in general, be at high risk of soil degradation, more or less pronounced in different parts of the country.
- Risk of soil degradation is increasing significantly because of climate change; vulnerability of soil and land, and risk of degradation can abruptly increase by inappropriate human interventions.
- Planning of land-based interventions must include re-assessment of soil and land degradation risk because of the increasing sensitivity of land components under climate changing conditions.
- Besides mitigating the currently endangered areas, planning and implementation of preventive soil and land degradation measures is necessary to address the degradation problem, so as to ensure the feasibility and effectiveness of the measures.
- Establishment of an integrated soil and land monitoring system supported by interdisciplinary and interinstitutional collaboration is required to improve understanding of degradation processes and to ensure the effectiveness of soil and land degradation prevention and reduction.

EXECUTIVE **SUMMARY**

In the Republic of Serbia, climate change has already had an impact on the natural environment, different economy sectors and human health, and negative impacts will continue and increase in the future.

Vulnerability and risk assessments for the past and future were provided by the National Communications of the Republic of Serbia and measures of adaptation to climate change for different sectors by the year 2030 are expected to be outlined in the upcoming National Adaptation Plan. Priority measures for both mitigation and adaptation are listed in the Nationally Determined Contributions draft, the adoption of which by the Government of the Republic of Serbia is pending.

Soil provides services to different human activities and to natural ecosystems and is impacted by them. Soil is an intrinsic component of the environment. Soil is one of the components of land, which includes terrestrial surfaces with ecosystems (managed and natural), near surface atmospheric conditions, human settlements, and interactions between different components. Soil interacts with the environment, provides services for food production and other human activities, and is also impacted by processes related to natural and managed ecosystems. Disturbance of soil functionality can be reflected in the degradation of soils and degradation of natural and managed ecosystems, as well as in human health (access to safe drinking water, air quality, and food production).

Soil is a component of the agriculture-forest-water nexus and the infrastructure-industry-urbanism nexus, and impacts of any land-based interventions should be assessed for impacts on soils. Soils are service providers to many sectors, and are highly impacted by the processes related to different sectors. Soil degradation reduces its functionality and weakens the functionality of other sectors and/or exacerbates the environmental and health risks from different sectors.

Besides exploitation and disturbance of soil functionality from human activities, climate change represents additional stress for soil health. Soil can be impacted by climate change directly by alteration of thermal and humidity conditions which are crucial for soil formation and maintenance of its quality and services it provides to the environment, and indirectly, by degrading vegetation which is one of the pedogenic factors and the main source of organic matter for soil.

Average surface air temperature increase in Serbia (2001–2020) **1.4°C**

Increase of temperature is the highest during the summer season (2011–2020) **2.4°C**

Compared to the 1961–1990 period, average surface air temperature increase in Serbia is 1.4°C for 2001–2020, and 1.8°C for the 2011–2020 decade, which is the warmest decade on record in Serbia. The Increase of temperature is highest during the summer season (2.4°C for 2011–2020) and higher during the growing season than the annual average (1.9°C for 2011–2020). The average temperature will increase by 2.5–3.1°C (more likely by 3.1°C) in the 2041–2060 period compared to 1961–1990. Temperature increase, increasing frequency and duration of heat waves and extreme heatwaves, and decreasing frequency of cold periods, impacts agricultural production, forest ecosystems and biodiversity, as well as human health, and, indirectly, other sectors. The future increase of temperature conditions and further intensification of extreme heatwaves is expected to have more pronounced impacts and represents a signal for urgency in planning and implementation of adaptation measures.

Average annual precipitation in Serbia has an inconclusive signal of change, without a significant rate of change. Precipitation is changing its annual distribution toward the colder period (currently from June to May, on average for Serbia), and its distribution by intensity toward more extreme precipitation events and reduction of moderate precipitation events. Accumulated precipitation in extreme precipitation events more than doubled in the 2011–2020 decade compared to 1961–1990. Dryness during the summer and growing season period is increasing, and drought increased in frequency and duration. Future estimates show continuing trends of this change, as well as further intensification of extreme precipitation events. Changes in precipitation along with temperature increase the impact on water availability.

Soil degradation in the Republic of Serbia is currently dominantly driven by human factors (land conversion, abandonment of agricultural fields, overexploitation of soil in agriculture), and the effects of climate change tend to exacerbate the degradation process and trigger and/or accelerate the degradation of natural systems. According to available data and information, the average soil organic carbon content (indicator of soil degradation and desertification) in Serbia has decreased and reaches the low category with further tendency to decrease, and is mostly impacted by land use and climate change. Also, soil erosion is a major form of soil degradation in Serbia.

The risk of desertification considering only the climate factor: in the recent climate period (2001–2020) 36% of Serbia was at moderate risk and in the 2041–2060 period 53% of the territory will be at moderate risk and 30% at high risk. The increase in temperature is the biggest cause of the water availability reduction and increasing aridity in Serbia, meaning that relatively slow changes and less variable characteristics of climate (unlike extreme events) will be rapid (far beyond any natural variability) and unmanageable by natural systems.

The risk of degradation from extreme precipitation considering only the climate factor: in the recent climate period (2001–2020) 45% of Serbia was at moderate risk and 7% at high risk, and in the 2041–2060 period 34% of the territory will be at moderate risk and 56% at higher levels of risk (high and very high). Extreme precipitation and, consequently, high surface runoffs and floods have already had significant impact in some areas of Serbia. In the 1961–1990 period risks were limited to local areas. Because of the shift of precipitation intensity toward more intense events with a continuously increasing trend in the past and further in the future, unlike average accumulated precipitation, the risk is progressively increasing.

Risk of soil degradation - % of territory of Serbia (2001–2020)

MODERATE	HIGH	VERY HIGH
29 %	28 %	14 %

The risk of soil degradation considering climate and land-related degradation factors (aridity/water availability, extreme precipitation, soil and vegetation vulnerability without surfaces under managed soils, and terrain features): in the 2001–2020 period 29% of the territory of Serbia was at moderate and 28% at higher risk levels (14% at very and extremely high risk levels), and in the 2041–2060 period 52% will be at moderate and 42% at high risk levels (25% at very and extremely high risk levels). On average, Serbian territory could be considered as a territory at high risk of degradation by the mid-century period. Assessment is done by using information on currently vulnerable land factors. In the recent climate period (2001–2020) and future period (2041–2060) the risk of degradation from extreme precipitation is the most pronounced in the country, but cumulative effects of land and soil degradation processes have more severe impacts, which means that true degradation assessment can be easily underestimated because of the complexity of the different processes, their interactions, limited knowledge and data in the region.

Managed (agricultural) soils are considered stable (not prone to degradation) because of the uncertainty of their management in the future and the assumption that currently suitable practices are applied. The risk level in these areas could only increase from future climate change impacts. In case they are continually stressed by overexploitation and mismanagement, rapid increase of their vulnerability to degradation is expected. The same is expected with inappropriate land use change. Soil fertility control carried out in Serbia shows loss of organic matter in soils due to agricultural activities and mainly due to change of land use. Soil and land degradation are highly sensitive to the human factor throughout soil management practices and conversion to agricultural land. Updated soil data collected through soil monitoring and the elaboration of climate impact on soils is necessary for the assessment of soil degradation risk.

For managed soils, future assessment of the risk of soil degradation under climate change requires the development of future scenarios of the human factor behaviour through soil management practices, which provides some expected outcomes for different soil and land vulnerability. This may be referred to as an assessment of human interventions, which can directly or indirectly impact soil stability and productivity in a positive or negative way. For such assessment, including the human factor is obligatory when considering the climate factor (changed climate conditions) because it has proven to be a risk factor and it can even put currently stable soils at increased risk.

Future human impact on soil degradation can be exacerbated by land use change. Besides interventions in managed soils, land use change can immediately increase the risk of degradation, by increasing the soil's exposure to increased climate stresses and by forcing soils into genesis changes, which could have positive and/or negative effects on soil productivity.

Planning of land-based interventions must include a re-assessment of degradation risks under the scenario which considers implementation of planned measures. Soil/land composition, terrain attributes, and climate change features in Serbia, make the spatial distribution of degradation risk spatially very variable, but a significant part of the territory highly vulnerable. Increased risk of soil degradation in Serbia under climate change in the next decades shows that vulnerability of relatively stable areas will rapidly increase, and degradation can be triggered and/or accelerated by human interventions.

Wind erosion in future climate conditions, with increasing drought events, will significantly increase in agricultural areas since they are located in the region affected with high winds and droughts (the Province of Vojvodina), which frequently coincide with periods of bare soils. Agricultural soils in Serbia could be highly erodible, which might be a dynamic soil property (might decrease over time). From such soils, wind erosion can remove large portions of topsoil and carry it over a significantly wider area, meaning that the effects of wind erosion can be much larger than the area of the wind's impact on soil. Besides degradation, such processes can reduce air quality and safety in case they occur near populated areas and roads. Soil structure deteriorates with decreased soil organic carbon content, which has been noted in other parts of Serbia.

Planning of preventive measures for soil and land degradation is necessary and urgent. Cost-effective approaches for reducing the risk of degradation, which is in the high risk category on average for Serbia and locally at very and extremely high risk by the mid-century, are preventive by nature. Considering the future scale of increasing risk, negative effects would most probably be unmanageable, meaning that the necessary funding most probably could not be achieved, human resources requirement would not be met, and that the degradation process is time-sensitive with an accelerating rate of progression.

Assessment of the soil and land degradation risk should be downscaled to the local level. To further assess the degradation risk and apply functional solutions to mitigate it, the quality of risk assessment should be ensured by including local data on high spatial scales. Risk assessment at the national level should be considered as a guiding reference for the selection of priority areas and developing a time schedule for addressing differently vulnerable areas.

An integrated land monitoring system should be established. Soil and land degradation are interconnected and highly sensitive to human and climate factors. There is no systematic approach at monitoring all the relevant components of land systems. Existing data and knowledge are scattered in different reports for different institutions and in scientific articles by scientists with different expertise. Interdisciplinary and interinstitutional collaboration is necessary to establish an integrated monitoring system with a repository of data collected by using defined methodology and in a defined format. An initiative at the national level is required for establishing such a system.

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CONTENTS

CHAPTER 1: **BACKGROUND KNOWLEDGE**

Soil is a natural component of **land**, which includes the natural components of the terrestrial part of the Earth's climate system, with human settlements and infrastructure, including interactions between these components. After oceans, global soil is the second largest natural carbon sink, and can, therefore, significantly contribute to the mitigation of climate change if its health and the services it provides are preserved or degradation processes reverted.

Understanding all aspects of the global impact that climate change has on soils is still under development, as well as methodologies for surveys on soil health. To overcome the problem of the complexity of interactions between soil and climate and to analyse urgencies related to the soil's condition which is jeopardised by climate change, the background knowledge review on the related issues given in this chapter provided guidance and support for the selection of factors relevant for the climate change impact analysis in this study. The basics required for understanding soil as a component of the climate system and for understanding the soil-related processes which can disturb other components of natural and managed systems are also given in this chapter, with the purpose of recognising the importance of inclusion of information on soil in planning the actions in other sectors. The terminology and important notes related to the issues discussed in this study can be found in Appendix 0.

1.1. SOIL IN THE MIDST OF CURRENT AND FUTURE CLIMATE

1.1.1. SOIL AND LAND

Soil is a component of land,[1] and requires special attention in the analysis of different direct and indirect climate impacts[2] because it represents the basis for normal development of natural and managed ecosystems. It interacts with other land components, and is affected by human activities, which makes any analysis related to soil very complex and sensitive to the choice and the quality of methodology and data. Soil interacts with climate change in two ways, it can mitigate/accelerate global warming due to its capacity to store/release carbon. According to FAO[3], the top 30 cm of global soil contains approximately two times more carbon than the atmosphere, and it represents the second largest natural carbon sink, after oceans.

Stressors that affect soil come from human activities directly (for example, because of unsustainable land management) and indirectly (climate change impacts soil degradation and soil formation). A more general scope for analysis of climate-soil related impacts, especially of the risks related to desertification, includes the land use component (Reichhuber et al., 2019). Land use may preserve soil health if climate-smart interventions are employed, such are Nature-based Solutions (NbS)[4] (Cohen-Shacham et al. 2016), or degrade soils if climate change is not considered in land use planning through climate change adaptation options. Climate change can accelerate the negative impact of excessive/unsustainable exploitation and multiply expected risks. EEA reported[5] that 13 EU Member States declared that they were affected by desertification. Also, the change in soil moisture because of increasing temperatures and the change of precipitation patterns have been measured, with decreasing trends of average values in the Mediterranean region and increasing in northern Europe, highlighting that these trends may differ in sub-regions and by season. Combating land degradation, meaning to achieve the land degradation neutrality (LDN, Orr et al. 2017) target, includes climate-smart actions for preventing soil degradation and restoring degraded soils.

1 Natural components of the terrestrial portion of the Earth's climate system, which are considered as a part of "land", are: soil, near-surface air, vegetation and other biota, and water (IPCC, 2019). Climate system includes the atmosphere, hydrosphere, lithosphere, cryosphere and biosphere and their interactions.

2 Direct effects of climate change are the ones that directly change soil properties, like disturbance of soil biodiversity and soil structure because of the changed heat conditions and water availability; Indirect effects are the ones that are consequences of reactions of other land components to climate change which interact with soil, like changes in vegetation cover.

3 The Food and Agriculture Organization of the United Nations (FAO) released a global map of soil organic carbon content: https://www.fao.org/news/story/en/item/1071012/icode/

4 Nature-based Solutions (NbS) are interventions which are targeting restoration and sustainable management of natural and modified ecosystems in an adaptive way, providing benefits for both humans and nature.

5 European Environmental Agency (EEA): https://www.eea.europa.eu/signals/signals-2019-content-list/articles/soil-land-and-climate-change

1.1.2. SOIL FORMATION AND CLIMATE

Soil is a porous, heterogeneous system, consisted of solid, liquid and gaseous phases, and inhabited by living organisms. The solid phase of soil consists of mineral and organic matter, while the soil's pores are filled with water and/or air in constantly changing proportions. The soil's inorganic and organic components respond to the inputs of matter and energy which are dictated by climatic conditions and topographic position (Buol et al., 2015). Soil is formed over a long period under the influence of pedogenic factors. Soil forming factors are parent material, climate, living and non-living organisms, topography, humans, shallow groundwater and floodwaters, and time (age of the land's surface). In its initial stages, soil formation includes direct effects of climatic factors and living and non-living organisms on the geological material, and indirect effects of topographic factors in a certain period. As an integral part of ecosystems, soil and soil characteristics cannot be understood isolated but require an understanding of how other components of terrestrial ecosystems influence soil formation. Globally, climate and soil gradients are quite congruent, and that is why the concept of zonation is included from the early days of pedology. Soils formed in different bioclimatic belts, belts with similar radiation and thermal conditions, have typical characteristics. Within the bioclimatic belts, bioclimatic zones have been singled out based on the humidity of the climate. Consequently, soils of different bioclimatic zones have their typical characteristics.

The action of pedogenic factors can be expressed through impacts of different intensities and directions, and they can stand in different mutual relations. A more pronounced effect of one pedogenic factor compared with other factors leads to the formation of soils in which the influence of one pedogenic factor in the genesis is dominant. In most soils, the action of pedogenic factors, the intensity of the action and its direction, as well as the interrelationship among factors, occur mutually, and it is called the constellation of pedogenic factors. The Serbian pedological school includes humans as separate pedogenic factors, which is included under organisms in Anglo-Saxon literature. Also, national pedologists have included flooded waters and groundwater as the seventh pedogenic factor.

Climate is an active soil formation factor that represents a source of matter and energy for soil formation. It represents the average state of meteorological factors over 20–30 years. The most important climatic components that affect the formation and further development of soil are temperature, precipitation, wind, relative humidity, insolation and intensity of sunlight, and evaporation. Although average climatic conditions are known to be related to soil properties, extreme weather conditions in many cases may play a critical role in shaping the soil properties (Buol et al., 2015). Climate is an active factor of pedogenesis, affecting the parent materials and soil by atmospheric precipitation, solar energy and wind. Soil receives matter and energy from the atmosphere through the action of climatic factors, i.e. water, heat and gases. **Atmospheric precipitation** affects the growth and development of plants, the activity of microflora and fauna, the processes of transformation of the mineral and organic matter in soils, and the processes of transfer of soil particles over and under the surface of the terrain. It is important to monitor all parameters of the soil water balance when assessing soil formation: infiltration, surface runoff, deep percolation, antecedent soil moisture, evaporation, transpiration, and interception; and to be familiar with soil water characteristics: soil water holding capacity, soil infiltration rate, and soil hydraulic conductivity. The ratio of evaporation and evapotranspiration to precipitation is also important for soil genesis and soil characteristics. **Sunlight** (**heat**) affects the temperature regime of the surface layer of the atmosphere and soil, which is the environment for rooting, growth and development of plants, and the activity of microflora and fauna. The direct effects of heat are reflected in the processes of evaporation, transpiration, as well as increased physical and chemical weathering of rocks and minerals, decomposition of organic matter in the soil, and water movement within the soil, and has a marked impact on the type and quantity of vegetation. These processes are underpinned by the rate of microbial activity, which is also temperature dependent. The impact of **wind** on soil formation is reflected through the direct movement of particles above the surface of the terrain – Aeolian erosion and their accumulation – Aeolian deposition, as well as through an indirect influence by modifying the climate in the ground layer of the atmosphere, which affects the soil water, air and temperature regimes. **Microclimate** is considered to be the climate in the first few meters above the soil's surface regarding soil genesis. It varies with relief features, soil colour and vegetation. In Serbia, southern slopes are warmer and drier compared with northern slopes. Soil is often thicker on northern slopes which affects the development of vegetation and water retention, as well as eluviation throughout the soil's profile. Soil water content and soil temperature are among the most important properties of soil which are often used as taxonomic criteria in pedology and are considered **dynamic soil properties**.

In the Republic of Serbia, there is **vertical zoning** of climatic factors, i.e. there is a decrease in temperature and an increase in the amount of precipitation with an increase in altitude. Moreover, there is also a bit less pronounced **horizontal zoning**, which is a consequence of the changes in latitude. As a result of this, the southern parts of the country are warmer than the northern ones.

1.1.3. SOIL DEGRADATION

Basic Concept

Soil degradation is characterised as one of the major issues of the modern era because it poses a serious threat to human well-being. The reasons are the rise in human population, the rise and increased expectations for living standards and estimated scarcity of natural resources. Consequently, a lot has been said and written on the subject, and the available literature, especially the statistics on land areas affected and its adverse impact on productivity, can be extremely confusing (Lal, 2018).

Four principal soil functions

1	**Sustain** biomass production and biodiversity including preservation and enhancement of the gene pool
2	**Regulate** water and air quality by filtering, buffering, detoxification, and regulating geochemical cycles
3	**Preserve** archaeological, geological and astronomical records
4	**Support** the socioeconomic structure, cultural and aesthetic values and provide an engineering foundation

Environmentalists and agronomists often have opposite points of view about the problem of soil degradation. In order to carefully assess the problem, it is important to understand the processes involved, identify the cause-effect relationships, conceptualise the issues and be objective, which is not possible without observing soil degradation in terms of its adverse effects on present or potential soil functions, and other concepts like soil resilience and soil quality. Also, soil degradation must not be confused with land degradation. Soil has to be observed as a component of land. Four principal soil functions are to (i) sustain biomass production and biodiversity including preservation and enhancement of the gene pool, (ii) regulate water and air quality by filtering, buffering, detoxification, and regulating geochemical cycles, (iii) preserve archaeological, geological and astronomical records, and (iv) support the socioeconomic structure, cultural and aesthetic values and provide an engineering foundation (Lal, 2018).

These soil functions are difficult to sustain at the same time, because some of them are exclusive, but soil degradation appears when soil loses the ability to perform one or more functions. Two principal soil degradation types are natural degradation and human-induced degradation. Soil degradation affects the overall agricultural productivity and it can be assessed in terms of land use – it can be land use specific, management – it is management prone and specific, in terms of prevalent weather conditions – it can be weather-triggered, and in terms of whether it can be assessed relative to a reference level, whether it is reversible or irreversible.

Knowing the important terms is required when considering soil degradation. **Soil stability** refers to the magnitude of change in its properties under natural or human-induced perturbations – susceptibility to change. **Soil resilience** refers to the ability of soil to recover, bounce, or spring back following a perturbation (Lal, 1993, 1994). **Soil quality** refers to the capacity of soil to perform economic, ecologic, cultural and aesthetic functions (Lal, 2018). Soil degradation, its severity and impact, is affected by soil resilience, soil quality, climate and weather, and management, including land use and farming systems. Mathematically explained, soil quality is the net effect of the difference between soil resilience and soil degradation. On the one hand, soil resilience is governed by inherent soil properties, climate, parent material, land use, and soil/crop management, whereas, on the other hand, soil degradation is affected by land use, management, and the soil's susceptibility to degradation processes, social, political and economic factors. **Soil restoration** is the reverse of soil degradation. Soil properties have their critical limits that are important for stopping and/or reversing degradation processes, and restoring soil functions and quality. Unfortunately, the critical limits of a property beyond which soil functions are drastically restricted are not known for principal soils and predominant land uses. Soil restoration relies on intrinsic soil properties, land use and choice of appropriate soil and crop management systems to reverse degradation trends. Soil reclamation and soil restoration are different terms. **Soil reclamation** improves soil properties but not to the extent to restore the soil to its original level. Soil rehabilitation and remediation are the very last procedures in combating soil degradation and these actions are undertaken when the soil degradation problem already exists.

The assessment of soil degradation is very difficult. There is an urgent need to develop and standardise methods to assess soil degradation by different processes (Lal, 2018), such as (i) soil erosion by wind and water, (ii) soil compaction, (iii) nutrient depletion, (iv) acidification, (v) reduction in soil organic matter content, and (vi) salinisation, and to relate them to the economic impact. These methods should be simple, inexpensive, easy to use, and should relate soil degradation to productivity, environmental regulatory capacity, and management. Unfortunately, there are no standard methods available for assessment of soil quality. Soil quality assessment methods differ among land uses (rangeland, arable land, silviculture, and so on). Other important obstacles in the assessment are the facts that soil degradation processes could occur at a different spatial scale of measurement and can alter in respect to the temporal scale. So, there is a necessity to scale or merge data from different scales, which is a very enthusiastic job.

Available statistics and presented data on soil degradation and its economic impact are not reliable (Lal, 2018). What are the reasons? There is a lack of standard definitions and criteria of soil degradation, and there is a lack of information on the effects of degradation on productivity and environmental quality.

The Main Types of Soil Degradation

Soil degradation is often divided into four types: soil erosion, and degradation of the soil's physical, chemical and biological properties (Lal, 2018). Soil erosion is going to be presented separately in the next sub-chapter.

Physical soil degradation is mainly a result of soil structure breakdown. In this process, soil aggregates are deformed by external or internal forces. At a further stage, soil can be compacted as a result of a combination of pressure and sliding forces as they are applied to the soil.

Human-induced **soil compaction** is one of the broadly distributed forms of soil degradation especially related to intensive agriculture. The main reason for soil compactions is wheel traffic by off-road vehicles because they create compactive stresses with their gears.

In mechanised agriculture, subsoil compaction by vehicles with high axle load is one of the major long-term threats to soil productivity (Håkansson and Voorhees, 2018). Compaction is characterised by a decrease in soil volume after extrusion of air. Consequently, an increase in soil density occurs. Soil compaction generally results in the decrease of soil productivity in terms of yield. Its detrimental effects are related to poor soil aeration and reduced root growth due to high penetration resistance. A suboptimal use of fertilizers, herbicides or fuel occurs under compacted soils. Compacted soils have a larger demand for energy required for tillage. It reduces the plant nutrient uptake and may increase denitrification under wet conditions. It also affects the parameters of the soil water balance by decreasing water infiltration and increasing resistance to penetration. Compaction concerns will continue to increase in the future due to more and more intensive agriculture. The most important effects of soil compaction are cumulative effects on crop yield and various environmental consequences which are difficult to assess. Compaction is one of the factors influencing the loss of soil productivity by erosion and crop production.

Soil crusting is recognised as one of the major forms of soil degradation. The term soil crusting is related to the processes of formation and the consequences of a thin layer at the soil's surface which has reduced the infiltration rate, soil porosity, and high penetration resistance. The surface crust inhibits the emergence of seedlings, initiates water movement over the top of the surface, and favours interrill soil erosion. In the GLASOD project Oldeman et al. (1991) included sealing and crusting in the same section as compaction caused by the use of heavy machinery, which is a great simplification of the problem.

Three major forms of **soil biological degradation** are the decline in soil organic matter (SOM), reduction in soil biodiversity and decrease in biomass carbon.

Loss of **soil organic matter** is a very important type of soil degradation, which occurs on wide areas of the world and it is especially related to agricultural activities. The imbalance between the humification and decomposition rates lead to a decline in soil organic matter. Soil organic matter stores nutrients and presents a source of soil fertility. It contributes to soil porosity and aeration, making soil less dense, and it is the principal component in formation of soil aggregates. It also improves infiltration rates and hydraulic conductivity, contributes to soil warming, and increases the soil's cation exchange capacity. Also, soil organic matter is a major energy substrate for soil microorganisms which constantly decompose soil organic matter for their purposes. The content of soil organic matter in soils is a necessary prerequisite for ecosystem health and productivity, for whichever of the above-mentioned roles. Declining levels of soil organic matter have led to soil degradation, increased erosion and desertification due to its effects on soil structure and overall soil fertility. The main factors responsible for the decline in soil organic matter are: the conversion of forests, grasslands and other natural vegetation into arable land, deep ploughing of arable soils, overgrazing, soil erosion, and forest fires (European Commission, 2005).

The principal forms of **soil chemical degradation** are soil acidification, soil salinisation/alkalisation, nutrient depletion, nutrient imbalance and toxicity, leaching, and soil contamination.

Soil acidification is a naturally occurring process, but it can be accelerated by anthropogenic activity, or slowed down by careful management practices. Industrial and mining activities lead to soil acidification caused by the emission of sulphur (S) and nitrogen (N) gases. Soil acidification is mainly caused by the release of protons (H^+) during the transformation and cycling of C, N, and S, and fertilizer reactions. If the soil does not have a high buffering capacity these processes can have adverse impacts. Serious soil degradation due to acidification may occur if the soil pH falls below 4.5–5.5 at which point toxic levels of Al and sometimes Mn begin to be found in many soils. The degradation caused by acidification outwardly manifests in reduced crop, forest or grassland productivity, and in certain instances, in the transfer of soluble Al to water bodies posing a threat to aquatic life (Sumner, 2018). If the soil base saturation is below 50% these soils are considered dystric. Roughly, base saturation of 50% corresponds to pH 5.5 in water. It is almost impossible to accurately estimate the economic impacts of acidification on crop production on a regional or global scale since they are crop-specific. Acidification tends to decrease the cation exchange capacity in variable charge soils. In acid soils Al tends to become more toxic and Ca and Mg become deficient, which sometimes also occurs with Mn. Nitrogen fixation is reduced by acidification, and therefore many legumes do not grow well under acid conditions due to Mo immobilisation. In Serbia, Dystric Cambisols cover around 1.3 million hectares. Other soil types like Rankers, Pseudogley Soils, Luvisols, Podzols, Calcomelanosols, and Syrozems can also be dystric, naturally or anthropogenically induced. The decrease of soil pH from neutral to mild acid is rarely considered in Serbia as acidification because the pH is higher than 5.5, but it can be a consequence of soil mismanagement and present an initial form of acidification.

Salt-affected soils develop when water-soluble salts or sodium start to accumulate in the soil's profile. Soil salinity can cause the reduction of soil productivity, decline of soil supporting capacity to sustain life, and decline in biodiversity.

Salinisation is considered to be part of the soil chemical degradation processes, but in fact, the environmental effect is much wider because the salt build up determines the soil's physical, chemical, biological, and even mineralogical properties. Excessive salinity reduces the availability of soil moisture due to the high soil osmotic potential, decreases hydraulic properties of soil, leads to toxicity in crops, and ultimately reduces soil fertility. Salts may cause dehydration of plants. The accumulation of soluble salts in soil profiles occurs when evapotranspiration rates are higher than precipitation and therefore the salts are not leached but remain accumulated. Salinisation can be a natural process – primary salinisation, whereas secondary salinisation is the term used to describe soil that has been salinised by human activities, mainly irrigation. The low quality of the irrigation water is a major contributor to soil salinity. Solonchaks are saline soils and are broadly defined as soils with rooting difficulties due to a high concentration of soluble salts. Solonetzes are alkaline soils which are broadly defined as soils with rooting difficulties due to high alkalinity and a high exchangeable sodium percentage. These two Reference Soil Groups from the World Reference Base for Soil Resources also exist in the national classification system in Serbia. Together, they cover over 110,000 ha in Serbia. Areas under Solonetz are four to five times more common compared to Solonchak. Highly saline soils are of little agricultural value and are mainly used for extensive grazing.

Sodic soils are widespread in arid and semi-arid regions of the world and have rooting difficulties due to high alkalinity and a high exchangeable sodium percentage. These soils have very restricted plant growth due to poor soil–water and soil–air relations and severe structural degradation. Sodicity represents the dominance of adsorbed sodium in the soil. It is associated with salt accumulation in soil profiles when evapotranspiration exceeds precipitation, but in some cases salts do not occur while sodium is present. The presence of salts reduces plant growth, directly affecting physiological functions through osmotic and toxicity effects, whereas the presence of sodium affects plant growth because sodicity degrades the physical behaviour of soils. The increased level of adsorbed Na+ which is very hydrophilic disperses soil aggregates, which significantly reduces soil porosity and permeability. Solonetz soils have a dense, strongly structured (massive, columnar or prismatic) clayey subsurface horizon with a high proportion of adsorbed Na^+ and in some cases also Mg^{2+} ions (IUSS, 2015). The suitability of Solonetz for agricultural production depends on the thickness of the topsoil horizon because sub-surface horizons are usually very dense and can present a barrier for root development. Sodic soils are prone to waterlogging, have poor crop emergence and establishment, and gully erosion or tunnel erosion may occur on them. The effects of excessive sodium in soils are realised in harvested yields which are far lower compared to other soils in the same climate conditions.

Soil contamination is defined as any addition of compounds that results in detectable adverse effects on soil functioning (Singh, 2018). The term **soil pollution** is used in cases where contamination becomes severe and adverse effects become unacceptable and lead to soil malfunctioning and consequently to soil degradation (De Haan et al., 1993). Therefore, the difference between soil contamination and soil pollution is in the degree of damage to the soil system. Soil contamination and soil pollution are types of soil chemical degradation. They can be caused by natural processes or by anthropogenic activities. They can be defined as combined negative effects of chemicals on properties that regulate the life processes in the soil. Soil contamination may occur via various diffused and pointed sources, and therefore we recognise contamination from local sources and soil contamination from diffuse sources. The contaminants are heavy metals, metalloids, organic pollutants, and radionuclides. Their increased concentrations reduce the growth and activities of microorganisms and other biota in the soil, plant growth and yield. Soil contamination and pollution are not going to be explained in detail in this report.

The publication "Global Land Outlook" (UNCCD, 2017) in a slightly different way emphasises multiple stressors which lead to soil degradation[6]: (1) soil erosion as physical soil degradation (extreme weather events increase soil erosion risks), (2) loss of soil organic carbon (SOC) as chemical soil degradation (climate change is an additional stressor which can cause SOC decline in natural soils or accelerate the loss of SOC in converted lands); (3) soil salinisation/sodification as chemical soil degradation (increased droughts can increase this risk); (4) loss of soil biodiversity as biological degradation (climate change disturbs the lifecycle of the soil's ecosystem); (5) soil contamination as chemical soil degradation (climate change can trigger floods which can spread the contaminated substances); (6) soil acidification as chemical soil degradation; (7) soil compaction as physical soil degradation; (8) soil sealing as physical soil degradation (climate change can exacerbate negative impacts of soil consumption). Stressors can intercommunicate and multiply the risks of soil degradation.

6 The list of stressors is derived from the publication "Global Land Outlook" (UNCCD, 2017); second edition is expected in 2021.

It is estimated that about a quarter of the land's surface, free of permanent snow/ice, is impacted by human-induced degradation (IPCC, 2019). One of the components of land degradation is soil degradation, which interacts with other land degradation components, like vegetation degradation, water degradation, etc. Degraded soils lose their productive capacity. A globally significant risk of degraded soils is that their capacity to act as carbon sinks is reducing, and can be reverted to sources in some areas that are highly exposed to degradation. The future soil degradation rate depends on combined global socio-economic development (SSP scenarios[7]) and climate change (RCP scenarios[8]).

Soil Degradation Assessment

The major land and soil degradation, and desertification assessments, in the past period referring to the global or large regions scale are as follows: Global Assessment of Human-Induced Soil Degradation – GLASOD (1987–1990), 1st edition of World Atlas of Desertification – WAD1 (1992), Assessment of Soil Degradation in South and Southeast Asia – ASSOD (1995–1997), The World Overview of Conservation Approaches and Technologies –WOCAT database (1992), Mapping of Soil and Terrain Vulnerability in Central and Eastern Europe – SOVEUR (1997), 2nd edition of World Atlas of Desertification – WAD2 (1997), The Millennium Ecosystem Assessment – MEA (2001–2005), Land Degradation Assessment in Drylands project – LADA (2006), Global Assessment of Land Degradation and Improvement – GLADA (2006–2009), Global Land Degradation Information System – GLADIS (2009–2011), and 3rd edition of World Atlas of Desertification – WAD3 (2018).

The need for global assessment of soil degradation has been increasing since the 1970s. The doctrine behind the methodology for the **Global Assessment of the Status of Human-Induced Soil Degradation (GLASOD)** was to develop a structured, informed opinion analysis system to tap into the wealth of knowledge among farmers, pastoralists, extension agents, scientists and conservationists in a meaningful way and to translate these observations into reasonably accurate maps (Oldeman and Lynden, 2018). The GLASOD project was conducted from 1987 to 1990. The result of the project was a creation of a world map regarding the status of human-induced soil degradation at a scale of 1:10 million. Regional institutions or individual scientists were appointed to give their expert opinion on the status of human-induced soil degradation in close consultation with national soil and environmental scientists. The world was divided into 21 regions. The status of soil degradation was mapped within loosely defined physiographic units (polygons), based on expert judgement using available geological, topographical, soils, climate and vegetation maps. The next step was to assess for each unit the occurrence of soil degradation types, their relative extent, the degree of soil degradation and the main causes of degradation. The 21 regions were then compiled into one world map. Twelve different types of soil degradation were considered in total, but it was decided to present its major types only: water erosion, wind erosion, deterioration of soil chemical and physical characteristics. The severity of soil degradation was presented in four classes, based on a combination of degree and relative extent of the degradation type within the mapping unit. The final list of **soil degradation types** to be included in the world map was restricted to twelve types: **Water erosion**: loss of topsoil (1), terrain deformation (2); **Wind erosion**: loss of topsoil (3), terrain deformation (4), overblowing (5); **Chemical deterioration**: loss of nutrients and/or organic matter (6), pollution (7), salinisation (8), acidification (9); **Physical deterioration**: compaction, sealing and crusting (10), waterlogging (11), and subsidence of organic soils (12).

