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Review

Water, Soil, and Plants Interactions in a Threatened Environment

Maria Gavrilescu

Department of Environmental Engineering and Management, "Cristofor Simionescu" Faculty of Chemical Engineering and Environmental Protection, "Gheorghe Asachi" Technical University of Iasi, 73 Prof. D. Mangeron Blvd., 700050 Iasi, Romania; mgav@tuiasi.ro

Abstract: The unprecedented pressure posed by a growing population on water resources generates a significant shortage between the available resources and water demand, which together with water scarcity, floods, and droughts, can affect the world population and various other consumers. On the other hand, soil resources, which represent an essential and complex environmental ecosystem, as a support for the biological cycle, source of nutrients, and water for cultivated and wild plants, forestry, etc., are a provider of raw materials, and are increasingly degrading due to unsustainable use. Since both soil and water are vital resources and support for growth and life of plants, their preservation and sustainable management have become an urgent issue for policy makers, governmental factors, academia, and stakeholders. An important question to be answered is what the disturbing factors of soil–plants–water cycles are and how their negative influence can be reduced, since they affect the quality of life and human health. This work proposes an overview on new research into the links between soil and water, and the interactions among soil, water, and plants in a changing and threatened environment, which can determine human welfare. The analysis addresses the global context of water and soil resources, factors that affect their equilibrium and dynamics, especially toxic pollutants such as heavy metals and others, and their mutual relationship with plant growth.

Keywords: climate; land degradation; plants; pollution; resource management; soil water; water use

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1. Introduction

The quality of life, the health of humans and ecosystems, and the state of the economy are dependent on how natural resources (water, land, energy, minerals, biomass, fossil fuels, etc.) are managed. The rapid development of the urban and industrial environment observed in the last decades has put significant pressure on the natural resources of the world, with consequences manifested by resource shortages, price growth, and instability and degradation of ecosystems. The study of the interactions between the biotic factor and the changes in the environment is very topical, as these interactions play a central role in how humanity can respond to global changes [1]. These circumstances suggest that the current models of resource exploitation and pollution management exceed the potential of the planet for resource regeneration and absorption of waste and emissions. In addition, the models of consumption and production, often unsustainable, are characterized by increased resources uptake and wasting [2]. Therefore, the Earth's resources should be managed in a sustainable way.

Sustainable resource management is a concept that refers to the need to consider both present actions and long-term approaches. Resources managed to meet the changing demands they are subjected to, now and in the future, without system degradation, can be termed "sustainable". Since 1977, the Law on Soil and Water Resources Conservation has provided the US Department of Agriculture (USDA) with the necessary tools for conservation, protection, and improvement of soil, water, and related natural resources, which were aimed at: assessing soil and water status, related resources and their tendencies to meet short, medium, and long term requirements; evaluation of management policies and programs; and the development of programs that consider the conservation of soil and water resources. In Europe, which is a continent with relatively limited mineral resources, soil is one of the most valuable resources, sometimes underestimated, although more than 95% of food and feed depend on soil management and conservation [3]. As unsustainable land use and land degradation can have a major impact on other resources (such as water, biomass, as well as human health, climate change, and food security), the European Commission adopted on 22 September 2006, The Thematic Strategy for Soil Protection [4] developed in using the framework of the Sixth Environment Action Programme with the aim of generating a common context to support soil protection throughout the European Union. This strategy established a work program of 10 years, also proposing the elaboration of a framework directive, as well as an estimation of the economic, social, and environmental impacts of the proposed measures. The Thematic Strategy for Soil Protection also aims to provide a review of new research on the relations between soil and water problems in Europe, to support the decision-making process for solving the problems regarding the unsustainable use of soil and water and the mutual relationship between the two categories of resources [5].

According to World Bank [6], "water security is the goal of water resources management". Water is seen as a relatively abundant resource in Europe, with a total freshwater resource of approximately 2270 km^3/year and, consequently, it is considered that there is sufficient water available to meet the demand [7]. However, the EEA Report highlights that water stress is increasing both in northern and southern Europe as a result of its unsustainable use. In addition, the effects of climate change are beginning to manifest in the severity and frequency of droughts, aggravating water stress, especially in the summer months. At the European Commission level, the "Communication from the Commission to the European Parliament and the Council addressing the challenge of water scarcity and droughts in the European Union" contains an initial set of policy options at European, national, and regional levels to address and mitigate the challenge of water deficit and drought in the EU [8].

Ecosystems can be significantly affected by changes in land and water use, in the sense of diminishing their capacity to integrate and support soil and water functions so as to ensure their sustainability [9]. Stakeholder awareness of this interdependence may contribute to reducing the negative impact on soil, water, and ecosystems as a consequence of inappropriate use (e.g., reducing erosion or maximizing carbon storage). Therefore, it is almost unanimously recognized that soil degradation and water pollution are major environmental issues, but it is less implicit that soil and water are in close connection and interdependence [10]. A good, healthy soil has the ability to perform a number of vital functions, such as to store water and nutrients, regulate water flow, and immobilize and degrade pollutants. Among the vital functions of the soil is to provide a favorable environment to plant growth and development, being a reservoir of nutrients for them. Furthermore, the soil hosts habitat forms of micro- and macro-organisms. For all forms of flora, the soil offers conditions to grow, release oxygen, and retain water, diminishing the effects of heavy rainfall, torrents, etc. In addition, the soil is the place where the waste is broken down, the pollutants are bound and/or degraded. Overall, the soil is the first link in the propagation of the food chain.

The practice demonstrates that land degradation means more than erosion or loss of soil fertility, and it must be extended to unbalanced ecosystems and loss of their functions in an integrated way by considering all ecosystem goods and services [11]. In this context, the paper addresses the relationships between soil and water as vital resources and support for plant growth and life, their mutual relationships in terms of sustainability as well as the interactions among soil, water, and plants in a changing environment.

2. Water and Soil—Valuable Natural Resources

2.1. Water in the Environment

2.1.1. The Need for Water Resource Management

Water is a fundamental and indispensable component to the human body and life on Earth. Water is a renewable, vulnerable natural resource, being a determining factor in maintaining the ecological balance. Water is one of the most widespread substances on planet Earth, since almost 70% of the total surface of the globe is covered by water, forming one of its shells: the hydrosphere. The continuous increase of the terrestrial population implies the increase of the agricultural land productivity, but also of the quality and quantity of water resources, while the statistics show that they are constantly decreasing. Whereas the world population has tripled, water use has increased six-fold, since irrigation accounts for 70% of global water, industry 20%, and municipal use 10% [12]. The World Commission on Water [13] estimates that water use will increase by about 50% until 2030.

Over time, water resources have brought numerous benefits and services to both humanity and the global economy. Unfortunately, there are areas of the world where neither, the minimum drinking water and sewage needs of the inhabitants, nor those of some ecosystems are ensured. Among the common causes of these situations are: inadequate, not maintained infrastructure; excessive consumption from surface waters; water pollution, including eutrophication and salinization, generated by industrial and agricultural activities; excessive fishing activities; floods and habitat changes as a result of anthropogenic actions; changes in water and sediment flow regimes [14]. Awareness of the crisis in terms of water reserves has led to the development of sustainable management strategies: Water Framework Directive (DCA) 2000/60/EC of the European Parliament and Council establishes the agenda for water policy at the Member State levels and a new approach of water management. This directive implies the quantitative and qualitative management of the water, aiming at achieving its "good state" and defining water as a heritage that must be protected, treated, and conserved as such [15]. Certainly, human well-being and environmental quality are considerably affected by natural changes and mostly by anthropic activities. In this context, water has become a critical matter of social-environmental systems, so that water management has been given absolute priority to water supply and flood control, but also to the protection of ecosystems possibly affected by the instability of water resources, and equitable access to water resources, as well.

Sustainable water management aims to use water so that the needs of the society are met both for the present and in the future, which implies short- and long-term measures, in parallel with understanding the processes of physical and social nature that affect water resources and that requires the integration of knowledge in the management of water resources. Sustainable management of water resources considers both the demand and the supply of water. Some areas of the globe are experiencing regular and massive flooding, due to the specific climate, others suffer from lack of water. The deficiency of adequate water resources according to the demand in some parts of the globe, has imposed the design and construction of a consistent infrastructure to ensure water capitals. These extreme conditions are often aggravated by increasing pollution of water resources [14].

Growing demand for water by various consumers (industry, agriculture, municipal consumers, environment) requires careful management of water resources [16]. In order to optimize the water supply for priority uses, water management has traditionally been based on technical and engineering knowledge, assuming also the hydroclimatic conditions. The reality has shown that landscape, demographic, and hydroclimatic changes have contributed to environmental degradation, loss of biodiversity, and disruption of water supply. Therefore, major efforts are required to balance the relationship between man and ecosystems, and therefore integrated approaches for water resource management have been proposed by reusing treated wastewater and stormwater and reducing flows by applying best management practices (BMP) (Figure 1).

