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Review

Unraveling the Interactions between Flooding Dynamics and Agricultural Productivity in a Changing Climate

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Abstract: Extreme precipitation and flooding frequency associated with global climate change are expected to increase worldwide, with major consequences in floodplains and areas susceptible to flooding. The purpose of this review was to examine the effects of flooding events on changes in soil properties and their consequences on agricultural production. Flooding is caused by natural and anthropogenic factors, and their effects can be amplified by interactions between rainfall and catchments. Flooding impacts soil structure and aggregation by altering the resistance of soil to slaking, which occurs when aggregates are not strong enough to withstand internal stresses caused by rapid water uptake. The disruption of soil aggregates can enhance soil erosion and sediment transport during flooding events and contribute to the sedimentation of water bodies and the degradation of aquatic ecosystems. Total precipitation, flood discharge, and total water are the main factors controlling suspended mineral-associated organic matter, dissolved organic matter, and particulate organic matter loads. Studies conducted in paddy rice cultivation show that flooded and reduced conditions neutralize soil pH but changes in pH are reversible upon draining the soil. In flooded soil, changes in nitrogen cycling are linked to decreases in oxygen, the accumulation of ammonium, and the volatilization of ammonia. Ammonium is the primary form of dissolved inorganic nitrogen in sediment porewaters. In floodplains, nitrate removal can be enhanced by high denitrification when intermittent flooding provides the necessary anaerobic conditions. In flooded soils, the reductive dissolution of minerals can release phosphorus (P) into the soil solution. Phosphorus can be mobilized during flood events, leading to increased availability during the first weeks of waterlogging, but this availability generally decreases with time. Rainstorms can promote the subsurface transport of P-enriched soil particles, and colloidal P can account for up to 64% of total P in tile drainage water. Anaerobic microorganisms prevailing in flooded soil utilize alternate electron acceptors, such as nitrate, sulfate, and carbon dioxide, for energy production and organic matter decomposition. Anaerobic metabolism leads to the production of fermentation by-products, such as organic acids, methane, and hydrogen sulfide, influencing soil pH, redox potential, and nutrient availability. Soil enzyme activity and the presence of various microbial groups, including Gram+ and Gram− bacteria and mycorrhizal fungi, are affected by flooding. Waterlogging decreases the activity of β-glucosidase and acid phosphomonoesterase but increases *N*-acetyl-β-glucosaminidase in soil. Since these enzymes control the hydrolysis of cellulose, phosphomonoesters, and chitin, soil moisture content can impact the direction and magnitude of nutrient release and availability. The supply of oxygen to submerged plants is limited because its diffusion in water is extremely low, and this impacts mitochondrial respiration in flooded plant tissues. Fermentation is the only viable pathway for energy production in flooded plants, which, under prolonged waterlogging conditions, is inefficient and results in plant death. Seed germination is also impaired under flooding stress due to decreased sugar and phytohormone biosynthesis. The sensitivity of different crops to waterlogging varies significantly across growth stages. Mitigation and adaptation strategies, essential to the management of flooding impacts on agriculture, enhance resilience to climate change through improved drainage and water management practices, soil amendments and rehabilitation techniques, best management

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practices, such as zero tillage and cover crops, and the development of flood-tolerant crop varieties. Technological advances play a crucial role in assessing flooding dynamics and impacts on crop production in agricultural landscapes. This review embarks on a comprehensive journey through existing research to unravel the intricate interplay between flooding events, agricultural soil, crop production, and the environment. We also synthesize available knowledge to address critical gaps in understanding, identify methodological challenges, and propose future research directions.

Keywords: agricultural floodplains and flood-prone areas; catchment; crop productions; nutrient dynamics; plant growth; soil properties; waterlogging

1. Introduction

According to a recent report by the Food and Agriculture Organization (FAO) [1], between 2008 and 2018, approximately USD 21 billion was lost in agricultural production worldwide as a result of floods. For example, in 2021, the Fraser Valley in British Columbia, Canada, witnessed the biggest agricultural disaster in the history of the province due to flooding [2]. In 2017, the Bay of Plenty in New Zealand experienced severe flooding, followed by major agricultural losses [3]. The two above-mentioned cases, the Fraser Valley and the Bay of Plenty represent a small fraction of flood-related natural disasters amplified by anthropogenic factors and their consequences on the agricultural sector. Extreme precipitation and flooding frequency associated with global climate change are expected to increase worldwide, with major consequences in floodplains and areas susceptible to flooding [4,5].

Floodplains and other areas susceptible to periodic flooding have an intricate history with agriculture. Floodplains originate from the activities of rivers on valley floors. The water sources naturally channel meanders across the landscape and deposit soil-forming materials, including sand and silt particles, during freshets and floods. The area turns into fertile soil, which is used for agricultural production. The fertile expanse of the Fraser Valley, with its rich agricultural legacy, is an example of floodplains providing beneficial services to the community [6]. Other examples include floodplains in Osterdalen and Gudbrandsdalen in Norway [7], Western Massachusetts [8], the Bay of Plenty in New Zealand [3], and several areas in Vietnam [9], and the Horn of Africa [10].

Flooding events characterized by their frequency and duration have significant implications on soil's physical, chemical, and biological properties in floodplains. Intermittent inundation and exposure to air following flooding affect soil structure and aggregation [11]. The transport and deposition of sediments and other particles with flood waters alter soil texture and can trigger the loss of topsoil and the redistribution of coarse particles along the soil profile [12]. Flooding events also have profound effects on soil chemical properties, including nutrient dynamics, soil organic matter (SOM) content, and, ultimately, soil fertility [13] and plant growth and development [14]. It is crucial to improve our understanding of how flood events impact soil properties to better manage soil health, nutrient cycling, and agricultural productivity in flood-prone areas. Flooding depletes oxygen in the soil, creating anaerobic conditions that affect microbial metabolism and the biogeochemical cycling of nutrients [15]. The impacts of flooding events on soil properties vary depending on factors such as flooding duration, intensity, and soil type, highlighting the need for adaptive soil management practices and flood mitigation strategies to enhance soil resilience and ecosystem sustainability in flood-prone regions.