GLASOD recognised five kinds of **human actions** that caused the present degradation of soil: deforestation and removal of natural vegetation, improper management of cultivated land, overgrazing, over exploitation of the natural vegetation for domestic use and (Bio)industrial activities. The vegetation degradation **is not assessed** in GLASOD, just soil degradation. Although having a lot of limitations, Thomas (1993) acknowledges that it is easy to criticise such an approach but difficult to suggest viable alternatives at this scale of investigation.

The Asian Network on Problematic Soils held a meeting in Bangkok in 1993 and recommended the preparation of a soil degradation assessment for South and Southeast Asia at a scale of 1:5 million, based on the GLASOD methodology, but modified according to regional circumstances where necessary.

The projects provide information on soil degradation in South and Southeast Asia, while striving to increase awareness on soil degradation among various stakeholders in the region. The ASSOD project describes the current status of human-induced soil degradation, but with a general indication of the "recent past rate". Moreover, the ASSOD has several changes in respect to the GLASOD methodology. It elaborates degradation trends and the impacts of degradation on productivity, while introducing elements of conservation/rehabilitation and providing linkages to the WOCAT project. Contrary to the GLASOD project where the main output was a map, the ASSOD project generated a comprehensive database on the soil degradation status in the region which can further be used for the production of different kinds of outputs. The WOCAT project is included as it aims to assess the results of soil and water conservation activities on a global scale through proposals of appropriate soil and water conservation technolo-

7 Shared Socio-economic Pathways (SSP): future assessment of socio-economic developments depending on the population growth, income patterns, and life habits, including food consumption patterns (IPCC,2019).

8 Representative Concentration Pathways (RCP): future scenarios of greenhouse gasses emission (IPCC,2013).

gies, through reporting on successful approaches, through creation of a world map of soil and water conservation activities and through a soil and water conservation expert system, for planning and implementation of soil and water conservation measures at the field level and for training purposes.

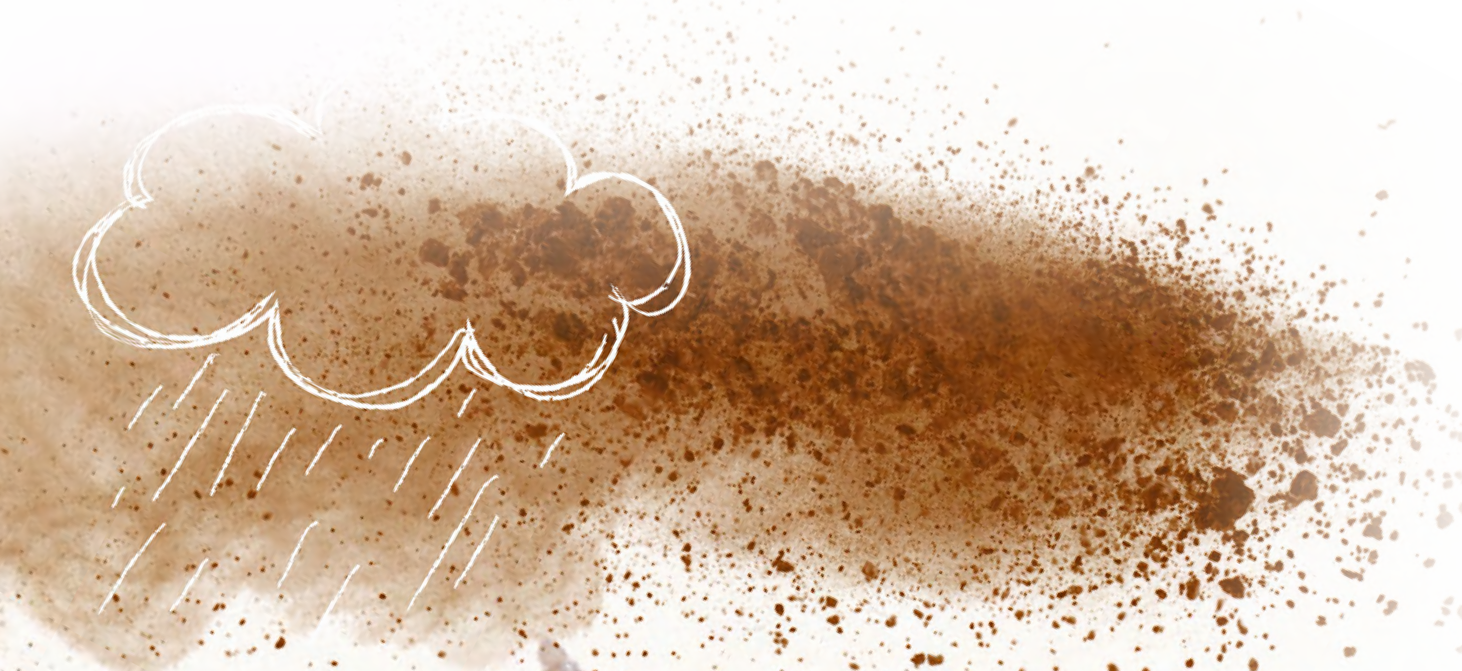
The important part of the ASSOD project is the rate of soil degradation. The recent past rate of soil degradation indicates the rapidity of degradation in a span of five to ten years. In other words, this methodology can assess the trend of soil degradation, which is a very important factor for planning purposes. A clear distinction should be made between the soil degradation status, rate and risk (Sanders, 1994). The soil degradation status is related to the current situation. The degradation rate (or trend) indicates the relative decrease or increase of degradation over the last five to ten years. The rate of degradation does not include areas that may be at risk of considerable degradation because the soils are inherently vulnerable to soil degradation.

Hence, a structured informed opinion is used in both the ASSOD and GLASOD.

1.1.4. SOIL EROSION

Basic Concept

Soil water and wind erosion are two major soil degradation types according to their occurrence on the planet. According to the GLASOD, soil water erosion affects about 56% of the total degraded land while wind erosion affects about 28% of the total degraded land area (Oldeman, 1994). The kinetic energy of runoff removes the topsoil particles, whereas the wind blows away loose and detached soil particles. Soil erosion poses a threat to sustainable agricultural land use and productivity of forestry, and leads to the serious and costly degradation of water and air quality, while also threatening transport and recreation. It has its on-site and off-site effects. On-site effects are related to the deterioration of soil properties, soil productivity and degradation of vegetation, whereas off-site effects are noted through sedimentation, pollution and increased flooding. Although soil erosion is part of natural processes, it is accelerated by humans. The main driving force of soil degradation in Southern, Central and Southeastern Europe is water erosion (EEA 1999, GIZ, 2017). In the process of soil erosion, topsoil particles are lost, and they usually present the parts of most fertile soil horizons. Therefore, the control and management of soil erosion are very important because the remaining soil is less productive and more vulnerable. Further, eroded soils may lose their carbon content, which provokes the emission of carbon to the atmosphere. That is why erosion control has the potential not only to restore degraded soils and improve water quality, but also the additional potential to sequester carbon and therefore to mitigate climate change. The magnitude of soil erosion and its impact on productivity depend on soil characteristics, topography, soil management, and climate conditions. Soil erosion as a naturally occurring process, at mild to moderate rate, cannot be prevented totally, but the excessive erosion must be reduced to a manageable or tolerable level to minimise adverse effects on productivity.



Soil water erosion occurs in the form of splash/interrill, rill, gully, tunnel, stream bank, and coastal erosion. **Runoff** occurs when precipitation rates exceed the water infiltration rates. Raindrop impact on topsoil and water runoff can cause soil particle detachment and transport. Soil water erosion is a typical and dominant form of erosion in humid and sub-humid regions characterised by frequent rainstorms, but it also occurs after intensive rainfall events in arid and semi-arid regions on bare soils and soils with sparse vegetation cover. **Wind erosion** is mainly the characteristic of arid and semi-arid regions, but it can also occur in sub-humid regions with the alteration of seasons. The material that is carried by the wind is usually the size of silt. On the one hand, deposition of this type of material in the past has led to the formation of loess, aeolian sediment, over which very fertile and deep soils developed. On the other hand, excessive wind erosion has caused the degradation of soils to a barren state in arid lands. Wind erosion is also accelerated by anthropogenic activities through deforestation and excessive tillage. High winds, low precipitation (<300 mm of total annual rainfall), high evapotranspiration, reduced vegetative cover, and limited soil development are the main driving forces of wind erosion in arid and semi-arid regions (Blanco and Lal, 2010).

The **main factors** influencing soil erosion are the erosivity of the eroding agent, soil erodibility, terrain slope and vegetation cover. Soil erosion is related to two types of rain events, short-lived intense storms where the infiltration capacity of the soil is exceeded, and prolonged storms of low intensity that saturate the soil (Morgan, 2006) and may produce runoff. **Rainfall erosivity** is expressed through the rainfall erosivity index based on the kinetic energy of the rain. It is the effect of rainfall intensity and duration, and of the mass, diameter and velocity of the raindrop, and can be defined as the intrinsic capacity of rainfall to cause soil erosion. **Runoff erosivity** is the ability of runoff to cause soil erosion (Blanco and Lal, 2010). **Wind erosivity** represents the capacity of wind to cause soil erosion. The wind erosivity value is a function of the mean velocity of wind speed and the duration of the wind. Fast winds cause more erosion than slow winds. **Soil erodibility** can be defined as the soil's susceptibility to erosion (Blanco and Lal, 2010). It defines the resistance of the soil to both detachment and transport. It varies depending on the grade of structure development, particle size distribution, soil organic carbon content and infiltration capacity. In practice, the stability of soil aggregates determines the resistance of the soil to erosion. The soil's resistance to wind erosion depends on dry aggregate stability and on the moisture content. Wind erodibility is a function of texture, crusts, dry aggregate size distribution, aggregate stability, soil surface roughness, soil water content, wind-affected areas, surface cover and management-induced changes. The effect of **slope** on soil erosion is related to the increased volume and velocity of surface runoff due to the increased slope gradient and slope length. The effect of **plant cover** is sometimes crucial in reducing soil erosion. Vegetation can be a protective layer or buffer between the atmosphere and the soil. Leaves and stems reduce the energy of falling raindrops, running water and wind, so that less is directed at the soil, while the below-ground components, comprising the root system, contribute to the mechanical strength of the soil (Morgan, 2006). Therefore, vegetation directly impacts soil erodibility and rainfall erosivity.

Soil erosion – % of territory in the world

OVERGRAZING	DEFORESTATION	EXCESSIVE CULTIVATION
35 %	30 %	28 %

(FAO, 1996)

Soil erosion contributes to global climate change projections. Large amounts of carbon are rapidly oxidised during erosion, exacerbating the release of CO_2 and CH_4 to the atmosphere (Lal, 2003). The effects of wind erosion refer to the alteration of atmospheric radiation, reduction of visibility and traffic inconvenience. Wind eroded particles penetrate urban areas, households, and water objects, deposit in bodies of water, causing pollution and increasing maintenance costs. Suspended particles can be deposited hundreds or even thousands of kilometres from the source. Airborne fine particulate matter with diameters of 10µm (PM10) and 2.5µm (PM2.5) are a threat to human and animal health, industrial and food production. The leading three causes of accelerated, human-induced, soil erosion are: deforestation, overgrazing, and mismanagement of cultivated soils (Blanco and Lal, 2010). About 35% of soil erosion in the world is attributed to overgrazing, 30% to deforestation, and 28% to excessive cultivation (FAO, 1996).

The most notable, and approximately measured, land degradation component is soil erosion, mainly caused by agricultural practices. The soil erosion rate on agricultural fields is by two orders of magnitude higher than the soil formation rate on fields with conventional tillage, and higher by one order of magnitude in croplands with no tillage (IPCC, 2019).

Soil Erosion Modelling

Soil erosion measurements allow rates of erosion to be determined at different positions in the landscape over various spatial and time scales. It is not possible to obtain the measurements on every point of the landscape, and that is why **models are used to predict erosion** under a wide range of conditions. A reliable use of models and their validation can be obtained after comparing modelling and measuring results. Most of the models used in soil erosion studies are of the empirical grey-box type, meaning that some details on how the system works are known. On the one hand, managers, planners and policy-makers require relatively simple predictive tools to aid decision-making, albeit about rather complex systems (Morgan, 2006). Researchers, on the other hand, seek models that describe how the system functions in order to improve understanding of the system and how it responds to change. Also, considering predictive models, decisions need to be made on whether predictions should be made for years, days, storms or short periods within storms; and whether they should be for fields, hill slopes or drainage basins (Morgan, 2006). Three widely recognised groups of erosion models have been distinguished: empirical models, conceptual models and physically based models. All these models differ based on their spatial and temporal scales, data demands – input, and output.

The most important empirical soil erosion models are USLE (Universal Soil Loss Equation; Wischmeier and Smith, 1978), RUSLE (Revised Universal Soil Loss Equation; Renard et al. 1997; Foster, 2005), SLEMSA (Soil Loss Estimator for Southern Africa; Elwell 1978), the Morgan–Morgan–Finney method (Morgan, 2001), EPM (Erosion Potential Method, Gavrilović, 1972) and WEQ (Wind Erosion Prediction Equation; Woodruff & Siddoway 1965).

The most important conceptual models are AGNPS (Agricultural Non-Point Source pollution model; Young et al., 1989), SWAT (Soil and Water Assessment Tools; Arnold et al. 1998), EPIC (Erosion Productivity Impact Calculator; Williams et al. 1983), STREAM (Sealing and Transfer by Runoff and Erosion related to Agricultural Management; Cerdan et al. 2001), and RWEQ (Revised Wind Erosion Equation, Fryrear et al. 1998).

The most important physically based models are WEPP (Watershed Erosion Prediction Project; Nearing, 1989), GUEST (Griffith University Erosion System Template, Rose et al. 1983), EUROSEM (European Soil Erosion Model; Morgan et al. 1998), Watem/Sedem (Water and Tillage Erosion Model and Sediment Delivery Model; Van Rompaey et al. 2001), LISEM (Limburg Soil Erosion Model; De Roo et al., 1996), PESERA (Pan-European Soil Erosion Risk Assessment model; Kirkby et al. 2008), WEPS (Wind Erosion Production System; Hagan, 1991), CSIRO/CaLM Model of Wind Erosion (Shao et al., 1996) and SWEEP (Tatarko et al., 2019).

Soil Erosion and Climate Change

The **predicted climate change** developments are expected to increase the risks of soil erosion, which can exacerbate soil degradation and desertification (Lal, 2006). The magnitude of these processes depends on local and regional conditions.

Average annual runoff rates are expected to increase in high latitudes **30–40%**

Average annual runoff rates are expected to decrease in arid and semi-arid regions **10–30%**

Soil water erosion and runoff are likely to worsen with increased precipitation under the new climate. Changes in rainfall intensity have greater influence on soil erosion than frequency and amount of rainfall. Average annual runoff rates are expected to increase by 30–40% in high latitudes, and decrease by 10–30% in arid and semi-arid regions prone to drought stress (IPCC, 2007). A certain **site-specific** dependence is expected to appear in the future. The effects of climate change on erosion are expected to be more severe in soils which are not managed with good agricultural practices, and which have lower inputs. **Landscape stability** will also be affected in the future, as well as sedimentation in downstream bodies of water. Landslides, streambank erosion, and mudflows may increase under saturated and concentrated runoff conditions in sloping lands, and landscape characteristics can be affected by an increased formation of ephemeral and permanent gullies. The stability of waterways will also be affected. This can also develop concentrated flow erosion in farmlands.

The expected increases in soil erosion due to climate change can influence the pollution of water resources with dissolved and suspended loads.

As soil warming stimulates decomposition and mineralisation of soil organic matter, the released nutrients and soil-borne chemicals can end up in runoff water, or be leached throughout the entire thickness of the soil profile and reach groundwater. This can cause eutrophication and acidification of water sources in some regions of the world. The reduction of the amount of precipitation will affect the moisture content in soils and drier soils are much more prone to **wind erosion**. Additionally, the increase in temperature in arid and semi-arid regions may increase evapotranspiration rates which can cause plant water shortages, which results in reduced vegetative cover and biomass production. This may decrease the protective role of vegetation. Nevertheless, these conditions can favour an increase in the velocity and erosive power of winds (Lee et al., 1996). The duration and intensity of dry seasons accompanied by strong winds can exacerbate the wind erosion risks (Blanco and Lal, 2010).

The impacts of the projected climate change developments on soil erosion are expected to be complex and variable, depending on ecological, landscape, management, and climatic characteristics (Blanco and Lal, 2010). Precipitation and temperature patterns are as variable as their effects on soil erosion, because of the complexity of the erosion process. There are soils the intrinsic properties of which are less sensitive to soil erosion than others. Therefore, prediction of climate change effects on soil erosion is uncertain because of the many interactions in the climate–soil–vegetation–landscape–human system, which is governed by the many interactive processes including rainfall erosivity, soil erodibility, vegetative cover dynamics, landscape dynamics and anthropogenic practices. In some regions, even small changes in precipitation can cause large increases in soil erosion, whereas in others precipitation increase can cause greater vegetation production together with a rise in temperature which may actually decrease rates of water and wind erosion.

1.1.5. SOIL INDICATORS

On the list of environmental protection indicators in the Republic of Serbia, within the section entitled ***Soil***, the following indicators have been recognised: land use change, soil erosion, soil organic carbon content, and management of contaminated sites. Indicator 4.28 is named **soil erosion**. Soil erosion is included in **the section titled *Pressures***. The soil erosion indicator shows the area and intensity of erosive processes as well as categories of actual and potential risk of soil erosion. An assessment of the degree of endangerment from erosion should be provided and soil losses presented in ton/ha/year format. The PESERA and USLE models are the recommended models. The necessary data to assess the risk of soil degradation by erosion are: soil type, soil texture, soil density and soil water and air characteristics, slope and slope length, percentage of soil cover, land use and land use categories, climate – precipitation pattern and wind characteristics, hydrological conditions, dominant factors of the erosion process, and a quantitative indicator of the degree of endangerment due to soil erosion – erosion coefficient Z, according to the erosion potential method. The data are collected throughout the soil erosion mapping project and through mapping soil erosion processes. Data collection frequency spans ten years. This document dates back to 2011 and the ministerial concept has changed.

The other important soil indicator on the list is **soil organic carbon (SOC)** – Indicator 4.29. Soil organic carbon is included in **the section titled *Status*.** The indicator monitors the soil organic carbon content in soil layers in order to determine the degree of soil degradation.

This indicator allows us to asses soil organic carbon stocks depending on soil type and land use in order to determine whether there is a risk to sustainable land management.

The indicator is provided based on the soil organic carbon content in soil. The data are presented in ton/ha of SOC in a 0–30 cm layer, and 0–100 cm layer. The necessary data for determining the risk of degradation due to a decline in SOC are the following: soil organic carbon content, soil texture, land use, and climate variations. The data are collected from the Systematic Soil Monitoring Programme, from soil surveys and other projects which can determine soil quality and asses soil degradation. Data collection is continual, with reports every third year. This document dates back to 2011 and the Ministerial concept has changed.

1.2. CLIMATE CHANGE

1.2.1. GLOBAL CLIMATE CHANGE

Global surface temperature[9] has increased about 1°C since the pre-industrial period, and is projected to increase by the end of the century by 1.5°C (according to RCP2.6), by 2°C (by RCP4.5 scenario) to 4°C (according to RCP8.5 scenario).[10] The observed global soil degradation rates include both the human and climate change impact. Those observations showed that climate change exacerbates the negative impacts of human practices, and the necessity for inclusion of climate change information in future planning of land use and adaptation of different sectors to climate change. Besides the benefits of using such information for the success of the implemented measures, there are co-benefits in maintaining or increasing climate change mitigation potential of soils. Healthy/productive soils are the basis for functional natural or managed ecosystems, which are expected to provide services for humanity and nature in an adaptive way. Those ambitious expectations are the goal of the NbS, and their implementation represents synergetic achievement of the targets set by three UN Conventions.[11]

The main indicator for measuring global climate change is the mean surface air temperature for a certain climate period (20 or 30 consecutive years), which is increasing. Also, temperature increase is happening in all regions of the world, with different rates depending on the region and season. It is caused by excessive heat maintained in the climate system because of increasing greenhouse gas emissions and their ability to absorb long-wave radiation from the surface. Relatively complex ocean and atmospheric currents caused by different distribution of received heat over the Earth, Earth's rotation, and regional and local features of the climate system (land portion, land cover, orography, soil characteristics) cause complex responses of the climate system to global warming.

So, climate change characteristics depend on the surface characteristics of an area, and its position on Earth, and can be locally somewhat altered by human land-based interventions.

Climate change impacts, vulnerability to climate change and climate change risks all depend on the same factors, but additionally depend on human activities in the area (the structure of economy sectors, living conditions, gender and age population structure, population density, etc.).

Assessments of vulnerability to climate change and related risks, and planning of response options (adaptation to climate change, preferably with co-benefits of mitigation) are done at the national level, by providing analyses of climate

9 Global surface temperature is the air temperature near surface (2m height), measured on average for the whole globe; it was adopted as an indicator of global climate change, and its increase is frequently addressed as "global warming".

10 RCP4.5 is a stabilization scenario that assumes stabilization of net greenhouse gases (GHGs) emission rates by 2040; RCP8.5 is a "business as usual" scenario that assumes continual increase of GHG emissions (IPCC, 2013).

11 UN Conventions are: United Nations Framework Convention on Climate Change (UNFCCC), United Nations Convention on Biological Diversity (UNCBD) and United Nations Convention to Combat Desertification (UNCCD)

change and prioritised assessments at the national level followed by selecting adaptation measures in the form of national adaptation plans, strategies and action plans (this process requires consideration of available national documents and information from different sectors, other climate change related documents, and putting in line priority recommendations, including the regional component, and coordination with regional assessments, if needed). Nationally determined contributions (NDC) compile the collected knowledge on climate change risks, adaptation and mitigation options and priorities within the country, and provide lists of actions-to-be-implemented targeting mitigation goals and adaptation to climate change at the national level. There is a strong recommendation from the UNFCCC and knowledge collected in IPCC Assessment Reports and Special Reports that planned measures should be a product of a nexus approach which protects and co-benefits other sectors in addition to a priority sector which implements the measure.

1.2.2. CLIMATE CHANGE IN SERBIA

Serbia is in the south-eastern part of Europe, with lowland and flat terrain in its northern part which belongs to the Pannonian basin (Vojvodina), and hilly and mountain terrain intersected with local river basins (central and southern Serbia) which form an area with relatively complex terrain with diverse small-scale features, including climate characteristics, land use characteristics, soil characteristics, etc. On the global map of precipitation change, induced by climate change, Serbia is approximately situated in the latitudinal belt south of which accumulated precipitation tends to decrease (Mediterranean region) and north of which precipitation tends to increase (central and north Europe). Future climate projections (IPCC, 2013) predict that this belt will shift in terms of precipitation and pass "somewhere" through the territory of Serbia, with significant uncertainty (some models predict a shift to the north and some to the south which causes uncertainties in assessing changes in this area). In addition to the complexity of the terrain features, these uncertainties require in depth climate change and impact analyses for Serbia, preferably in high resolution.

Recommendations on climate change impacts and adaptation provided in the assessments done in the First (2010), Second (adopted in 2017, draft done in 2013) and Third (draft done in 2018) National Communications of the Republic of Serbia,[12] are in an agreement, but successively provide updated data, knowledge, and wider interdisciplinary content, using the latest inputs and methodologies from the IPCC ARs (a selection of GHG scenarios and periods for future climate modelling and related assessments). TNC includes a climate change analysis of the observed available data up to 2017, and future projections using a multi-model approach from the EURO-CORDEX database according to the RCP4.5 (adopted as a lower-end scenario) and RCP8.5 (adopted as a higher-end scenario).[13]

The mean surface temperature for Serbia for the 1998–2007 period increased by 1.2°C with respect to the 1961–1990 reference period. The increase in temperature has been more pronounced in the recent period. For the 2008–2017 period it was 1.5°C to 2.0°C over the territory of Serbia. The highest increase was recorded for the summer season (+1.8°C for 1998–2017) and the maximum daily temperature (in the summer, average maximum daily temperature increased by 2.2°C, and for the 2008–2017 decade 2.5°C over the larger part of Serbia). There has been no significant change in precipitation (about 4% increase on average annual accumulated precipitation over the territory of Serbia for the 1998–2017 period, with a somewhat more pronounced change in southern Serbia in the 2008–2017 period (in the range of 10–20% increase). The most significant change is in the summer accumulated precipitation (the change on average annually accumulated precipitation over Serbia is −18% for the 1998–2017 period, and 20–30% for the 2008–2017 period over the central and southern parts).

Analyses of the change of climate indices, related to the change in the number of days with low and high temperature, show significant reduction in days with temperatures below 0°C, causing lesser duration or absence of snow cover, and increase in days with high temperatures (above 30°C) for about, on average, 20–30 days per year for the 2008–2017 period in lowlands and 10–20 days in hilly and lower mountain regions.

Summer precipitation is decreasing and mean monthly maximum of precipitation is shifting to spring, which means that annual distribution of precipitation is changing. Precipitation distribution is also changing in intensity. The number of days with extreme precipitation events (over 20–40 mm) is increasing over most of Serbia, and they were considered as relatively rare events in the past. In the 2000–2017 period there were seven years with drought on average for the whole territory of Serbia, while in the 1950–1999 period only three such years were recorded. Variations of drought frequency depend on the region.

The overall conclusion was that climate variability has increased. Extremely cold periods have become less frequent but still happen, while extremely warm periods have been increasing in frequency and intensity. Precipitation variability

12 https://www.klimatskepromene.rs/

13 The publication "Climate changes observed in Serbia and future climate projections based on different scenarios of future emissions" (Djurdjevic et al., 2018) includes a short overview of the climate change analysis. The publication "Climate change impacts on Serbian agriculture" includes an overview of the climate change impact analysis and adaptation recommendations (Stričević et al., 2019). Both were based on the work done for the Third National Communication (TNC) of Serbia to the UNFCCC (still in draft version, meaning it has not been adopted by the government). Publications can be found at https://www.klimatskepromene.rs/; Some additional information on climate change over Serbia can be found in Vukovic et al. (2018).

has increased since it was recorded that drought frequency had increased as well as extreme precipitation events. Increased variability is also visible in the annual accumulated precipitation.

Years 2018 and 2019, after the study was presented in TNC, were the warmest on record (since mid-20th century, since measurement data were digitalised and quality checked). Analysis of the temperature data for the 1961–2020 period shows that the ten warmest years in Serbia happened in the 2000–2020 period, and seven of them in the 2010–2020 period.[14]

Soil moisture has decreased 0–10% over most of Serbia. There is a decreasing trend in soil moisture in central and southern Serbia. There is a decrease in river discharge in the rivers in central and southern Serbia, and in annual discharge, while the changes are more pronounced on the seasonal level. Potential evapotranspiration rates have increased by over 5% in most of Serbia. Years with drought coincide with minimums in annual soil moisture in central and southern Serbia, and with the record warmest summers. This shows a significant impact of rising temperatures on draught frequency and intensity.

Future climate change assessment depends on the choice of model ensembles, because there are large variations in the performance of models depending on region. The most representative value derived from a model ensemble is median value, which represents the 50th percentile of ensemble member values. The ensemble chosen for future climate change analysis consists of nine selected models from the EURO-CORDEX database. The observed trends of change will continue and intensify in the future. By the end of the century, the total increase in temperature on average over the territory of Serbia is expected to be 2.6°C according to the RCP4.5 and 5.1°C according to the RCP8.5 with respect to the 1961–1990 reference period, with a more pronounced increase in central and southern parts. In the second part of the century, winter season warming will accelerate according to the RCP8.5, probably because of the absence of snow cover. Projections show that, in the future, the central and southern Serbia will suffer a decrease in annual precipitation, while the northern parts will experience some increase. The summer season will continue to dry while the colder part of the year will receive more precipitation.

By comparing the results of the ensemble median from future climate projections with observed values, it was concluded in the RCP4.5 scenario that the projected changes for the near future period have been exceeded and coincide with projected changes for the mid-century. From the analyses of extreme events from the ensemble median in comparison with observed values, it was concluded that median values underestimate the change in frequency of extreme events, and that trends of change coincide more with the 75th percentile for increasing values and the 25th percentile for decreasing values. To be able to comprehend more extreme conditions and ensure proper risk assessment, the use of data from the model ensemble's most probable range (25th – 75th percentile) is advised.

The National Adaptation Plan (NAP) of the Republic of Serbia was drafted using the information from TNC and updated information on the model ensemble's uncertainty and water resources vulnerability for the agriculture sector (due to the high sensitivity of proposed measures on water availability and extreme weather risks). TNC also assessed the vulnerabilities of forest, water, biodiversity, heath, energy and infrastructure sectors, and proposed general adaptation measures. In the NAP, adaptation measures for selected sectors are specifically planned and tailor-made according to defined priorities and urgencies. Environmental factors that affect all the sectors are weather/climate, water resources, and soil condition. The agriculture–water nexus is recognised and implemented in the NAP. Because of the lack of understanding of climate change impact on soil in Serbia, recommendations that aim to protect soil from degradation are enlisted as general measures in the form of sustainable land management (SLM, Sanz et al., 2017).

Priority measures for mitigation and adaptation were decided on and listed in the Nationally Determined Contributions (NDC) of the Republic of Serbia.[15] Measures that consider interventions related to land would co-benefit from understanding the climate change impact on soil.

14 http://www.hidmet.gov.rs/ciril/meteorologija/klimatologija_produkti.php

15 NDC– revised is currently in draft version.

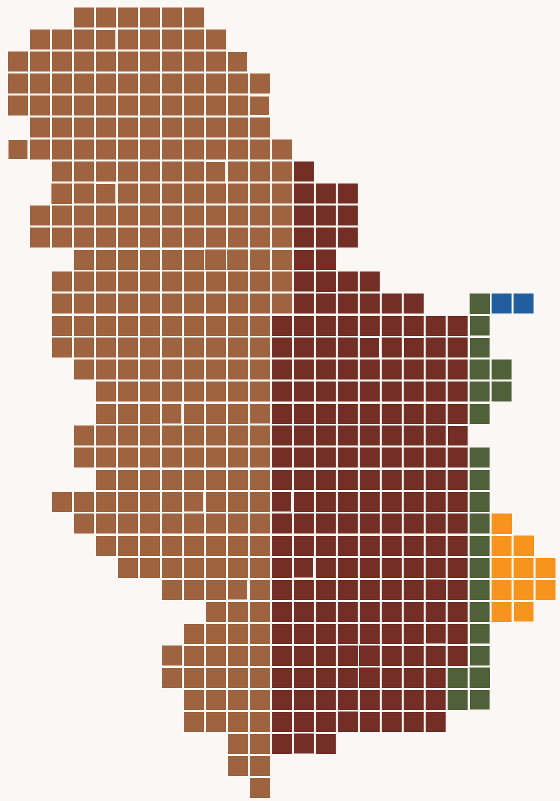
1.3.

SOIL DEGRADATION AND SOIL EROSION IN SERBIA, AND CLIMATE CHANGE

1.3.1. BASIC ISSUES

The total land area in Serbia[16] is 87,730 km², and consists of: cropland surfaces (49,283 km²), tree-covered areas (32,616 km²), grassland (4,100 km²), artificial surfaces (1,539 km²), and wetlands (119 km²). Conversions of tree-covered areas to cropland and cropland to artificial surfaces are enlisted as the most negative factors for land degradation, along with the loss of soil organic carbon (SOC). Besides land degradation, in relation to land use change, soil degradation is one of the components of land degradation that can be affected by land use change or can be the cause of the land use change.

Soil erosion is one of the most pronounced processes of soil degradation observed in Serbia and the cause of decrease in soil quality.[17] About 80% of agricultural land is affected by erosion processes of different intensities. Erosion caused by water is more pronounced in central Serbia, while in Vojvodina it is erosion caused by wind. Some terrains are affected by landslides. Potential soil contamination is present on over 700 locations, and is caused by uncontrolled and improper waste disposal within industrial lands. Analysis of SOC content and its spatial distribution showed that land use, formation processes and climate factors have the highest impact on low SOC levels in the top 30 cm, which is 1.58% on average – it is considered to be low SOC content with tendency for further decrease (Serbian environmental protection agency, 2018). The proposed measures for combating soil degradation, based on the observed trends in degradation and soil health condition, are: (1) institutional capacity building for soil degradation management and soil protection, (2) revision of the Law on Soil Protection, (3) enhancing knowledge on contaminated soils, creating mechanisms for reporting on soil contamination, implementing efficient response actions, and developing a National Strategy with Action Plan for soil contamination management, (4) implementing integrated soil management according to local characteristics, including adaptive management of soil characteristics to climate characteristics, soil types and land use, (5) planning and implementation of actions for fulfilling the sustainable Development Goals[18] that include soil protection and preservation of ecosystem services related to soil.



LAND AREA IN SERBIA

Cropland surfaces	49,283 km²
Tree-covered areas	32,616 km²
Grassland	4,100 km²
Artificial surfaces	1,539 km²
Wetlands	119 km²

16 Land area in UNCCD is defined as the part of the land excluding water surfaces; Serbia occupies 88488 km², and 759 is total surface of water bodies. Listed information on land use and land conversion are from the Report of the Republic of Serbia submitted to UNCCD (2018), https://knowledge.unccd.int/countries/serbia

17 Report on soil condition in the Republic of Serbia for 2016-2017 (in Serbian), Agency for Environmental Protection of Republic of Serbia, ISSN 2466-2968, http://www.sepa.gov.rs/download/zemljiste/Zemljiste2016_2017.pdf

18 Sustainable Development Goals (SDGs) – Agenda 2030.

Integrated soil management as a measure for prevention or mitigation of soil degradation, as listed above, considers soil management adaptable to local conditions including climate conditions. As climate conditions are changing outside of natural variability (Vukovic et al., 2018), and will change in the future, this measure for combating soil degradation requires inclusion of knowledge on the climate change impact on soil. Because soil condition highly depends on other land components, integrated soil management should be understood as integrated land management.