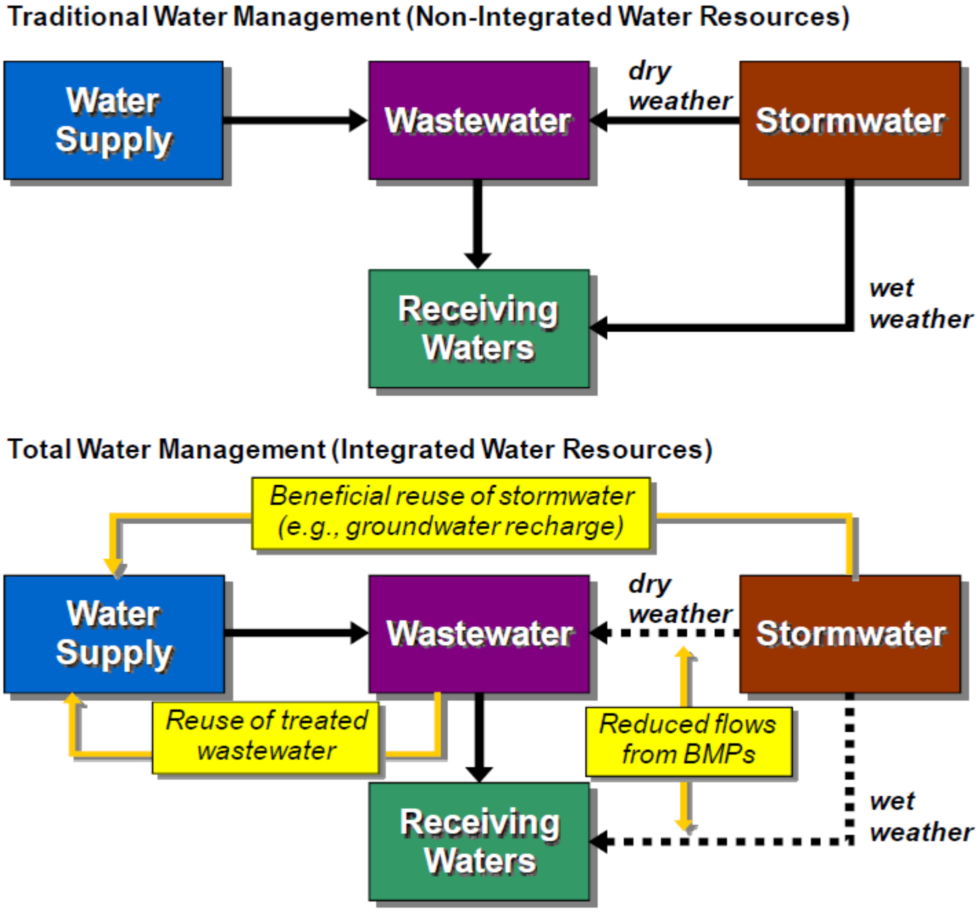

Figure 1. Traditional vs. total water management for municipal separate storm sewer systems (reused from O'Connor et al. [17], licensed by CCC Marketplace^{TM}).

Although soil and water are natural essential resources for the biosphere, the absence of sustainable management and utilization contributed significantly to their degradation and depletion. To all these, climate change has been added, which has put its marks on the quality of water and soil, their mutual relationship, and influence on ecosystems.

2.1.2. Water in Soil

Water existing in soil is a vital resource which cannot be overstated, for both plants—since water is a key element for plant growth and development, consumed in relatively large quantities—and for various types of ecosystems. The water content of soil is particularly important, as it influences its moisture, the amount of nutrients available to plants, and the aeration state of the soil. Soil water refers to water that exists naturally in soil as gravitational water, capillary water, and hygroscopic water, depending on the functions of the soil (Figure 2). The extent to which water is stored or redistributed in soil depends on the size of the soil pores and their dimensional distribution, which, in turn, depend on soil texture and structure (Figure 3) [18,19]. Usually, clay soils have a high-water retention capacity because the space between the pores is large, but this is not a measure of the availability of water for plants or of the way in which water moves freely through the soil [20] (Figure 4). The soil will be saturated with water when the total space of the pores is filled with water (as it happens after heavy rainfall or after irrigation of the soil).

In this situation, the potential of the water is almost equal to that of the pure water free to flow under the action of gravitational force (0 kPa), and the water content in the soil will be equivalent to the total volume of the soil pores [19,21]. These aspects of soil water behavior depend on the potential energy gradients that govern the redistribution of soil moisture and water losses. The direction of the potential energy gradient is down, through the soil profile if the soil reaches saturation, and the flow mechanism is due to the action of the gravitational force, especially at the level of the soil macropores. As the soil loses water, it dries through the drainage of the macropores and can reach the field capacity, which means the amount of soil water that was retained by the matric forces that are opposite to the gravitational force (in micropores and mesopores). As the water content in the soil continues to decrease, the intensity of the matric forces is reduced, and the water is maintained by cohesion forces from water molecules and mineral particles (capillary forces). Water retained between saturation and field capacity is subjected to free drainage for different periods of time and is considered unavailable for plants, while water held at field capacity is available to plants [19,20].

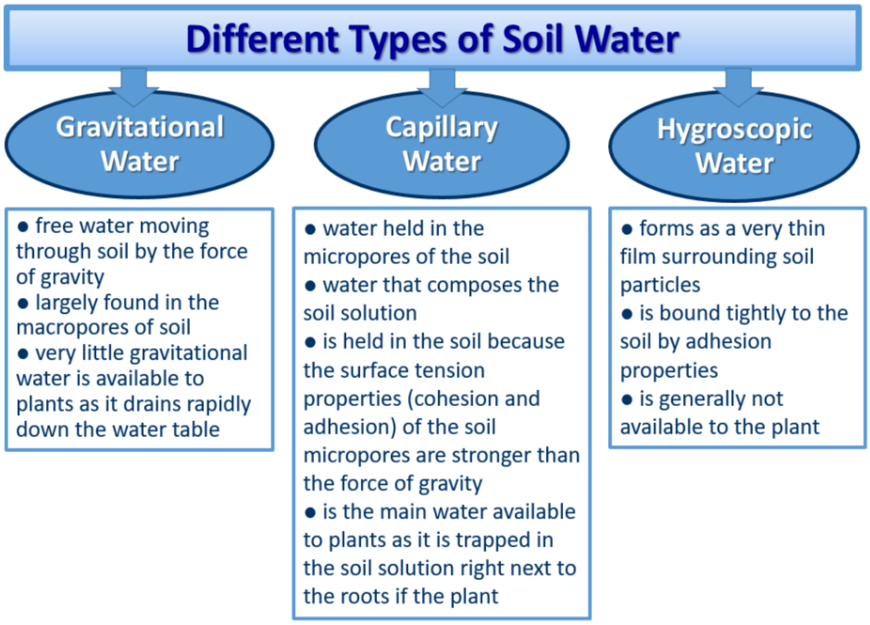

Figure 2. The three main types of soil water-gravitational water, capillary water, and hygroscopic water.

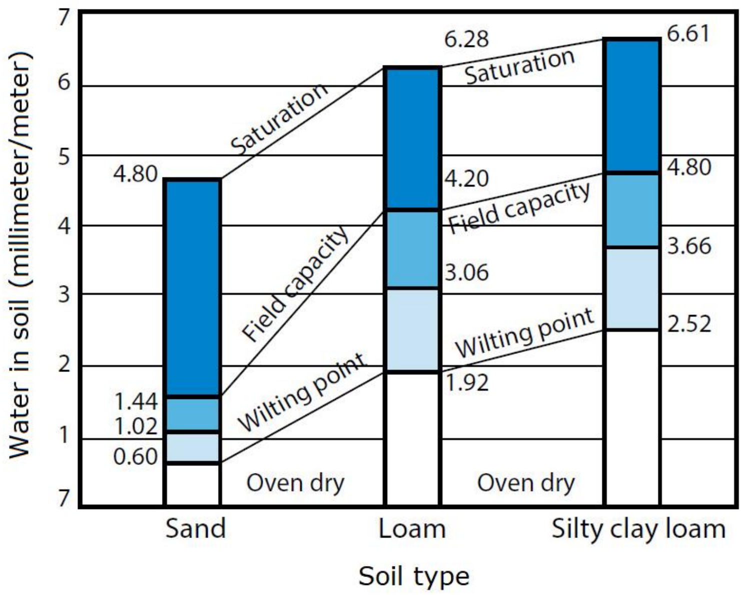

Figure 3. Typical soil water content within three soil textures (reproduced upon Ball [18], with permission of Noble Research Institute).