The relationship between flooding events and the delicate balance of soil properties holds profound implications for agricultural ecosystems, particularly in regions susceptible to periodic inundation. The fertile expanse of floodplains, with their rich agricultural legacy, faces the dual challenge of periodic flooding and consequential shifts in soil properties and agricultural production. Against this backdrop, the necessity arises to explore the nuances of flooding events, both natural and anthropogenic, and their frequency, causes, and regional characteristics. The stage is set to unravel the intricate tapestry of soil responses to flooding, from changes in physical and chemical properties to the intricate interactions within microbial communities.

In areas prone to flooding, where the confluence of nature and agriculture defines the landscape, this literature review strives to be a beacon of knowledge, a guide for navigating the challenges posed by flooding events, and a roadmap for fostering resilience in floodplains and agricultural soil. This literature review embarks on a comprehensive journey through existing research to unravel the intricate interplay between flooding events, agricultural soil, crop production, and the environment. The current review is not focused on flooding but on the impacts that floods have on soil properties in agricultural landscapes with an emphasis on nutrient cycling, including nitrogen (N) and phosphorus (P). However, we will present some characteristics of flooding to guide the readers, with a background in agriculture or agronomy. We guide the readers to expert reviews [16,17]. By synthesizing available knowledge, this review seeks to address critical gaps in understanding, identify methodological challenges, and propose future research directions.

Following the introduction, the remaining parts of this review are structured as follows: Section 2 discusses the causes and characteristics of flooding, including natural and anthropogenic factors. Section 3 presents the effects of flooding on soil properties, including physical, chemical, and biological properties. Section 4 discusses plant responses to flooding, including seedling emergence, young plant growth, and crop yield. Section 5 explores the technological advances in assessing flooding, including remote sensing, GIS, machine learning, and modeling. Section 6 presents the challenges and gaps in the current knowledge. Section 7 presents future perspectives and research directions. Finally, Section 8 presents the concluding remarks.

2. Flooding Events: Causes and Characteristics

Flooding events represent one of the most significant hazards worldwide, impacting both human communities and ecosystems. Flooding has two major causes, including natural and anthropogenic factors. They are also characterized by properties such as frequency, velocity, depth of water, and duration. This section provides a brief overview of the natural and anthropogenic factors contributing to flooding and their major characteristics.

2.1. Natural Causes of Flooding

Floods are the most common natural disasters and occur when an excess of water inundates typically dry land [18]. There are three common types of floods. The first is flash flooding, also known as pluvial flooding, which occurs due to rapid and heavy rainfall that increases water levels, potentially inundating rivers, stream channels, or roads over a short period. Intense rainfall events, often associated with convective storms or atmospheric rivers, can lead to rapid runoff and localized flooding in susceptible areas. The second type is river flooding, which occurs when sustained rainfall or melting snow causes a river to surpass its capacity. Snowmelt during the spring thaw can contribute to elevated river levels and flooding, particularly in mountainous regions [19]. The third type is coastal flood, which results from surges likened to tropical cyclones and tsunamis [16]. Storm surges, driven by strong winds and low atmospheric pressure, pose a significant risk to coastal flooding [20]. In low-elevated coastal areas, flooding can be a source of large quantities of seawater that salinizes fresh groundwater resources and terrestrial coastal zones [21]. Upstream localized flooding can occasionally occur when ice jams (the accumulation of floating river ice due to a topographic feature of the river), formed by the accumulation of ice floes, large pieces of floating ice in rivers and streams, obstruct flow [22]. Other authors have distinguished six types of flood events based on causes and meteorological conditions, including (1) flash floods, (2) short-rain floods, (3) long-rain floods, (4) rain-on-snow floods, (5) snowmelt floods, and (6) groundwater floods [23,24].

2.2. Anthropogenic Factors Contributing to Flooding

Human activities exacerbate flooding risks through land cover changes, drainage alterations, and deforestation [25]. Urbanization and agricultural expansion increase surface runoff, reducing infiltration and prolonging inundation. Urban development accelerates water flow into rivers via impermeable surfaces and drainage systems. The reduction in green spaces diminishes rainwater absorption, while the construction of drains further elevates water influx into adjacent rivers. Human activities significantly contribute to flooding through various means. This includes occupying floodplains, implementing upstream embankments, and altering water regimes [26]. Agricultural practices, like fallow fields and downhill plowing, also influence water flow. Poorly designed infrastructure, such as dikes and dams, as well as climate change-induced shifts, further contribute to flooding [27].

A new type of extreme event coined a "drought-flood abrupt alternation (DFAA)" has increased significantly in frequency and intensity [28]. This term refers to persistent drought for a certain number of continuous days in one region or basin, followed by sudden heavy precipitation, resulting in rapidly rising water, flooding, and the waterlogging of farmland [5]. A recent study showed that DFAA events occurred more frequently in the Huang-Huai-Hai River Basin, China, from 1961 to 2020 compared to the pre-industrial period [29]. Relatively little information exists on the effects of DFAA on agricultural production and soil properties, including nutrient dynamics and cycling [5]. Flood risks are also worsened by a reduced river channel capacity due to debris accumulation, waterway restrictions, and industrial activities like mining, showcasing the complex impact of human interventions on natural hydrological systems. Anthropogenic radiative forcing, the net change in the energy balance of the earth system due to imposed perturbation, alters the global water cycle, intensifying precipitation extremes and flooding [30].

From 2010 to 2013, 64% of floods were influenced by anthropogenic climate change, amplifying occurrences in some regions while suppressing them in others [25]. High occurrences of flooding are observed in many regions in South Asia, Southeast Asia, Northern Eurasia, eastern and low-latitude Africa, and South America, and decreases in northern and eastern Europe, Central Asia, Central North America, and southern South America [25]. Anthropogenic floods, driven by human activities, are increasingly common and warrant recognition.

2.3. Frequency and Duration of Flooding

The frequency of flooding is the likelihood that a flood of a specific magnitude takes place in any given year. This characteristic is important when assessing flood risk and designing resilient infrastructure and flood mitigation measures. Floods are increasingly occurring with greater frequency, which is a trend expected to persist due to climate change [18]. The analysis of historical flood records and hydrological modeling studies offers insight into the variability and trends in flood occurrences [31]. Studies have shown that flood frequency is non-stationary [32], challenging the assumption of stationary flood occurrence or the magnitude used in water management designs based on past patterns. Although there is evidence of a general increase in extreme precipitation events in the past, observed changes in flooding vary with catchment sizes or hydro-climatological characteristics [33,34]. Smaller catchments tend to exhibit changes similar to precipitation patterns [33], while larger catchments may experience other changes, such as decreases in soil moisture and snowmelt dominance [34].