Climate change in Serbia can impact physical, chemical and biological soil degradation and can trigger or exacerbate degradation processes.

Additionally, degradation or mismanagement of other land components can impact soil degradation. TNC, NAP and NDC include measures that aim to enhance the adaptability of the sectors and prevent or mitigate land degradation, for example (sustainable land management, afforestation and reforestation, peatland restoration, etc.). An uncertainty that remained is the analysis of climate change impact on soil done so far, which can contribute to better planning of actions for implementation of measures and to long-term success of the implemented measures.

The rising rate of temperature increase and significantly changed temperature conditions impact sub-surface ecosystems and the soil formation process. The combined effects of changes of temperature and precipitation can cause the change of climate classification in Serbia in terms of water availability (characteristics of aridity/humidity and dryness/wetness of different periods during the year). This may significantly disturb the climate conditions under which vegetation cover and soil are formed and function in a stable way. The increasing frequency and intensity of extreme events, like drought and precipitation (both observed and projected to increase in Serbia) can contribute to enhancing degradation by erosion (wind erosion during droughts and erosion by runoff during extreme precipitation events), soil compaction and spread of contamination. Such events can especially increase the rate of observed tendency of SOC reduction. Soil salinisation can be caused by frequent drought periods. Soil acidification can be caused by extreme rainfall events. These are just some of the potential risks for soil degradation related to characteristics of climate change in Serbia. The combined impacts of climate change stressors can accelerate the process of degradation. Degradation can be simultaneously impacted by human activities, which can mitigate negative climate change impacts or contribute to soil degradation.

The annual cost of land degradation in Serbia is estimated at 254 million United States dollars (USD), which is 7.6% of the country's agricultural Gross Domestic Product, and estimated returns for mitigating land degradation are four times the money invested.[19] The overall assessment of land degradation and the impacts of climate change for Serbia is still unknown, as well as the impact of climate change on soils on the territory of Serbia.

Information and data on climate change impact on soils in Serbia would provide benefits in: (1) enhancing knowledge on soil degradation risks and, thereby, on land degradation risks, (2) better planning of adaptation measures, (3) better assessment of mitigation potential of soils in Serbia; (4) preventing or reversing soil degradation and land degradation (improved planning of related priority actions), (5) supporting implementation of the NbS according to the NbS Standard (Vuković Vimić at al., 2021), etc.

19 From: Investing in Land Degradation Neutrality: Making the Case – An Overview of Indicators and Assessments (Country Profile – Serbia), Global Mechanism of the UNCCD, https://www.unccd.int/sites/default/files/inline-files/Serbia_1.pdf

1.3.2. LITERATURE REVIEW

Physical, Chemical and Biological soil Degradation

Gajić (2013) assessed the long-term cumulative effects of change in land-use type on some soil properties. Conversion of forest to grassland and arable soil has led to a significant decrease in total porosity, infiltration rate and soil organic matter. The bulk density was lower in forest soil compared to grassland and arable soils. In addition, microaggregate stability was significantly higher in forest than in grassland and arable soil. The results of this study indicate that the removal of permanent vegetation in the conversion process from forest and grassland areas to cultivated land may lead to loss of soil productivity and serious soil degradation.

Obviously, there is a need for greater attention to developing sustainable land use practices in management of these ecosystems to prevent further degradation of soils in the region.

Since the critical limits of soil properties are not determined, it is rather difficult to identify the above-mentioned changes as serious soil degradation (author's personal note). Ćirić et al. (2013) investigated the effects of native vegetation conversion on soil aggregate stability and SOC concentration in the Province of Vojvodina. The conversion of native vegetation to cropland caused the mean weight diameter reduction in three soil types. The silt and clay fraction (<53 mm) showed the highest level of SOC preservation. Tolimir et al. (2020) determined that the conversion of forestland into agricultural land without appropriate measures to conserve soil organic matter (SOM) leads to the degradation of physical and rheological soil properties. The findings suggested that SOM content strongly affected specific density, bulk density, total porosity, and liquid and plastic limits. Manojlovic et al. (2011) investigated the concentration and stock of organic carbon (SOC) in soils of Golija Mountain, Serbia. This study demonstrates that the land use system and altitude are important factors affecting SOC. Belić et al. (2013) examined the soil organic carbon (SOC) stock in the South-eastern Panonnian Basin in ten different soil types. The results showed differences between soil types and soil depths and could be valuable for monitoring SOC change and for recommending measures for SOC conservation. Nesic et al. (2014) determined the contribution of organic agriculture to soil structure improvement. The organic agriculture deteriorated the distribution of soil structural aggregates, improved soil aggregate stability, and increased soil organic matter content. Jakšić et al. (2021) investigated the influence of slope gradient and aspect on SOC in the Region of Niš. The results showed that the slope aspect significantly influenced the spatial distribution of SOC in the forest and vineyard soils, where Northern and North-western facing soils had the highest level of organic carbon in the topsoil. Vidojević et al. (2015) investigated the spatial distribution of SOC in soils in the Republic of Serbia. The analyzed SOC stocks were higher in forestland and semi-natural areas than in agricultural soils. Zivotic et al. (2020) was determining soil organic carbon stocks in the soils of foot and toe slopes of Mountain Vukan. The results indicated that global estimates of SOC stocks were underestimated. The obtained results show that SOC stocks determination on small areas can face large variations. In this case, the variations might be related to the impact of landscape as a pedogenic factor, and land use practices. Those variations were noticed in soil mapping units. Therefore, for estimating SOC stocks by modelling, soil types should be seen as proxies. Cakmak et al. (2015) assessed soil acidification for the period up to 2100 in relation to the long term critical and target loading of soil with S and N on the territory of Krupanj municipality by applying the VSD model. Land management, particularly in areas susceptible to acidification, needs to be focused on well-balanced agriculture and the use of crops/seedlings to achieve the optimum land use and sustainable productivity for the projected 100-year period. Ćirić et al. (2017) simulated the response of Vojvodina soils to climate change. The authors found an increase of up to 3.5°C in mean annual soil temperature in the 0–10 cm surface layer and a decrease of up to 0.039 kg in mean soil moisture. Chernozems proved to be more sensitive to temperature increase. Mihailović et al. (2015) investigated the impact of climate change on soil thermal and moisture regimes in Serbia. In the future, warmer and drier regimes can be expected for all Reference soil groups in Serbia. Soils in Serbia are classified with respect to climate change impacts as (1) less sensitive (Vertisols, Umbrisols and Dystric Cambisols) or (2) more sensitive (Chernozems, Eutric Cambisols and Planosols).

Soil erosion

Several authors (Zivotic et al., 2012; Perović et al., 2012; Perovic Belanovic et al., 2013; Perović et al., 2013; Perović et al., 2016; Vulevic et al., 2018; Miljkovic and Belanovic-Simic, 2020) have applied the USLE model in different conditions in Serbia. Zivotic et al. (2012) applied USLE, GIS and remote sensing for the assessment of erosion rates in the river Nišava basin. Very high and severe erosion rates were identified on 21.4% of the basin. The river Nišava basin was classified under the high erosion rate category. Belanovic et al. (2013) assessed soil erosion intensity in the river Kolubara basin. The authors concluded that the tendency of erosion reduction resulted from the abandonment of large agricultural areas. Miljkovic and Belanovic-Simic (2020) compared the USLE and WaTEM/SEDEM models in the river Polomska catchment. The authors obtained slightly higher results with the WaTEM/SEDEM model for all land uses. Polovina et al. (2021) calculated soil erosion loss using the G2 erosion model. A comparative analysis of the two time periods identified a slight reduction in total soil loss. Perović et al. (2019) used the InVEST sediment delivery ratio model, integrated with the EBU-POM regional climate model to quantify erosion intensity in the Vranjska Valley region by the end of the twenty-first century. The reduction of accumulated precipitation, obtained according to this model and scenario, is supposed to reduce erosion in the Vranjska Valley and thereby reduce average soil loss by the end of the century when compared to the baseline period. At the time being, it is believed that the increase of heavy precipitation events may pose a greater threat (Djurdjevic et al., 2018). The effect of climate change on spatial and temporal patterns in the Vranjska Valley will lead to the reduction on average soil loss by the end of the century when compared to the baseline period due to the decrease in the total amount of precipitation. Petrovic et al. (2016) estimated soil erosion rates in the Pčinja and South Morava river basins using Cs137 measurements. The estimates of soil redistribution rates derived by using the PD and D&M models were found to differ substantially and this difference was ascribed to the assumptions of the simpler PD model that cause it to overestimate rates of soil loss. Petrovic et al. (2016) investigated the vertical and spatial distribution of Cs137 in the eroded soils of Pčinja and South Morava river basins. One of the main reasons for the uneven spatial pattern of Cs137 in the area studied may be soil erosion. The erosion potential model (EPM) is a national erosion model developed in the conditions in the Grdelica gorge. Several authors (Kostadinov et al., 2017; Milanovic et al., 2017; Manojlovic et al., 2017; Kostadinov et al., 2018; Manojlovic et al., 2018; Ristanovic et al., 2019; Gocic et al., 2020) recently applied the EPM model in different conditions in Serbia. Baumgartel et al. (2020) identified areas sensitive to wind erosion (in March) in the AP Vojvodina by using fuzzy logic, remote sensing data, and geographical information systems (GIS).

The results show that the hazardous sensitivity category covers approximately 60.4% of the research area, while the medium sensitive category accounts for 36% of the Vojvodina area. The drawback of the analysis is the lack of options to quantify the erosion processes and determine the wind erosion rate in measurable units.

Land Degradation

Kadović et al. (2016) conducted the assessment of sensitivity to land degradation of Deliblato sands using the MEDALUS model. Results showed that 56.3% of the area is classified as critical; 43.2% as fragile; 0.55% as potentially affected and 0.01% as not affected by degradation. Perović et al. (2021) used the MEDALUS method to identify sensitivity to land degradation and desertification (LDD) in Western Serbia between 1986 and 2005 and to assess the possible effects of climate change on land degradation processes. The study revealed that degradation processes in the area studied were found to be most influenced by anthropogenic drivers. Critical areas of LDD susceptibility account for nearly 37% of the study area, and are projected to expand by 33.6% (RCP4.5) and 51.7% (RCP8.5) by 2100.

The vulnerability of forests to climate change in Serbia has been well studied and critical climate change impacts have been detected. The reduction of forest productivity is a component of land degradation and, consequently, eventually contributes to soil degradation. Forest degradation may cause significant weakening of carbon sinks and carbon storage. For example, if no adaptation is implemented, beech forests most probably will not survive late 21. century climate conditions in current habitats, as is recognised in the Second National Communication of the Republic of Serbia and Stojanovic et al. (2013), and on the regional level for the West Balkan Region (Vukovic and Vujadinovic, 2018). For example, in a recently published paper by Miletić at al. (2021), vulnerability to climate change is assessed for ten most important tree species in Serbia. According to the highly reliable results, it is concluded that the current habitats will be partially (but significantly) endangered by climate change by mid-century, and by the end of the century almost all analysed habitats will be under unsuitable climate conditions for species survival. Considering the time scales for implemented measures to become effective in forestry, urgent planning is needed.

1.4. DEFINING THE TOPICS FOR IMPACT ASSESSMENT IN THIS STUDY

The main conclusions derived from the literature analysis:

- ✓ The rate of change of climate characteristic in Serbia is accelerating – changes with slow onset, like general aridity/humidity characteristics (temperature/water relations), and transition to less pronounced continental climate characteristics is observed, and projected to increase and most likely lead to significant changes of general climate features (high temperature conditions can impact water availability);
- ✓ Extreme weather events are increasing in intensity and frequency (drought, heatwaves, high/extreme precipitation), and annual distribution of precipitation is changing at a more rapid pace – soil erosion is found to have the most pronounced effect on soil degradation and extreme weather events will most probably increase the risk of erosion;

- ✓ Vegetation cover and soils, which were formed under past climate conditions, will most probably suffer from the impacts of the changing climate, because of the excessive heat conditions and reduced water availability – the climate is changing to warmer and less humid conditions (change of main climate features) which requires response in the natural environment like adaptation of soil biodiversity, soil formation, migration of natural vegetation cover, etc.; rapid climate change enables natural processes to adapt; decrease in functionality of those systems is expected, which is the basis for the initiation of desertification;
- ✓ The effects of erosion to soil degradation are more pronounced (already observed), as the impacts of extreme weather events – the most represented being erosion by increasing intensity of precipitation, and erosion by wind over the exposed areas;
- ✓ Managed ecosystems (like agricultural lands or managed forests) are impacted by the human factor (human activities) and can be protected from degradation by the implementation of sustainable practices, but can also be more vulnerable if they are additionally disturbed/overexploited – the assessment of risk of degradation for those areas highly depends on the human factor and requires development of future scenarios of human impacts to assess their vulnerabilities and related risks from combined climate–human factors;
- ✓ Managed soil surfaces, like agricultural surfaces, have low to moderate SOC content with the tendency of SOC to decrease, which enhances the risk of degradation from both water and wind erosion, but especially of wind erosion if the soil surface is exposed (without vegetation, for example, after the vegetation period in crop production), because of the deterioration of its structure and the fact that these locations are mainly situated in areas affected by higher winds;
- ✓ Natural lands are expected to adapt naturally to climate change, but they are affected by rapid climate change and increasing weather extremes – those areas are most vulnerable to climate change.

Considering all the above, the research in this study should focus on the following topics:

- ✓ updating the knowledge on climate change in Serbia because recent years are among the top warmest on record;
- ✓ assessment of risk of desertification – (1) risk derived from the climate factor, and (2) risk derived from integrated vulnerabilities derived from land-related factors and the climate factor;
- ✓ assessment of risk of soil degradation from extreme precipitation (contribution to the assessment of soil water erosion) – (1) risk derived from the climate factor, and (2) risk derived from integrated vulnerabilities derived from land-related factors and the climate factor;
- ✓ vulnerability including land factors without the human factor impact in soil degradation risk assessment and mapping for Serbia, which considers presently vulnerable areas, is feasible; the future change of the human factor is unknown and thereby areas under dominant impact of the human factor are considered as areas with good management practices;
- ✓ assessment of vulnerability to wind erosion including agricultural soils (managed soils) should be carried out, if possible, since the decrease of SOC is observed in agricultural soils, under extreme weather conditions conducive to this degradation component, bearing in mind many uncertainties related to the human factor change and other future degradation impacts in these areas;
- ✓ assessment on soil degradation using climate and land factors to be done for the mid-century period (2041–2060) because it should target the planning of urgent mitigation of existing risks and planning of preventive measures, it can afterwards be assumed that land factors may change significantly and scenarios of land factor changes should be developed for the latter period, besides climate factors which can be assessed in advance from climate models which include the change of the dominantly responsible component for climate change (the emission of greenhouse gasses).

CHAPTER 2: **ASSESSMENT OF THE CLIMATE CHANGE IMPACT ON SOILS IN SERBIA**

This chapter presents a short analysis of the climate change in Serbia according to surface air temperature and precipitation change. To assess the impact of the climate change in Serbia, the focus was on negative impact assessment, soil degradation caused by desertification and the increasing risk of extreme precipitation events.

The analysis of selected climate change indicators, which provide input information for soil degradation assessment, is given in sub-chapter 2.1. Sub-chapter 2.2 presents an assessment of soil degradation using climate, climate change, soil, terrain, and land cover information. The risk maps were obtained for the 2001–2020 near-past climate period and 2041–2060 mid-century climate period according to the RCP8.5 emission scenario. The future period is selected based on the purpose of this study – to provide information on future soil degradation risk induced by the climate change impact and to plan and implement measures for prevention of increasing degradation in the future. After the mid-century period, the results according to the RCP4.5 and RCP8.5 start to deviate from one another, with RCP4.5 showing a significant slowdown of climate change and RCP8.5 showing a continuing rapid increase. According to both scenarios, interventions for the prevention of negative impacts by mid-century are necessary. Chapter 2.3 additionally presents a rather general risk assessment of wind erosion, and the possible impacts of future climate change.

2.1. CLIMATE CHANGE INDICATORS

An overview of climate change assessments for Serbia is given in Chapter 1. This Chapter provides an updated analysis of the most relevant indicators of climate change and of indicators that are used for the assessment of the climate change impact on soil. Analyses of observed changes of selected indicators were done for the 2001–2020 climate period and the warmest decade on record in Serbia (2011–2020), compared to the 1961–1990 base period. Future change analysis was done according to the RCP8.5 scenario for the 2021–2040, 2041–2060 and 2081–2100 periods, compared to the 1986–2005 base period.[20]

For the assessment of the impact of climate change on soil, among many possible impacts, two soil degradation components were selected, which were noted (and observed in some parts) as potentially severe consequences of climate change impacts on soil globally as well as in Serbia. They are: desertification and erosion by water. The indicators selected to assess those negative impacts are: the Aridity Index (for the assessment of risk of desertification) and the extreme precipitation indicator (for the assessment of risk of erosion by water).

2.1.1. MAIN FEATURES OF CLIMATE CHANGE IN SERBIA

The average temperature for Serbia and total accumulated precipitation over Serbia were used to provide a short overview of the main features of climate change in Serbia.

Observed Changes of Temperature and Precipitation

For the analysis of the changes for the observed period (1961–2020), the EOBS dataset has been used (more information on EOBS data and their limitations are given in Appendix 1; supplementary material for this analysis is given in Appendix 2).

The changes on average temperatures over the territory of Serbia (mean, maximum and minimum), for the 2001–2020 and 2011–2020 periods compared to the 1961–1990 period, are presented in Table 1. Values are given for average annual (ANN), seasonal (DJF, MAM, JJA, SON) and vegetation periods (VEG=April–October). The average temperature over Serbia for the 2001–2020 period has increased by 1.4°C, and by 1.8°C for the 2011–2020 decade, compared to the average temperature for Serbia for the 1961–1990 period. The highest increase was during the summer (JJA), by 2.0°C for the 2001–2020 period and by 2.4°C for the 2011–2020 decade. The increase on average maximum temperature was higher (1.6°C and 2.0°C) than the average minimum temperature (1.3°C and 1.6°C). The average maximum temperature became higher by 2.6°C for the 2011–2020 decade compared to the 1961–1990 period.

▼ **Table 1.** Anomalies (changes) of average temperatures (°C) for Serbia: Tmean – mean daily temperature, Tmax – maximum daily temperature, Tmin – minimum daily temperature; results are given for periods: annual (ANN), winter (DJF), spring (MAM), summer (JJA), autumn (SON), growing season period (April–October: VEG); anomalies are calculated with respect to the values for the 1961–1990 base period.

	ANN	DJF	MAM	JJA	SON	VEG
Tmean						
2001–2020	1.4	1.3	1.2	2.0	1.1	1.5
2011–2020	1.8	1.7	1.4	2.4	1.8	1.9
Tmax						
2001–2020	1.6	1.5	1.5	2.2	1.1	1.5
2011–2020	2.0	2.0	1.7	2.6	1.7	2.0
Tmin						
2001–2020	1.3	1.3	1.0	1.8	1.2	1.4
2011–2020	1.6	1.7	1.1	2.1	1.7	1.6

20 In the IPCC AR5, TNC (draft), NAP (under construction) and in the study which provides the findings of the TNC "Analysis of observed climate changes in Serbia and future climate projections" (https://www.klimatskepromene.rs/en/publications/) for future climate change assessment the 1986–2005 period was chosen. Future periods were changed compared to AR5 and TNC, and correspond to the NAP (agriculture) and better fit the timing of this study. The base period for the observed climate change assessment is the same as in TNC and NAP.

Changes in accumulated precipitation over the whole territory of Serbia in selected periods are given in Table 2. The average annually accumulated amount of precipitation over Serbia increased by 8% in the 2001–2020 period and by 5% in the 2011–2020 period, compared to the average annually accumulated precipitation over Serbia during the 1961–1990 period. For the 2011–2020 decade the highest increase (of 20%) is in MAM, but a decrease of 8% happened in JJA. The maximum of annual distribution of precipitation moved from JJA to MAM (supplementary material in Appendix 2), meaning that precipitation events from June (the month with the highest precipitation on average during the past climate conditions) shifted to May.

▼ **Table 2.** Anomalies (change) of accumulated precipitation over Serbia (%) for selected periods as in Table 1, with respect to the values for the 1961–1990 period.

	ANN	DJF	MAM	JJA	SON	VEG
Prec.						
2001–2020	8.0	6.0	9.6	-0.2	18.6	9.0
2011–2020	5.2	4.9	20.0	-7.9	5.0	5.5

The spatial variability of precipitation change is much higher than temperature change. The analysis of spatial distributions of temperature and precipitation changes can be seen in available documents discussed in Chapter 1 and are not shown here.

Future Changes of Temperature and Precipitation

The assessment of future changes of mean temperatures and accumulated precipitation over Serbia was done using eight selected models for the EURO-CORDEX database, which were bias corrected (details about CORDEX data, data processing and limitations are given in Appendix 1; supplementary material to this analysis can be found in Appendix 2).

The changes of average temperatures over the territory of Serbia (mean, maximum and minimum), for the selected future climate periods (2021–2041, 2041–2060, 2081–2100) with respect to the 1981–2005 base period are given in Table 3 (changes in annual, seasonal, and vegetation period values). The values presented in the table are the median values of the models' results and the values of the 75th percentile of models' ensemble (the 75th percentile is presented because those values correspond better to the continuity of observed change than median values).

The temperatures for all periods selected for the analysis have been increasing and will continue to increase in the future. For the 2041–2060 period, which was chosen for the assessment of soil degradation, the increase on average annual temperature over Serbia will more likely be 2.6°C (according to the 75th p.) than 2.0°C (according to median value), compared to the average temperature for the 1986–2005 period. Since the annual temperature already increased by 0.5°C in the 1986–2005 period compared to the 1961–1990 period, this means that the total increase of average temperature in Serbia will be 3.1°C in the mid–century climate period. For the 2081–2100 period, the total increase of average annual temperature is expected to be 5.8°C compared to the 1961–1990 period (according to the 75th p. values).

The highest increase is expected for the JJA season. The expected increase for the 2041–2060 period, according to 75th percentile values, is 2.8°C compared to the 1986–2005 period. The summer season (JJA) in this base period already increased by 1.1°C compared to the 1961–1990 period, meaning that the total increase in JJA is expected to be 3.9°C. In the 2081–2100 period, the temperature for JJA is expected to increase by 6–7°C compared to the 1961–1990 period. The increase in the average maximum temperature is somewhat higher than in the average minimum temperature.

▼ **Table 3.** Anomalies (changes) of average temperatures for Serbia: Tmean – mean daily temperature, Tmax – maximum daily temperature, Tmin – minimum daily temperature; results are given for periods: annual (ANN), winter (DJF), spring (MAM), summer (JJA), autumn (SON), growing season period (April–October: VEG); anomalies are calculated with respect to the values for the 1986–2005 base period; the given values are median values and values of the 75th percentile of climate models' ensemble.

	ANN	DJF	MAM	JJA	SON	VEG
Tmean – median						
2021–2040	1.1	1.1	1.1	1.2	1.3	1.2
2041–2060	2.0	1.8	1.9	2.2	2.1	2.0
2081–2100	4.4	4.5	4.1	4.6	4.2	4.3
Tmean – 75. perc.						
2021–2040	1.7	2.0	1.6	1.4	2.3	1.6
2041–2060	2.6	2.6	2.0	2.8	3.1	2.7
2081–2100	5.3	5.4	4.4	5.8	5.8	5.5
Tmax – median						
2021–2040	1.1	1.2	1.1	1.2	1.4	1.2
2041–2060	2.0	1.9	1.9	2.3	2.2	2.1
2081–2100	4.5	4.9	4.2	4.9	4.3	4.4
Tmax – 75. perc.						
2021–2040	1.8	2.2	1.5	1.5	2.4	1.7
2041–2060	2.7	2.7	2.0	2.9	3.1	2.8
2081–2100	5.5	5.7	4.5	5.9	5.7	5.5
Tmin – median						
2021–2040	1.1	1.0	1.1	1.2	1.2	1.2
2041–2060	1.9	1.8	1.8	2.0	2.0	1.9
2081–2100	4.3	4.2	4.2	4.5	4.2	4.3
Tmin – 75. perc.						
2021–2040	1.6	1.9	1.6	1.5	2.1	1.5
2041–2060	2.4	2.4	2.0	2.7	2.9	2.6
2081–2100	5.1	5.1	4.4	5.5	5.6	5.3

Future changes of precipitation accumulated over the whole territory of Serbia in selected periods are given in Table 4, with respect to the 1986–2005 base period. Because of the large uncertainty in assessment of future precipitation change, the values are given for the climate models' ensemble median, the 25th and 75th percentile. The average annual accumulated precipitation over Serbia will most likely decrease in the range of -0.5 to -9.0% for the 2041–2060 period, compared to the 1986–2005 period. According to the observed shifts in precipitation patterns (from JJA to MAM), it is very probable that precipitation will continue to shift further to the colder period of year (values of the 75. perc., 14.6% for DJF) and that the dry season will further suffer the decrease of precipitation which will extend in duration (over 20% decrease of precipitation in JJA according to the 75th perc.). In the 2081–2100 period, it is likely that annual accumulated precipitation will decrease in the range of 7.9 to 13.6%, and in the range of 24.9 to 42.5% in JJA. The loss of precipitation during the growing season (vegetation period), combined with increasing temperature, pose a great risk for plant development, among many other impacts.

▼ **Table 4.** Anomalies (changes) of accumulated precipitation over Serbia (%) for selected periods as in Table 3 with respect to the values for the 1986–2005 base period; the given values are median values and values of the 25th and 75th percentile of climate models' ensemble.

	ANN	DJF	MAM	JJA	SON	VEG
Prec. – median						
2021–2040	-1.3	6.4	6.6	-1.0	-1.8	-0.2
2041–2060	-0.5	10.9	1.5	-13.7	1.6	-9.1
2081–2100	-7.9	17.3	1.9	-24.9	-4.4	-17.8
Prec. – 25. perc.						
2021–2040	4.8	12.2	9.5	2.7	7.5	1.6
2041–2060	4.8	14.6	6.3	-3.3	8.8	-0.9
2081–2100	6.7	28.5	15.8	-13.4	5.8	-5.3
Prec. – 75. perc.						
2021–2040	-3.2	-6.9	-7.3	-6.0	-15.3	-6.6
2041–2060	-9.0	-1.9	-6.1	-22.9	-2.5	-12.2
2081–2100	-13.6	3.7	-9.1	-42.5	-11.5	-27.2

As in the analysis of the observed data, spatial variability of temperature and precipitation change is not considered here. The main conclusions about spatial distribution can be seen in other literature provided in Chapter 1, like the one that the decrease of precipitation will be more pronounced in central and southern Serbia, and that there will be a slight increase in north Serbia.

2.1.2. ARIDITY INDEX ANALYSIS AND RELATION TO RISK OF DESERTIFICATION

For the assessment of the climate change impact on the risk of desertification, the chosen indicator is the Aridity Index. Risk levels are assigned according to the Aridity Index values. The analysis of values and changes of the Aridity Index over Serbia are presented in the following text.

Aridity Index

Rapid climate change disturbs the process of soil formation and the processes which maintain soil functionality as part of the climate system – climate change causes soil degradation. The climate indicator that provides information on the humidity/aridity of the area is the Aridity Index (AI), and has been correlated with the desertification risk.

The Aridity Index is calculated as the annual average accumulated precipitation divided by the average annual accumulated potential evapotranspiration for the chosen climate period. In this assessment, potential evapotranspiration was calculated according to the Hargreaves formulae.[21] More details about the methodology used for calculating the AI for the past and future periods, and other relevant information, can be found in Appendix 2.

The classification of climate according to the AI is given in Table 5, along with corresponding levels of risks from desertification. For the assessment of AI values on the seasonal level, which would provide information about interannual variations of dry/wet conditions, classes for classification of the dryness of a period or season were adopted as in Table 5.[22]

21 This formulae for the calculation of potential evapotranspiration is used by the Republic Hydrometeorological Service of Serbia for monitoring this parameter over the territory of Serbia, and is used for assessments in the National Adaptation Plan of the Republic of Serbia (currently under construction).

22 "Aridity" is used for measuring persistent drier conditions (lack of precipitations) over some area, and cannot be used for assessing a certain period of the year, which is why "dry/wet" categories are defined for the seasonal and vegetation period analysis; areas with long-lasting dry conditions are considered "arid".

▼ **Table 5.** Classifications according to the Aridity Index (AI) for: climate (aridity classes), risk of desertification in relation to climate classes, and dryness classes for the classification of dryness of selected periods.

AI	Aridity Classes	Desertification risk	Dryness Classes
AI < 0.05	hyper-arid	-	very dry
0.05 < AI < 0.20	arid	very high	dry
0.20 < AI < 0.5	semi-arid	high	semi-dry
0.50 < AI < 0.65	dry sub-humid	moderate	moderate
0.65 < AI < 0.75	humid	low	wet
0.75 < AI	hyper-humid	-	very wet

Observed Changes of the Aridity Index

The average values of the AI for Serbia and their changes for the 1961–2020 period are given in Table 6. On average, in the 2001–2020 period, Serbia had a climate characteristic on the upper threshold of the "humid" class (Ai = 0.75). JJA is the driest season with "semi-dry" conditions (AI = 0.42). For the growing season period (VEG=April–October) the value of the AI is 0.55 which classifies this period as a period with "moderate" conditions. The AI for the 2011–2020 decade shows that the impact of higher temperatures on evapotranspiration is notably increasing. The annual value is somewhat reduced, and the highest decrease in AI value happened for the JJA season. The change in the annual distribution of precipitation and shifts of maximum accumulations from June to May cause a high increase of the AI for the MAM season. The growing season period also suffered a small decrease of the AI. The obtained results show how much the observed increase in temperature and the change of precipitation impacted the change of the AI.

▼ **Table 6.** The AI average values for the territory of Serbia: annual (AI), December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), September–October–November (SON), the vegetation period (VEG); the change of the AI (AI_{dif}) is given in comparison to the 1961–1990 period.

Period	Variable	ANN	DJF	MAM	JJA	SON	VEG
2001–2020	AI_{ave}	0.75	2.67	0.77	0.42	1.18	0.55
	AI_{dif}	0.012	-0.09	0.037	-0.033	0.095	0.015
2011–2020	AI_{ave}	0.72	2.56	0.84	0.39	0.99	0.53
	AI_{dif}	-0.02	-0.192	0.108	-0.071	-0.09	-0.011

Since this index represents a rather general assessment of aridity, dividing the climates into a few groups worldwide, it can be considered as an index that is not very sensitive to usual climate variability, even to the observed rates of temperature increase, meaning that its change highlights that there is a significant disturbance in the heat–water balance in the area. For desertification to happen, caused by climate change and not by negative direct human impacts through land-based interventions, climate shifts need to be rapid and changed conditions need to be persistent over some area. For this reason, the annual AI represents a good indicator to use for assessing risk of desertification caused by climate change.

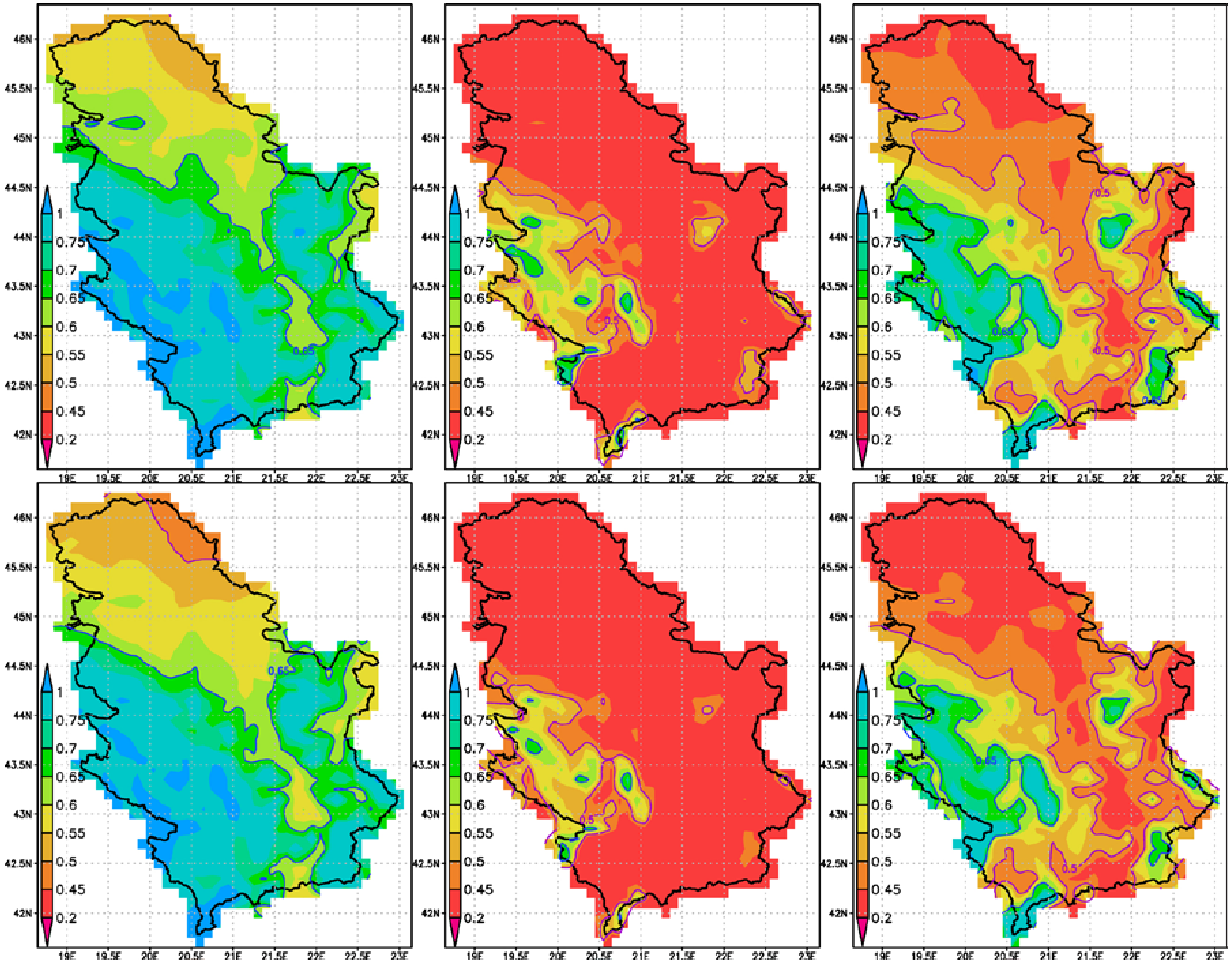
The AI values for selected periods during the year show an uneven distribution of dry/wet periods during the year, and that in the summer season soil and land cover are most exposed to stress from drier conditions. Growing season conditions, on which agricultural production highly depends, are close to the "semi-dry" class, meaning that some years experienced dry conditions, very unsuitable for the majority of agricultural production.