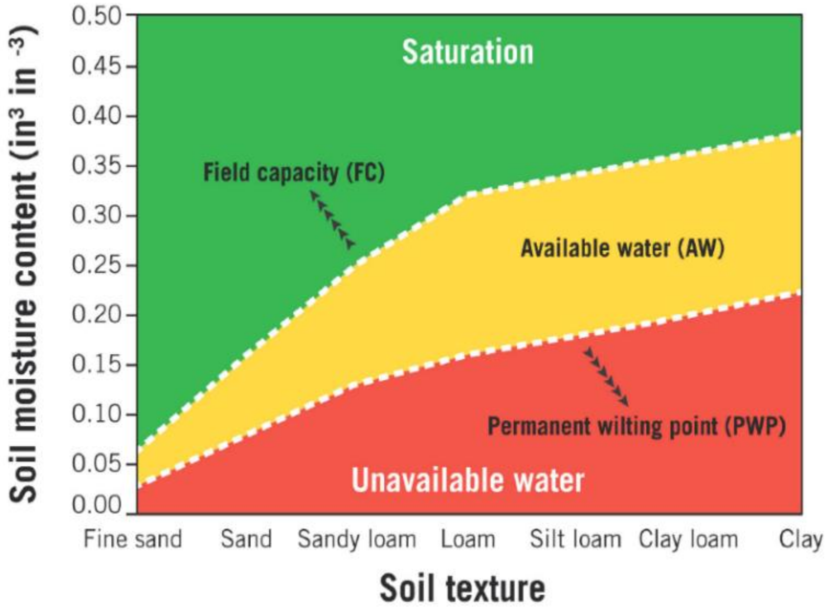

Figure 4. The relationship between soil saturation, field capacity, soil available water, permanent wilting point, soil unavailable water, and soil texture (reproduced upon da Silva et al. [22], with permission).

The water supply to the soil comes largely from precipitation and can be easily lost through transpiration (so-called "green water") and leakage that enters aquifers and groundwater (so-called "blue water") [23]. While the most consuming activity of fresh water concerns the production of biomass for human consumption (agricultural crops, wood), the policies regarding water are focused largely on irrigation in agriculture, which uses almost 25% of the water requirement for agriculture globally. In addition, about 10% of humanity's water need is meant for industrial and domestic water supply, which represents less than 10% of human direct water requirements [24]. This situation generated by the increasing water needs for plants and agricultural crops, under the conditions of climate change and the emergence of dry agricultural areas with water deficit in the soil, imposes adequate policies regarding soil water management, both for agricultural crops and for natural ecosystems.

Therefore, the requirement of adapting the policies concerning water management, also regards the natural ecosystems, since the agriculture expands and some unsustainable agricultural practices have generated and continue to cause severe degradation of the terrestrial and aquatic ecosystems. This context involves making decisions regarding the balance between the "green water" and the "blue water" (that is, the consumption of rainwater versus groundwater or surface water), considering their usages and interactions, as well as the relations with consumers [23].

2.1.3. Water Pollution

Water pollution means any change in the composition or quality of water, as a result of human activities or natural processes, so that it becomes less suitable for different usages. The decrease of freshwater resources worldwide is the result of its severe pollution, as a consequence of waste discharging, the massive generation and the inadequate treatment of wastewater, and the lack of the sanitary systems that favor the contamination of the water resources [25] (Table 1).

Pollution can be permanent, systematic, periodic, or accidental, when the period of time the pollutant acts is considered. Groundwater, surface water, and oceans are subjects of continuous pollution from point sources, non-point sources, or transboundary pollution. The following are among the most common types of water contamination: agricultural, sewage and wastewater, oil pollution, radioactive substances, etc. The effects of water pollution impact environmental and human health. The pollutants can affect the water resources depending on their type and source of origin, which is predominantly anthropic. Table 2 describes succinctly some well-known major categories of pollutants in water and their potential impacts and sources [26–31].

Table 1. Severe problems worldwide associated to water pollution.

Threats to Water	Effects	References
Waste (sewage, industrial, agricultural etc.) discharged in water	2 million tons of waste in water/day	[32]
Wastewater produced by humanity	1500 km^3/year (six times more than water from all rivers)	[32]
People living without adequate sanitation, which causes water contamination	2.5 billion people without sanitation	[33]
Species of freshwater fish at risk of extinction	50% of native freshwater fish under threats	[34]

Table 2. Major categories of water pollutants and their impacts.

Category of Pollutants	Examples	Effects	Sources
Biological/infectious agents	Pathogenic bacteria, pathogenic yeasts, pathogenic protozoa, parasitic worms, enteroviruses, coliform organisms, saprophytic bacteria, fungi, algae, crustaceans, etc.	• Infectious diseases	Human and animal waste, domestic sewage
Oxygen-demanding waste/biodegradable organic compounds	Organic waste (animal waste, plant debris) able to be biodegraded by aerobic microorganisms	• Depletion of water from dissolved oxygen by aerobic microorganisms, affecting the life forms from water • Can cause colour, taste, and odour problems	Sewage, feedlots, paper mills, food processing
Organic chemicals/slowly or non-biodegradable organic compounds (refractory)	Pesticides, personal care products, drugs, organic solvents, oil with its refining and processing products, tannins and lignins, cellulose and phenols	• Resistant to biological degradation • Toxic to organisms, having cumulative effects and cause severe problems at the higher end of the food chain • Threatens human health, can cause nervous system damage, reproductive disorders, endocrine disruption, cancer • Harms fish and wildlife	Industrial effluents, household cleansers, runoff from farms and yards
Inorganic chemicals	Water soluble acids, compounds of toxic metals (arsenic, cadmium, chromium, copper, lead, mercury, silver, zinc, etc.), salts (primarily chloride and sulfate, nitrites and nitrates), fluorides	• Can make fresh water unusable for drinking and irrigation • Threatens human health: can cause skin cancer, affect the nervous system, liver, kidney damage • Harms fish and wildlife • Diminishes crop yields • Metals corrosion exposed to contaminated water	Industrial effluents, surface runoff, household cleansers, pesticides

Table 2. *Cont.*

Category of Pollutants	Examples	Effects	Sources
Nutrients	Water soluble compounds containing nitrogen, phosphorous (as NO^-_3, PO_4^3, NH^-_4) (macronutrients)	• Can determine excessive growth (eutrophication) of algae and aquatic plants (which die, decay, and deplete oxygen from water, with consequences for fish and aquatic life)	Sewage, organic waste (manure, biosolids), fertilizers
Radioactive materials	Radioactive isotopes of iodine, radon, uranium, cesium, and thorium	• Genetic mutations • Birth defects • Cancers	Power plants (nuclear- and coal-based)Mining and processing of radioactive oresProduction of nuclear weapons
Sediments	Soil, silt, and other solid matters	• Can reduce photosynthesis due to water clouding • Disrupt aquatic food webs • Can transport pesticides, bacteria, and other harmful substances • Can destroy feeding and spawning grounds of fish • Clog lakes, reservoirs, channels, harbors	Erosion, runoff
Thermal pollution	Excessive heat	• Dissolved oxygen at low levels • Increase vulnerability of organisms to diseases, infectious agents, and toxic chemicals	Cooling water in power plants, industrial plants

A category of pollutants that generate critical environmental problems, particularly for water, is microplastics, mainly particles with a diameter of less than 5 mm. Microplastics can also pose an emerging threat to the plant–microbiome–soil relationship, as they can alter soil properties (influencing soil organic matter behavior and the nutrient cycle), plant crop performance due to toxicity, and microbial communities [29]. In addition, chemical compounds from the class of emerging pollutants—synthetic or naturally occurring chemicals, constantly penetrate the environment and affect the aquatic environment, soil, flora, and fauna due to toxicity and bioaccumulation capacity. They are often endocrine disruptors, but there is still insufficient information about the mechanisms of action, especially on human health. Examples of such pollutants are pharmaceuticals, personal care products, pesticides, surfactants, and other industrial chemicals (polychlorinated biphenyls, flame retardants) [30,31,35–38].

2.2. Soil

2.2.1. Soil Resource

The soil is represented by the layer from the surface of the Earth's crust consisting of mineral particles, organic matter, water, air, and living organisms. The soil formation process (pedogenesis) takes place under the influence of pedogenic factors: climate, microorganisms, vegetation, and land. The population of the globe depends essentially on the soil for many fundamental purposes that may belong to the environmental, social, and economic space [39–42] (Figure 5). The main functions of the soil entail: food/biomass production; storage, filtration, and transformation of many substances; source of biodiversity, habitats, species, and genes; it serves as a platform/physical environment for humans and human activities; a source of raw materials, carboniferous basin; and geological and archaeological heritage.