Flood frequency is also related to rainfall and catchment characteristics [35]. One method used to forecast flood frequency is the design storm method, which consists of estimating a hydrograph with a given peak discharge probability from a synthetic rainstorm with the same probability using a rainfall-runoff model [36]. The rational formula is another method that transforms rainfall to flood frequency by estimating peak streamflow from a critical rainfall intensity [35]. The concept of elasticity, defined as the relative change in streamflow divided by the relative change in precipitation, is also often used to relate rainfall and flood frequency [37].

Flood frequency can be influenced by the wetness of the catchment [38]. The storage capacity of the wet catchment is limited and tends to increase runoff events, and, therefore, flood frequency. In contrast, in dry catchments, infiltration dominates and, therefore, runoff events are mainly random [39]. The spatial distribution of rainfall and high rainfall intensities exceeding a threshold of soil storage capacity also play significant roles in flood frequency [40,41]. Studies have also shown that runoff routing may impact flood frequency since the largest floods tend to occur when storm duration runoff response times are synchronized [42].

The duration of flooding is usually assessed as the number of days of submersion [17]. The time the waterlogged soil takes to dry and reach field capacity in agricultural plots, which may be influenced by soil texture, can also be included in the duration of flooding. The effect of soil texture suggests that for the same flood duration, damage to soil and crops can be different. The duration of flood events has been altered by climate change, and patterns of interrelations with drought events have been highlighted [43]. These observations have led to the new extreme climate event, DFAA, that consolidates flood and drought events occurring consecutively in a short period, with the accumulated impact usually exceeding the sum of individual events [5,28]. Biogeochemical processes, such as organic matter turnover and other forms of nutrient cycling, including P, are altered in soil under inundation, indicating the role of the duration of submergence and fluctuations in water levels [44].

The increased frequency of flooding has impacts on agricultural land, especially in floodplains. These areas are usually characterized by fertile and easy-to-cultivate soil. Farmers, therefore, become vulnerable to floods. In 1995, central eastern Norway was affected by severe floods, with an estimated 4000 million cubic meters of snowmelt or 100 mm of precipitation in less than one week. It was estimated that 14,000 hectares of agricultural land were flooded in Osterdalen and Gudbrandsdalen [7]. In 2011, flooding caused by tropical storm Irene resulted in damage to over 2550 hectares of farmland in Western Massachusetts and approximately 3680 hectares in Vermont [8]. In 2017, the Bay of Plenty along the northern coast of New Zealand experienced severe flooding that resulted in major agricultural losses [3]. In Vietnam, prediction models showed that for 10%, 5%, and 1% annual exceedance probability flood events, agricultural land was flooded nationally by 27%, 31%, and 33%, respectively, with a significant impact on rice crop production [9]. Over the past two decades, the Greater Horn of Africa, including Kenya, has experienced a number of extreme weather and seasonal climate events [10,45]. In 2018, recorded rainfall exceeded the long-term mean, and at many stations, the rainy season (March, April, and May) was the wettest compared to historical trends. This led to flooding across the country, with at least 311,164 people being displaced [8,46]. The Fraser Valley, British Columbia, Canada, is the seat of river floods as a result of sustained rainfall or melting snow, causing the Fraser River and its tributaries to surpass their capacity. Statistics show an increase in rainfall frequency in British Columbia. The specific challenge in flooded agricultural soil is the alteration of soil properties, which can affect nutrient dynamics and nutrient loss (notably P) from soil to water sources, which then poses risks to water quality and eutrophication. Another challenge in the Fraser Valley is the high soil P due to the annual application of inorganic fertilizer and manure in cropping systems such as silage corn used for feed in dairy cow production. This leads to a surplus of 50 kg of P ha^{-1} in corn and ryegrass rotations and then increases soil P saturation and raises the risk of P transport [47]. Water sources in the Fraser Valley show signs of algal blooms. Understanding the impacts of flooding on high soil P and on the process of P loss is crucial (Figure 1). In the past century, three major floods have occurred in the Fraser Valley with important negative consequences on the local economy and infrastructure. These major flooding events include 1894, 1896, and 1948. The flood of 1948 was the most costly and destructive of the 20th century, with 28,300 hectares of flooded land and 2300 homes under water [6]. The recent flooding event that occurred in 2021 was the biggest agricultural disaster in the history of the province, with more than 1100 farms, 15,000 hectares, and 2.5 million livestock affected [2]. Agricultural lands were flooded for several weeks, with standing waters maintaining soil under waterlogging conditions. In the Sumas area, nutrient concentrations such as nitrogen (N) and P increased in surface waters, reaching 43 and 20 times, respectively, compared to that of upstream reference sites [48]. In addition, dissolved oxygen levels in surface waters were 52% lower than upstream reference sites, implying that fertilizer, manure, and wastewater effluents contributed to degrading water quality during the flooding. Between 15 December 2021 and 27 January 2022, there was an 84% increase in the concentration of N and a 40% increase in P concentrations [48]. Water samples collected across the Sumas Prairie following the flooding of 2021 showed declining total concentrations of P at all sampling locations, indicating that the storm event responsible for the flood contributed to an increase in total P in the surface waters [48]. In the Canadian Prairies, approximately 80% of the runoff volume that Lake Winnipeg receives derives from snowmelt runoff [49].