The spatial distribution of the annual AI, JJA and growing season values for the 2001–2020 and 2011–2020 periods is presented in Figure 1. The results for other periods can be found in Appendix 1. Vojvodina and the majority of lowlands in central, southern and eastern Serbia have "dry sub-humid" characteristics, while other parts have more humid conditions. In the 2011–2020 decade, compared to the 2001–2020 climate period, dry sub-humid climate conditions expanded somewhat over a larger territory. At the north-east part of Serbia the AI shows the intrusion of semi-arid climate. A similar spatial trend of change in increasing dryness conditions of the JJA and VEG periods is observed. In the growing season period, semi-dry conditions are present in the majority of lower altitude areas.

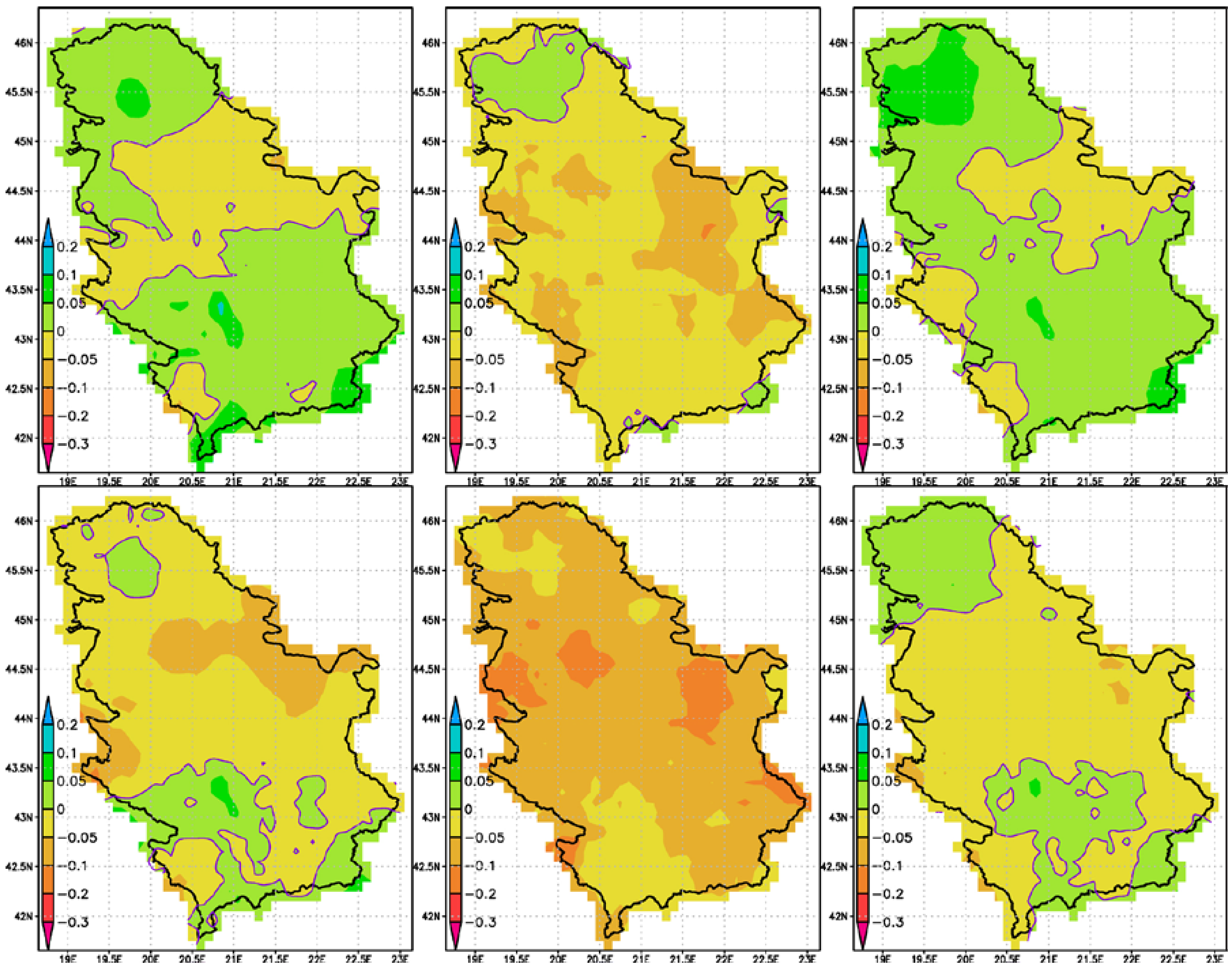
The spatial distribution of the difference in AI values for the selected periods compared to the 1961–1990 period is presented in Figure 2. For the 2001–2020 period the change in the annual AI was in the range of ± 0.05 which is related to the combined (but opposite) effects of increasing precipitation and increasing temperature. For the 2011–2020 period, the decrease of the AI was more pronounced, meaning that the signal of increasing aridity over Serbia due to increasing temperatures began to be notable over the larger part of the territory, indicating the possibility that the AI will continue to decrease further in the future, and that the change of future conditions may increase the risk for desertification. During the JJA season, dryness was increased by 0.05 in the 2011–2020 decade throughout Serbia. During the growing season, the changes were in the range of ± 0.05, but in the 2011–2020 decade, a decrease of AI values was present in the larger part of Serbia.

While some changes in the AI are insignificant, some may be sufficient (in areas with lower AI values) to initiate disturbances in soil and land cover conditions, especially when those surfaces are additionally stressed by direct human impacts.

The results presented on AI values and their changes during the past period show that, currently, the risk of desertification caused by climate change is low. North Serbia (Vojvodina) is affected by changing conditions that can most probably lead to high risk of desertification in the near future, if such trends of AI change continue. Some parts of central, southern and eastern Serbia are under increasing risk.



▲ **Figure 1.** Average AI for the 2001–2020 (upper panels) and 2011–2020 (lower panels) periods: annual (left column), JJA (middle) and VEG (right).



▲ **Figure 2.** Change of AI for the periods 2001–2020 (upper panels) and 2011–2020 (lower panels) compared to 1961–1990: annual (left column), JJA (middle) and VEG (right).

Future Changes of the Aridity Index

The assessment of future changes of AI is done using the climate models' ensemble median and 25th percentile of AI change for future periods (2021–2040, 2041–2060, 2081–2100) with respect to the base period 1986–2005, for average annual values, seasonal (DJF, MAM, JJA, SON) and vegetation period (VEG). According to the observed changes of AI, changes according to 25th percentile are more probable for the future. Changes of average AI for Serbia are presented in Table 7 (other relevant results and comments are given in Appendix 2).

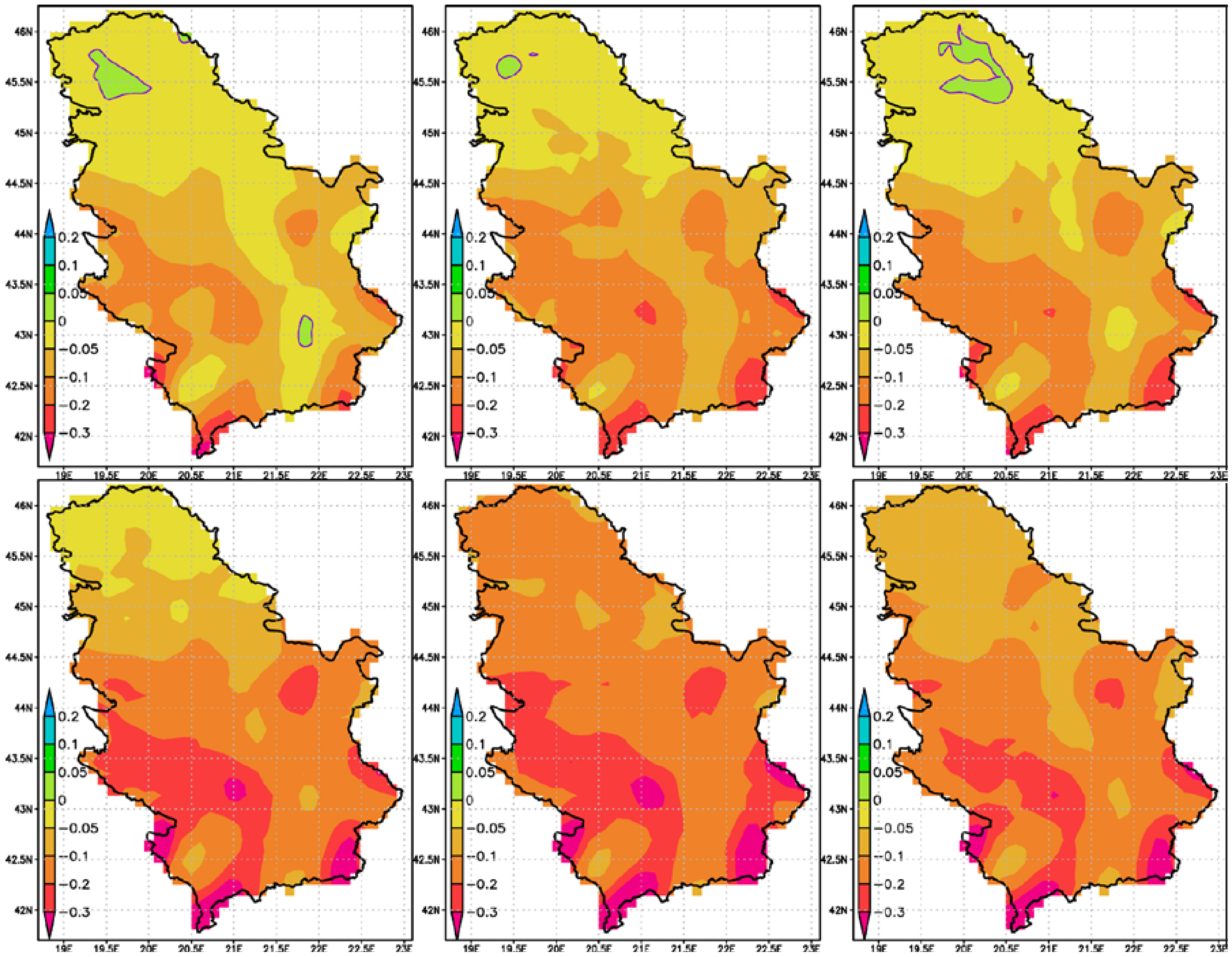
Average annual AI for Serbia is decreasing further in the future. In the 2041–2060 period AI is in the "dry sub-humid" category, with "moderate" risk of desertification on average over Serbia, which indicates that some areas in Serbia may be more severely under conditions conducive to desertification. In the 2081–2100 period average climate conditions in Serbia are categorised as "semi-arid", which reflects high risk of desertification on average for Serbia. Most severe reduction in AI, which indicates significant increasing dryness is further decrease of AI for JJA, the season which was already categorised as "semi-dry" in the past period. In the vegetation period, in the near-future, average conditions are "semi-dry" and continue to change toward increasing dryness.

▼ **Table 7.** Changes of average AI for the territory of Serbia: annual (AI), December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), September–October–November (SON), vegetation period (VEG); changes of AI (AI_{dif}) are given compared to 1986–2005, median ensemble values of change and values of 25th percentile; presented AI value for future period is obtained by adding the 25th percentile of models' ensemble change to average observed value of AI for the period 1986–2005; by colour is marked the category from Table 5.

Period	Variable	ANN	DJF	MAM	JJA	SON	VEG
2021–2040	AI_{dif} -median	-0.04	-0.13	0.02	-0.02	-0.07	-0.02
	AI_{dif} -25. p.	-0.07	-0.22	-0.08	-0.06	-0.32	-0.07
	AI -25. p.	0.64					
2041–2060	AI_{dif} -median	-0.06	-0.15	-0.04	-0.10	-0.10	-0.09
	AI_{dif} -25. p.	-0.14	-0.38	-0.10	-0.15	-0.14	-0.12
	AI -25. p.	0.56					
2081–2100	AI_{dif} -median	-0.18	-0.33	-0.07	-0.18	-0.22	-0.18
	AI_{dif} -25. p.	-0.23	-0.63	-0.16	-0.26	-0.26	-0.24
	AI -25. p.	0.47					

Annual, JJA and VEG spatial distribution of AI changes (median and values of 25th percentile) for the 2041–2060 period, which was selected for future desertification risk assessment, are given in Figure 3 (other results can be found in Appendix 2). A higher decrease of AI is expected in central and southern Serbia than in the north part. Areas with a decrease higher than 0.1 can be considered to be affected with a significant shift of climate conditions toward more arid conditions. The same is obtained from the increasing dryness for JJA and VEG (JJA - the season with already semi-dry conditions over the large part of Serbia and VEG – the period which has semi-dry conditions in lower altitudes). In these periods, it is possible that some regions will be in the "dry" category in the future.

The changes in annual AI values (as an indicator of aridity related to the risk of desertification), for the 2041–2060 period (compared to the 1986–2005 period), are used for future desertification risk assessment. The map of this climate risk was made by adding AI anomalies, obtained as 25th percentile values of results of the model' ensemble, to the average annual AI values for the 1986–2005 period calculated from observed data.



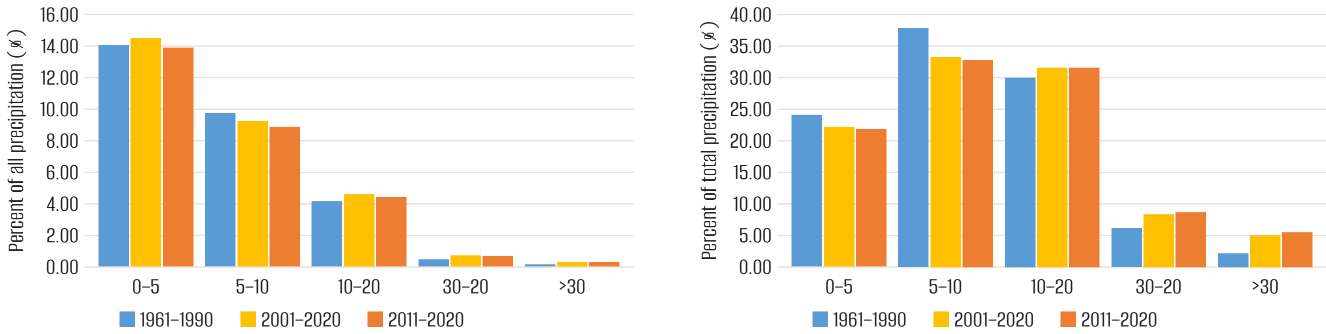
▲ **Figure 3.** Change in the AI for the 2041–2060 period compared to the 1986–2005 period: annual (left column), JJA (middle) and VEG (right); the upper panels represent median values of the climate models' ensemble, the lower panels represent the 25th percentile.

2.1.3. EXTREME PRECIPITATION ASSESSMENT AND RELATION TO RISK OF EROSION

The change in annual distribution of precipitation and the change in distribution of precipitation by intensity are already observed in Serbia, as well as the corresponding risks from increasing events with high surface runoff, which is causing an increasing number of flesh floods. Previous analysis of future projections showed that accumulation of precipitation in high precipitation events will increase further. For this reason, supported by the evidence, it is considered that the risk of erosion of soil by high precipitation events is increasing and contributes to an increasing soil degradation risk. For the assessment of impact of this climate change feature on soils in Serbia, an indicator for extreme precipitation is chosen. The indicator is based on processing the data on extreme daily precipitation, which were relatively rare events in the past, but have the observed tendency of an increase.

Extreme Precipitation Indices

The distribution of days with precipitation within a certain range and the distribution of accumulations of precipitation are presented in Figure 4. Most of the daily precipitation in Serbia is below 5 mm, but the highest accumulations of precipitation happen on the days with precipitation ranging from 5 mm to 10 mm. In the 2001–2020 and 2011–2020 periods, the number of days with precipitation between 5 mm and 10 mm decreased and the number of days with higher precipitation increased. Accumulated precipitation increased during the days with precipitation between 5 mm and 10 mm and decreased during the days with precipitation between 10 mm and 20 mm, which made the accumulations in these two categories almost the same. A significant increase in precipitation accumulations happened during the days with very high precipitation (20–30 mm) and with extreme precipitation (above 30 mm). The latter is considered as a rare event in Serbia, but the accumulated precipitation in such events in the 2001–2020 and 2011–2020 periods compared to the value for the 1961–1990 period doubled. The increase is more pronounced for the 2011–2020 decade. More on these results can be found in Appendix 3.



▲ **Figure 4.** The number of days with precipitation within a certain range (left) expressed as a percent of all precipitation data (all daily data for Serbia during the selected period), and precipitation accumulated during the days with precipitation within a certain range expressed as a percent of total accumulated precipitation for different climate periods (right).

The use of information on the events of extreme precipitation (>30 mm) is chosen for further analysis and defining an indicator, which will reflect the high risk of precipitation impacting the soil, assuming if such a relatively rare event happened, it would very likely affect exposed soils in a negative way.

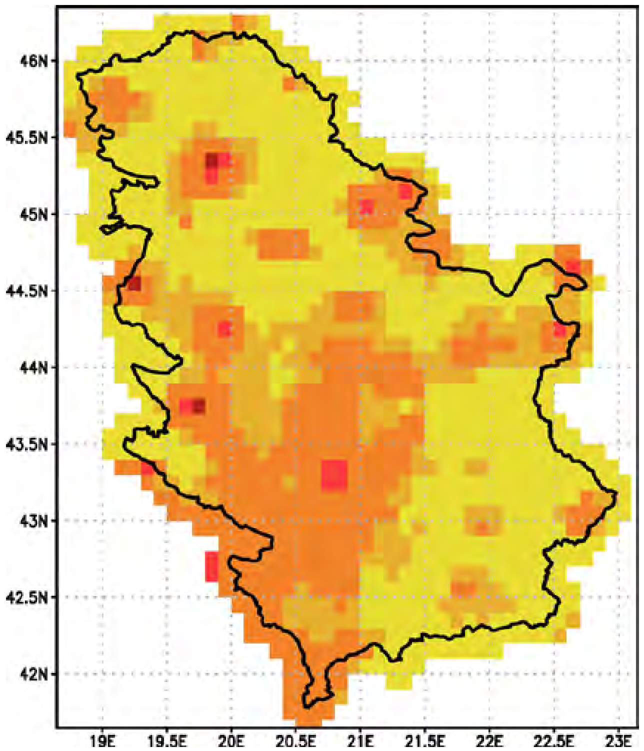
▼ **Table 8.** Extreme precipitation indicator (EPI) and the corresponding risk level.

Range of values for PR30ND and PR30AC: one condition should be realised	Risk level
PR30ND < 1 or PR30AC < 30	lower or inconclusive
1 < PR30ND < 2 or 30 < PR30AC < 50	moderate
1 < PR30ND < 2 or 50 < PR30AC < 70	high
2 < PR30ND < 3 or 70 < PR30AC < 90	very high
3 < PR30ND or 90 < PR30AC	extremely high

Analysis is done for several indices related to extreme precipitation events:

- ✓ PR30ND – average number of days per year with precipitation over 30 mm [days],
- ✓ PR30AC – average accumulation per year on days with precipitation over 30 mm [mm],
- ✓ PR30YY – percentage of years in a climate period when at least one day with precipitation over 30 mm happens [%].

The indicator for risk assessment is created based on the number of days (PR30ND) and accumulation of precipitation during the extreme precipitation events (PR30AC). Threshold values and corresponding risk level from extreme precipitation are given in Table 8. It is required that at least one of the two selected indices have the value in the recommended range. In this case, weaker condition in general is related to accumulated precipitation index. Extreme precipitation indicator (EPI) can be defined by using only one, but well-adjusted index to reflect both pieces of information (frequency and intensity). Recommended thresholds are defined to distinguish areas more and less affected by extreme precipitation per decade at the national level, but adjustments of the indicator are probably required at the local level, after the analysis of relations of high precipitation events with detected consequences. A map of the risk level for the 2001–2020 climate period is shown in Figure 5. The maps of the risk level for other selected past periods are shown in Appendix 3. Representation of data in these maps is such that the resolution of data is clearly visible. According to this definition of risk level, in the 1961–1990 period, the risk was present only in some small-scale areas in Serbia, and values for the 2011–2020 decade show the expansion of the area with a high risk. Analysis that supports such a definition of the extreme precipitation indicator (EPI) is presented in the following text.



▲ **Figure 5.** Risk level determined with the extreme precipitation indicator (EPI) for the 2001–2020 period; colours correspond to the risk level in Table 8.

Observed Change of Extreme Precipitation Indices

The values of extreme precipitation indices (PR30ND, PR30AC, PR30YY) for the selected periods (2001–2020 and 2011–2020) are shown in Figure 6, and their change with respect to the 1961–1990 base period in Figure 7 (other results can be found in Appendix 3).

The major part of Serbia in the 2001–2020 period had an average number of days with precipitation above 30 mm (PR30ND) above 0.5 per year, meaning that such events in these recent periods could happen every second year. Values above 1 mean that such events could happen once per year, which is considered a high frequency for such severe weather events. This is not necessarily the case, there can be several days with extreme precipitation during some years, and during others, not one of these events happened.

To further expand the knowledge on such events, average values of accumulated precipitation in days with precipitation over 30 mm were calculated per year (PR30AC). The values are shown in mm and not in % of total accumulation, which is a more common way of presenting these results, because the goal was to show the distribution of precipitation accumulations and not their fraction compared to the total accumulation which differs from one place to another. These results indicate the areas where more water is precipitated in the form of extreme precipitation. Values over 30 mm distinguish more and less affected areas. It can be understood that if the average accumulated precipitation per year of such events is above 30 mm, the average number of days with precipitation above 30 mm should be 1 or higher. This is not necessarily the case, as can be seen comparing areas with PR30ND above 1 and PR30ACC above 30 mm, meaning that some of those events have also notably higher intensity than 30 mm per day.

The percent of years when the days with extreme precipitation happened (PR30YY) are calculated to determine in how many years such events, here recognised as "rare", happened. The results show that in a large part of Serbia, the values are above 50%, meaning that in 10 out of 20 years in the 2001–2020 period, days with extreme precipitation were recorded, and in the 2011–2020 period, 5 out of 10 were recorded. Larger values indicate for sure that a risk of extreme precipitation exists in some consecutive years.

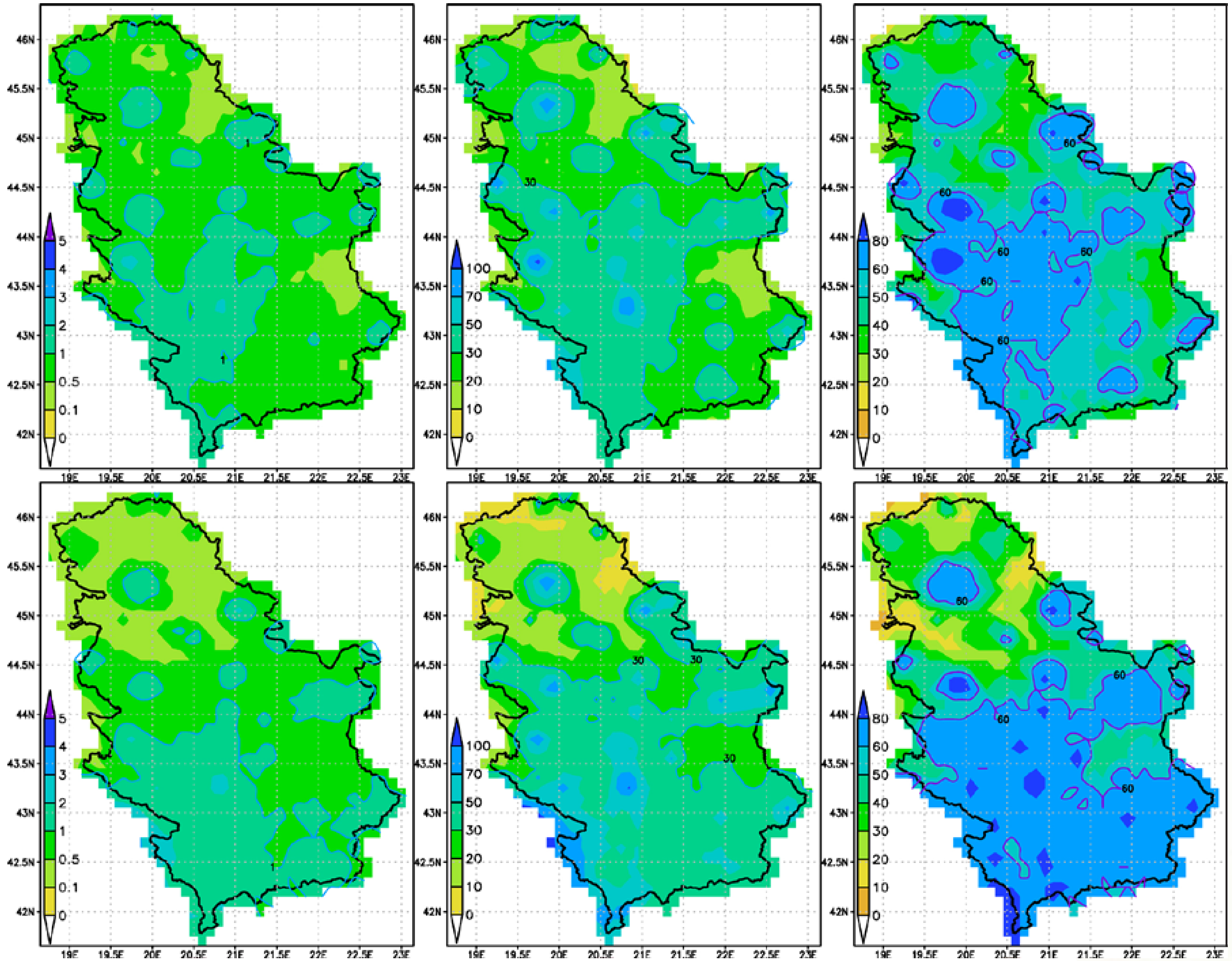
The results of all analysed indices show higher values (indicating an increasing level of risk) and a larger area of coverage (a spatially increasing risk) for the 2011–2020 period, compared to values for the 2001–2020 climate period, more in central and southern Serbia (approximately in the part of Serbia south of the Sava and Danube rivers) than in the north region.

The analysis of observed values and changes of selected indices, which are chosen to present the risk of extreme precipitation, show that such events were not so rare during the 2001–2020 climate period, and especially during the 2011–2020 decade.

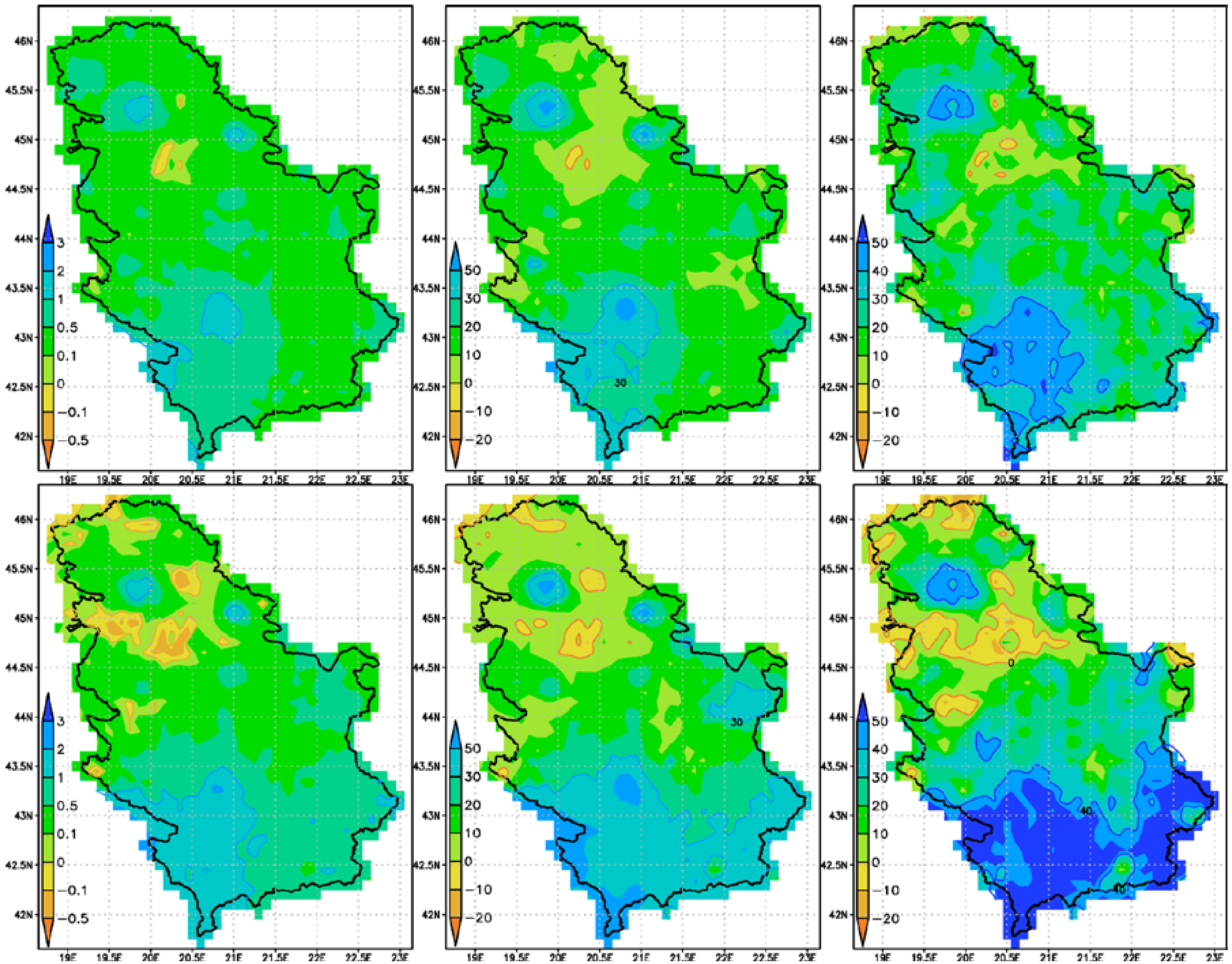
The increasing frequency of extreme events which were the consequence of extreme precipitation were also recorded during these periods. How much extreme precipitation changed compared to the 1961–1990 base period is further investigated. It is evident from Figure 4 that there is a change of distribution of precipitation in Serbia toward higher precipitation. Figure 7 shows spatial distribution of anomaly (change) of selected indices. Values of anomalies in the range ±0.1 for the PR30ND, ±10 mm for the PR30AC, and ±10% for the PR30YY are not considered significant, but can contribute to the assessment of areal coverage of increasing or decreasing change. An increase in all indices happened in the majority of Serbia. The most affected by the change are the central and southern parts, with higher values of increase in southern Serbia. A higher increase also happened in some parts of Vojvodina. Values of indices increase are comparable with their values for 2001–2020 and 2011–2020 periods, meaning that in the 1961–1990 period, values were significantly lower and thereby Serbia was under a much lesser risk of such extreme precipitation events. For example, the percentage of years with extreme precipitation events doubled in the majority of Serbia.

Extreme precipitation events shifted under climate changing conditions from relatively rare extreme precipitation events to extreme precipitation events with potential for significant risk in Serbia, especially in the central and southern parts of Serbia.

The data limitations from which these conclusions are derived are discussed in Appendix 1. Supplementary material with additional results and comments that may help in understanding derived conclusions is provided in Appendix 3.



▲ **Figure 6.** Values of PR30ND (left panels), PR30AC (middle) and PR30YY (right) for the 2001–2020 period (upper panels) and the 2011–2020 period (lower panels).

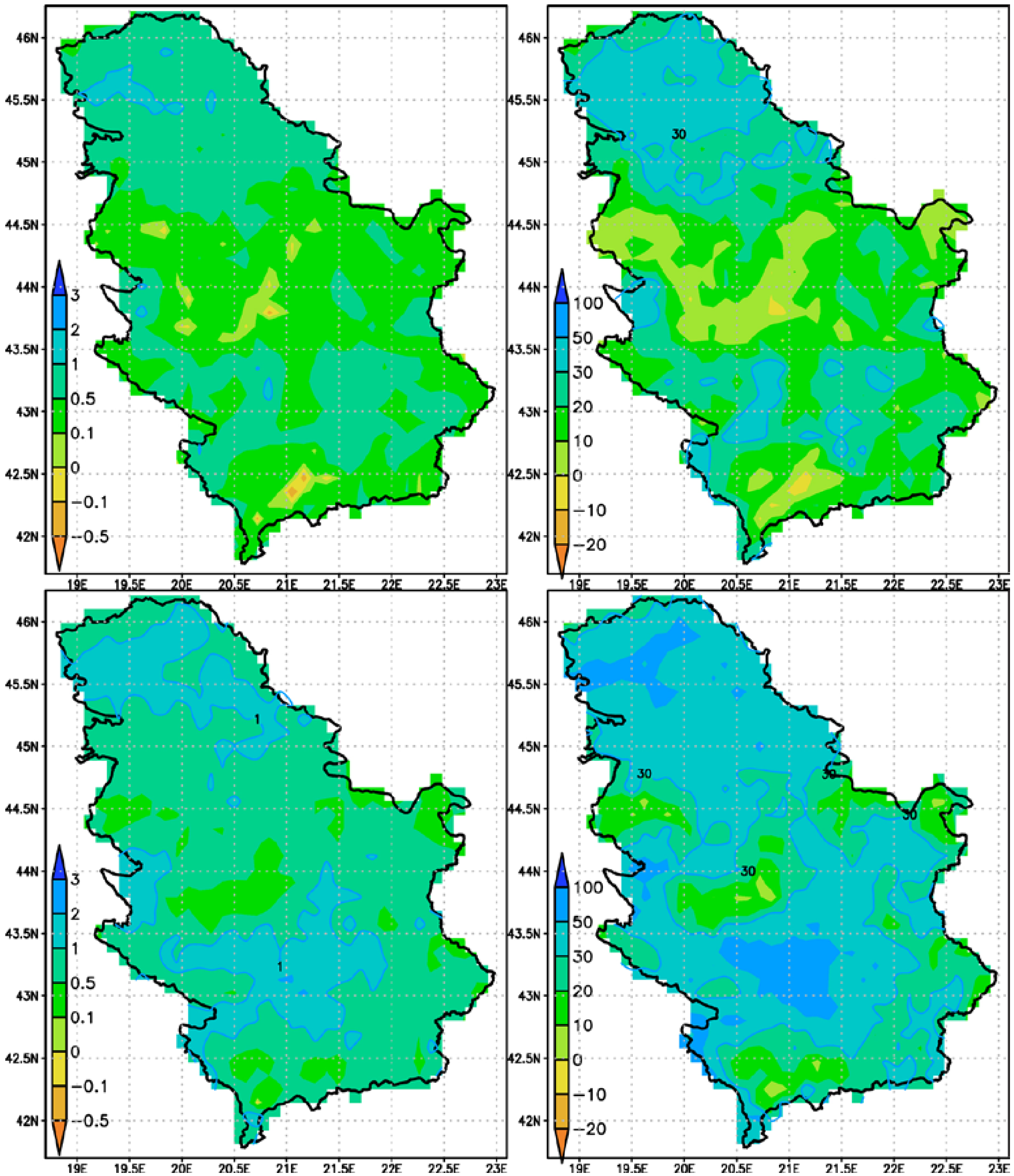


▲ **Figure 7.** Anomaly (change) of PR30ND (left panels), PR30AC (middle) and PR30YY (right) for the 2001–2020 period (upper panels) and 2011–2020 (lower panels) with respect to the values for the 1961–1990 period.