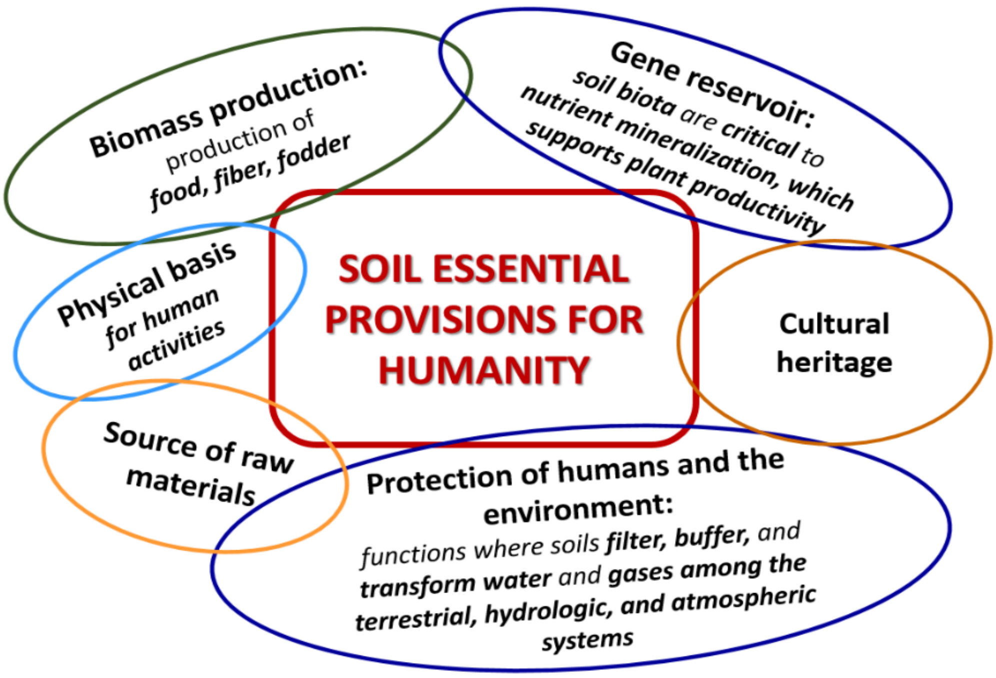

Figure 5. The essential role of soil in providing humanity support for life.

Therefore, soil is one of the most valuable resources on Earth, essential for food security on a global level. However, as the climate changes, the pressure on both soil and water resources intensifies, which is why the need for sustainable management becomes more and more demanding. One strategy recommended as being potentially effective and lasting for mitigating climate change is the safe storage of atmospheric carbon as a substantial potential sink for greenhouse gases (GHG) [43]. A quality (healthy) soil is characterized by several physical, chemical, and biological properties such as: the content of organic matter in adequate proportion; adequate structure; and suitability as a habitat for various organisms. These properties allow the soil to perform a number of functions, in balance with its environment [44]. Soil properties are largely dependent on its composition, which includes four basic materials: minerals (almost 45%), organic matter (around 5%), water (almost 25%), and air (about 25%). The proportion of these materials should ensure a good balance so as to support the physical, chemical, and biological properties and processes in soil. Another important soil property is texture, which addresses the proportion of solid materials in soil (sand, silt, and clays) and can determine soil fertility, water content, air movement, etc.

2.2.2. Soil Pollution

Soil pollution occurs by accumulating persistent toxic substances, chemicals (acids, bases, salts), radioactive materials, and pathogens, which have negative influences on soil quality, with adverse consequences on water resources, plant growth and development, and animal and human health [45]. Soil pollutants can be contained within two leading groups: the organic pollutants (OPs) and the inorganic pollutants (IPs). Soil degradation due to contamination is a major problem in Europe and worldwide. In 2013, the estimated number of potentially contaminated sites in the EU-27 was about 4.5 million, most of them in France, Germany, and the Netherlands. Of these, 490,000 sites were identified and another 175,000 were remediated [46].

Soil pollution is understood as land degradation due to the presence of chemical compounds from anthropogenic sources (Figure 6) at higher-than-normal concentrations: petroleum hydrocarbons, polynuclear aromatic hydrocarbons, solvents, pesticides, heavy metals), or other soil changes, due to natural or anthropogenic causes (industrial activities, agricultural works, and improper disposal of waste). A number of newer concerns focus on so-called emerging pollutants, which are synthetic chemicals or natural microorganisms not commonly observed in the environment, having "the potential to penetrate the environment and cause known or suspected ecological and/or human health effects" (such as: pharmaceuticals, endocrine disruptors, hormones and toxins, soil micropollutants, bacteria and viruses) [47]. These conditions can produce an accumulation in the soil of persistent toxic chemical compounds, radioactive materials, and pathogens, which induce adverse effects on plant growth and animal health [48].

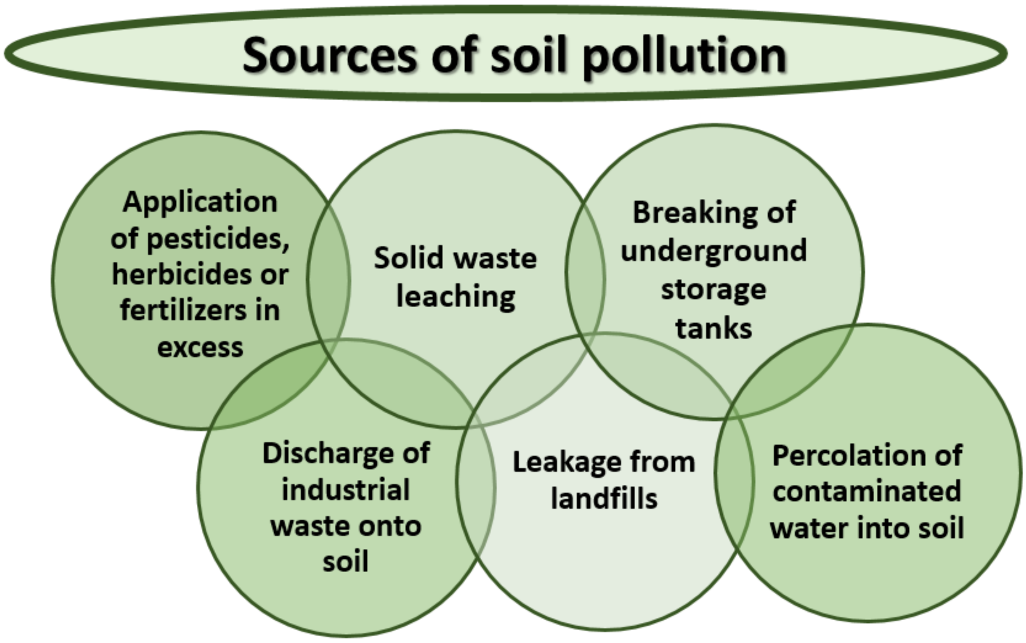

Figure 6. Some relevant sources of soil pollution.

Soil pollution is closely related to pollution of the atmosphere and hydrosphere due to the natural circulation of matter. Soil is the space where various categories of pollutants, such as powders in the air and toxic gases transformed by rain into the atmosphere, are deposited and accumulated. Therefore, soil is the most exposed to the negative effects of these substances, which has led to an intense pollution and degradation of about 15% of the total arable land [49]. Furthermore, irrational soil management methods have seriously degraded its quality, causing pollution and accelerated erosion. The infiltration waters impregnate the soil with pollutants, dragging them deeper; the polluted rivers infect the flooded or irrigated surfaces; almost all the solid residues are deposited by agglomeration or only accidentally thrown on the ground. According to the EU Soil Thematic Strategy, besides point and diffuse pollution, other certain major pressures to soil in Europe are associated with compaction, waterproofing, loss of organic matter, and loss of biodiversity [4,48,50].

Some pollutants can be mobilized (solubilized in soil moisture) or others are immobilized on soil particles (adsorbed on the surface of minerals and organic fractions or chemically fixed, as precipitated or co-precipitated) in solid compounds, a situation which largely depends on the physical and chemical properties of the soil. Physical properties provide the spatial and mechanical conditions for promoting interactions between pollutants and soil /water particles and their migration through the soil, until they reach other environmental compartments. Chemical properties can favor the reactions of pollutants that determine their structure and toxicity, as well as their behavior and mobility in soils [51]. The interest for the study of soil pollution is generated largely because it induces health risks. The polluted soil can affect human health, either by direct contact with the soil, by inhaling vaporized soil pollutants, or as a result of pollutants infiltration into aquifers and groundwater potentially used for human consumption. In the context of soil pollution, food security is reduced, both by reducing agricultural crop production as a result of the toxicity of soil pollutants at high concentrations, and by the fact that crops obtained on polluted soils may be unsafe for consumption by animals and humans.

2.3. Soil and Water Interactions

2.3.1. Mechanisms of Interactions

Water exists in soil as thin films outside of soil particles, and in pore spaces (such as gravitational water and capillary water), determined by the texture, bulk density, and structure of soil. Water-holding capacity represents the soil capacity to store water from rainfalls and available for plants. This is a highly essential soil property for growing plants, especially during dry periods. Capillary water plays the most important role for plants because it is held by the particles of soil against the force of gravity, as opposed to the gravitational water that moves in the ground as a result of the action of gravity. The two forms of soil water are in competition: as the water seeps into the soil, it fills the pores' spaces with water, which as the pores fill up, moves through the soil due to gravity and capillary forces, until a balance between the two categories of forces is reached.