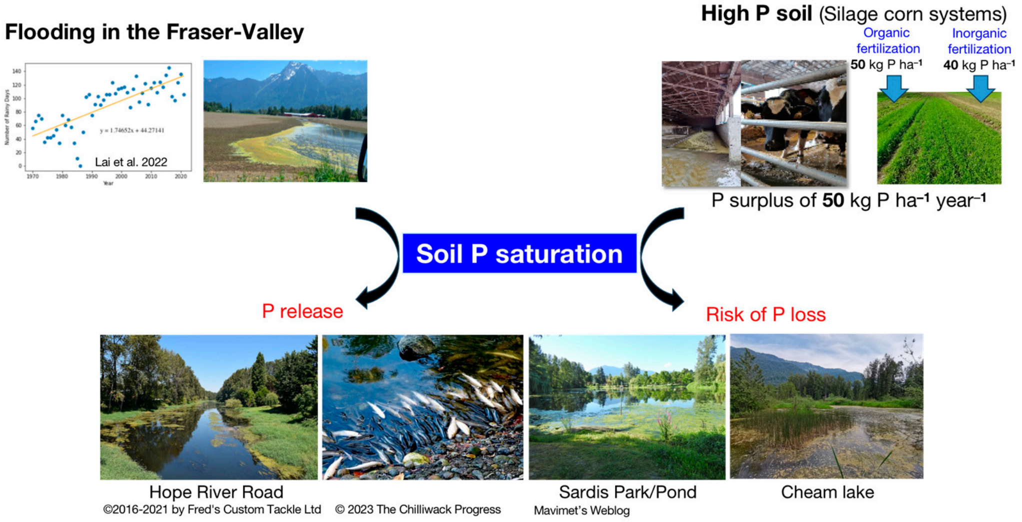
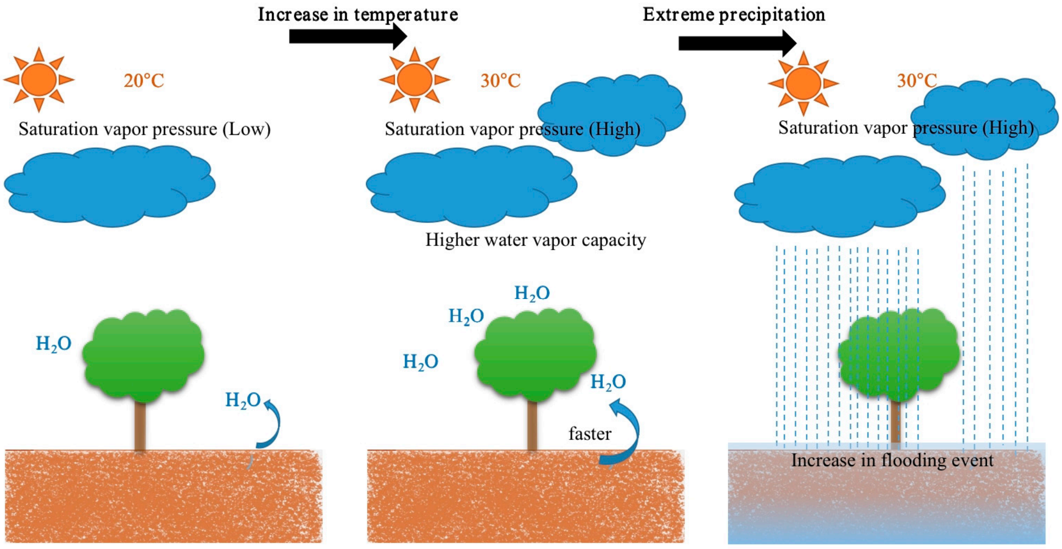


Figure 1. Schematic representations of the link between flooding, local geography, and heavy rainfall in the Fraser valley of British Columbia, Canada (Lai et al. [50]).

2.4. Climate Change, Extreme Precipitation, and Flooding

As global temperatures rise due to increased greenhouse gas emissions, the capacity of the atmosphere to hold moisture also increases [51]. The Clausius–Clapeyron relationship suggests that for every 1 °C rise in temperature, the atmosphere can hold approximately 7% more water vapor [52]. A small increase in temperature results in a relatively larger increase in water vapor capacity. As temperature increases, the molecules of water move faster and are more likely to break free from the liquid surface and enter the gaseous phase. Therefore, more water molecules can exist in the gas phase without condensing. This increases the amount of water vapor that the air can hold before reaching saturation (Figure 2). Increased atmospheric moisture content enhances the hydrological cycle, leading to more intense and frequent precipitation events. This is because more water vapor can lead to heavier rainfall when the conditions for precipitation are met. The impacts of climate change on precipitation patterns can vary by region. Some areas may experience more intense and frequent rainfall, while others may see reductions in average precipitation, leading to droughts interspersed with heavy downpours.

Extreme precipitation events, characterized by short periods of intense rainfall, can overwhelm drainage systems, rivers, and soil, leading to flash floods and urban flooding. These events are becoming more common as the climate warms up. With more frequent and intense precipitation, the risk of riverine and pluvial (surface water) flooding increases. River systems may receive higher-than-normal inflows, leading to the breaching of banks and flooding of adjacent areas.



Water vapor capacity refers to the maximum amount of water vapor that the air can hold at a specific temperature and pressure before it becomes saturated.

Figure 2. Schematic representations of linkages between increases in temperature, extreme precipitation, and flooding.

3. Effects of Flooding on Soil Properties

Flooding events, through their characteristics such as frequency and duration, have significant implications on soil physical, chemical, and biological properties.

3.1. Impact on Soil Physical Properties

3.1.1. Soil Structure and Aggregation

Soil structure describes the arrangement of soil particles into larger aggregates of varying sizes and shapes [53]. It influences air, water, and nutrient flow, resistance to soil compaction and erosion, and overall plant growth [54]. Soil aggregation is interrelated to soil structure as it involves the binding together of soil particles into secondary units through soil organic matter (SOM) [55]. These two properties are strongly associated with soil health and agricultural productivity. One key indicator of soil structure and aggregation is its resistance to slaking, which occurs when aggregates are not strong enough to withstand the internal stresses caused by rapid water uptake [56]. It is specifically through this indicator that flooding impacts soil structure and aggregation. The intermittent inundation and exposure to air associated with flooding are intensive disturbance factors for soil structure and aggregation [11]. Different mechanisms controlling the stability of soil aggregates are reviewed in the literature. In soil dominated by 2:1 minerals, organic matter plays the main role as a binding agent [57], whereas in soil where 1:1 minerals prevail, oxides of iron and aluminum have the major role [58]. There are conflicting views in the literature on the response of soil aggregation to flooding, which is highly dependent on properties such as clay, organic matter, and oxides. The duration of flooding controls the presence of oxygen in the soil and, therefore, the extent of anaerobic conditions. Decreasing oxygen concentrations in the soil due to flooding impacts organic matter dynamics and the redox reactions of oxides of iron and aluminum, which are processes controlling the binding agents of soil structure and aggregation. Prolonged inundation and waterlogging promote soil compaction and dispersion, reducing soil pore space and impairing soil structure. The disruption of soil aggregates can increase soil erosion and sediment transport during flooding events, contributing to sedimentation in water bodies and the degradation of aquatic ecosystems [59]. The restoration of soil structure following flooding may require management practices such as tillage, organic matter addition, and cover cropping to promote soil aggregation and improve soil health.