Future Change of Extreme Precipitation Indices

Assessment of future changes of extreme precipitation indices is done for selected future climate periods (2021–2040, 2041–2060, 2081–2100) with respect to the 1986–2005 base period, using climate models' ensemble data from EURO-CORDEX database (information on the source of data, data processing and data limitations are provided in Appendix 1). Future changes of extreme precipitation indices are shown in Figure 8 for 2041–2060, which is the period selected for the future risk assessment, median values and values of the 75th percentile of the models' ensemble results. The changes are shown only for PR30ND and PR30AC. The change of PR30YY from climate projections cannot be used due to the limitations of future climate data, because the results overestimate annual appearance of such events, and change of this index is small or zero because it already reached high (or maximum) values in the past and further increase of its values is not possible besides the fact that there is an increasing trend in extreme precipitation events. Supplementary material to this analysis can be found in Appendix 3.

According to the climate models results, extreme precipitation will increase further in the future. The values of change according to the 75th percentile of models' ensemble better correspond to the rate of observed change. Compared to the 1986–2005 period, the increase of accumulated precipitation in the days with precipitation above 30 mm (PR30AC) is especially notable. The areas which are already affected by extreme precipitation will be further affected by the increase higher than 50 mm of average per year accumulations during extreme precipitation events. The increase of the average number of days per year with extreme precipitation does not show significant



increase compared to the observed trend, which could be the consequence of limitations of the model's data, but the conclusion that the frequency and intensity will continue to increase further in the future can be derived when looking at the results obtained for all three future climate periods (Appendix 3).

For the assessment of future impact of extreme precipitation on soils in Serbia, it is chosen to derive values of the extreme precipitation indicator as: values of change according to the 75th percentile of climate models' ensemble added to values of indices obtained for the 1986–2005 period from the observed data. Results may be affected by limitations of both datasets (observed and future data). Important notes about the reliability of obtained results for extreme precipitation indicator can be found in Appendix 3.

◄ **Figure 8.** Anomaly (change) of PR30ND (left panels) and PR30AC (right) for the 2041–2060 period with respect to the 1986–2005 period; median values of anomalies are in the upper panels and the 75th percentile in the lower panels.

2.2. CLIMATE CHANGE IMPACT ON SOIL DEGRADATION

The primary soil and other associated features that have been considered as criteria to determine soil vulnerability to climate change are described in this section. This data are paired with data on chosen climate change indicators. Assessments of soil degradation risks related to desertification and intense precipitation are the final product of the assessment of climate change impact on soils in Serbia.

2.2.1. SOIL INTRINSIC CHARACTERISTICS

The soil degradation issues are assessed from the soil classification aspects. The soil classification does not solely collect and systematise soil information based on its characteristics and defined criteria, but it also serves as a tool for the assessment of soil production and soil ecological value. The soil classification system used in Serbia is based on genetic principles, whereas the World Reference Base (WRB) for soil resources is based on diagnostic principles. In the WRB, soil properties defined in terms of diagnostic horizons, diagnostic properties, and diagnostic materials, have to be measurable and observable in the field to the greatest extent possible. The National Classification System (NCS) provides an opportunity to classify soils without numerous analytical procedures. The central unit of the NCS is the soil type. Soil types of the NCS are going to be elaborated briefly from the point of view of their intrinsic characteristics, resistance to external pressures and human-induced changes.

Information about soils relevant for this analysis is summarised in Table 9 where the dominant potential degradation drivers, the types of soil degradation and, most important, the level of susceptibility to degradation (grades 1 to 5) are presented for each soil type of the relevant soil class of NCS dominant land use and sector. Along with these, other information about soil classes/soil types, such as dominant pedogenic process and soil characteristics, potential restriction to root growth and dominant prevention measures, and a short analysis of relevant information is given in Appendix 4. Soil inheritance or susceptibility/sensitivity to degradation is assessed from 1 to 5 based on the summarised opinion about soil intrinsic characteristics from the information from the tables in Appendix 4.

▼ **Table 9.** Soil classes, corresponding soil types, main features related to soil types and susceptibility to degradation (scale 1–5).

	Dominant land use / sector	Dominant potential degradation drivers	Type of soil degradation	Susceptibility to deg. (1–5)
1. Class of weakly developed soils				
Lithosols	Natural vegetation	natural	inherited low capability	5
Sirozems - Regosols	Natural vegetation, forestry	natural and deforestation	soil water erosion	5
Arenosols	Natural vegetation, forestry	natural	soil aeolian erosion	5

	Dominant land use / sector	**Dominant potential degradation drivers**	**Type of soil degradation**	**Susceptibility to deg. (1–5)**
Colluvial soils	Agriculture and various natural vegetation	soil agricultural management	soil erosion, soil physical and chemical deterioration	*2–3*
2. Class of humus accumulative soils				
Chernozems	Agriculture	soil agricultural management: ploughing, irrigation, fertilisation, crop protection	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification, salinisation, alkalisation; aeolian erosion; soil biological degradation – SOC decline	*2–3*
Vertisols	Agriculture	soil agricultural management	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil biological degradation – SOC decline	*1–2*
Calcomelanosols	Forestry and pasturing	grazing	Soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	*2–3*
Rankers	Forestry and pasturing	deforestation, grazing	Soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	*2–3*
Rendzinas	Agriculture, forestry and pasturing	deforestation	Soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	*3*
3. Class of cambic soils				
Eutric Cambisols	Agriculture	soil agricultural management	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil biological degradation – SOC decline	*2*
Dystric Cambisols	Forestry	deforestation	soil water erosion; soil physical degradation: deterioration of soil structure; soil chemical degradation: acidification; soil biological degradation – SOC decline	*3–4*
Terra Rossa	Natural vegetation, agriculture, forestry and pasturing	deforestation, soil agricultural management	soil erosion; soil physical degradation; soil biological degradation – SOC decline	*2*
Calcocambisols	Forestry and agriculture	deforestation and soil agricultural management	soil erosion; soil physical degradation; soil biological degradation – SOC decline	*2*
4. Class of eluvial-illuvial soils				
Luvisols	Agriculture, forestry	soil agricultural management and deforestation	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	*3*
Podzols	Forestry	natural, deforestation	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	*4*

	Dominant land use / sector	Dominant potential degradation drivers	Type of soil degradation	Susceptibility to deg. (1–5)
Bruni-podzols	Forestry	natural, deforestation	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	*4*
5. Class of pseudogley and fluviatile soils				
Pseudogley soil	Agriculture	soil agricultural management	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	*3–4*
Fluvisols	Agriculture, Forestry	soil agricultural management, floods	soil physical degradation: soil compaction; soil chemical degradation; soil biological degradation – SOC decline	*2–5*
6. Class of Semigleic and Gleic Soils				
Humofluvisols	Agriculture	soil agricultural management, groundwater fluctuations, floods	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification, soil salinisation, soil alkalisation; soil aeolian erosion; soil biological degradation – SOC decline	*1–2*
Humogleys	Agriculture	soil agricultural management, groundwater fluctuations, floods	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, salinisation, alkalisation, acidification; soil biological degradation – SOC decline	*1–2*
Eugleys	Natural vegetation	groundwater changes	soil chemical degradation: salinisation, acidification; soil biological degradation – SOC decline	*1*
Peats	Natural vegetation	Natural, management, groundwater changes	soil physical degradation: soil compaction; soil chemical degradation: acidification; soil biological degradation – SOC decline, biomass over exploitation	*1–5*
7. Class of acute saline and eluvial illuvial alkalised soils				
Solonchaks	Natural vegetation	natural, grazing	soil physical degradation: deterioration of soil structure, waterlogging, soil compaction; soil chemical degradation: salinisation, alkalisation; soil biological degradation – SOC decline; soil aeolian erosion	*4–5*
Solonetz	Natural vegetation	natural, agriculture, grazing	soil physical degradation: deterioration of soil structure, waterlogging, soil compaction; soil chemical degradation: alkalisation, salinisation; soil biological degradation – SOC decline; soil aeolian erosion	*3–5*

2.2.2. SOIL VULNERABILITY MAPPING

Vulnerable Soils

The genetic principles of soil classification used in the NCS enable the classification of soils into quality classes and cadastral classes. It is therefore very important to have as much information about the soils as possible. This is possible only up to a certain extent at the level of soil type. Sonolochaks and Solonetz are without a doubt soils with constraints related to among others, salinity and/or alkalinity. But, on the other side, Calcocambisols and Terra Rossas could be very vulnerable if they are thin, or could be much less vulnerable if they are thick. Here, vulnerability can be related to the water holding capacity. For example, shallow Calcocambisols with the total available content of 15% per volume can hold 30 mm of water at 20 cm depth. On the other hand, Calcocambisols, 60 cm thick, can hold 60 mm of water, twice as much.

The water holding capacities are an important part of soil water balance, which include, among others, rainfall, deep percolation, surface runoff, evapotranspiration, residual water content, and, in some cases, capillary rise.

The relationship between soil water content and vegetation can be simplified and observed in two ways. The vegetation that absorbs water from the soil along with the biomass above the ground, can protect soil. If there is no water, vegetation reduces its biomass and, depending on the water scarcity level, it can be sparse or very sparse, or less affected, but in all cases it loses its protective role. This is why soil water holding characteristics are important.

In preparation of this report, we used the soil map of the Republic of Serbia, previously obtained from the Ministry of Agriculture, Forestry and Water Management. The map has 20 soil mapping units, given in Table 10 below. The following soil mapping units (SMU) are determined to be in the first vulnerability group due to the following characteristics:

1. SMU 2 – Solonchaks and Solonetz – soil salinity and/or alkalinity,
2. SMU 7 – Arenosols and Sirozems on sands – low water holding capacity,
3. SMU 13 – Rankers, Sirozems, Lithosols on schists and gneiss – shallow solum; Note that Rankers can be thicker but they cannot be separated in this way,
4. SMU 14 – Rankers, Sirozems, Lithosols on andesite, dacite and tuff – shallow solum; Note that Rankers can be thicker but they cannot be separated in this way,
5. SMU 15 – Calcomelanosols, Sirozems, Lithosols on limestones – shallow solum; Note that Calcomelanosols can be thicker but they cannot be separated in this way,
6. SMU 16 – Rankers, Sirozems, Lithosols on serpentinites and mafic rocks – shallow solum; Note that Rankers can be thicker but they cannot be separated in this way,
7. SMU 17 – Rankers, Sirozems, Lithosols on sandstones, flysch sediments and cherts – shallow solum; Note that Rankers can be thicker but they cannot be separated in this way,
8. SMU 18 – Rendzina, Sirozems, Lithosols on calcareous substrates – shallow solum; Note that Rankers can be thicker but they cannot be separated in this way,
9. SMU 20 – Rankers, Sirozems, Lithosols on granite, granodiorite, quartz-latites – shallow solum; Note that Rankers can be thicker but they cannot be separated in this way.

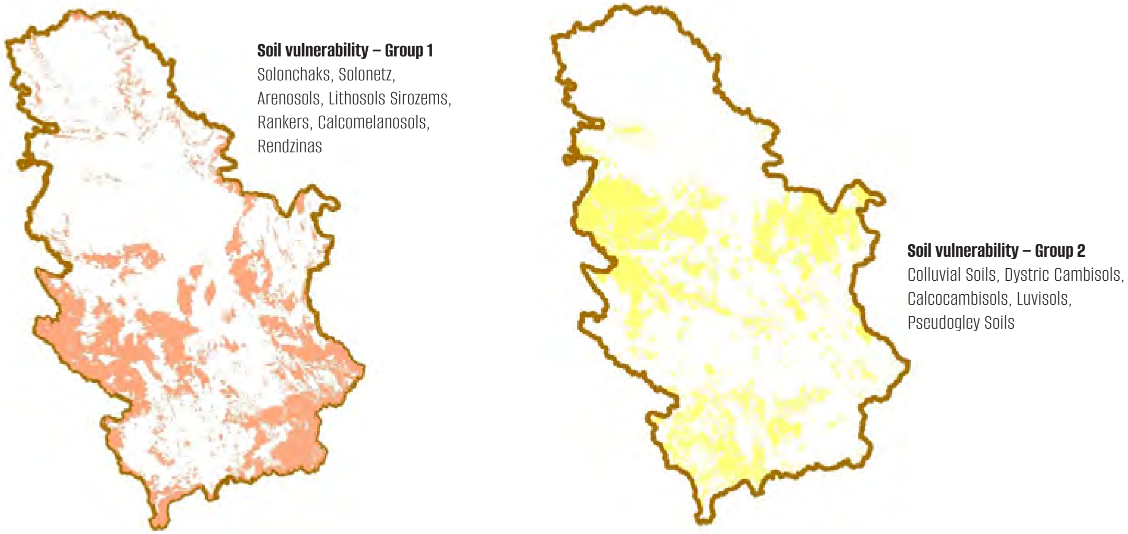
These nine SMUs have obvious constraints in current climate conditions and consequently, it can be expected that under future climate, they might be even more vulnerable. Together, they cover an area of 2,296,554 ha or 26.1% of the whole territory. The second soil vulnerability group encounters the following soil mapping units:

1. SMU 9 – Dystric Cambisols and partially Rankers – pH in water lower than 5.5; Eutric Rankers have pH in water higher than 5.5, but they are minor here, and cannot be isolated separately,
2. SMU 19 – Calcocambisols and Calcomelanosols; Calcocambisols are thicker than Calcomelnosols, but they can also be thin,
3. SMU 11 – Pseudogley Soils can have shallow physiological depth and can be acid,
4. SMU 6 – Colluvial Soils have heterogeneous characteristics and can be often very gravelly,
5. SMU 12 – Luvisols and illimerised Soils can have pH in water lower than 5.5

These five SMUs cover an area of 1,788,657 ha, or 20.3% of the territory. Figure 9 presents the distribution of these two soil vulnerability groups in the Republic of Serbia. Humofluvisols, Humogley, Eugley and Fluvisols are SMUs which could potentially be affected by the changes in the amount of surface water in rivers, by the changes in the occurrence of floods and fluctuations of ground water level. They cover an area of 1,597,496 ha, or 18.1% of territory. Humofluvisols, Humogleys and partially Fluvisols are very important agricultural soils. These SMUs are not included in Soil vulnerability groups for this report, because they depend on water resources behaviour in the future: rivers, streams, floods and groundwater. Chernozems, Vertiosols, and Eutric Cambisols are very important agricultural soils and they cover an area of 2,819,251 ha, or 32.0% of the territory. These soils, as well as other agricultural soils, are under natural climate change threats, but also very dependent on the soil management applied. Also, they are not considered for the vulnerability groups here.

▼ **Table 10.** Distribution of soil mapping units on the territory of the Republic of Serbia

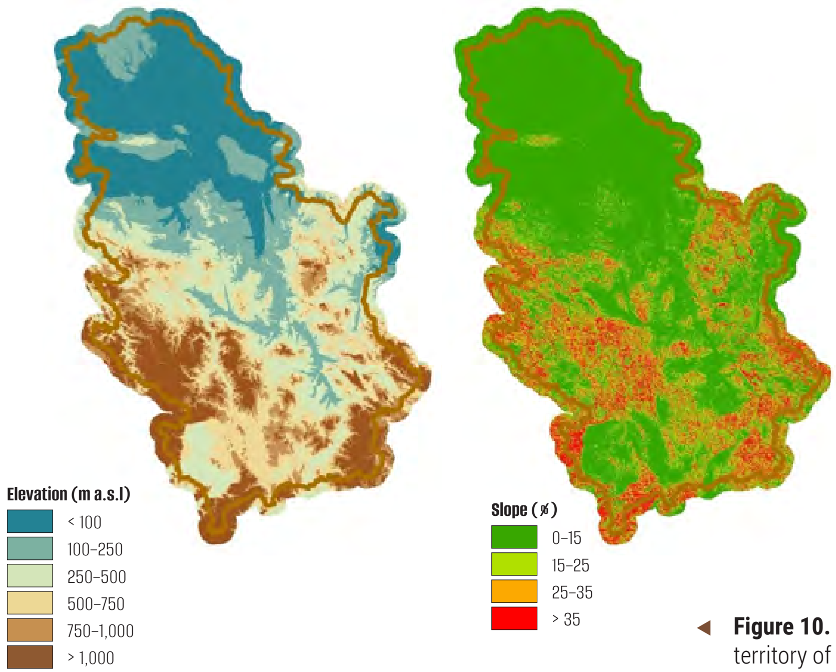
No.	Soil mapping unit - SMU	Area (ha)
1	Chernozems	1,049,356
2	Solonchaks and Solonetz	114,029
3	Humofluvisols	448,552
4	Humogley and Eugleys	446,890
5	Fluvisols	702,054
6	Colluvial Soils	127,935
7	Arenosols and Sirozems on sands	57,123
8	Vertisols	683,665
9	Dystric Cambisols and partially Rankers	719,361
10	Eutric Cambisols	1,086,231
11	Pseudogley Soils	492,219
12	Luvisols and illimerised Soils	449,142
13	Rankers, Sirozems, Lithosols on schists and gneiss	566,560
14	Rankers, Sirozems, Lithosols on andesite, dacite and tuff	71,059
15	Calcomelanosols, Sirozems, Lithosols on limestones	509,136
16	Rankers, Sirozems, Lithosols on serpentinites and mafic rocks	322,454
17	Rankers, Sirozems, Lithosols on sandstones, flysch sediments and cherts	397,063
18	Rankers, Sirozems, Lithosols on calcareous substrates	162,197
19	Calcocambisols and Calcomelanosols	305,241
20	Rankers, Sirozems, Lithosols on granite, granodiorite, quartz-latites	97,033
	Total	**8,807,299**



▲ **Figure 9.** Groups of soil vulnerability on the map of the Republic of Serbia.

Topography

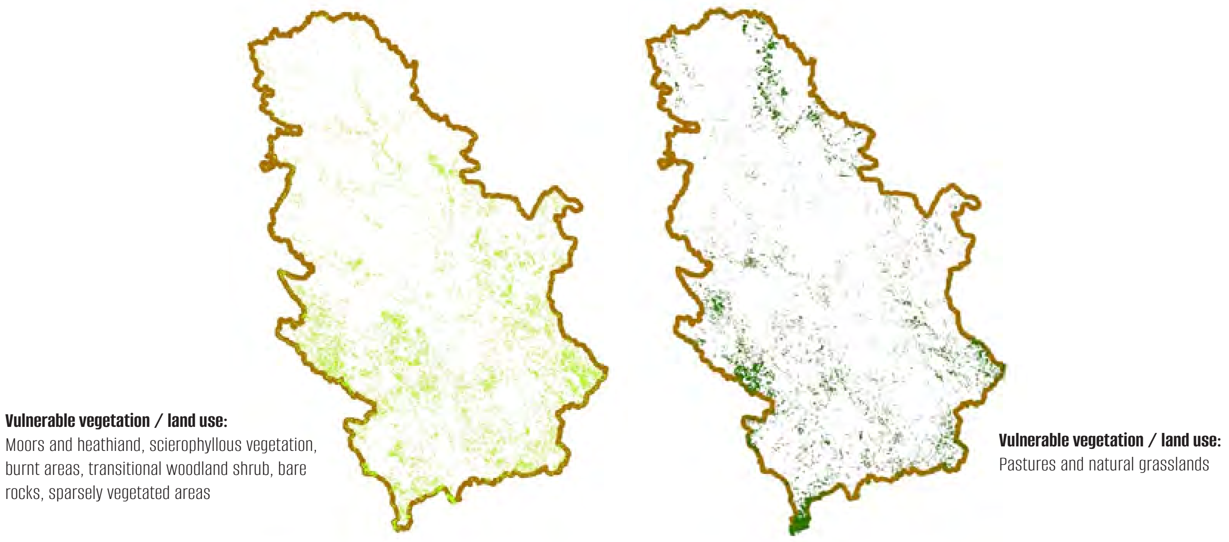
Topographic conditions are very important factors that can contribute to an increased soil degradation risk. Among them, the effect of slopes on soil erosion is related to the increased volume and velocity of surface runoff due to increased slope gradient and slope length. Slopes higher than 15% can be used for agricultural production only with soil conservation measures. Figure 10 presents elevation and slope maps for the territory of the Republic of Serbia derived from 90 m digital elevation model, the data used as input for soil degradation assessment.



◀ **Figure 10.** Elevation and slope map for the territory of the Republic of Serbia

Land Use / Vegetation Cover

The land use / vegetation cover characteristics play an important role in the water cycle, and are also important factors that affect soil degradation. *Corine* land cover[23] vulnerable classes (CLC) are used in this report to present areas which are potentially more prone to soil degradation in respect to other land uses and vegetation types. These CLCs are moors and heathland, sclerophyllous vegetation, burnt areas, transitional woodland shrub, bare rocks, sparsely vegetated areas, which cover 690,830 ha or 7.8% of the Serbian territory together. Figure 1 also presents natural grasslands and pastures that cover 505,099 ha or 5.7% of the territory. These vegetation classes are distributed mainly on steep terrains, southern aspects, and shallow soils.



▲ **Figure 11.** Vulnerable vegetation/land use.

Ranking of Land Factors Related to Soil Degradation

Factors related to land, which characterise exposure and vulnerability of soils on degradation, include soil characteristics (selected soil types), land use / vegetation (selected vulnerable groups), terrain characteristics (slope). Ranks of those factors by their intensity of contribution to soil degradation, along with marked relevance to the types of soil degradation analysed here, are presented in Table 11.

▼ **Table 11.** Ranks assigned for land-related factors according to the factor type (class) and their relevance to the desertification risk assessment (DR) and the degradation from extreme precipitation risk assessment (EPR).

Factor type	Factor class	Rank	DR	EPR
Soil characteristics	Soil vulnerability group 1	2	+	+
	Soil vulnerability group 2	1		
	Other	0		
Land use / vegetation	Vulnerable vegetation	2	+	+
	Other	0		
Topography	Slope <15%	0		+
	Slope from 15–25%	1		
	Slope from 25–35%	2		

23 European Environment Agency, 2013. CORINE Land Cover (CLC) 2006.

2.2.3. ASSESSMENT OF RISK OF DESERTIFICATION

Aridity Index (AI) is adopted as an indicator for climate change impact on desertification and represents the risk related to climate change in assessment of risk of desertification, based on Table 5. Spatial distributions of desertification risk levels derived from AI values, for 2001–2020 and 2041–2060 periods, are presented in Figure 12.

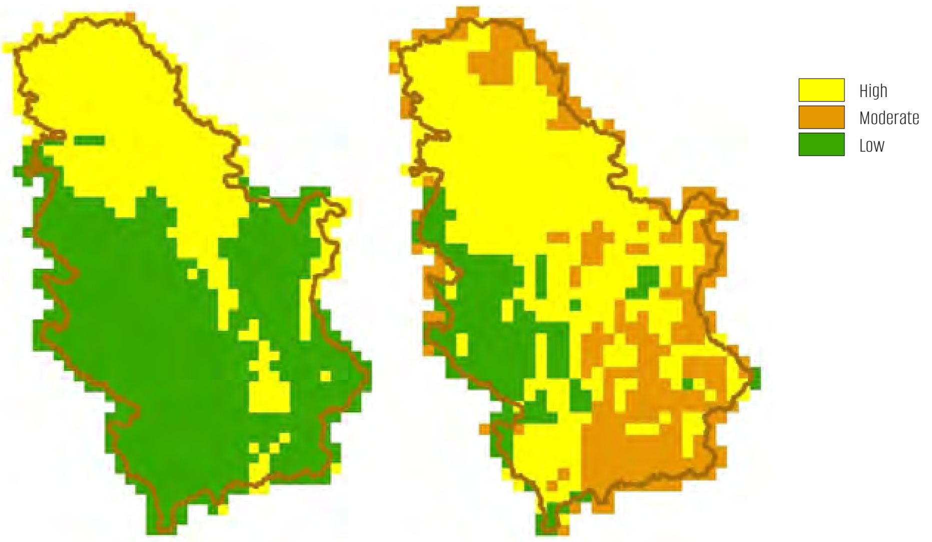
Ranks assigned to risk levels according to AI (climate factor) are: "high" with rank 2, "moderate" with rank 1, "low" or none with rank 0.

In the 2001–2020 climate period, according to climate conditions:

- ✓ 63.6% of the territory is under low or no risk of desertification (rank 0);
- ✓ 36.3% of the territory is under moderate risk of desertification (rank 1);
- ✓ 0.06% of the territory is under high risk of desertification (rank 2);
- ✓ range of AI values 0.49–1.65, average 0.75.

In the 2041–2060 climate period, according to climate conditions:

- ✓ 17.4% of the territory is under low or no risk of desertification (rank 0);
- ✓ 52.8% of the territory is under moderate risk of desertification (rank 1);
- ✓ 29.8% % of the territory is under high risk of desertification (rank 2; north-eastern part of the country, in Kosovo and Pčinja district, around the Južna Morava, Nišava and Timok rivers);
- ✓ range of AI values 0.28–1.04, average 0.56.



▲ **Figure 12.** Desertification risk levels according to AI (climate factor) for 2001–2020 (left) and 2041–2060 (right) climate periods.

The assessment and mapping of risk of desertification is done using georeferenced maps of ranks from Table 11, relevant to desertification risk, and georeferenced maps of ranks according to the climate factor (AI values). The sum of all ranks is then calculated. The results are divided by the maximum value, and thereby scaled to values 0 to 1. The risk classes are assigned according to risk levels as follows: <0.2 – low, 0.2-0.4 – moderate, 0.4-0.6 – high, 0.6-0.8 – very high, >0.8 – extremely high. Surfaces under defined risk levels for both periods are given in Table 12. The maps of desertification risk for the 2001–2020 period and the 2041–2060 future period are presented in Figure 13. The results are available in raster files and it is possible to derive assessments on the local level and provide information on locations of areas under higher risks and/or increasing risks, but it is recommended to include local data in the risk assessment.

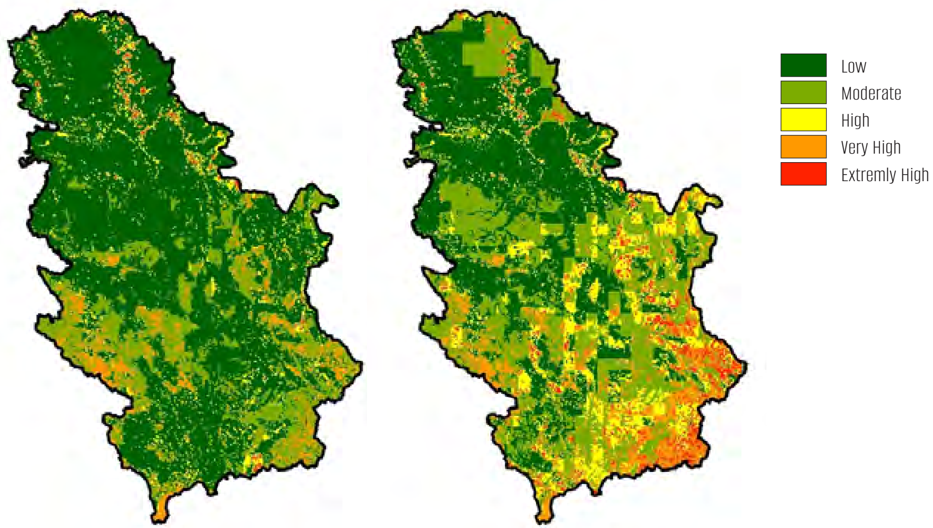
A few main conclusions which are derived from this assessment of risk of desertification are:

- ✓ In the 2001–2020 period, the risk of desertification is "low" at two thirds of the country's territory, "moderate" risk is present at more than 21% of the area, whereas different categories of high desertification risk are present at almost 13% of the territory;
- ✓ In the 2041–2060 period, the risk of desertification is "low" at 38.6% of the country's territory, "moderate" risk is present at almost 32% of the area, whereas different categories of high desertification risk are present at almost 30% of the territory;
- ✓ The largest area of increased risk is in southern and eastern Serbia, where an "extremely high" risk is projected for the future and requires immediate preventive measures planning, as in other highly affected areas scattered across Serbia.

- ✓ The analysis does not include contribution to the risk of managed (agricultural) soils, because of the uncertainty of their characteristics in the future (human factor), but aridity characteristics increase in those areas, and due to the climate factor alone, the impact risk increased from "low" to "moderate" and can be increased further with poor soil management and loss of organic content.

▼ **Table 12.** Surfaces affected with desertification risk (DR) in [ha] and in [%] of total surface area of Serbia.

DR classification		2001–2020		2041–2060	
Risk class	Risk level	Area (ha)	Area (%)	Area (ha)	Area (%)
Low	<0.2	> 5,835,000	66.0	> 3,408,000	38.6
Moderate	0.2–0.4	1,863,864	21.1	2,820,345	31.9
High	0.4–0.6	518,486	5.9	1,318,993	14.9
Very high	0.6–0.8	560,489	6.3	894,602	10.1
Extremly high	>0.8	59,722	0.7	395,931	4.5



▲ **Figure 13.** Risk of desertification (DR) for the 2001–2020 (left) and 2041–2060 (right) periods.

2.2.4. ASSESSMENT OF RISK OF SOIL DEGRADATION FROM EXTREME PRECIPITATION

The Extreme Precipitation Indicator (EPI) is adopted as an indicator for climate change impact on soil degradation caused by extreme precipitation, based on Table 8. Spatial distributions of risk levels according to EPI, for 2001–2020 and 2041–2060, are presented in Figure 14.

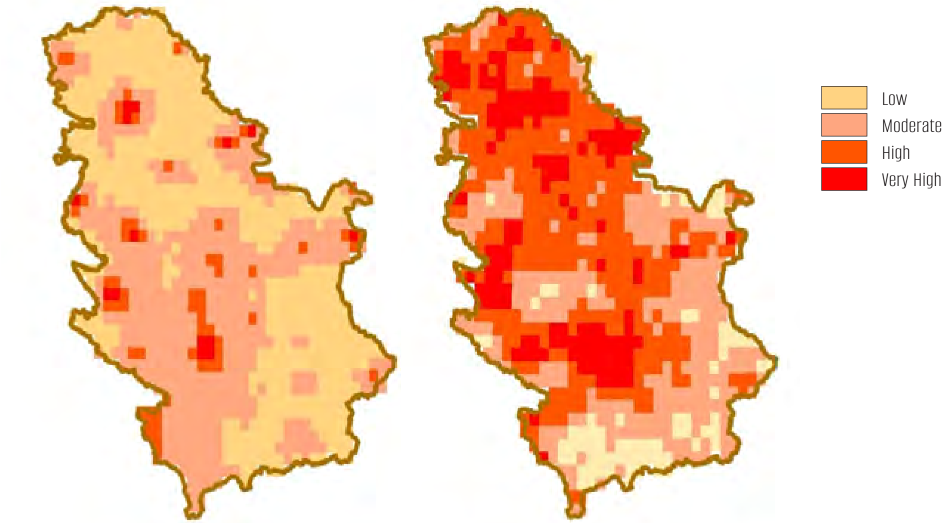
The ranks assigned to risk levels according to EPI (climate factor) are: "high", "very high", "extremely high" with rank 2, "moderate" with rank 1, "low or inconclusive" with rank 0.

In the 2001–2020 climate period, according to the EPI:

- ✓ 48.4% of the territory is under low or inconclusive risk of degradation caused by extreme precipitation (rank 0);
- ✓ 45% of the territory is under moderate risk of degradation caused by extreme precipitation (rank 1);
- ✓ 6.6% of the territory is under higher risks from degradation caused by extreme precipitation (rank 2).

In the 2041–2060 climate period, according to the EPI:

- ✓ 9.7% of the territory is under low or inconclusive risk of degradation caused by extreme precipitation (rank 0);
- ✓ 34.1% of the territory is under moderate risk of degradation caused by extreme precipitation (rank 1);
- ✓ 56.2% of the territory is under higher risks from degradation caused by extreme precipitation (rank 2; high risks are in Vojvodina region and central and western regions of Serbia).



▲ **Figure 14.** The Extreme Precipitation Indicator (EPI) for the 2001–2020 (left) and 2041–2060 (right) periods.

The assessment and mapping of risk of soil degradation caused by extreme precipitation is done using the georeferenced maps of ranks from Table 11 relevant to this risk, and the georeferenced maps of ranks according to the climate factor (EPI values). The sum of all ranks is then calculated. The results are divided by the maximum value (scaled to values 0 to 1). The risk classes are assigned according to risk levels as follows: <0.2 – low, 0.2–0.4 – moderate, 0.4–0.6 – high, 0.6–0.8 – very high, >0.8 – extremely high. Surfaces under defined risk levels for both periods are given in Table 13. The maps of risk of degradation from extreme precipitation for the 2001–2020 period and the 2041–2060 future period are presented in Figure 15. The results are available in raster files and it is possible to derive assessments on the local level and provide information on locations of the areas under higher risks and/or increasing risks, but it is recommended to include local data in the risk assessment.