The most commonly defined soil water content values are saturation, field capacity, wilting point, and oven dried. At *saturation,* all pore spaces in the soil are filled with water. The amount of water remaining in the soil after rapid percolation has occurred is defined as *field capacity.* The soil water content at which the potential or ability of the plant root to absorb water is balanced by the water potential of the soil defines *wilting point*. *Oven dried* soil is used as a reference point for determining soil water content. Under unsaturated conditions, the mechanisms accountable for the total potential of soil water are: gravity, osmosis, and matric potential. Mathematically, the total potential can be written as given by Equation (1) [52], where u_t = total potential, u_g = gravitational potential (equal to the work needed to elevate a unit volume of soil water above a reference point), u_o = osmotic potential due to the dissolution of solutes in the soil water, and u_m = matric potential.

$$u_t = u_g + u_0 + u_m. \tag{1}$$

The *matric potential* of the unsaturated soil is determined by capillarity and adsorption phenomena. Adsorption processes are determined by molecular interactions, essentially electrostatic in nature, which involve coulombic interactions between nuclei and electrons [53]. *Capillarity* results from air–water, air–water–solid interactions, while *adsorption* is related to water–solid interactions. Besides, *soil water retention curve* (SWRC) shows the state of energy balance between the matrix potential and the water content in unsaturated soil [54]. The SWRC of a soil is a quantitative measure of the link between the soil-water energy level and the water-soil content. Various soil constituents, such as heavy metals and radionuclides, pesticides and other refractory or emerging organic contaminants can be transported through the soil pore system or the preferential channels generated between soil particles. The preferential flow channels can modify the hydrological regime of the soil and its response regarding the transport of nutrients, the retention of some solutes necessary for the plants, especially if they are vertically oriented and have continuity. The preferential channels are also formed by the interaction between the roots of the plants and soil and the promotion of the movement of some water flows and the transport of some solutes, which increases the risk of soil pollution [55].

2.3.2. Soil Management for Water Use Efficiency

The water cycle holds a key component—soil water retention capacity (SWR)—which in turn influences water infiltration, groundwater percolation, and evapotranspiration.

These processes are determined by the water potentials resulting from the different forces applied to the ground water (gravitational forces, matrix forces—capillarity and adsorption, vapor pressure and osmotic pressure). The water retention capacity in the soil can be improved by controlling the infiltration, water storage capacity, restoration of groundwater stocks, and exchanges with the atmosphere. All of these involve the improvement of soil surface permeability, high porosity, balanced pore size distribution, and soil stabilization, in close relationships with physical, chemical, biological, climatic, and factors related to water [56] (Figure 7). All these factors can control the capacity of soil to capture, retain, and release water, both directly and by mutual interactions.

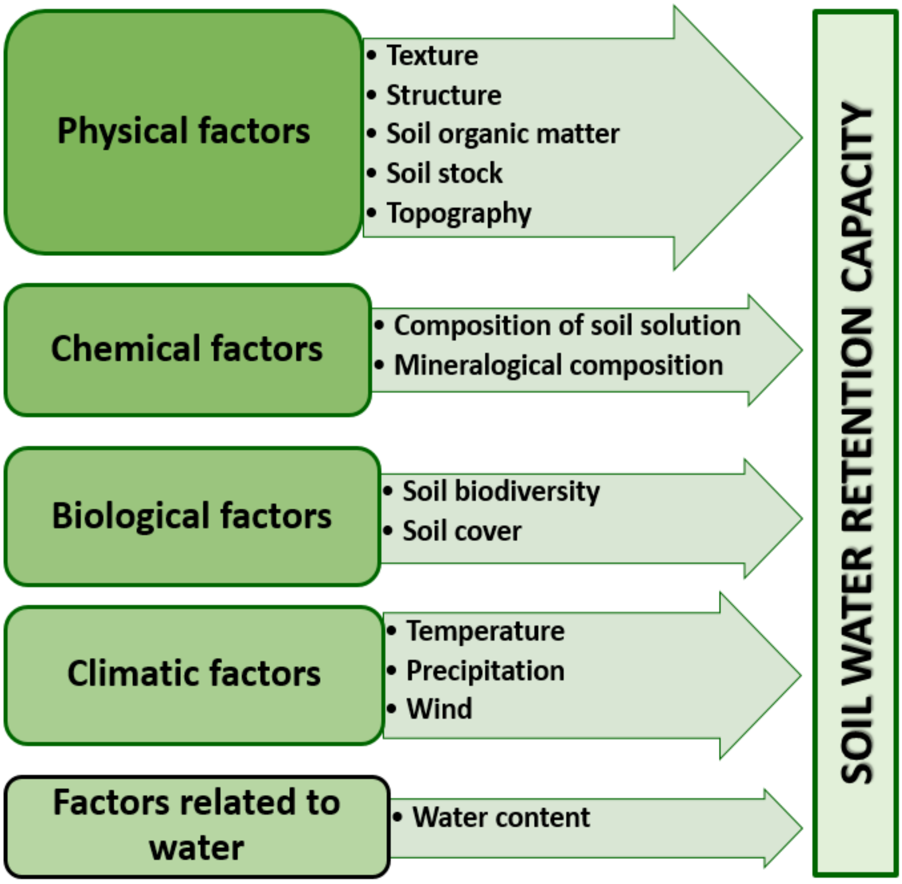

Figure 7. Factors which affect the water retention in soil.

The application of specific management practices of soil and water resources can influence the availability of water and nutrients for plants, which could change the water utilization efficiency by ±15 to 25% [57]. The concept of water efficiency (WUE) was introduced about 100 years ago to determine the relationship between plant productivity and water use, i.e., the amount of biomass produced per unit of water used by a system [58]. For plants, WUE depends on temperature, precipitation, and carbon dioxide (CO_2) level. Basso and Ritchie [59] have shown that the productivity of some plants is not always directly proportional to the level of water use, this being the consequence of climate change, which affects the rate of water use by plants. This behavior depends on a number of factors such as: carbon dioxide concentration, precipitation level, temperature rise, and humidity variations (Figure 8).

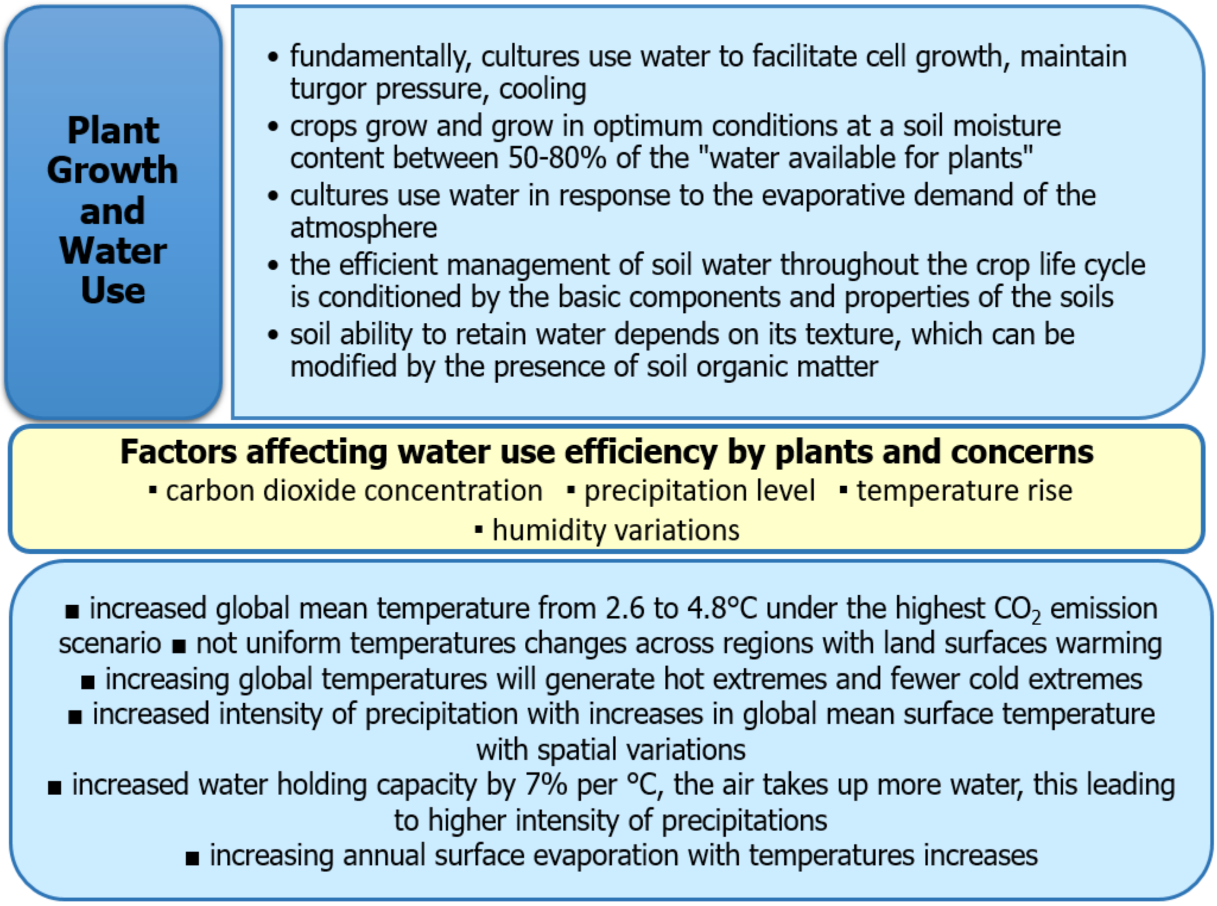

Figure 8. Factors changing in the climate that affects water use by plants.