3.1.2. Soil Porosity and Water-Holding Capacity

Soil porosity is a fraction of the total volume of soil that is occupied by pore space [60]. Pore space plays a key role in the availability and movement of air or water within the soil environment [61]. Kostopoulou et al. [62] studied the effects of seasonal flooding on pore size distribution in a rice field and found that after two years, textural porosity increased at the expense of structural porosity. The authors also found that a percentage of drainage pores collapsed into storage pores. In contrast, other studies reported that a reduction in total porosity is typical of flooding [63]. Flooding affects soil porosity differently with depth. In the topsoil, flooding reduces macroporosity, while for root depth, decreased drainage pores have been observed [62,64]. For root depth, the soil is supplied with organic compounds that stabilize the structure and create macropores that are resistant to the slaking induced by flooding [65]. A recent study using climate projections for the end of the 21st Century conducted in the USA showed that increasing humidity by 2080–2100 will reduce soil microporosity in most regions of the U.S., leading to less infiltration of water, more surface runoff and erosion, and more flash flooding [66]. Flooding can alter soil porosity and water-holding capacity, influencing soil water dynamics and nutrient availability. Saturated conditions during flooding reduce soil porosity and air-filled pore space, limiting oxygen diffusion and root growth [67]. The diffusion of oxygen in water is about 10,000 times slower than in air [68]. After 24 h of flooding, the concentration of oxygen in the soil is significantly reduced, and anaerobic conditions begin to prevail at oxygen concentrations below 1% [69]. Pore clogging and compaction further restrict water infiltration and drainage, exacerbating waterlogging and anaerobic conditions in flooded soils. Changes in soil's water-holding capacity affect plant water uptake and nutrient availability, impacting crop productivity and soil fertility [70]. The restoration of soil porosity and water-holding capacity post-flooding may require practices such as deep tillage, soil aeration, and organic matter amendments to improve soil structure and hydraulic properties.

3.1.3. Soil Texture

Soil texture is the composition of particle size, including sand, silt, and clay. It is a stable characteristic of soil and influences biophysical properties. During flooding events, the deposition of sediments, erosion, and particles can induce changes in soil texture. Sediment deposition in low-lying areas can result in the accumulation of fine particles and organic matter [13]. Conversely, soil erosion and sediment transport can lead to the loss of topsoil and the redistribution of coarse particles, affecting soil texture gradients and landform morphology [12]. Changes in soil texture due to flooding may influence soil fertility, drainage characteristics, and land use suitability, requiring careful management and rehabilitation measures to restore soil productivity and ecosystem functions [71]. The impacts of flooding events on soil's physical properties vary depending on factors such as the flooding duration, intensity, and soil type, highlighting the need for adaptive soil management practices and flood mitigation strategies to enhance soil resilience and ecosystem sustainability in flood-prone regions.

3.1.4. Soil Organic Matter Turnover in Flooded Soils

Soil organic matter includes organic materials or classes of carbon-containing compounds found in soil that are, or have been, part of living organisms [72]. In its simplest conceptualization, SOM is primarily in the form of particulate (POM), mineral-associated, and dissolved organic matter (DOM) [73]. These forms are defined on the basis of their physical properties, including mineral-associated properties being heavier (>1.6–1.85 g cm^{-3}) and finer (<50–60 μm) than POM and DOM being water soluble [74]. The physical properties of the different forms of SOM are the main factors controlling its fate during flooding events. Oeurng et al. [75] studied the transport of suspended sediments and organic carbon during flooding events in a large agricultural catchment in southwest France. The authors found that total precipitation, flooding discharge, and total water are the main factors controlling the suspended mineral-associated, DOM, and POM loads. Dissolved organic matter is a major form of SOM, and it is vital in modulating aquatic basal food webs, nutrient cycling, and carbon sequestration [76]. A mixture of complex organic substances makes up DOM, including humic acids, fulvic acids, amino acids, carbohydrates, polysaccharides, and *N*-containing molecules [77]. Flooding events have profound effects on DOM in soil and aquatic areas. The concentration of DOM increases during storm flows in response to the enhanced leaching of originally fixed biomass and organic matter in riparian soils [78]. The supplementation of rainwater and groundwater during storm events can subsequently decrease the concentration of DOM during flooding [79]. The literature provides contrasting views on the reactivity of DOM during flooding events, which could be explained by changing the sources and factors contributing to accumulation in the soil [80]. Shang et al. [81] showed that the flow event is usually a significant driving factor in regulating DOM dynamics, among other factors, such as point or non-point source pollution and land use. Pang et al. [82] linked the unique molecular complexity of DOM to flood periods. The authors found up to 4927 unique molecular formulas of DOM during high discharge periods with lignin degradation products as dominant components, likely due to more intensive soil leaching. Sao et al. [83] found that DOM was directly and indirectly affected by flood duration and post-flooding through changes in physical conditions and exchanges between the soil and flood water. Based on the above, DOM is ubiquitous in flood waters and is the main form of SOM and its constituents, including C, N, and P. It originates from the surrounding terrestrial landscape, including agricultural soil, and plays a key role in regulating ecosystem functions and structure. It is important to improve our understanding of how DOM interacts and is affected by flooding.

3.2. Impact on Soil Chemical Properties

Flooding events have profound effects on soil chemical properties, including nutrient dynamics, pH levels, SOM content, P availability, alterations in soil chemical composition, and, ultimately, soil fertility. Understanding these impacts is crucial for managing soil health, nutrient cycling, and agricultural productivity in flood-prone areas.