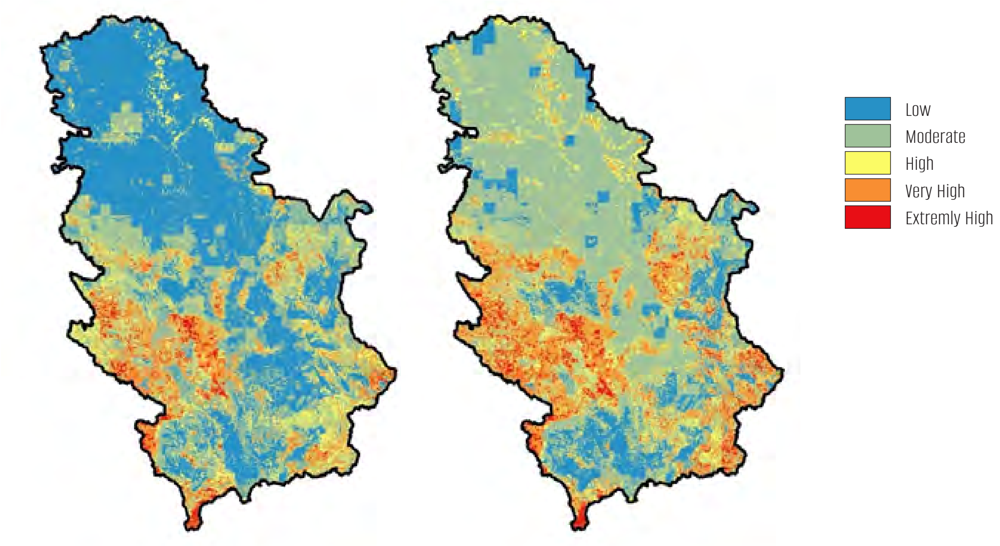
A few main conclusions which are derived from this assessment of risk of soil degradation from extreme precipitation (EPR) are:

- ✓ In the 2001–2020 period: the risk is "low" at 44.5% of the country territory, "moderate" risk is present at 31.8% of the area, whereas different categories of high risk are present at almost 24% of the territory;
- ✓ In the 2041–2060 period, risk is "low" at only 12.9% of the country territory, "moderate" risk at 53.3% of the area, whereas different categories of high extreme precipitation risk are present at 33.8% of the territory, or more than one third of the area;
- ✓ The largest area of increased risk is in the west and central-west parts of Serbia, south-east and east; areas under higher risks are observed in near-past period and are projected to increase by the mid-twenty first century; those areas may be more affected by other consequences of extreme precipitation, like floods, and require immediate measures planning to prevent and/or reduce negative effects;

✓ The analysis does not include the contribution to risk of managed surfaces, because of the uncertainty of their characteristics in the future (human factor); in those areas where EPI increases, meaning that, due to the climate factor impact alone, risk increases from "low" to "moderate", and can be further increased with poor soil and land management (for example, deforestation).

▼ **Table 13.** Surfaces affected by risk of degradation from extreme precipitation (EPR) in [ha] and in [%] of total surface area of Serbia.

EPR classification		2001–2020		2041–2060	
Risk class	Risk level	Area (ha)	Area (%)	Area (ha)	Area (%)
Low	<0.2	> 3,931,000	44.5	> 1,137,000	12.9
Moderate	0.2–0.4	2,810,919	31.8	4,710,972	53.3
High	0.4–0.6	997,533	11.3	1,267,861	14.3
Very high	0.6–0.8	936,524	10.6	1,451,094	16.4
Extremely high	>0.8	162,325	1.8	271,155	3.1



▲ **Figure 15.** The risk of soil degradation from extreme precipitation (EPR) for the 2001–2020 (left) and 2041–2060 (right) periods.

2.2.5. SOIL DEGRADATION RISK – COMBINED EFFECTS

In order to provide an overall assessment of risk of soil degradation for Serbia, the obtained risk maps are combined. A higher value of soil degradation is chosen for each grid point. The risk classes for combined risk of soil degradation are assigned according to risk levels as follows: <0.2 – low, 0.2–0.4 – moderate, 0.4–0.6 – high, 0.6–0.8 – very high, >0.8 – extremely high. The surfaces under defined risk levels for the 2001–2020 and 2041–2060 periods are given in table 14. The maps of combined soil degradation risk for 2001–2020 and 2041–2060 periods are given in Figure 16.

A few main conclusions which are derived from the assessment of risk of soil degradation derived from both the risk of desertification and the risk of soil degradation from extreme precipitation, are:

✓ On average, for the 2001–2020 period, the risk level for Serbia is "moderate" class of combined risk, with 27.6% of the territory under higher risk (classes: high, very high, extremely high); on average, for the 2041–2060 period, the risk level for Serbia is in the "high" class of combined risk, with 42% of the territory under higher risk (classes: high, very high, extremely high);

✓ In the 2001–2020 period: the risk is "low" at 43.2% of the country's territory, "moderate" risk is present at 29.2% of the area, whereas different categories of high risk are present at almost 28% of the territory;

✓ In the 2041–2060 period, the risk is "low" at only 6.4% of the country's territory, "moderate" at 51.6% of the area, whereas different categories of high risk are present in 42% of the territory;

- The areas with higher risks are mostly in the areas south of the Sava and Danube rivers (central-west, west, south-east, east Serbia), but recognised higher risk areas are also identified locally in Vojvodina (also up to an extremely high-risk level);
- The analysis does not include contribution to risk of managed surfaces, because of the uncertainty of their characteristics in the future (human factor); in those areas where risk increases, meaning that, due to the climate factor alone, the risk of degradation will be increased; in such areas human factor may be of crucial importance, it could prevent/mitigate or increase the soil degradation risk;
- The human factor (change of the area of interventions and practices) cannot be predicted, and thereby was not included in this analysis; negative impacts in stable areas (prone to risk) can trigger soil and land degradation and increase vulnerability to climate change (for example, deforestation, poor land and soil management, overuse of soils, change of land use, etc.).

Table 14. Surfaces affected with combined risk of soil degradation (CR) in [ha] and in [%] of total surface area of Serbia.

CR classification		2001–2020		2041–2060	
Risk class	Risk level	Area (ha)	Area (%)	Area (ha)	Area (%)
Low	<0.2	3,817,696	43.2	562,119	6.4
Moderate	0.2–0.4	2,584,433	29.2	4,561,389	51.6
High	0.4–0.6	1,224,670	13.9	1,512,727	17.1
Very high	0.6–0.8	990,353	11.2	1,641,311	18.6
Extremely high	>0.8	220,809	2.5	560,415	6.3

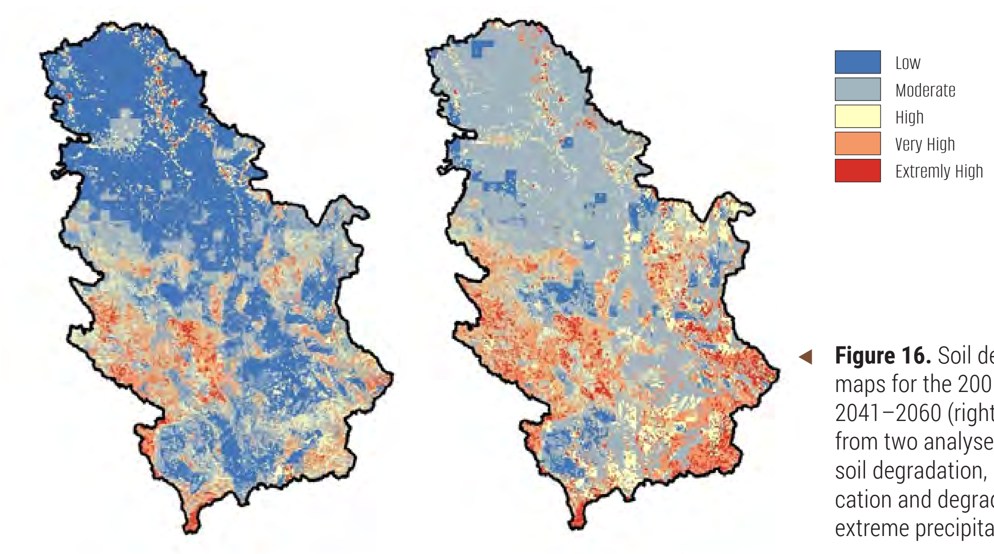


Figure 16. Soil degradation risk maps for the 2001–2020 (left) and 2041–2060 (right) periods, derived from two analysed components of soil degradation, risk of desertification and degradation caused by extreme precipitation.

2.2.6. WIND EROSION

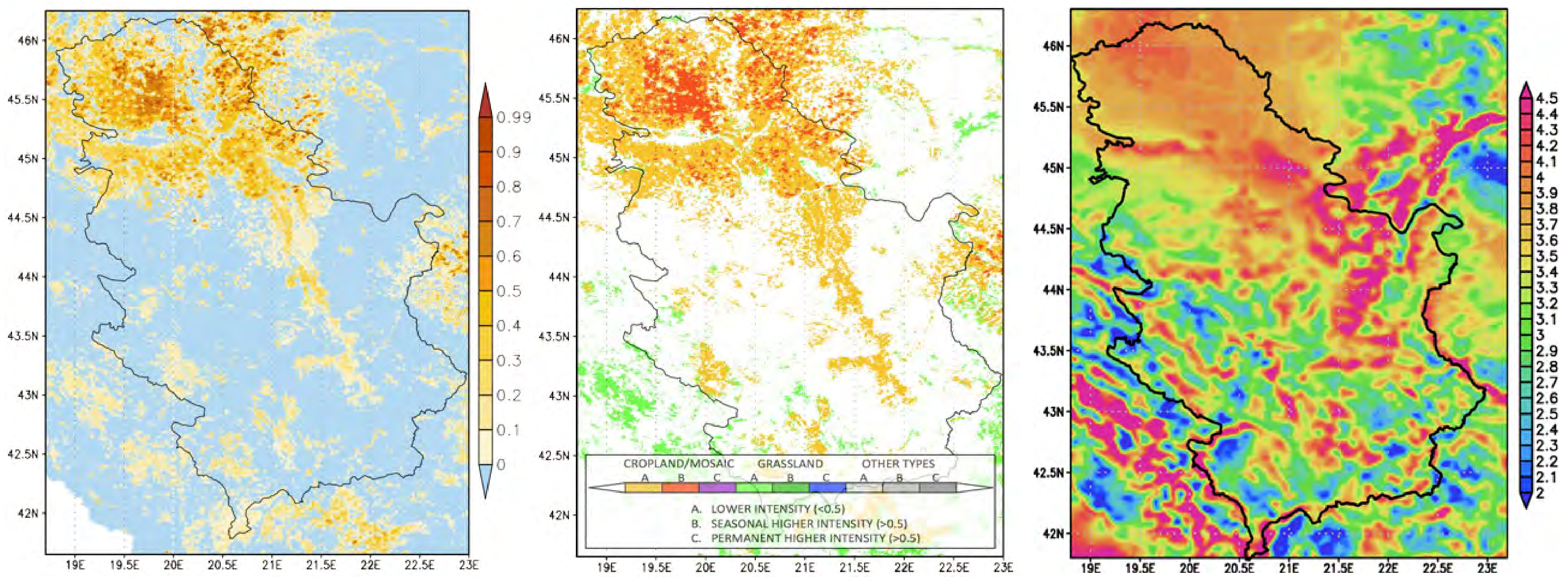
During droughts when soil moisture is low, and soil is exposed (in barren and sparsely vegetated areas, and immediately before and after the vegetation period in case of annual plants), there is an increased risk of wind erosion. This risk is pronounced in the northern part of Serbia (Vojvodina), which is a lowland, a relatively flat area, predominantly under croplands. An assessment of risk of wind erosion in Vojvodina can be found in Baumgertel et al. (2019).

Wind erosion can have significant impact if soils are left uncovered, soil structure is disturbed, and weather conditions cause low top-soil moisture conditions. This component of soil degradation under climate changing conditions is not assessed for Serbia. Because of the increasing drought frequency and duration, and increasing heat waves, which can accelerate the drying of top-soil caused by climate change, it can be assumed that wind erosion will have an increasing effect in the future climate.

From the UNCCD's global map of sand and dust sources, a map of potentially dust productive areas for Serbia is derived and presented in Figure 17. This map shows the distribution of soil surfaces which are detected as surfaces that can act as dust sources, meaning that these areas can have favourable conditions for wind erosion in case of high winds. The values on the map are maximum values of soil susceptibility to wind erosion, observed during the 2014–2018 period in different seasons, including impacts of extreme weather events. During the summer season, the values are at zero because of the existing land cover, but after the vegetation period, in the autumn and winter seasons, surfaces were exposed (uncovered) and low soil moisture conditions were present (with the above soil reaching freezing temperatures in winter), showing that favourable top-soil conditions in these areas can exist. The information on soil texture and MODIS EVI (Enhanced Vegetation Index), and soil surface conditions are used for this mapping, but the soil structure and organic content can reduce the soil's susceptibility to wind erosion. The surfaces are croplands, meaning that there is a high dependence on the human factor (implemented practices for soil management), which can have both a negative effect with contribution to the soil's increasing susceptibility to wind erosion and a positive effect which can mitigate the risk of wind erosion (preventive agricultural practices, and by avoiding practices that cause reduction of soil structure).

The average annual wind velocities are also presented in Figure 17 to show the areas affected with higher velocity winds, and thereby, the higher vulnerability to wind erosion. Both maps show that in Serbia (mainly in Vojvodina), the risk of wind erosion exists, and that there is a high probability it will increase in the future due to climate change and an increase in weather extremes which are favourable for wind erosion.

This component of soil degradation, impacted by climate change is not included in the combined assessment of the soil degradation risk, because it exists in cropland areas in Serbia and it is highly dependable on the human factor. Since the projections do not show a change in wind velocity in the future climate, just the intensification of storm weather which can increase risk of wind dusts, a crucial climate factor which can increase this risk are droughts. The analysis of aridity index shows the significant shift of climate characteristics to a semi-dry climate by the mid-twenty-first century in these areas, and it can be assumed that dry and weather conditions intensify combined with increasing temperatures. Wind erosion can be considered as a component of the desertification process, among other factors which contribute to land degradation. The soil types potentially more prone to wind erosion due to characteristics of their texture and structure are presented in Figure 18. These soil types are Chernozems, Humofluvisols, and Pseudogleys as important agricultural soils; Solonetz and Solonchaks as salt-affected soils with low agricultural value covered mainly with natural vegetation; Dystric Cambisols as forest soils; Luvisols as both agricul-



▲ **Figure 17.** Potential for dust emission (left), land use and dust emissivity (middle), average wind velocity (right).

tural and forest soils; Rankers on acid igneous rocks, and Rendzinas. Soils which have large structural aggregates can be prone to wind erosion only in the pre-sowing period, and after ploughing periods. Zero values might refer to a permanent vegetation cover. Chernozems and Humofluvisols are more susceptible to other soil types extracted from soil map due to the fact that they cover the area of Vojvodina and are used for intensive agricultural production.

Main conclusions on the wind erosion risk in Serbia are:

- ✓ Cropland areas are most affected;
- ✓ During the periods when the vegetation cover is not present, dry surface soil conditions appear – the soil is exposed to wind erosion, exposure is of seasonal character;
- ✓ High wind velocities are present over the areas with higher exposure to wind erosion;
- ✓ The main climate factor which will contribute to an increasing risk is the increase in dry weather conditions combined with increasing temperatures, thereby increasing the aridity of the area;
- ✓ Extreme weather conditions under which a high exposure to wind erosion in the near-past period is detected will become the common climate condition in the future – wind erosion impacted by climate change may become a persistent feature of the area;
- ✓ The risk of wind erosion is highly dependable on the human factor in the croplands – sustainable soil management (maintaining or improving soil structure and organic content) and other preventive agricultural practices (for example, cover crops), in vulnerable areas, can prevent degradation from wind erosion.
- ✓ Soils with higher silt content, friable and used in agricultural production are more susceptible to wind erosion and present the areas of potential dust emissions.

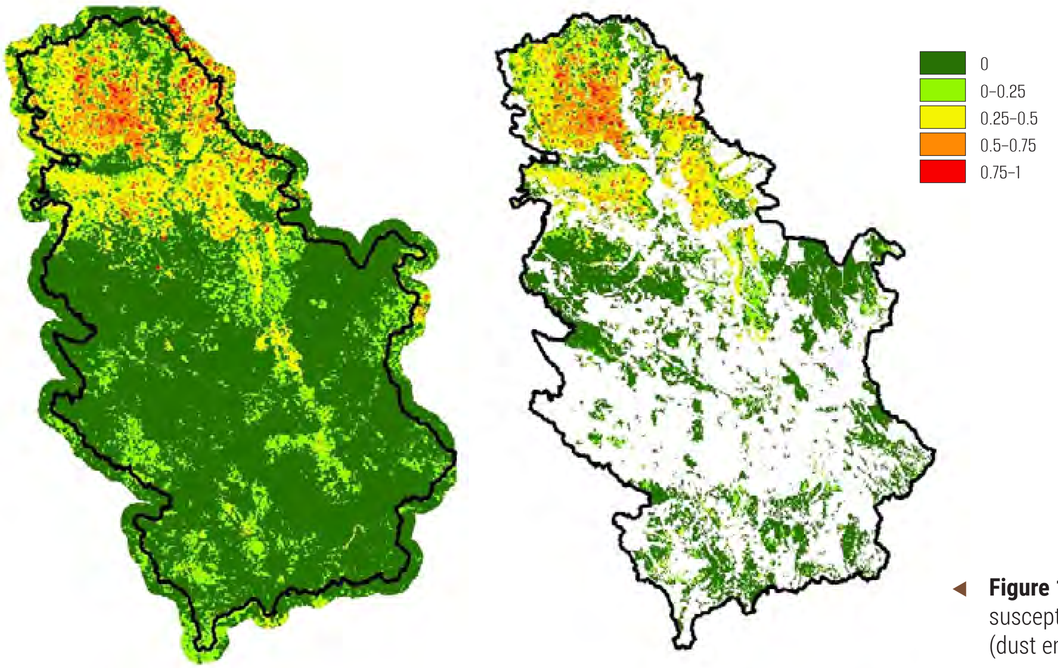


Figure 18. A map of soil types susceptibility to wind erosion (dust emissions)

CHAPTER 3: **FOREWORD**

The collection of background knowledge on soil degradation risks globally, and other possible impacts of climate change on soils, proves that soil is an important storage of carbon, and soil-related processes can mitigate climate change, or intensify global climate and socio-economic crisis because of the increasing trend of degradation worldwide. There are two main stressors on global soils: climate change and increasing population.

The increasing demand for food production and change of soil/land uses under changing climate with increasing extreme events is a great challenge for humanity. Healthy soils are the basis for the health of the living environment, food security and the ecosystem's stability. In Serbia, observed climate change features show that there is an increasing risk of droughts, heatwaves and extreme precipitation. Their combined effect is used to assess the risk for soil degradation over the entire territory of Serbia, with the focus on vulnerable areas. The main conclusions and recommendations are listed in this chapter, which rely on the knowledge collected in previous chapters, providing information relevant for future planning of adaptation measures and advising on further analysis required for the improvement of understanding the climate change impact on soils. The results should be considered as a tentative assessment of soil degradation at the national level, while the complexity of the soil degradation process and the diversity of drivers require more data for local-level assessments. Information gained from this kind of analysis can be used as an additional input, along other climate change information, for policy and decision makers, which is also discussed in this chapter.

3.1.

CONCLUSIONS AND RECOMMENDATIONS

Climate change and soils have a two-way interaction. Climate change impacts soils, mainly in a negative way, as a driver of soils' degradation, which requires planning of adaptation measures, preferably preventive measures. Soils are a large storage of carbon and the return of carbon in soils can have a mitigation effect on climate change. Preventive adaptation measures would contribute to protection of all systems that benefit from soils and would prevent additional release of carbon from soils.

Climate change mainly impacts the soils in a negative way, directly (for example, by triggering erosion, through disturbance of soil biodiversity, etc.) and indirectly (by disturbing the vegetation cover which protects the soils), both contributing to soil degradation. There is no unique methodology for soil degradation assessment adopted at the global level. Several, rather general, assessments of soil degradation are done at the global scale (like using the GLASOD methodology), but smaller scale features remain unrecognised in these assessments. Soil degradation is site- to region- specific, and its analysis requires background knowledge and data verified in the area (soil surveys) in order to address the most important issues and provide a quality assessment. Thereby, choice and/or designing a methodology for the soil degradation assessment is sensitive to the problem and to the area of the analysis.

In the soil degradation assessment, soils' intrinsic properties classify them as more or less prone to soil degradation and can be changed by human activities. Human activities can cause an increase in soil vulnerability to degradation and climate change, or in the case of implementation of good practices, they can increase the resilience of soils under changing climate conditions. *Land-related factors*, selected for the assessment of soil degradation in Serbia, are soil properties, vegetation types and terrain features. The selection of vulnerable soils is based on the currently available knowledge and data about their spatial distribution. Agricultural soils were not considered as vulnerable soils because they are affected by the *human factor* (human activities), which can significantly alter the vulnerability of soils and cannot be predicted with certainty. The assessment of future climate change impacts on such soils requires the development of possible future scenarios of soil/land-related interventions, which should be designed according to the needs of the assessment. The *climate factors* which are selected as most relevant and supported by the existing evidence found in the literature, for soil degradation assessment are aridity and extreme precipitation. The level of aridity/humidity of the region is a combined effect of precipitation and temperature, and extreme precipitation is defined according to the observed distribution of precipitation by intensity and its change. Agricultural soils are considered in a separate assessment of potential wind erosion impact in a rather general descriptive way, knowing that such soils are mostly found in the region where high-velocity winds happen.

This study provides an assessment of the current risk of soil degradation based on the analysis of observed data for the 2001–2020 period, and the future risks for the 2041–2060 period derived from the climate models' ensemble results. The future climate period is selected to provide the information required for on-time planning of preventive measures, along with measures required to reverse present risks from degradation in case the degradation is already an ongoing process. The study also provides the change of defined climate factors that impact soil degradation for past periods and for future periods, from near-future to end-of-century periods (in Appendices), which can be useful for long-term planning and for the assessments of future climate change for different scenarios of human factor impacts.

The risk of desertification. According to the Aridity Index, on average, Serbia will shift from the presently humid category to a dry sub-humid by 2041–2060 and semi-arid by 2081–2100 in a large portion of its territory. According to the climate factor only, the risk of desertification, in the 2001–2020 period is moderate in 36.3% of the territory of Serbia and in 2041–2060 in 52.8%. In the future period, 29.8% of the country will be under a high risk of desertification. The most responsible is the increase in temperature, because the change of annual precipitation was much less pronounced. The most probable expected change of average temperature for 2041–2060 is 2.6°C and 5.3°C for 2081–2100, compared to 1961–1990. Unfavourable annual distribution of precipitation (increasing drought and extension of the dry season within the growing season) and high temperatures may accelerate increasing risk impacts. Considering both factors, climate and land (soil, vegetation), the risk of desertification in 2001–2020 is moderate in 21.1% of Serbia and higher levels of risk (high, very high, extremely high) in 12.9% and in 2041–2060 moderate risk is in 31.9% and higher risk levels in 29.5% of the country.

The risk of soil degradation from extreme precipitation. The impact of extreme precipitation on soil degradation is assessed by assuming that extreme precipitation appears on days with precipitation over 30 mm. Such events were rare in past climates, but their frequency and accumulations are continuously increasing. In the 2001–2020 period compared to the 1961–1990 period, their frequency and precipitation accumulations doubled on such days. The extreme precipitation indicator was defined using the annual frequency of occurrence and the annual accumulation on such days. According to the climate factor alone, the risk of degradation from extreme precipitation is progressing quickly. In the 1961–1990 period, it was found to be significant only in some local areas but, already, in the 2001–2020 period, 45% of Serbia's territory is at moderate risk and 6.6% is under higher levels of risk, and in the 2041–2060 period, 34.1% is at moderate and 56.2% at higher risk levels. Considering both factors, the climate and the land (soil, vegetation, slope), in the 2001–2020 period, almost 24% is at higher risk, and in 2041–2060, 33.8%. A smaller portion of the surface under higher risk levels, by considering both factors, shows the importance of surface resilience to degradation in climate-changing conditions (if they are maintained).

According to the presented results, climate change in Serbia is significantly increasing the risk of soil degradation in Serbia. Areal coverage of higher risks of degradation (combined desertification and degradation from extreme precipitation) is found to increase from 28% to 42% of the territory of Serbia. Land-related factors (soil properties and vegetation cover) are considered to be the same in both periods, but they may change if no adaptive interventions are implemented or some harmful interventions happen in the meantime, meaning that this assessment may underestimate future risks. The risk of extreme precipitation is more pronounced according to currently available data. Increasing risks show the consequence of climate change impacts because the land vulnerability factor is assumed to be the same in both periods. The risk is also increasing for less vulnerable soils, among which are agricultural soils and other presently considered non-vulnerable areas, which highlights the fact that soil degradation can be triggered in the future only by climate change impact or in combination with negative human impacts.

Wind erosion in Serbia can have significant impact in areas affected with high wind velocities, if soils are erodible (weakly developed soil structure, lower soil organic carbon content). Such areas in Serbia are mostly under croplands (Vojvodina Province). In the periods when there is no vegetation cover, under the conditions of low soil moisture, wind erosion events will have an increasing tendency of appearance and duration in the future. Along with increasing desertification risk, wind erosion will have impact in these areas (especially in areas with values over 0.5) so these areas may become highly dust-emissive areas. Agricultural practices that protect the soil surface (like cover crops) and do not damage the soil structure (preserve or improve organic matter content, utilize conservation tillage), should be considered necessary to prevent future high risks.

Future increase of risk levels of determined indicators across Serbia shows the urgency for planning and implementation of preventive interventions, which can reduce severe negative impacts from climate change projected for the mid-twenty first century (2041–2060). In order to cope with soil degradation, sustainable soil management practices should be utilised together with soil conservation measures, and ameliorative measures. Also, it is very important to educate young researchers and increase soil degradation awareness through the educational system. Regarding adaptation measures, it is necessary to find sustainable solutions such as the nexus solutions that provide benefits to different sectors (avoiding harmful consequences to all potentially affected sectors and areas) and, if applicable, the solutions that can be self-sustainable to ensure long-term gain and reduce future costs (like the implementation of Nature-based Solutions). Irrigation, as a broadly used agricultural measure, can be applied in agricultural production in case it is based on the use of the official methodology considering optimal water use and increase of water use efficiency and water productivity, which will conserve soils and the environment from soil pollution and discourage degradation of the soil's structure. If no optimal solution is applicable (for example no sustainable water resources), cultivated culture/variety/hybrid should be replaced with a more resilient one.

The quality of the assessment of risks caused by climate change depends on the availability of data, their quality, and the relation of determined risk levels to observed impacts. The assessment given in this study provides information usable on the national level, with the goal to measure the rate of increasing risks and provide a general assessment of the spatial distribution of the higher risk levels. The change of scale (scaling-down), of climate change impact analysis on soil degradation risk and of other detected impacts, requires the inclusion of local data and information, the adaptation of methodology (adjustment of thresholds or change of definition of indicators) to address the risks found to be significant at those scales and in the area of interest, and to support the selection of indicators with the evidence (background knowledge). Each vegetation/land cover unit is specific regarding soil degradation, and the focus on soil degradation should be at the site/region/watershed level, and direct action should be taken. In case local data on soils are not available, it is recommended to collect soil data in soil surveys.

This study found that the soil degradation risk in Serbia can be severe in certain areas and in large part it will progress to potentially higher levels of risk. To enhance the knowledge and reduce the uncertainties of the assessments of climate change impacts, it is recommended to establish an all-inclusive (integrated) monitoring system of the land factors relevant to the soil degradation (soil and vegetation related at minimum, with georeferenced data). Such data, supplemented with reporting on observed impacts of weather extremes and assessed damages can help in designing the best site-adjusted methodology for degradation assessment. To ensure the success of the land-based interventions and to reduce their potentially harmful impact on the environment, it is recommended to reassess future risks under a scenario that considers the implementation of planned measures. Because of the uncertainty of the human factor in the assessment of climate change impact on managed soils (and ecosystems), in order to assess the future risks, it is recommended to develop future scenarios of human impacts and assess the range of possible risks.

3.2.

CLIMATE CHANGE IMPACT ON SOIL DEGRADATION RISK IN NATIONAL DOCUMENTS AND POLICY RECOMMENDATIONS

Implementation of information on climate change impact on soil degradation in national documents and policy recommendations is of importance to fulfill the obligations under the UN conventions: UNFCCC, UNCCD and UNCBD. More precisely, data and results on climate change impact on soil degradation could be used in development of National Adaptation Plan and Low Carbon Development Strategy of the Republic of Serbia as requested by the UNFCCC; development of plans for achievement of the Land Degradation Neutrality (LDN) and UNCCD National Action Programmes (NAP) for land degradation; and, taking into account that land degradation and biodiversity loss are strongly related, they could significantly contribute to the Biodiversity strategy.

In accordance with the Law on soil protection, Article 14, results of this study and its recommendations could contribute to Soil Protection Plan and Annual programme for soil protection. In addition, these results could be seen as a basis for Soil monitoring programme.

Law on agriculture and rural development, in Article 4, prescribes development of the Strategy for agriculture and rural development. In Articles 5 and 6, two national programs that have a role to frame ways of achievements of the strategic goals, are defined: programme for agriculture and programme for rural development. Considering significant potential impact of climate change on soils in Serbia, and high uncertainties in future assessments of climate change impacts on managed soils which highly depend on the implemented practices, in order to reduce and/or prevent extensive soil degradation in the future, it is highly recommended to consider additional stress on soils from climate change in constructing those strategic documents.

The Law on Planning and Construction defines the planning system and represents a top-down hierarchy of planning documents in Serbia. The law defines five main groups of spatial and urban planning documents: 1) planning documents (different types of urban and spatial plans), 2) documents for the implementation of spatial plans (implementation programmes), 3) urban-technical documents, 4) the Sustainable Urban Development Strategy (SUDS) and 5) the National Architectural Strategy. The Sustainable Urban Development Strategy of the Republic of Serbia 2030 is the umbrella national urban development policy document, while the Spatial Plan of the Republic of Serbia (SPRS) is the main document for spatial planning and spatial development. Results could be useful for these two, and in general for development of listed documents 1) to 4).

National Disaster Risk Management Program and Action Plans for the Implementation of the National Disaster Risk Management Programme can directly benefit from the obtained results on risk from soil degradation from climate change impact.

It is significant contribution of results for establishment of the monitoring and reporting system for landslides cadastre and the Sustainable Development Goals. Due to the significant role of soil in natural and human functionality and survival, soil degradation may represent a setback for any of the SDGs, if it is not properly monitored and managed, considering the future high negative climate change impact which can endanger soil quality, productivity, and carbon storage capacity.

Inclusion of information on climate change impact on soil degradation, obtained results and recommendations in this study, may contribute to crating sustainable Forestry management strategy and Water management strategy. Both are dealing with the nexus components of the environmental services in which healthy soils represent a necessary component with unbreakable linkage to both forests and water. Good actions can contribute to preventing or mitigating climate change impact on soil degradation and can benefit from sustainably healthy soils.

Other users (decision- and policy- makers) of the data, results and recommendations on climate change impact on soils, can be found on different levels, form national to local. Since the risk of soil degradation caused by climate change is still relatively unrecognized in Serbia, and most likely will rapidly increase in the future, its effects might largely increase future risk levels of other sectors. Reversing the processes of progressive degradation over larger scales could be unfeasible if not managed on-time.

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APPENDICES

APPENDIX 0:

TERMINOLOGY

Soil is a three-dimensional natural body consisting of inorganic and organic components. It is the most fundamental and basic resource that provides a wide array of socio-economic and environmental functions. It is a porous, heterogeneous system, consisting of solid, liquid and gaseous phases, and inhabited by living organisms. Although it is often perceived as a body of insignificant value, humans cannot survive without soil because it is the basis of all terrestrial life. Soil provides food, fuel and fibre and acts as a cornerstone of food security and environmental quality affecting human well-being. The significance of soils is realised in the conditions when soil is degraded to the extent that it cannot provide its services. Soil is a non-renewable resource, it is very dynamic, and prone to rapid degradation without appropriate land use. Productive soils are a finite resource covering <11% of earth's surface and supplying food to almost eight billion people. Therefore, the widespread degradation of soil resources can severely threaten global food security and environmental quality.

Soil degradation can be defined in several ways. In a narrow sense, it is the physical, chemical and biological decline in soil productivity and/or quality. In a broader sense, it can be defined as a change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries. Soil degradation processes and their evaluation are very complex. Soil degradation is an element of the land degradation process. The major types of soil degradation are soil erosion and deterioration of the soil's physical, chemical and biological properties.

Soil erosion is the removal of the most fertile top layer of soil by water and wind. It can be defined as detachment and movement of soil material from the upper part of the profile by the action of wind or running water, especially as a result of changes brought about by human activity (Jackson et al., 2005). It is a process consisting of two phases. The first phase comprises the detachment of individual soil particles from the soil mass and their transport by erosive agents such as water and wind. When the energy of the erosion agents is no longer available to transport the particles, a third phase, the deposition process, occurs.

Soil erosion as a term is often confused with soil degradation. In fact, soil erosion is one of the soil degradation processes which refer to absolute soil losses in terms of topsoil and nutrients. This is the most visible type of soil degradation.

Two main types of soil erosion are geologic and accelerated erosion. Geologic erosion is a normal process that generally occurs in soils as the result of pedogenesis over a long period and is not influenced by human activity. Accelerated erosion is a type of erosion triggered by anthropogenic causes and it becomes a major concern when the rate of erosion becomes rapid.

Multiple functions of land

1	Storing minerals and raw materials for human use
2	Agricultural and industrial use (e.g. food, fibre, fuel)
3	Space for settlements, social and technical infrastructure and recreation
4	Buffer or filter for chemical pollutants, and a source and a sink for greenhouse gases
5	Space for surface and ground water
6	Habitat for plants, animals and micro-organisms
7	Basis for livelihoods, a homeland and a place of ancestry
8	Object of investment and speculation

According to the UNCCD definition (UN, 1994): "**Land** is a delineable area of the earth's terrestrial surface, encompassing all attributes of the biosphere immediately above or below this surface, including those of the near-surface climate, the soil and terrain forms, the surface hydrology (including shallow lakes, rivers, marshes, and swamps), the near-surface sedimentary layers and associated groundwater reserve, the plant and animal populations, the human settlement pattern and physical results of past and present human activity (terracing, water storage or drainage structures, roads, buildings, etc.)."