Water deficit is one of the major causes of plant crop loss, representing a critical situation, with consequences on the average yield, which could decrease by more than 50% [60]. Therefore, the availability of water (or water available for plants, PAW), either from rainfall or stored soil water determines the possibility of maximizing the increase of water use efficiency. Soil processing by tillage, although sometimes considered unsuitable for maintaining soil quality and its sustainable exploitation, is still an agricultural practice that can promote water conservation in the soil, by controlling the leakage and improving the infiltration [61].

WUE can be positively influenced by the presence of nutrients in the soil, which also favors the growth and development of some plants, with a decisive role on the transpiration phenomenon. With increasing soil water retention capacity by applying appropriate soil management practices that, for example, increase the soil organic matter content, crop yields can be improved, thus increasing WUE. Hatfield et al. [62] showed that practices that favor the increase of soil water content, especially in the upper portion of the root zone, positively influence WUE, as a consequence of increased water availability for plants and improved nutrient uptake.

High water efficiency can reduce the costs for crops cultivation and reduce energy supplies for water extraction. Increasing the efficiency of water use is particularly important in agriculture, in the case of scarce water resources, when it is necessary to take advantage of all the potential benefits associated with the use of fertilizers, high quality seeds, tillage, skilled labor, energy, and of some high-performance equipment [63].

2.3.3. Soil Moisture

The definition of soil moisture may vary depending on the context, denoting any reference deposit of water. In general, soil moisture represents the amount of water stored in the unsaturated zone of the soil. Soil moisture is a source of water for atmospheric moisture, through the evapotranspiration of plants and bare soil evaporation [64]. Natural eco-systems can evolve normally if high soil moisture is maintained, which is closely related to climate conditions, soil conservation, landscape management and, last but not least, agricultural production [65].

Soil moisture can be expressed in several ways [66]:

- *Plant-available volumetric soil moisture* (W), the depth of a column of water contained in a given depth of soil;
- *Total volumetric soil moisture* (WT), the volumetric percentage of water in a given soil depth;
- *Porosity* (P), the fraction of soil consisting of pores filled with water or air;
- *Total water holding capacity* (W0), the fraction of soil consisting of pores completely filled with water.

At soil saturation (WT = W0), if the gravitational drainage occurs up to a negligible value, the water quantity remained in the soil is *the field capacity* (Wf). When plants extract water from soil until they become wilted, the residual soil moisture is *the wilting level* (W *), which is unavailable to plants (Figure 9). Soil moisture is an important parameter in the hydrological cycle, especially since it is known and deeply studied and plays a key role in the water–energy balance and determines the sharing of mass and energy flows between soil and atmosphere. Soil moisture is the source of water for plants. Additionally, soil moisture is involved in the modeling and forecasting processes of some phenomena such as floods, landslides, drought, and weather conditions [67]. Soil productivity may be largely limited by soil moisture, which may be affected by the soil ability to absorb water, maintain moisture, as well as by the rate of loss or use of soil moisture. The water content can be crucial in the development of microbial activity in different environments (food, soil, biofilms, and salt water). Microbial activity can be inhibited by low water availability, as a consequence of diminishing intracellular water potential, which leads to reduced enzymatic activity, hydration, and nutrient supply [68].

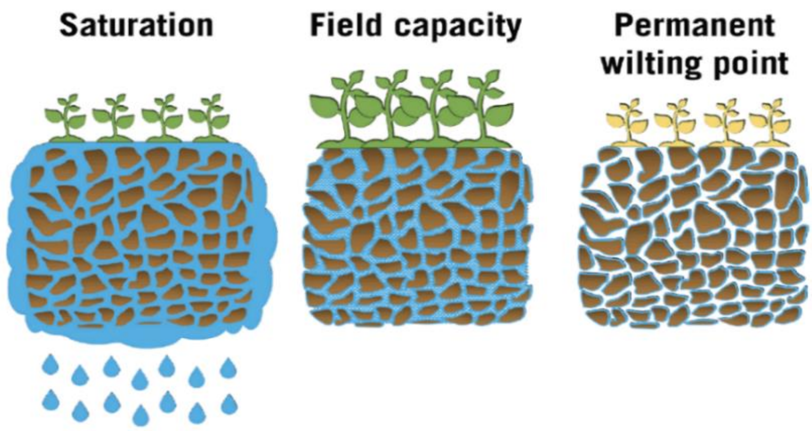

Figure 9. Schematic representation of soil saturation, field capacity, and permanent wilting point (reproduced upon da Silva et al. [22], with permission).

3. Plants Interactions with Soil and Water

Water and soil are crucial environmental components, which interact in many ways. Water can have both beneficial effects for the soil, especially from a fertility point of view, but also negative, especially when it is excessive. On the other hand, the soil can be a balancing factor concerning the consequences of some meteorological peaks, as it helps to avoid floods or drought and, above all, it supports the water cycle. Soil plays an essential role in the growth of plants, as it provides the basis for fixing the plants through roots and allows their spread. Additionally, soil pores contain water available for plants, as well as oxygen for respiration. Together, water and soil are essential for the development of plants and microbial flora, all of these components being in a strong and continuous interaction. Water and soil quality significantly govern plant growth and development, particularly agricultural crops.

Plant growth and development (phenology) is considerably dependent on temperature, soil nutrient resources, water, light, and carbon dioxide concentration. In turn, these factors are significantly influenced by global climate change and, therefore, changes in plant phenology would appear, that is, the decisive moments in the development of roots and leaves, parts of plants that extract resources or plants from soil and transport them together with water [69]. Plants are capable of changing the quality of the environment, acting on microclimatic conditions, with impact on other organisms and on changing macroclimatic conditions [70].

3.1. Soil–Plants Interactions

The soil fulfills an essential function in the growth of plants, since it is a supplier of nutrients and oxygen, being also a physical support for plants, and providing them water and heat. Soil ecosystems contain, besides plants, the so-called flora consisting of microscopic life forms (bacteria, fungi, actinomycetes, protozoa, and algae), which play a significant role in deserving soil fertility, nutrient cycling, and preserving plant diversity. Of these different microorganisms, bacteria are the most common, accounting for 95% of the total microorganisms in the soil [71–73]. In soil and in the presence of soil water, plants can be beneficially associated with soil microorganisms, located on and within their roots (rhizosphere). These microbial communities and their associated genes—generically referred to as the root microbiome, demonstrate great diversity and play an important role in increasing plant tolerance and resistance to abiotic stress generated mostly by some pollutants in the soil [74,75].

Soil mycorrhizae represent a functional group of organisms, important in soil ecosystems, especially in establishing direct links between plant roots and soil texture, which play a key role in soil–plant interactions, especially in nutrient uptake and organic carbon deposition, as plants fight against pollutant toxicity [76]. Free living bacteria from the soil and rhizobacteria that colonize the rhizosphere can promote plant growth, which is why they have been termed as plant-growth promoting bacteria (PGPB). The use of PGPB generates beneficial effects on soil, plant growth, and crop productivity. In addition, PGPB develops a synergistic mechanism with plants, which can thus cope with biotic and abiotic stresses [72,74].

3.2. Effects of Soil Pollution on Plants and Flora

Soil pollution disrupts the ecological balance of any system. Changing the chemical characteristics of the soil as a result of the pollution can have large consequences, affecting the plants in the sense that they hardly adapt, or some cannot adapt, to changes in soil properties in a short period of time. At the same time, the microbial flora and earthworms involved in the soil–plant relationship can be affected to such an extent that additional problems arise, such as intensification of soil erosion. In case of a soil used for agricultural crops, its fertility decreases slowly, with adverse consequences for agricultural crops, both quantitatively, by diminishing production and soil yield, and qualitatively, as a result of the propagation of pollutants from the soil, in plants, and therefore in the food chain.

Soil acidity (pH) is an important property of the soil, because it depends on the development and behavior of some processes in the soil. For example, cations of heavy metals are highly mobile in acidic soils, becoming available for extraction by plants or migration to water sources.

Plants grown on soil polluted with heavy metals—as a result of the intensification of anthropogenic activities, suffer a decrease in growth, performance and yield as crop plants.