3.2.1. pH and Soil Acidity/Alkalinity

The information obtained from paddy rice cultivations shows that flooded and reduced conditions neutralize the soil pH, but the changes in pH are reversed upon draining the soil [84]. These changes in soil pH have several effects, including greenhouse gas emissions, the decomposition of organic matter, and nutrient availability. In an incubation experiment investigating changes in soil pH following flooding and drainage, the authors found that throughout flooding duration, soils with an initial pH < 6.5 exhibited an increased soil pH to near 7.0, while soils with an initial pH > 6.5 exhibited a decrease in soil pH at the beginning of the incubation period followed by an increase to approximately 7.0 [84]. Flooding alters soil pH levels, affecting soil acidity or alkalinity and influencing nutrient availability and microbial activity. Anaerobic conditions during flooding promote the release of acidic metabolites, leading to soil acidification [85]. In a rootstock × flooding experiment conducted in Florida, USA, the flooded soil pH was 0.3 units higher than non-flooded soil [86]. The authors found that flooded soils were compacted with reduced water content in the pore space, which resulted in anaerobic conditions and increased soil pH. Changes in soil pH can impact nutrient solubility, metal mobility, and plant growth, with implications for soil health and ecosystem functioning [87]. Other studies have shown that alternating flooding and drying events also affect soil properties, such as pH, redox potential, and ionic strength [88]. A recent study conducted in Halifax, Canada, showed that intermittent shallow flooding can rapidly increase moisture content and soil salinity in surficial sediments and, in turn, adversely affect conditions suitable for agricultural production [89]. Coastal flooding can salinize surficial sediments in coastal zones, contaminating freshwater aquifers and rendering groundwater unsuitable for human consumption and irrigation [16].

3.2.2. Nutrient Dynamics: Availability, Losses and Redistribution

Flooding leads to nutrient losses and redistribution in soils due to leaching, erosion, and sediment deposition. Soluble nutrients such as N, P, K, and S are susceptible to leaching during flooding events, resulting in soil nutrient depletion and water pollution [70]. The driving factor of change in the dynamics and cycling of nutrients in flooded conditions is the absence of oxygen in the soil and, hence, anaerobic conditions. Microorganisms use oxygen associated with other electron acceptors, such as nitrate, iron, sulfate, and manganese, leading to a reduction in these elements [90]. Studies have shown that the availability of nutrients, including macro- and micro-nutrients in flooded soils, is two to four times lower than that in well-oxygenated soil [68].

Changes in N cycling in flooded soils are related to decreases in oxygen concentrations, the accumulation of ammonium, and the volatilization of ammonia. Studies have shown that the primary form of dissolved inorganic N in sediment porewaters is ammonium [91]. In central Chile, it has been shown that surplus N in maize-cropping systems could be leached by the excessive irrigation water during the growing season, while up to 6% of the total nitrate load could be lost through leaching in autumn–winter during flush-flooding events [92]. In floodplains, nitrate removal can be enhanced due to high denitrification when intermittent flooding provides the necessary anaerobic conditions [93]. The nitrate abatement function of the cultivated flood plain can be lost during fallowing, with flood events directly moving nitrate down to the shallow groundwater [92].

Flooding impacts P availability in soil through complex chemical and biological processes. The reductive dissolution of minerals releases P into the soil solution, increasing soluble P concentrations in flooded soil [94]. Flooding mobilizes soil P and can increase its availability during the first weeks of waterlogging, but its availability decreases with time [95]. Other studies have also shown that rainstorms can promote the subsurface transport of P-enriched granules, and colloidal P can account for up to 64% of total P in tile drainage water [96]. Sharma et al. [97] also found that in field runoff plots, colloidal P accounts for 90% of the P forms and fluxes lost via runoff, throughflow, and leaching. Ding et al. [98], investigating the effects of flooding and drying cycles on alkaline calcareous soil, found that the colloidal P content of the flooding event was always greater than that of the drying event during flooding and drying cycles. A recent study showed that the incorporation of calcium cyanamide and straw reduced P leaching in flooded agricultural soil [99]. In an incubation experiment testing the effects of soil moisture content on P solubility, it was found that soil maintained under extended anoxic conditions increased soluble and plant-available P and, subsequently, the risk of P transport to surface waters [100]. Phosphorus released from acidic and anaerobic soils is closely associated with the reductive dissolution of Fe and Mn phosphates [101]. Bi et al. [5] studied the effects of DFAA, a new type of climate change event, on P transformation in farmland systems. The authors found that DFAA breaks down soil aggregates and increases soil porosity, resulting in an increase in available P in topsoil. Snowmelt volume can also affect dissolved reactive P loads, indicating that management practices that reduce the volume of snowmelt discharge could be more effective for reducing the P loss from manured soil [102].

Flooding induces changes in soil chemical composition, affecting elemental concentrations, mineralogy, and redox reactions. The reductive dissolution of minerals leads to the release of trace metals and metalloid elements into the soil solution. Changes in soil redox conditions influence chemical speciation and mobility, impacting soil fertility and contaminant transport.

Sediment deposition can redistribute nutrients across landscapes, influencing nutrient availability and plant growth in flood-affected areas [13]. However, P sorption onto sediments and organic matter may reduce P availability and affect nutrient cycling in aquatic ecosystems. The impact of flooding on soil chemical properties has significant consequences for soil fertility and agricultural productivity. Nutrient losses, changes in pH, alterations in SOM content, and shifts in P solubility and availability affect nutrient availability, plant growth, and crop yields. Implementing soil fertility management practices such as fertilization, liming, and organic amendment is essential for restoring soil fertility and optimizing agricultural production in flood-prone areas. Sustainable soil management strategies that promote soil health and resilience to flooding are essential for maintaining agricultural sustainability and food security.