Land has multiple functions. It can be used i) for storing minerals and raw materials for human use, ii) for agricultural and industrial use (e.g. food, fibre, fuel), iii) as a space for settlements, social and technical infrastructure and recreation; iv) as a buffer or filter for chemical pollutants and a source and a sink for greenhouse gases; v) as a space for surface and ground water; vi) as a habitat for plants, animals and micro-organisms; vii) as a basis for livelihoods, a homeland and a place of ancestry; and viii) as an object of investment and speculation (GIZ, 2011).

Land degradation has a wider sense compared to soil erosion and soil degradation. It covers all negative changes in the capacity of the ecosystem to provide goods and services, including biological, water-related and land-related social and economic goods and services. Land degradation refers to a loss or reduction in the productivity of the land, which arises as a result of various natural processes, often accelerated by an anthropogenic perturbation (Lal, 1993). It is characterised by the reduction and loss of the biological and economic productive capacity of land (LDN TSP). Land degradation is a global phenomenon, with often immediate detrimental impacts at the local level. It can be caused by human activities, and exacerbated by natural processes such as climate change. The World Overview of Conservation Approaches and Technologies (WOCAT: https://www.wocat.net) identifies six main types of land degradation: soil erosion by water, soil erosion by wind, soil chemical deterioration, soil physical deterioration, water degradation, and biological degradation. First four types of land degradation, refer to soil degradation, whereas the water and biological degradation comprise water and biological related goods and services, which represent the wider extent than soil degradation.

Land degradation cannot be assessed independently of its spatial, temporal, economic, environmental and cultural context (Warren, 2014). It can be a consequence of different types of human activities and natural causes, but it is usually the result of the complex interaction of different types of land degradation drivers. Drivers of land degradation can be direct or proximate, linked to local land use system, and indirect or underlying which can be local, national or global and include demographic, economic and socio-political circumstances (LDN TSP).

The main **direct drivers** of land degradation are improper management of the soil, improper management of annual, perennial, scrub and tree crops, deforestation and removal of natural vegetation, over-exploitation of vegetation for domestic use, overgrazing, industrial activities, waste deposition and mining, urbanisation and infrastructure development, discharges, release of airborne pollutants, disturbance of the water cycle, over-abstraction of water, and natural causes.

The main **indirect drivers** of land degradation are population pressure, human migrations, land tenure, poverty/wealth, labour availability, inputs (including access to credit/financing) and infrastructure, education, access to knowledge and support services, war and conflict, governance, institutional settings and policies (including taxes, subsidies and incentives).

United Nations recognised desertification, land degradation and drought (DLDD) as the major environmental and developmental concerns worldwide and therefore established the **United Nations Convention to Combat Desertification (UNCCD)** in 1994. The Convention was adopted by the Intergovernmental Negotiating Committee for the elaboration of an international convention to combat desertification in those countries experiencing serious drought and/or desertification, particularly in Africa during its Fifth session held in Paris.

The 2030 Agenda for Sustainable Development includes 17 Sustainable Development Goals (SDG) and 169 targets. The target 15.3 of SDG 15 "Life on Land" aims to "combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world" by 2030. The twelfth session of the Conference of Parties (COP) of the UNCCD, endorsed SDG target 15.3 and the concept of land degradation neutrality (LDN) as a strong vehicle for driving the implementation of the Convention. The indicator adopted to measure the achievement of SDG target 15.3 is "Proportion of land that is degraded over total land area".

Land degradation neutrality is defined as "a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales" (LDN Technical guideline). LDN aims to maintain the land-based natural capital and associated ecosystem functions and provides services.

The main services required to be maintained are **food availability, water quality, raw materials,** and **medical services**. The main regulating services are **climate regulation, climate change mitigation, disaster risk reduction, habitat regulation of pests and diseases, pollination** and **water regulation**. The main supporting services are **water cycling** and **soil fertility**, whereas the main cultural services that tend to be maintained are cultural heritage, recreation and tourism.

Sustainable land management (SLM), integrated landscape management (ILM), integrated water management (IWM), and rehabilitation and restoration of degraded land are the key concepts of LDN.

Desertification is defined as land degradation of land in arid, semi-arid and dry sub-humid areas, resulting from various factors, including climatic variations and human activities (UNCCD, 1994). Also, it is stated that desertification is a term used for land degradation in dryland areas and/or the irreversible change of the land to such a state that it can no longer be recovered for its original use.

Prevention represents the use of conservation measures in order to maintain natural resources and their environmental and productive capacity.

Mitigation is defined as an intervention intended to reduce ongoing degradation. The mitigation impact is assessed in the short to medium term. The term is also used to describe the reductions of the impacts of degradation.

Rehabilitation is applied when the land is already degraded to such an extent that the original use is no longer possible and the land has become practically unproductive. It requires longer-term and costly investments to have an impact.

Climate change is the global phenomenon referring to climate transformation characterised by the changes in the measures of the planet's climate over a long period that are especially caused by human activities. Climate change threatens the sustainability of the planet's ecosystems, the future of humankind and the stability of the global economy. **Global warming** is just one aspect of climate change which refers to the rise in global temperatures mainly due to the increasing concentrations of greenhouse gases in the atmosphere.

APPENDIX 1:

INFORMATION ABOUT THE DATA, DATA PROCESSING AND DATA LIMITATIONS

The dataset used for analyses of parameters for the past (observed) period is the E-OBS database (gridded daily temperature and precipitation), which includes daily temperature (mean, maximum and minimum) and precipitation, and is used for many climate change studies for Serbia, but most importantly in the Third National Communication and National Adaptation Plan (both in draft version). The spatial resolution of the data is 0.11°.

A total of 28 stations in Serbia are used for spatial interpolation of data (this number may change depending on the data sent from Serbia to international exchange). Verification of this dataset using other available observations in Serbia shows that there is a high reliability of these data in general for Serbia, with a somewhat lower correlation coefficient for daily precipitation data (0.85) than for daily temperature data (0.99), according to the assessment in Djurdjevic and Krzic (2013). The quality of data for extreme precipitation is not assessed. It seems that the data for the Kosovo territory are not well-represented since the high temperature area in low altitudes is not visible in E-OBS data, but is present in climate projections, which can represent the spatial temperature distribution (distinguish colder and warmer areas) well. Because the methodology for interpolation is the same for the overall period of the analysis, it may be assumed that changes in climate indices are well-represented by using this dataset. Because of the relatively low resolution of data, higher altitudes are not well-represented by this dataset.

Some irregular data may exist in the dataset as a consequence of the data interpolation process, which may be found here for the temperature: on some days, the maximum temperature is lower than the minimum temperature, and at some points, there are unrealistic numbers for some days (non-existing data) such as 1010. Data were corrected simply, by changing maximum to minimum temperature and vice versa, and non-existing data were replaced by the values from the previous day.

The E-OBS datasets are regularly updated with available observed data. The quality of datasets is better in the areas where a higher density of available measurements can be found. More information on these data can be found at: https://www.ecad.eu/dailydata/index.php.

For the risk assessment on the local level, one should be aware about the limitations of these data and it is recommended to use local measurements.

Data from climate models are derived from the EURO-CORDEX database. A list of models which form a climate models' ensemble used for the analysis of future climate change in this study is given in Table A1. The results from these models are also used for the TNC and the NAP. The models were selected so that the ensemble results represent the spatial distribution of observed changes in temperature and precipitation well. The models' data are bias-corrected, meaning that persistent deviation of models' results from observed data in some areas and parts of the year are reduced to an absolute minimum.

All the calculations for the analysis presented in this study are done for each model separately and the median, while the values of the 25th and the 75th percentile are derived from the obtained ensemble of the results. Comparing the models' ensemble results derived from a part of the period with the results from E-OBS data, it is concluded that certain percentile values correspond more to the observed values than the ensemble median value. For all calculated parameters, both the median and the chosen percentile values are presented in Appendix 3. Future changes of selected parameters are calculated using models' results for both the future climate period and the base period.

No.	Period	Model
1	1951–2100	gcm-ICHEC-EC-EARTH-rcm-CLMcom-CCLM4-8-17
2	1951–2100	gcm-ICHEC-EC-EARTH-rcm-DMI-HIRHAM5
3	1951–2100	gcm-ICHEC-EC-EARTH-rcm-KNMI-RACMO22E
4	1951–2100	gcm-MOHC-HadGEM2-ES-rcm-CLMcom-CCLM4-8-17
5	1951–2100	gcm-MOHC-HadGEM2-ES-rcm-KNMI-RACMO22E
6	1951–2100	gcm-MPI-M-MPI-ESM-LR-rcm-CLMcom-CCLM4-8-17
7	1951–2100	gcm-MPI-M-MPI-ESM-LR-rcm-MPI-CSC-REMO20091
8	1951–2100	gcm-MPI-M-MPI-ESM-LR-rcm-MPI-CSC-REMO20092

Table A1. A list of EURO-CORDEX models, from which data were used for future climate change analysis, and the period for which the data are available.

The comparison of the results for extreme precipitation indices for the past period, from models' data and from E-OBS data, which is considered as a representative value, showed that such events are much overestimated in all the models. This could be the consequence of statistical bias correction applied on models' results, rather than the poor performance of all models for such events. For this reason, the PR30YY index was not applicable in the assessment of its future changes, because it reached its maximum or near-maximum value in the past.

APPENDIX 2:

SUPPLEMENT TO TEMPERATURE, PRECIPITATION AND ARIDITY INDEX ANALYSIS

In addition to the comments presented in the study, the analysis of temperature, precipitation and the Aridity Index for the past (observed) periods show the that the dynamics of changes in temperature and precipitation across Serbia impacted the change of the Aridity Index in different ways. During the 1986–2005 period (chosen as a base period for future projections), the average accumulated precipitation decreased during the DJF, MAM and SON seasons, which impacted the decrease of average accumulated precipitation compared to the values for the 1961–1990 period. The average temperature increased by 0.5ºC. This led to the decrease of average AI for Serbia for 1986–2005 to 0.71 compared to 1961–1990 (0.74). The decrease in precipitation which happened during this period had a more pronounced impact (Vukovic et al., 2018; Djurdjevic et al. 2018). Later, temperature continued to increase, and precipitation increased above the values for the 1961–1990 period. The precipitation accumulated annually over Serbia during the 2001–2020 period increased by 8%, and average temperature increased by 1.6ºC, compared to 1961–1990. The increase in precipitation impacts the increase in the AI, but the increase in the temperature impacts the decrease of the AI because it causes higher potential evapotranspiration. Besides the fact that precipitation was higher during the 2001–2020 period, the values of both periods are very close because an already high temperature increase had a significant impact. For the 2011–2020 period, the average annual precipitation accumulated over Serbia was 5.2% higher than for the 1961–1990 period, and a temperature increase of 1.8ºC caused the average AI (0.72) to drop below the average value for the 1961–1990 period. This means that the effect of increasing temperature became a significant factor in the potential increase of aridity in the future, even if precipitation does not change significantly. Seasonal AI change shows a continual increase in dryness during the JJA due to both factors, the decrease in precipitation in this season and the increase in temperature. Since the change in the annual distribution of precipitation showed that precipitation increased in MAM during this season, wetness increased on average for Serbia. These conclusions were drawn for average values across the territory of Serbia, while changes and values differ spatially.

Figure A2.1 shows the spatial distribution of AI values for all past periods (1961–1990, 1986–2005, 2001–2020, 2011–2020) for all selected periods during the year (seasons and vegetation period). Spatial distributions of the AI changes for the 1986–2005, 2001–2020 and 2011–2020 periods, with respect to the 1961–1990 period, are shown in Figure A2.2. These figures are supplementary material for the analysis, presented in the study, of the spatial distribution of the AI values and their changes for the observed periods.

Figure A2.3 shows the median results of the models' ensemble for changes of extreme climate indices, and Figure A3.4 shows the values of the 25th percentile. The 25th percentile values correspond better to the observed rate of change of the AI, and it is assumed that it is more probable that these changes will happen rather than the ones presented with the ensemble median values.

The AI values across Serbia for the 2041–2060 selected future period, which is used for desertification risk assessment, the changes obtained as the 25th percentile values of the models' ensemble are added to the values for the 1986–2005 period obtained from EOBS data. This gave the values of the AI for the future period, and is more valid than the future AI calculated from the models' results.

Table A2.1. Anomalies (changes) of average temperatures (°C) for Serbia: Tmean – mean daily temperature, Tmax – maximum daily temperature, Tmin – minimum daily temperature; results are given for periods: annual (ANN), winter (DJF), spring (MAM), summer (JJA), autumn (SON), growing season period (April-October: VEG); anomalies are calculated with respect to the values for the 1961–1990 base period.

	ANN	DJF	MAM	JJA	SON	VEG
Tmean						
1986–2005	0.5	0.5	0.3	1.1	0.1	0.6
2001–2020	1.4	1.3	1.2	2.0	1.1	1.5
2011–2020	1.8	1.7	1.4	2.4	1.8	1.9
Tmax						
1986–2005	0.7	0.9	0.5	1.3	0.1	0.7
2001–2020	1.6	1.5	1.5	2.2	1.1	1.5
2011–2020	2.0	2.0	1.7	2.6	1.7	2.0
Tmin						
1986–2005	0.5	0.4	0.2	1.0	0.4	0.6
2001–2020	1.3	1.3	1.0	1.8	1.2	1.4
2011–2020	1.6	1.7	1.1	2.1	1.7	1.6
Prec.						
1986–2005	-1.9	-7.0	-6.0	-5.3	12.1	1.7
2001–2020	8.0	6.0	9.6	-0.2	18.6	9.0
2011–2020	5.2	4.9	20.0	-7.9	5.0	5.5

Table A2.2. AI average values for the territory of Serbia: annual (AI), December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), September-October-November (SON), vegetation period (VEG), for the selected periods; colours correspond to Table 5.

Period	ANN	DJF	MAM	JJA	SON	VEG
1961–1990	0.74	2.76	0.74	0.46	1.08	0.54
1986–2005	0.71	2.40	0.67	0.41	1.17	0.53
2001–2020	0.75	2.67	0.77	0.42	1.18	0.55
2011–2020	0.72	2.56	0.84	0.39	0.99	0.53

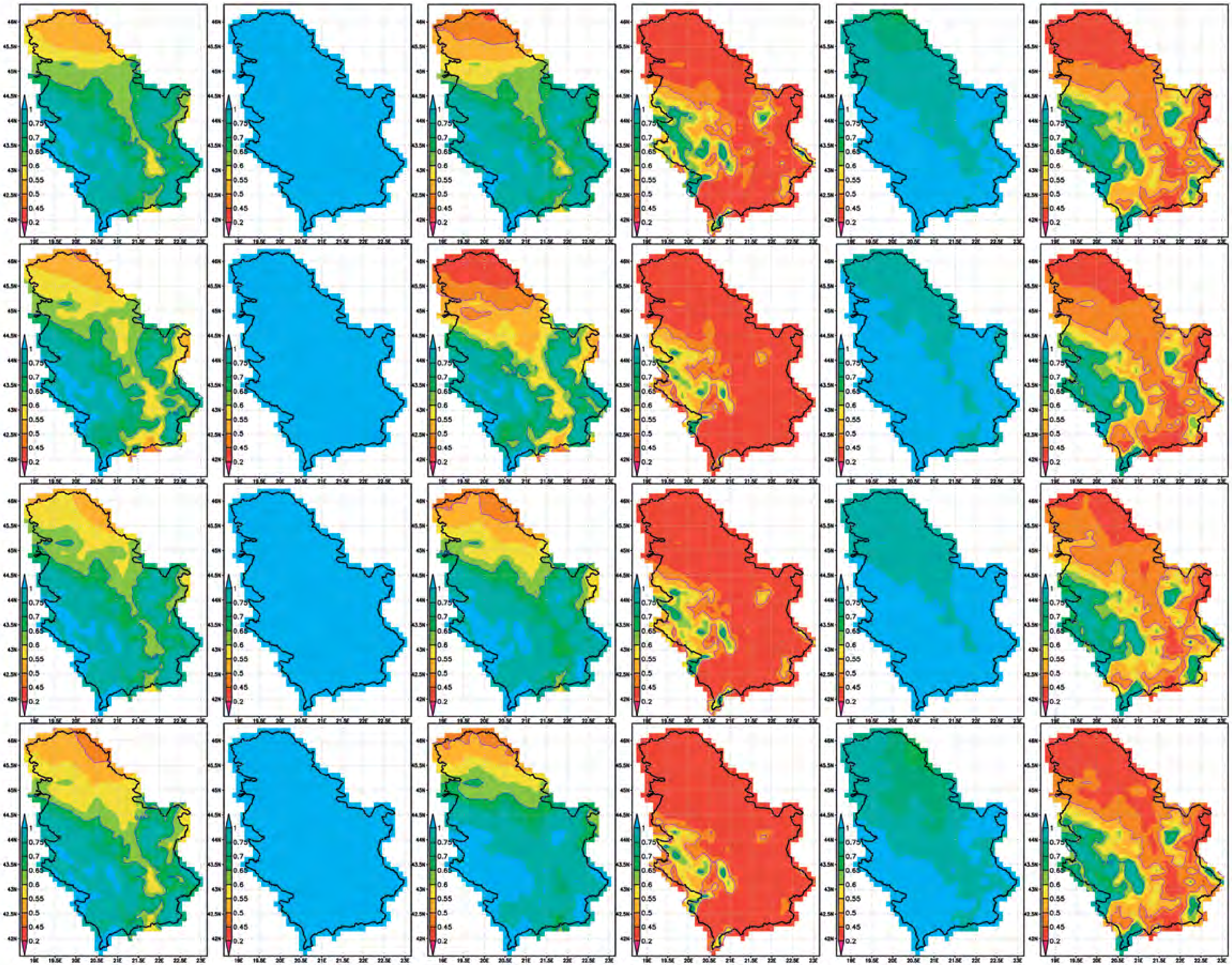
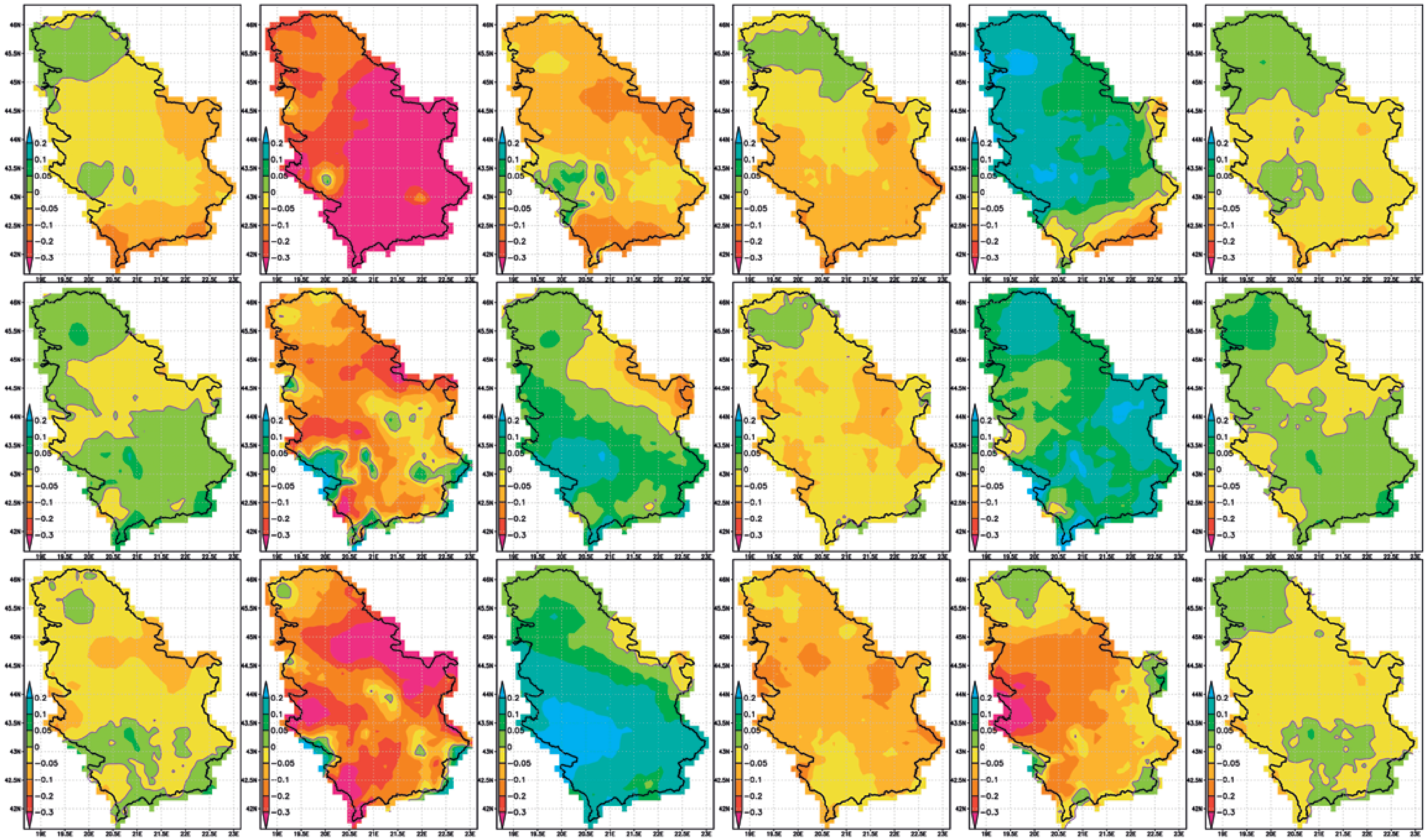
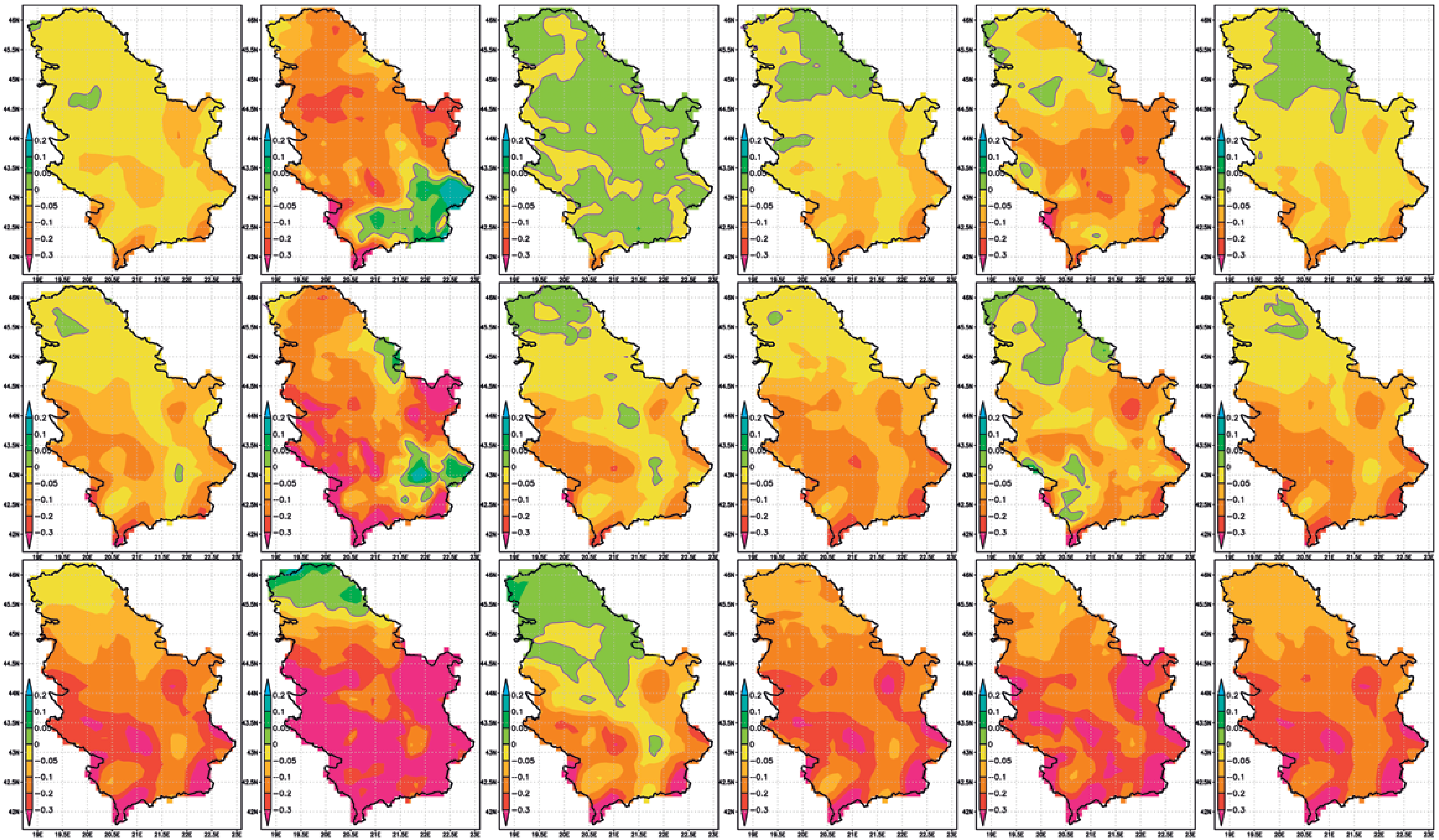


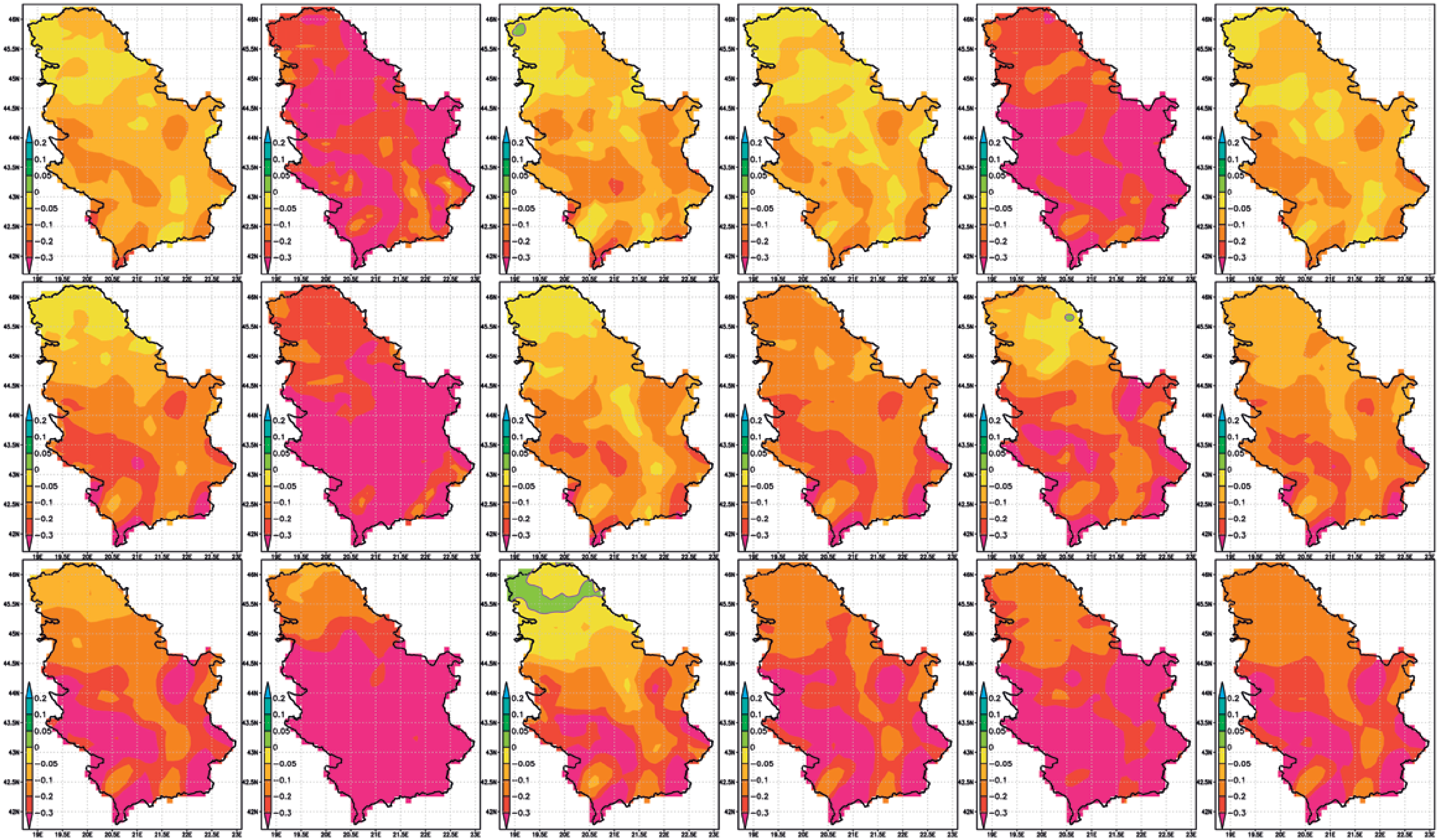
Figure A2.1 AI for the 1961–1990 (first row), 1986–2005 (second row), 2001–2020 (third row) and 2011–2020 (last row) periods: annual (first column), DJF (second column), MAM (third column), JJA (fourth column), SON (fifth column) and VEG (last column).



▲ **Figure A2.2** Anomaly (change) of the AI for the 1986–2005 (first row), 2001–2020 (second row) and 2011–2020 (last row) periods: annual (first column), DJF (second column), MAM (third column), JJA (fourth column), SON (fifth column) and VEG (last column) with respect to the 1961–1990 period.



▲ **Figure A2.3.** Median values of climate models' ensemble for anomaly (change) of the AI for the 2021–2040 (first row), 2041–2060 (second row) and 2081–2100 (last row) periods: annual (first column), DJF (second column), MA (third column), JJA (fourth column), SON (fifth column) and VEG (last column) with respect to the 1961–1990 period.



▲ **Figure A2.4.** The 25th percentile values of climate models' ensemble for anomaly (change) of AI for the 2021–2040 (first row), 2041–2060 (second row) and 2081–2100 (last row) periods: annual (first column), DJF (second column), MAM (third column), JJA (fourth column), SON (fifth column) and VEG (last column) with respect to the 1961–1990 period.

APPENDIX 3:

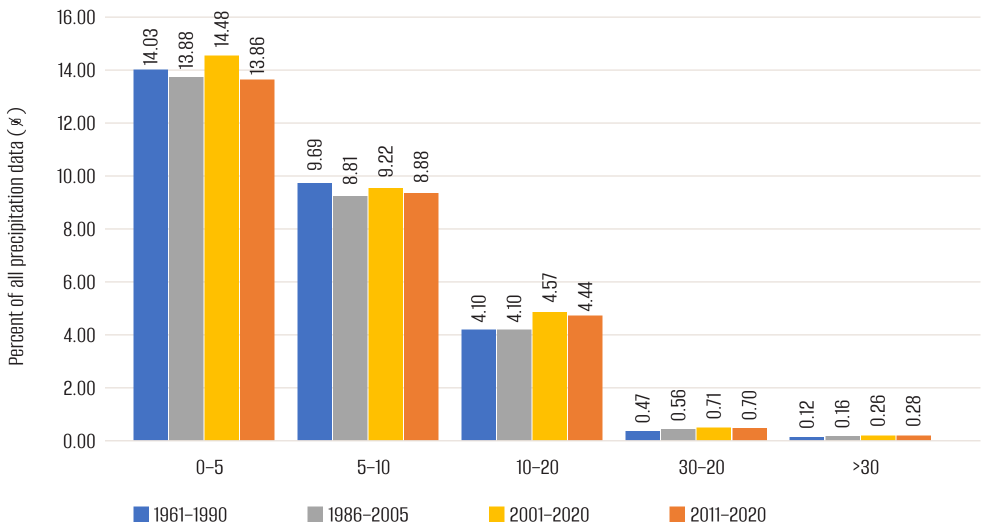
SUPPLEMENT TO EXTREME PRECIPITATION INDICATOR ANALYSIS

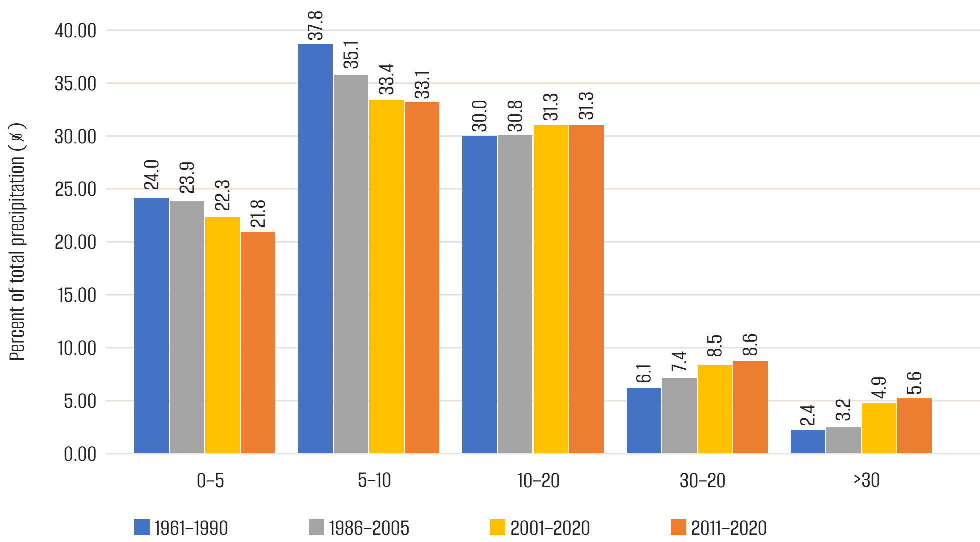
Figure A3.1 contains supplement data to Figure 4 in the study. It shows the continuous change of precipitation distribution across Serbia toward more extreme events, defined as days with certain amounts of precipitation.

Figure A3.2 presents spatial distribution of the values of extreme precipitation indices (PR30ND, PR30AC, PR30YY) for the past periods (1961–1990, 1986–2005, 2001–2020, 2011–2020). Anomalies (change) of extreme precipitation indices for the three latter periods with respect to the 1961–1990 period are given in Figure A3.3. In addition to the analysis of extreme precipitation change given in the study, and the analysis of precipitation change of all periods, it can be seen here that extreme precipitation increases from the 1961–1990 period to the last decade continuously in the majority of Serbia (except in the south, the area close to the southern border, according to the dataset used for this analysis). In the last periods, and with more pronounced changes in the 2011–2020 periods, extreme precipitation indices increased significantly above the values in 1961–1990 period.

According to the 1986–2005 period, the increase is higher in central and northern Serbia, while later changes became larger in central and southern Serbia. Events with extreme precipitation (over 30 mm daily), increased in frequency (number of appearances), precipitation accumulations, and in the number of years when they are appearing.