These effects are the consequence of physiological changes and biochemical processes, caused by the presence of toxic metal ions, and they are more obvious as the metal is more toxic and more available to plants. Soil properties and especially pH affect the availability of metals in soil in various ways. Additionally, some physical properties of the soil (soil density, moisture, water retention capacity, charge of soil colloids, complexation with ligands, and specific surface area) may alter the bioavailability of some heavy metals for plants, as well as metals toxicity in plants [77–79]. The effects of heavy metal toxicity on plants and flora are manifested by: (i) oxidative stress that leads to inhibition of cytoplasmic enzymes and cell damage; (ii) replacement of essential nutrients in the cation exchange sites of plants; reducing the number of beneficial microorganisms of the soil, which diminishes the degree of decomposition of organic matter; (iii) decrease of enzymatic activity; (iv) preventing the normal growth of plants. Organic matter and hydrous ferric oxides decrease the bioavailability of heavy metals in the sense that they immobilize them in the soil [73,74].

Agricultural soils may contain organic pollutants (polychlorinated biphenyls (PCBs), antibiotics, pesticides, bisphenol A (BPA), polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs), etc.). These contaminants in soil, as well as in water, affect the phytomicrobiome and contribute to unbalances in the bacterial communities, with serious detrimental effects on plant viability/growth [29,37,38]. For example, Bisphenol A, also known as an endocrine disruptor, widely used as a product of the plastics industry, can pose problems in soil in terms of potential effects on crops. It can bioaccumulate in plant and animal tissue, thus increasing through trophic levels. At high concentrations in the soil and in the aquatic environment it affects plants because it disrupts the process of photosynthesis and affects plant growth and microbiome development [30–33].

For this reason, it is necessary for research to focus on studies regarding the ecotoxicity of Bisphenol A and similar compounds, and the ecological and human health risk of this compound, for which there is not yet enough information.

These pollutants can be extracted from the soil by plants, through the roots and then translocated to the stems and leaves, causing substantial damage to the plants. The physical properties (among them, molecular mass and hydrophobicity with K_{OW} (the partition coefficient between octanol and water) and K_{OA} (the partition coefficient between octanol and air) parameters, and chemical properties of the organic pollutants, the biological characteristics of plants and the environmental conditions greatly affect the extraction and transport of organic pollutants in plants [48,80].

Plants can more easily absorb organic compounds dissolved in soil water through the roots, but this is not a mandatory condition for these compounds to be absorbed by plants [81]. Organic pollutants pass from the root surface into roots along with soil water, cross cell walls near the root tip, and then move to the xylem transporter tissue at the root, along the free intercellular space (the apoplastic pathway) or into the cells, in the intracellular space (the symplastic way) [82]. As a result, these pollutants may have toxic effects manifested at the level of plant cell ultrastructure, DNA structure, biosynthesis, and membrane stability. Besides, organic pollutants can affect plants by inhibiting biological processes (mitosis, germination, root growth, leaf formation, synthesis of pigments), enzyme functions, production of hormones, etc. [73,82].

3.3. Plant Growth and Water Use

The use of water by plants implies its role as a carrier for soil nutrients in the plant. Soils fulfill important functions for plants and microorganisms, such as: storage of nutrients for plants; habitat for soil microorganisms; support for plant roots; and water tank for plants evapotranspiration requirements. Typically, the amount of water present in the soil for the use of the vegetation depends on its physical and chemical properties, while, in certain situations, the water supply could be increased to ensure optimum conditions for plant development (e.g., irrigation of agricultural crops). The amount of water in the soil, as well as soil relationship with the plants and the interaction between soil, water, and air are determined by soil physical characteristics: texture, structure, bulk density, and porosity. Among other factors limiting plant development are: soil water content and nutrient bioavailability, which can decisively influence plant growth and productivity, by reducing physiological responses, inhibiting photosynthesis, and disrupting carbohydrate and amino acids metabolism. On the other hand, the extremely high levels of water and fertilizers in the soil generate a series of phenomena associated with excessive consumption of resources, reduced efficiency of water use, increased risk of groundwater contamination, etc. [83,84]. Plants induce an impact on the surface water cycle and groundwater dynamics as a consequence of two phenomena: evapotranspiration (ET) and root water absorption (RWU). These water flows are very heterogeneous and vary in space and time, being also controlled by the physical properties of the soil, climatic and meteorological factors, and the physiological properties of the plants. For these reasons, quantitative evaluation of ET and RWU is problematic [85].

Plants contribute to the restoration of soil moisture, thus regulating the flows between the terrestrial and the atmospheric hydrological system, as well as transferring the water from precipitation to the soil. Oxygenation level and water availability, which are particularly important for plants development, depend to a large extent on the solid/water/air ratio in the soil. The high porosity of the soil can reduce the availability of water for plants, especially during dry periods and drought. On the other hand, water excess can create anoxic conditions in soil, which is unfavorable to plants.

Therefore, there are some constraints regarding water use, which can be described by global relationships according to the concept of water balance, which provides the context for the quantification of how, for example, precipitation could be divided into various components. For example, Zhang et al. [86] elaborated the water balance in the form of Equation (2), which includes specific terms, as precipitation (P), evapotranspiration (ET), surface runoff (R), recharging to groundwater (D), and changes in soil water storage (ΔS).

$$P = ET + R + D + \Delta S \quad (2)$$

In the equation of water balance, precipitation (P) is the term with the highest value and varies spatially and temporally. Equation (2) is based on the hypothesis that precipitation does not depend on the type of vegetation, but there are other hypotheses according to which the type of vegetation can affect precipitation. Evapotranspiration (E) is important in water balance, being the second or third in weight in the balance equation, while runoff (R) is affected by vegetation structure and precipitation [87–89]. Although evapotranspiration influences energy and water exchanges in the atmosphere, hydrosphere, and biosphere, direct measurement of ET is difficult as a consequence of the complexity of the soil–plant–atmosphere system, which is why a number of methods for evaluating ET at regional level have been developed and proposed [90].

In the last five decades, a series of equations have been proposed that have generated the Budyko framework, according to which the long-term water balance is controlled by atmospheric water (precipitation and evapotranspiration) and which is effective in studying the hydrological behavior of water. With the help of Budyko equations you can build the Budyko curve [91,92]. In the last five decades, a series of equations have been proposed that have generated the Budyko framework, according to which the long-term water balance is controlled by atmospheric water (precipitation and evapotranspiration) and which is effective in studying the hydrological behavior of water. With the help of Budyko equations you can build the Budyko curve. Methods for evaluating ET/runoff variation that apply Budyko equations can quantitatively identify the contributions of climate change and human activities on this variation ratio [90].

Another constraint is associated with salinity occurrence, which limits plant growth and crop productivity. Currently, about 800 million hectares of arable land are affected by salinity worldwide, the harmful effect of which can vary depending on climatic conditions, plant species, or soil conditions. The adaptation of plants to counteract the effects of salinity is manifested by activating different physiological (morphology, anatomy), biochemical (photosynthesis, hormonal profile) mechanisms for regulating the salt content by exclusion, elimination, maintenance, and redistribution. Currently, investment is being made in the implementation of salt interception schemes (drilling, groundwater pumping) to protect plants from the adverse effects of salinity [93–95].

Plants play a favorable role in water and soil interaction, in terms of its fertility, biodiversity conservation, the presence of microorganisms, the thermal and hydric regime, by means of the roots, which also contribute to increasing the stability of soil aggregates and consolidating its matrix, modeling the environment and soil development from the surface. In addition, through preferential flow pathways created around the roots, the physical action of the plant roots enhances the chemical and biological activities of the rhizosphere [96]. Plants can only extract water from soil that is in contact with their roots (main roots, lateral roots, Figure 10), whose distribution is usually near the soil surface.

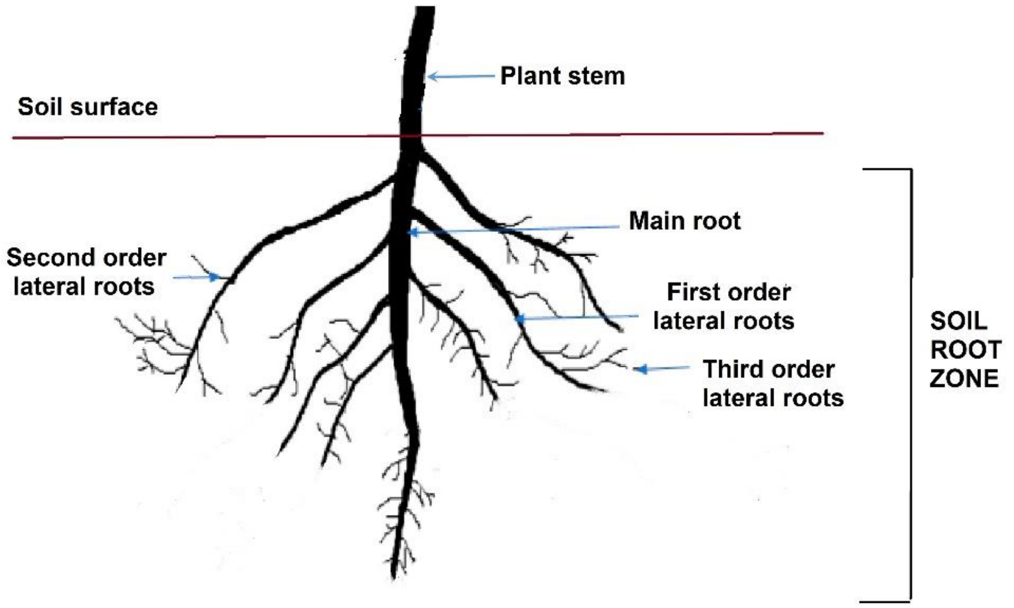

Figure 10. A typical root system architecture.