3.3. Impact on Soil Biological Properties

3.3.1. Microbial Communities in Flooded Soils

The stability and resilience of microbial communities are central to the response of soil to environmental stresses. Soil flooding frequency and intensity caused by global climate change are among the future major environmental stressors of agroecosystems [103]. One consequence of soil flooding is the depletion of oxygen due to stagnant water and the deposition of sediments in the macropores. Another consequence of flooding is the impact on soil C availability and nutrients, which affect microbial metabolism. Under anaerobic conditions, the diversity and composition of the soil microbial community is profoundly altered [104]. Flooding creates anaerobic conditions in the soil, affecting the microbial metabolism and biogeochemical cycling of nutrients. Anaerobic microorganisms utilize alternative electron acceptors, such as nitrate, sulfate, and carbon dioxide, for energy production and organic matter decomposition. Anaerobic metabolism leads to the production of fermentation by-products, such as organic acids, methane, and hydrogen sulfide, influencing soil pH, redox potential, and nutrient availability. These changes can be transient, leading to progressive shifts from aerobic to anaerobic communities. These changes could be seen as the predominance of anaerobic communities over aerobic communities and not the complete disappearance of the latter. The predominance of one community, here anaerobic, over the other, aerobic, is marked by changes in soil functions affecting the resilience of ecosystems. Anaerobic conditions during flooding favor the proliferation of anaerobic microorganisms, such as fermenters, sulfate reducers, and methanogens [15]. Shifts in microbial communities influence nutrient cycling, organic matter decomposition, and soil biogeochemical processes, with implications for soil health and ecosystem services and functioning. Shifts in microbial diversity and composition affect nutrient transformations, organic matter decomposition, and soil C sequestration. Alterations in microbial activity and metabolism influence soil fertility, greenhouse gas emissions, and contaminant mobility, with implications for ecosystem functioning and resilience [105].

3.3.2. Enzyme Activity in Flooded Soils

The fate of microbial communities and enzyme activities in soil environments are intertwined. Most soil enzymes are the products of microorganisms released into the soil. Any impact of flooding on soil microorganisms can, therefore, have ripple effects on soil enzyme activity. Flooding affects soil enzyme activity and the presence of various microbial groups, including Gram-negative and Gram-positive bacteria and mycorrhizal fungi [44,103]. In an incubation study where soils were exposed to 60-day flooding, it was shown that fungi were more sensitive than bacteria to changes occurring with flooding conditions [106]. Indeed, flooding affects the input of nutrients and the energy necessary for metabolism reactions linked with enzyme activity. In flooded soil, copper content influences the richness and diversity of bacterial and fungal communities and, therefore, enzyme activity [106]. Enzymes, including invertase, urease, and cellulase, have been found to decrease in high copper-flooded soil due to the suppression of cellular activities and inactivation of extracellular enzymes [107].

Rupngam et al. [108] conducted a greenhouse experiment using lysimeters to compare soil moisture regimes, including waterlogging on enzyme activity, P leaching, and plant growth. The authors showed that waterlogging decreased the activity of β-glucosidase and acid phosphomonoesterase but increased *N*-acetyl-β-glucosaminidase in soil. The authors concluded that since these enzymes control the hydrolysis of cellulose, phosphomonoesters, and chitin, soil moisture content can impact the direction and magnitude of nutrient release and availability, including C, N, and P. We also used a schematic representation to describe soil processes and reactions taking place under flooding conditions in the acidic soil of the Fraser Valley (Figure 3). Phosphorus is mainly bound to soil particles through oxyhydroxides of Fe, Al, and Mn. When the soil moisture is in excess, it creates anaerobic conditions under which microorganisms use alternative electron acceptors like nitrate and Fe and then release P and organic carbon, which bind to Fe. This is called a reduction reaction, which produces greenhouse gases as byproducts. Another process of interest is mineralization, which breaks down organic into inorganic compounds. Soil enzymes catalyze this transformation. The dissolved nutrients can either be taken up by plants and microorganisms or can be lost in water sources. Understanding these processes provides insights into how they respond to climate change and agricultural practices.

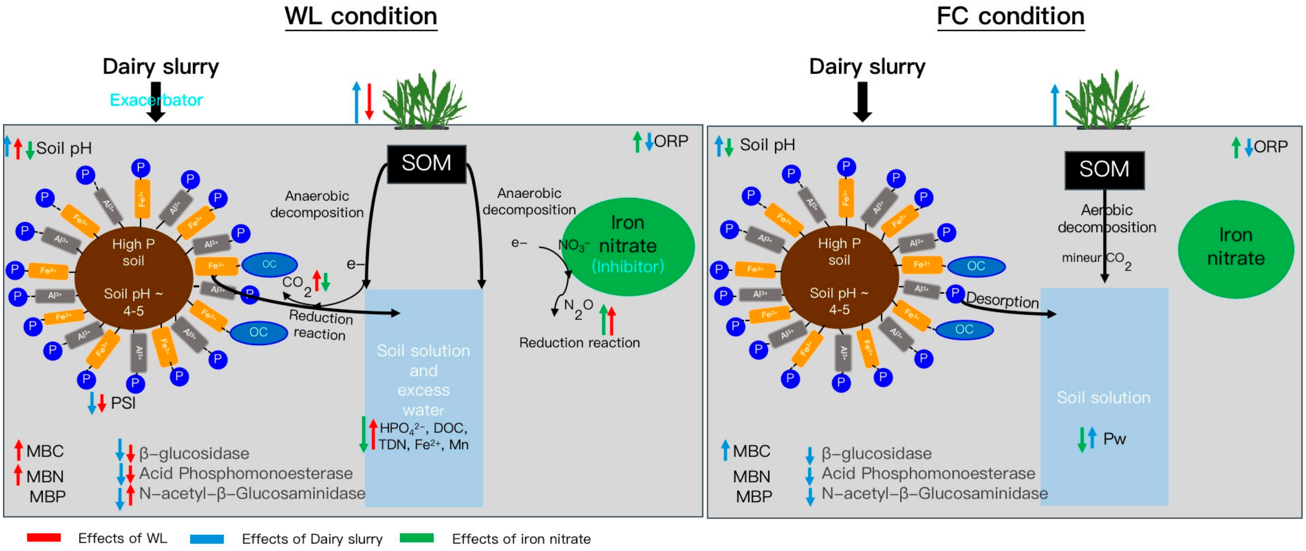


Figure 3. Schematic representation of the processes and reactions occurring in flooded soils. WL = waterlogging, and FC = field capacity. The effects of the WL condition were compared to the FC condition. Exacerbation means that dairy slurry acts as an exacerbating agent of WL's effects in terms of the reduction in iron and the release of phosphorus (P). Inhibition means that iron nitrate acts as an inhibitor of the reduction in iron and the release of P. The effects of iron nitrate on crop yield and soil enzyme activity were not studied [Authors].