The analysis of the climate models values for the 1986–2005 base period, which is selected as a base period for the future climate change analysis, and the 2021–2040, 2041–2060 and 2081–2100 future climate periods showed as follows: for the 1986–2005 base period compared to the values of the observed data, all models significantly overestimate extreme precipitation, the tPR30YY already exceeded values of the majority of Serbia by 80% and in some parts by 90%, meaning that further increase of this index caused by the future rate of increase of extreme precipitation cannot be used as relevant for the assessment of the future change of extreme precipitation because its maximum value is 100%, and thereby shows small changes.

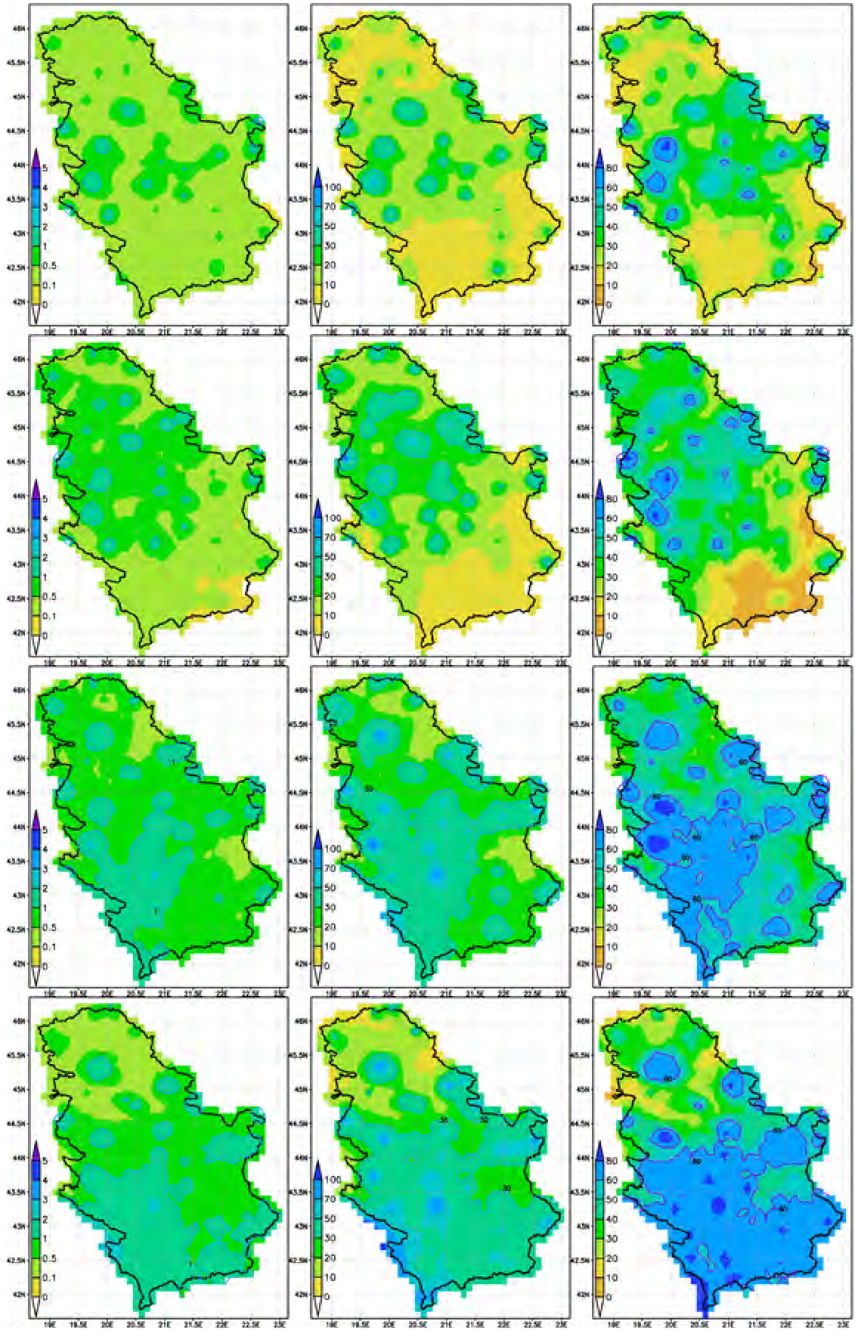




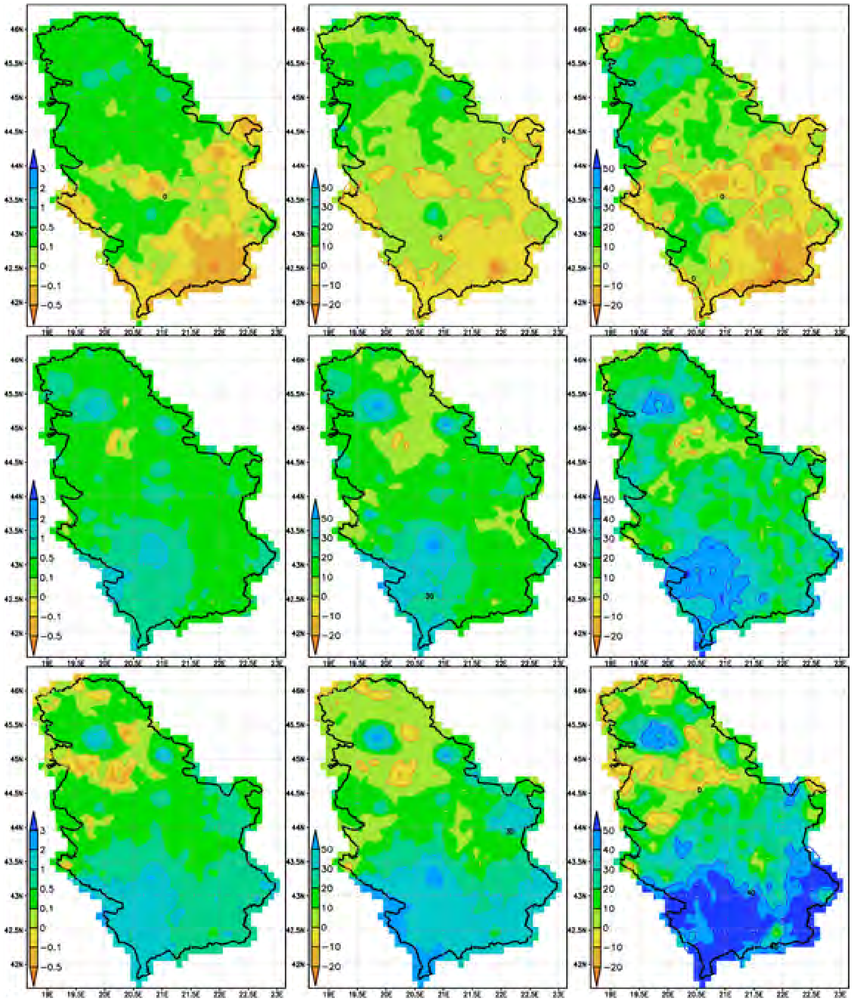
▲ **Figure A3.1.** The number of days with precipitation in a certain range (left) expressed as a percent of all precipitation data (all daily data for Serbia during the selected period), and precipitation accumulated in days with precipitation in a certain range expressed as a percent of the total accumulated precipitation (right) for different periods: 1961–1990, 1986–2005, 2001–2020, 2011–2020.

Figure A3.4 shows the values of anomalies of extreme precipitation indices for the future climate periods compared to the 1986–2005 period, the median values of climate models' ensemble. The increase of extreme precipitation indices escalates further in the future, but in the near future, the period results show a lesser rate of increase than observed for central and southern Serbia, which is the reason to choose the 75th percentile values as more probable (Figure A3.5). Since the dynamics in the models are well-represented and consequently spatial patterns of higher and lower changes and values can be considered more reliable than interpolated data only from the available stations as in the EOBS, it can be concluded that the increase is expected in the whole territory of Serbia. It is highly likely that the 75th percentile values underestimate the future change because they also show a smaller change than in the near past period, but a somewhat greater one than the median value. Once again, it should be mentioned that the models' results were processed for reduction of statistical bias correction, which may induce much higher values, and smaller changes, and it is less probable and possible that all the models have a bias in extreme precipitation to greatly overestimate their appearance, but the conclusion about the increasing changes for the future, comparing models' results for future periods to the base period, can be assumed as reliable.

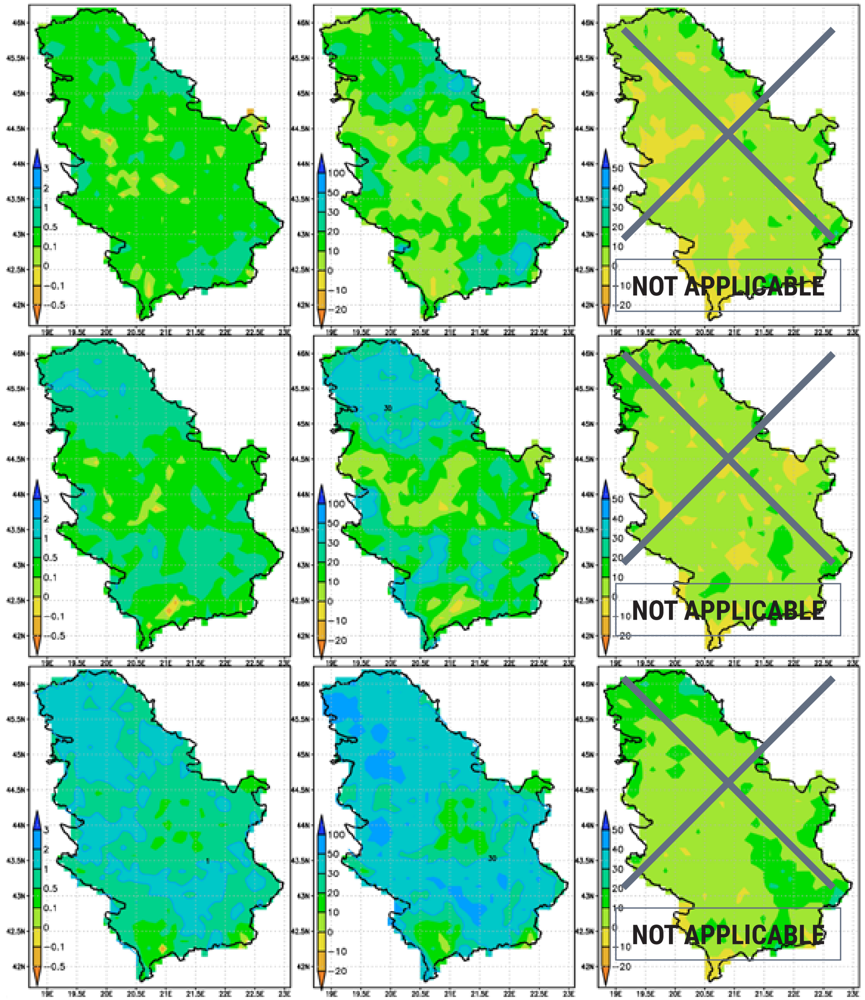
Figure A3.6 shows spatial distributions of risk levels according to the extreme precipitation indicator (as defined in Table 8), for the 1961–1990, 2001–2020 and 2011–2020 periods. In the 1961–1990 period, the risk of extreme precipitation impact was low in the majority of Serbia, and it significantly increases in the near-past period, especially in central and southern Serbia.



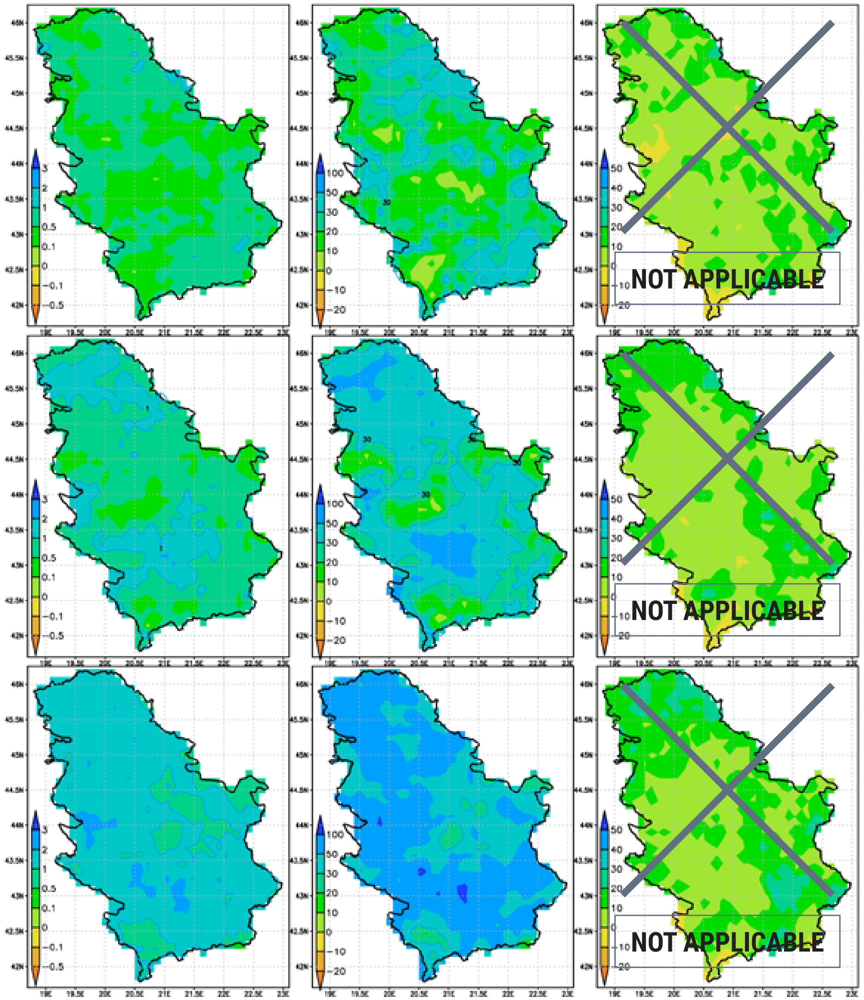
◄ **Figure A3.2.** Values of extreme precipitation indices for the 1961–1990 (first row), 1986–2005 (second row), 2001–2020 (third row) and 2011–2020 (last row) periods: PR30ND (first column), PR30AC (second column), PR30YY (third column).



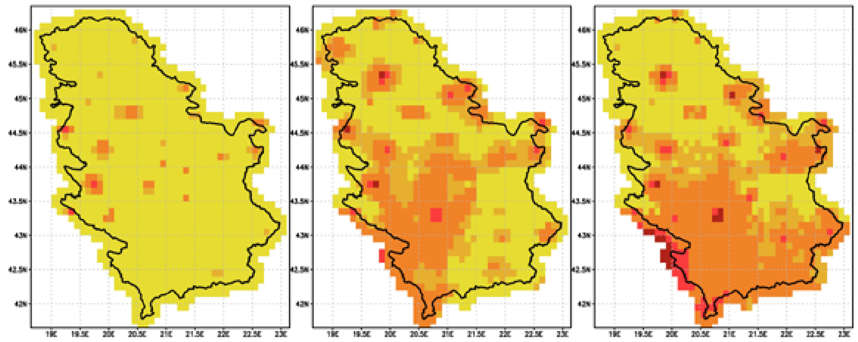
▲ **Figure A3.3.** Anomalies (change) of extreme precipitation indices for the 1986–2005 (first row), 2001–2020 (second row) and 2011–2020 (last row) periods, compared to the 1961–1990 period: PR30ND (first column), PR30AC (second column), PR30YY (third column).



▲ **Figure A3.4.** Median values of climate models' ensemble for anomalies (change) of extreme precipitation indices for the 2021–2040 (first row), 2041–2060 (second row) and 2081–2100 (last row) periods, compared to the 1986–2005 period: PR30ND (first column), PR30AC (second column), PR30YY (third column).



▲ **Figure A3.5.** The 75th percentile values of climate models' ensemble for anomalies (change) of extreme precipitation indices for the 2021–2040 (first row), 2041–2060 (second row) and 2081–2100 (last row) periods, compared to the 1986–2005 period: PR30ND (first column), PR30AC (second column), PR30YY (third column).



▲ **Figure A3.6.** Risk level according to the extreme precipitation indicator for the 1961–1990 (left), 2001–2020 (middle) and 2011–2020 (right) periods, defined as in Table 8; yellow – low or inconclusive, light orange – moderate, orange – high, red – very high, dark red – extremely high (colours correspond to colours in Table 8).

APPENDIX 4:

SUPPLEMENT TO SOIL INTRINSIC CHARACTERISTICS

The class of weakly developed soils (Table A4.1) is part of automorphic soil order and has four soil types: Lithosols, Arenosols, Sirozems, and Colluvial Soils. In temperate regions, these soils are formed a) on consolidated rocks characterised by physical weathering, weak chemical weathering and humus accumulation, b) on unconsolidated rocks with intensive surface migration of soil particles, c) as a consequence of aeolian erosion, and d) as a result of the colluviation process. These soils have a weakly developed initial horizon – (A), characterised by the initial grade of structure development and low humus content. Because of the soil type specific reasons, these soils remain with a (A) – C, or (A) – R soil horizon sequence. As they do not have a well-developed humus accumulative horizon, these soils are very fragile, sensitive to changes, vulnerable bodies prone to degradation. In fact, they require prevention measures in the current climate conditions. These soils are either dominantly under degraded natural vegetation, or are sparsely vegetated areas, or already afforested. Rock outcrops, soil depth, water holding characteristics or high content of coarse fragments are potential limitations to root growth. Their use is restricted due to their low productivity and they are usually prone to natural degradation drivers, and less to human-induced changes. Lithosols inherited very low productivity, Sirozems are prone to soil water erosion, whereas Arenosols are formed and changed by aeolian erosion. Colluvial soils might be prone to physical and chemical soil deterioration as they are used for agricultural production if they have higher productivity. Dominant prevention measures on these soils are afforestation, erosion protection measures and less often sustainable agricultural practices.

The class of humus accumulative soils (Table A4.2) is part of the automorphic soil order and consists of five soil types: Chernozems, Vertisols, Calcomelanosols, Rendzinas and Rankers. All these soil types are characterised by well-developed humus accumulative horizons. Chernozems are highly productive, deep, fertile, agricultural soils, with no restriction to root development. Potential degradation drivers are agricultural practices such as tillage and fertilisation practices, irrigation, and crop protection. Chernozems are prone to soil compaction, deterioration of soil structure, soil mining, acidification, salinisation, alkalisation, aeolian erosion, and SOC decline. Dominant prevention measures are sustainable agricultural practices (tillage, irrigation, fertilisation) and the rise of forest belts. Vertisols are productive and highly productive, deep and moderately thick, very fertile agricultural soils, with restriction to root development in case of the existence of very intensive shrink-swell clays. Potential degradation drivers are tillage, fertilisation management, irrigation, and crop protection. Vertisols are prone to soil compaction, deterioration of soil structure, soil mining, acidification, soil water erosion, and SOC decline. Dominant prevention measures are sustainable agricultural practices. Calcomelanosols, Rendzinas and Ranker Soils are mainly soils of hilly mountainous regions, less productive soils, often thin and rich in coarse fragments, under forests, pastures, natural grasslands, and less often agricultural production. Potential degradation drivers are grazing mismanagement and deforestation, whereas soil water erosion, aeolian erosion, and SOC decline are soil degradation types. Dominant prevention measures are afforestation, appropriate forest management, and soil erosion protection measures.

The class of cambic soils (Table A4.3) is part of the automorphic soil order and consists of four soil types: Eutric Cambisols, Dystric Cambisols, Calcocambisols, and Terra Rosas. All these soil types are characterised by well-developed humus accumulative horizons and a subsurface cambic horizon. Eutric Cambisols are productive, moderately deep and deep, moderately fertile agricultural soils, with no restriction to root development and good water holding properties. Potential degradation drivers are agricultural practices such as tillage and fertilisation practices, irrigation, and crop protection. Eutric Cambisols are prone to soil compaction, deterioration of soil structure, soil mining, acidification, soil water and wind erosion, and SOC decline. Dominant prevention measures are sustainable agricultural practices and erosion protection measures. Dystric Cambisols are soils of hilly mountainous regions, dominantly under forests. These are less productive, moderately thin and thin soils with low fertility, acid, and low to moderate water holding capacity. A potential degradation driver is deforestation. Dystric Cambisols are prone to deterioration of soil structure, acidification, soil water erosion, and SOC decline. Dominant prevention measures are afforestation and erosion protection measures. Calcocambisols and Terra Rossas are mainly soils of hilly regions, moderately productive soils, moderately thick, well structured, under forests, pastures, natural grasslands, and agricultural production. Potential degradation drivers are site-specific and can include forest mismanagement and deforestation, whereas soil water erosion, aeolian erosion, and SOC decline are main soil degradation types. Dominant prevention measures are: afforestation, appropriate forest management, soil erosion protection measures, and sustainable agricultural practices.

The class of illimerised soils (Table A4.4) is part of automorphic soil order and consists of three soil types: Luvisols, Podzols, and Brunipodzols. All these soil types are characterised by eluviation and illuviation processes. Luvisols are used for agricultural production. They could be productive, moderately deep, moderately fertile agricultural soils, often with no restriction to root development (subsurface compaction), and good water holding properties. Potential degradation drivers are agricultural practices and deforestation. Luvisols are prone to soil compaction, deterioration of soil structure, soil mining, acidification, soil water and wind erosion, and SOC decline. Dominant prevention measures are sustainable agricultural practices, erosion protection measures and afforestation. Podzols and Brunipodzols are soils of hilly mountainous regions, dominantly under forests. These are the least productive, moderately thin soils with low fertility, highly or extremely acid, and could display element toxicity. A potential degradation driver is deforestation. Podzols are prone to deterioration of the soil structure, acidification, and soil water erosion. Dominant prevention measures are afforestation and erosion protection measures.

Rigosols and Hortisols are part of anthropogenic soils which are formed after the application of deep ploughing and/or agricultural practices to other soils in order to prepare them for sustainable agricultural production. Fragility of these soils depends on initial pre-anthropogenised soil and the applied measures. Dominant potential degradation drivers are related to soil agricultural management and the results of that are soil specific degradation processes. Prevention measures depend on the initial soil condition and degradation drivers.

Deposols and Technosols are soils changed or formed as a result of mining or industrial activities and limitation to root growth appears as a presence of technic hard material, acidity and different heavy metal concentrations. These soils are not part of this report.

The pseudogleic class (Table A4.5) consists of one soil type: Pseudogley. Pseudogley soils are characterised by humus accumulative horizons and subsurface low water permeable horizon over which water stagnates. Pseudogleys can be moderately productive, moderately deep, moderately fertile agricultural soils, with bad water holding properties. Potential degradation drivers are agricultural practices such as tillage and fertilisation practices, irrigation, and crop protection. Pseudogleys are prone to soil compaction, deterioration of soil structure, soil mining, acidification, soil water and wind erosion, and SOC decline. Dominant prevention measures are sustainable agricultural practices.

The class of fluviatile soils (Table A4.5) are represented by the Fluvisol soil type. These are soils of flooded river valleys, mainly used for agricultural production. They have wide array of soil characteristics and are often productive, thick, with moderate fertility, and can have restriction to root development by means of layers of gravel at some depth in the soil profile. Potential degradation drivers are soil management and flooding. Fluvisols are prone to deterioration of the soil structure, soil chemical deterioration, and SOC decline. Dominant prevention measures are: sustainable agricultural practices, flood protection, and nature-based solutions.

Semigleic soils are represented by one soil type – Humofluvisols, whereas Gleic class is represented by two soil types (Table A4.6): Humogleys and Eugleys. All these soils are characterised by well-developed humus accumulative horizon and gleisation processes which occur at different depths within the soil profile. The groundwater level can be a restriction to root development in Humogleys and Eugleys. These are soils of river valleys and depressions with groundwater fluctuations. Humofluvisols and Humogleys are deep and very deep, very productive, fertile, well-structured soils, with good water holding characteristics and mainly under agricultural production. Potential degradation drivers are soil agricultural management, groundwater fluctuations, and flooding. Types of soil degradation might be multifold: soil compaction, deterioration of soil structure, soil mining, acidification, salinisation, alkalisation, soil aeolian erosion, and SOC decline. Dominant prevention measures are sustainable agricultural practices, and flood protection.

Eugleys are characterised by a high groundwater level, flooding occurrences, presence of natural vegetation, and present areas prone to salinisation, acidification, and SOC decline. Dominant prevention measures are nature-based solutions, flood protection and hydro ameliorations.

Peat Soils are characterised by the accumulation of organic material in anaerobic conditions. The process of paludisation mainly occurs in cold and humid conditions. Usually, a small portion of organic material is humified. In Serbia, these are not agricultural soils, but are often under natural hydrophilic vegetation. Potential degradation drivers are related to human management, groundwater fluctuations and changes in the natural cycles, whereas SOC decline, soil compaction, acidification, and biomass overexploitation are main soil degradation types. Dominant prevention measures are appropriate management and nature-based solutions.

Anthropogenic hydromeliorated soils are soils in which natural pedogenesis has changed its direction after the human interventions, such as embankment raising and designing drainage systems. The dominant potential degradation drivers on these soils are soil agricultural management, groundwater fluctuations, and flooding. Soil degradation types depend on the initial soil conditions and ameliorating measures, and dominant prevention measures depend on the degradation type and extent.

The class of acute saline and eluvial illuvial alkalised soils (Table A4.7) are represented by two soil types: Solonchaks and Solonetz. Solonchaks have a high concentration of soluble salts at some time in the year in the soil profile. These soils are known as saline soils or salt-affected soils. In higher concentrations, the salts may be directly toxic to plants. Strongly salt-affected soils are used for extensive grazing. Dominant potential degradation drivers are grazing and natural drivers. Solonchaks are prone to soil physical degradation: deterioration of soil structure, waterlogging, and soil compaction; soil chemical degradation: salinisation, and alkalisation; soil biological degradation – SOC decline; and soil aeolian erosion. Dominant prevention measures are part of sustainable agricultural practices and amelioration measures.

Solonetz soils have a dense, strongly structured, massive, clayey subsurface horizon that has a high content of adsorbed Na and in some cases also Mg ions. Solonetz are strongly alkaline. Dominant pedogenic process is alkalisation. Soils are deep but physiologically shallow. Dominant potential degradation drivers include natural conditions, rarely agricultural production and grazing. Dominant prevention measures are part of sustainable agricultural practices and amelioration measures.

▼ **Table A4.1.** Class of weakly developed soils

Soil type	Land cover / land use / sector	Dominant pedogenic process, and characteristics	Potential limitation to root growth ****	Soil fragility (Soil inheritance /susceptibility/ sensitivity to degradation) (1–5)	Dominant potential degradation drivers	Type of soil degradation	Dominant prevention measure
Lithosols	Natural vegetation	Physical weathering	Rock outcrops, thin, rock fragments	5	natural	inherited low capability	Afforestation
Sirozems – Regosols	Natural vegetation, forestry	Physical weathering, surface migration, low grade of structure development	thin, coarse fragments	5	natural and deforestation	soil water erosion	Afforestation, erosion protection measures
Arenosols	Natural vegetation, forestry	Surface aeolian migration, low grade of structure development, water holding characteristics	No, bad water holding characteristics, water aridity	5	natural	soil aeolian erosion	Afforestation, erosion protection measures
Colluvial soils	Agriculture and various natural vegetation	Colluvial and deluvial process	Heterogeneous	2–3	soil agricultural management	soil erosion, soil physical and chemical deterioration	Sustainable agricultural practices

▼ **Table A4.2.** Class of humus accumulative soils.

Soil type	Land cover / land use / sector	Dominant pedogenic process, and characteristics	Potential limitation to root growth ****	Soil fragility (Soil inheritance /susceptibility/ sensitivity to degradation) (1–5)	Dominant potential degradation drivers	Type of soil degradation	Dominant prevention measure
Chernozems	Agriculture	Melanisation	no	2–3	soil agricultural management: ploughing, irrigation, fertilisation, crop protection	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification, salinisation, alkalisation; aeolian erosion; soil biological degradation – SOC decline	Sustainable agricultural practices, forest belts
Vertisols	Agriculture	Melanisation and pedo-turbation	Alternating wet-dry conditions, shrink-swell clays	1–2	soil agricultural management	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil biological degradation – SOC decline	Sustainable agricultural practices, erosion protection measures
Calcomelanosols	Forestry and pasturing	Chemical and physical weathering and melanisation	thin	2–3	grazing	Soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	Sustainable agricultural practices, afforestation, erosion protection measures
Rankers	Forestry and pasturing	Melanisation and physical weathering	thin or with many coarse fragments	2–3	deforestation, grazing	Soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	Afforestation, sustainable agricultural practices, erosion protection measures
Rendzinas	Agriculture, forestry and pasturing	Chemical and physical weathering and melanisation	thin or with many coarse fragments	3	deforestation	Soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	Afforestation, erosion protection measures, sustainable agricultural practices

Table A4.3. Class of cambic soils.

Soil type	Land cover / land use / sector	Dominant pedogenic process, and characteristics	Potential limitation to root growth ****	Soil fragility (Soil inheritance /susceptibility/ sensitivity to degradation) (1–5)	Dominant potential degradation drivers	Type of soil degradation	Dominant prevention measure
Eutric Cambisols	Agriculture	Melanisation and chemical weathering	generally no	2	soil agricultural management	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil biological degradation – SOC decline	Sustainable agricultural practices, erosion protection measures
Dystric Cambisols	Forestry	Chemical and physical weathering and melanisation	thin, low pH, element toxicity	3–4	deforestation	soil water erosion; soil physical degradation: deterioration of soil structure; soil chemical degradation: acidification; soil biological degradation – SOC decline	Afforestation, erosion protection measures
Terra Rossa	Natural vegetation, agriculture, forestry and pasturing	Melanisation and argilloaccumulation	thin	2	deforestation, soil agricultural management	soil erosion; soil physical degradation; soil biological degradation – SOC decline	Afforestation, sustainable agricultural practices
Calcocambisols	Forestry and agriculture	Melanisation and argilloaccumulation	thin	2	deforestation and soil agricultural management	soil erosion; soil physical degradation; soil biological degradation – SOC decline	Afforestation, sustainable agricultural practices

Table A4.4. Class of eluvial-iluvial soils.

Soil type	Land cover / land use / sector	Dominant pedogenic process, and characteristics	Potential limitation to root growth ****	Soil fragility (Soil inheritance /susceptibility/ sensitivity to degradation) (1–5)	Dominant potential degradation drivers	Type of soil degradation	Dominant prevention measure
Luvisols	Agriculture, forestry	iluviation of clay	subsurface compaction	3	soil agricultural management and deforestation	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	Sustainable agricultural practices, afforestation, erosion protection measures
Podzols	Forestry	illuviation of clay, humus and sesqui-oxides	element toxicity	4	natural, deforestation	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	Afforestation, erosion protection measures, sustainable agricultural practices
Bruni-podzols	Forestry	illuviation of clay, humus and sesqui-oxides	element toxicity	4	natural, deforestation	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	Afforestation, erosion protection measures, sustainable agricultural practices

▼ **Table A4.5.** Class of pseudogleic and fluviatile Soils.

Soil type	Land cover / land use / sector	Dominant pedogenic process, and characteristics	Potential limitation to root growth ****	Soil fragility (Soil inheritance /susceptibility/ sensitivity to degradation) (1–5)	Dominant potential degradation drivers	Type of soil degradation	Dominant prevention measure
Pseudogley soil	Agriculture	Pseudogleisation	Stagnating water, abrupt textural difference, subsurface compaction	3–4	soil agricultural management	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification; soil water erosion; soil aeolian erosion; soil biological degradation – SOC decline	Sustainable agricultural practices
Fluvisols	Agriculture, Forestry	Material deposition	thin – layers of gravel	2–5	soil agricultural management, flooding	soil physical degradation: soil compaction; soil chemical degradation; soil biological degradation – SOC decline	Sustainable agricultural practices, flood protection, nature based solutions

Table A4.6. Class of semigleic, gleic and Peat Soils.

Soil type	Land cover / land use / sector	Dominant pedogenic process, and characteristics	Potential limitation to root growth ****	Soil fragility (Soil inheritance /susceptibility/ sensitivity to degradation) (1–5)	Dominant potential degradation drivers	Type of soil degradation	Dominant prevention measure
Humofluvisols	Agriculture	Melanisation and gleisation	no	1–2	soil agricultural management, groundwater fluctuations, flooding	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, acidification, soil salinisation, soil alkalisation; soil aeolian erosion; soil biological degradation – SOC decline	Sustainable agricultural practices, flood protection
Humogleys	Agriculture	Melanisation and gleisation	groundwater level	1–2	soil agricultural management, groundwater fluctuations, flooding	soil physical degradation: soil compaction, deterioration of soil structure; soil chemical degradation: soil mining, salinisation, alkalisation, acidification; soil biological degradation – SOC decline	Sustainable agricultural practices, flood protection
Eugleys	Natural vegetation	Melanisation and gleisation	thin, groundwater level	1	groundwater changes	soil chemical degradation: salinisation, acidification; soil biological degradation – SOC decline	Hydromelioration or nature based solutions
Peats	Natural vegetation	Paludisation	groundwater level	1–5	Natural, management, groundwater changes	soil physical degradation: soil compaction; soil chemical degradation: acidification; soil biological degradation – SOC decline, biomass over-exploitation	Managed exploitation, nature based solutions

▼ **Table A4.7.** Class of acute saline and eluvial iluvial alkalised soils.

Soil type	Land cover / land use / sector	Dominant pedogenic process, and characteristics	Potential limitation to root growth ****	Soil fragility (Soil inheritance /susceptibility/ sensitivity to degradation) (1–5)	Dominant potential degradation drivers	Type of soil degradation	Dominant prevention measure
Solonchaks	Natural vegetation	Salinisation and alkalisation	High concentration of soluble salts, adsorbed Na	4–5	natural, grazing	soil physical degradation: deterioration of soil structure, waterlogging, soil compaction; soil chemical degradation: salinisation, alkalisation; soil biological degradation – SOC decline; soil aeolian erosion	Sustainable agricultural practices
Solonetz	Natural vegetation	Alkalisation	High content of exchangeable Na, soil compaction	3–5	natural, agriculture, grazing	soil physical degradation: deterioration of soil structure, waterlogging, soil compaction; soil chemical degradation: alkalisation, salinisation; soil biological degradation – SOC decline; soil aeolian erosion	Sustainable agricultural practices

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