Customarily, plants have a higher concentration of roots near the soil surface, while the density decreases with soil depth. Therefore, during the growing season, plants generally extract more water from the upper part of their root zone than from the lower part (40% extraction capacity). If the soil is well aerated, most of the roots are in the soil horizon are 40–60 cm, so the plants extract water in sufficient quantities from this area. If water becomes less available here, the plants extract water from the lower soil layers, where the root density is lower (maximum 10% extraction capacity due to the low density of roots), which is why the plains may suffer from wilting.

The reaction of plants to various factors related to growth and the quality of the environment was correlated with the absorption of water and salinity. Water absorption by plants is considered as the result of the action of physiological factors, but is often described as a pure physical process on the soil–plant–atmosphere path (SPAC), the consequence of potential energy differences (from an area with relatively high water potential, to an area with relatively low water potential, among soil, root, stem, leaf, and atmosphere). SPAC is an integrated dynamic system, in which various processes, such as: the capture of solar energy, the sweating of plants, the movement of water through the plant system, and the movement of water from the soil to the roots of plants occur simultaneously and independently. According to Ali [97], the water potential in soil is higher than that in root saps or other fluids (Table 3). The driving force of water movement is represented by these differences in water potential (or potential gradient).

Table 3. Water potentials in different plant which support water movement in soil–plant–atmospheric continuum.

Part of Plant	Water Potential (bar)
Soil	−0.5
Roots	−0.4
Stem	−7
Leaf	−10
Atmosphere	−500

Root water uptake and transport are tight in relation to soil-moisture and can be described using a saturated Darcy-equation [97,98]. Under natural conditions, the roots of the plants develop in the moist soil, while stems and leaves develop in a relatively dry atmosphere. As a consequence of the potential differences on the water flow path, water is transported from the soil through the plant, to the surfaces on which it evaporates, in the sub-stomata cavities of the leaves.

To predict the interrelationships between plants and the environment in the conditions of variability and climate change, for inconstant quality of water and soil, analytical tools have been created [16]. These tools (e.g., structural equation models [99], environmental indices [100], the hierarchical patch dynamics paradigm [101]) are capable of considering the multiple interactions between the environmental variables and their combined effects on plant response. Previously, Kroll et al. [102] extended the number of variables that modelled the interactions among climate, water, soil, agricultural and socio-economic processes, with focus on climate change impacts. The water flow on the soil–plant–atmosphere pathway can be calculated with a relation analogous to Ohm's law for electrical current. The flow is directly proportional to the potential difference between soil–leaves and inversely proportional to the resistance to flow.

3.4. Soil–Plant–Water Relationship

As it is already acknowledged, soil and water are the natural resources on which the development of plants depends. Soil represents the growth environment and nutrient reservoir needed for plants. A high number of the essential nutrients for plant growth can be found in soil (Nitrogen, Phosphorus, Potassium, Calcium, Magnesium, Sulfur, Boron, Chlorine, Copper, Iron, Manganese, Molybdenum, Nickel, and Zinc) and if one essential element is missing, plants are not able to grow along their phonological cycle.

Dynamic interactions between water, soil, vegetation, as key elements for Earth's life, affect and are affected by anthropic activities. The relationship between solids/water/air in soil is imperative for plants, especially for adequate oxygen levels and water availability. Sandy or gravel soils, for example, which are characterized by high porosity, can reduce the availability of water for plants, especially during dry periods, when the groundwater is at greater depths. On the other hand, too much water, in poorly drained regions, can generate anoxic conditions in the soil, which is toxic to some plants. "Plant available water is an indicator of the amount of water held at field capacity that can be evapotranspirated and theoretically used by plants" [56]. Therefore, water is essential for plant life, being extracted from the soil through their roots along with nutrients, to maintain a favorable hydraulic balance. The flow of water through the plants helps to maintain a favorable temperature by water evaporation. Water is also a vital substrate for the biochemical reactions in plant organisms, while water absorbed from the soil transports nutrients to the top of the plants. The water content of the soil largely determines the content of gases in the soil, especially oxygen, essential for ensuring root function and plant development.

Thus, soil water management, especially in the root zone of plants is a critical factor, determining the biophysical activity of plants. The water balance in soil depends, on the one hand, on the ability of water from precipitation or irrigation to enter the soil through the surface and to be stored in the soil reserve, and on the other hand, on the capacity to drain water from the root zone by the gravitational force, runoff of water that does not enter the soil through its surface, water lost from the surface by evaporation, and water absorbed by plant roots and used for transpiration [103].

As mentioned before, soil is a water reservoir, which is not fully available for plants and from which plants extract their necessary water. This ability of the soil to store water and slowly release it to plants has the advantage that it also supports microorganisms and ensures the availability of nutrients for plants, prevents or delays water deficiency during droughts (thus contributing to attenuating drought impacts) and, in certain areas, can prevent desertification. Therefore, it is possible to exploit the soil water retention capacity (SWR) by adapting plant, soil, and water management, which could be very beneficial for agriculture [56].

The intensity of water use by plants is influenced by a number of factors, which include: the daily water requirement determined by the climatic conditions, and the growth stage; soil quality, water quality, depth, and root configuration of plants. Climate change is an important factor for water use by plants, being also the consequence of inadequate management of water resources and activities, since the non-stationary climate, superimposed on human interventions, can further deteriorate the quality of the relationship among soil–water–plants [19]. Nevertheless, the water requirement of plants depends on their growth stage. If the plants are young, the water requirement is lower than in the reproductive stage, and as they reach maturity the plants need less water (as illustrated by Rogers et al. [19], in Figure 9 from the cited paper).

Some plant species are able to specifically adapt to extreme conditions regarding water supply, such as deserts and wetlands. The adaptation depends on the configuration of the roots and the depth at which the roots reach the available water. For example, trees, which are high water users, with a high rate of evapotranspiration compared to other plants, can reduce the overall water content of the soil due to their high adaptability.

The water supply of the soil and, implicitly of the plants by precipitation or irrigation, can sometimes be exceeded by evapotranspiration, which intensifies the stress of the water in relation to the plants and leads to the lack of groundwater recharge. The selection and management of plants influence their water needs and determines how and when they can benefit from soil water. Choosing a crop species and variety adapted to the climate is important to maximize the use of ground water and reduce the stress for surface or aquifer water bodies. Therefore, a decisive step for optimizing the use of water is represented by the selection of those varieties of plants that have a demand for water in accordance with the soil and local climatic conditions [58,104].

If it is not possible to select the plant species, then it is possible to consider changing the planting and harvesting calendar to avoid the periods when the water supply is low or the drought. Plant water stress occurs especially in areas with shallow soils and unfavorable soil water conditions prior to the flowering stage. However, in some cases, a shortening of the vegetative cycle for some plants may reduce the duration of long-term water demand: for example, a shortening of the cycle of customary plants cultivated as of summer crops, could reduce water needs, provided that there is constant planting data [105,106].

4. Concluding Remarks and Perspectives

Water is one of the most important factors which determine plant growth and development and numerous studies have clearly shown this. In addition, the loss of water from the soil leads to a significant decrease in the yield of some agricultural crops. Moreover, water is essential for the photosynthetic process, which ensure the accumulation of photosynthetic products. These products can be affected by environmental factors (soil quality, water content in soil, nutrients) that can change the physiological pathways of plant metabolism.

Soil properties (mostly salinity, pollution, and water deficiency) can affect several plant functions, including nutrient uptake and utilization, water uptake and water-plant relationship, and physiological processes. Soil problems usually occur in climates with little or no rainfall, or when evapotranspiration is more intense than water intake in the soil. Poor management of water resources can cause an increased disruption of soil quality and consequently of plant growth and yield.

Therefore, it is vital that these issues are brought under control and that new or improved ways are found to ensure the proper management of water resources. This would ensure the proper water usage for both soil and plants. More than that, integrated soil and water resource management can be beneficial for plants, humans, and environmental security. Therefore, poor management of water resources can cause an increased disruption of soil quality and consequently of plant growth and yield.

The rationalization of anthropogenic activities and the elaboration of sustainable strategies, on scientific bases, for the protection of water and soil resources, as well as of biodiversity can normalize the interactions between these elements of ecosystems.

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