The activity of polyphenol oxidase and peroxidase, two extracellular enzymes, can also be affected by the co-occurrence of metals in soil and flooding conditions. The literature shows that high levels of metal in soils interact with phenolic compounds, known as inhibitors of other enzymes, thus affecting microbial activity, decomposition rates, and nutrient cycling [109]. Huang et al. [110] quantified and evaluated soil microbial metabolic limitations along a gradient of flooding duration and found that it was primarily limited by C and P. The authors found that limitations were linked with the direct and indirect effects resulting from plant features (plant community diversity, biomass, and nutrient properties) and soil nutrient ratios. It is important to improve our understanding of how soil microbial metabolic processes respond to environmental stressors such as flooding, given the predicted rise in extreme weather events with climate change.

4. Plant Responses to Flooding Stress

According to FAO (2021 [1]), farmers lost approximately USD 21 billion in crops and livestock between 2008 and 2018 as a result of the floods. As discussed before, flooding alters conditions in the rhizosphere of plants that result in the depletion of the oxygen concentration, changes in porosity, pH, nutrient dynamics, SOM, microbial communities, and enzyme activity. In response to these changes triggered by floods and other environmental or abiotic stresses, plants exhibit various physiological and morphological adaptation responses, with a marked impact on growth, development, and productivity. Understanding these adaptation responses is crucial for developing flood-tolerant crops and enhancing agricultural resilience to flooding.

4.1. Physiological Changes in Flood-Exposed Plants

Flooding stress induces physiological changes in plants, including alterations in respiration, photosynthesis, hormone signaling, and nutrient uptake. The diffusion coefficient of oxygen in water is extremely low, which limits its supply to submerged plant tissues [111]. The limited supply of oxygen affects mitochondrial respiration [112]. Oxygen deprivation during flooding inhibits aerobic respiration and adenosine triphosphate (ATP) production, leading to energy deficits and metabolic imbalances in flooded tissues [113]. The reduced respiration rate in flooded plants leads to fermentation as the only viable pathway for energy production, which under extended waterlogging conditions is inefficient and generally results in the death of plants [14]. The fermentation pathway leads to the production and accumulation of toxic metabolites, such as ethanol and acetaldehyde, which are physiologically toxic substances in plants, leading to cell damage [114]. Flooding stress impairs seed germination by decreasing sugar and phytohormone biosynthesis. Perata et al. [115] showed that wheat and barley seeds cannot germinate under anoxic conditions. In contrast, rice (*Oriza sativa*) germinates and thrives under waterlogging conditions due to its unique capacity to express alpha-amylase under low oxygen conditions [116]. Alpha-amylase converts starch into soluble sugars, including sucrose, to facilitate germination.

Photosynthesis requires CO_2 and light to produce carbohydrates. Waterlogging conditions prevailing in the soil during flooding limit the concentration of CO_2 as well as light intensity. During flooding, the low oxygen concentration around the root system has ripple effects on the extent of gas exchange between plant parts and the surrounding environment. Typically, the closing of stomata on the leaves is triggered by the physiological stress experienced by the roots, which lowers gas exchange and photosynthesis [117]. Reduced photosynthetic activity and chlorophyll degradation impair carbon assimilation and biomass accumulation in flood-exposed plants. Stomatal closure was observed in *Brassica oleracea* [118], *Brassica napus* [119], and Arabidopsis [120]. Bharadwaj et al. [14] found that chlorophyll content, catalase activity, and volatile emissions were reduced among the flooded lentils, probably due to cell death and reduced photosynthesis. The closure of stomata under waterlogging could be attributed to the loss function of root signaling, which can lead to plant senescence and death [121].

Changes in hormone signaling pathways, such as ethylene, regulate plant response to flooding stress, including adventitious root formation and stomatal closure [122]. Ethylene, due to its gaseous nature, can build up to high levels in flooded roots and, therefore, can be used as an early flood-warning cue [123]. Among the other hormone cues triggered by hypoxic conditions in roots are redox-active reactive oxygen species (ROS) and nitrous oxide, which can cause tissue injuries [124]. Ethylene biosynthesis is a canonical pathway that involves, in brief, the conversion of amino acid methionine to S-adenosyl-methionine, followed by the formation of 1-aminocyclepropane-1-carboxylic acid [125]. Short-term 3% hypoxia in Arabidopsis seedlings induced ethylene biosynthesis in the root and shoot [126]. High levels of ethylene associated with flooding inhibit root elongation [127].

4.2. Waterlogging Duration and Yeld Loss

Waterlogging, a condition where the soil is saturated with water, significantly impacts crop growth and yield. Understanding the relationship between waterlogging duration and yield loss is crucial for developing effective agricultural practices and management strategies. Studies have shown that waterlogging reduces yield and other quality attributes, with the extent of loss varying by crop and growth stage.

In cotton, waterlogging significantly reduces morphological properties, yield, and physiological parameters, with the most severe impact during the flowering stage (38.8% yield reduction), followed by squaring (27.9%), seedling (18.3%), and boll-opening (7.6%)

stages [128]. Quality attributes like upper half mean length, uniformity index, and micronaire values were also reduced. Critical waterlogging durations were four days at the squaring stage and just two days at the flowering stage. At the seedling stage, waterlogging for up to six days allowed recovery by the boll-opening stage with timely drainage.

In wheat, waterlogging during stem elongation decreased yield by about 2% per day, primarily affecting pre-anthesis spike growth [129]. Another study found high yield loss for wheat with waterlogging from sowing to collar initiation and from heading time to mature grain filling, while low yield loss occurred from double ridge to awn primordium and from mature grain filling to harvest [130]. A rain-shelter experiment with nine wheat genotypes under four waterlogging durations (0, 10, 20, and 30 days) showed significant yield losses, averaging 44%, mainly due to reductions in tiller number and kernels per head [131]. Genotypes like 'Terral LA 422', 'Shelby', and 'Pioneer 2691' exhibited high waterlogging tolerance, while others, such as 'Coker 9663' and 'FFR 502W', showed lower tolerance despite their high yields under normal conditions. A study on the critical period for waterlogging in wheat and barley found the most significant yield losses from Leaf 7 appearance to anthesis, with lower impact during grain filling [132]. Reduced grain numbers per spike in wheat and variations in spike number per plant in barley were key factors in yield reduction. The period around anthesis was identified as the most susceptible to waterlogging in both crops. Delaying sowing dates increased the negative effects of waterlogging, emphasizing critical vulnerability during the anthesis stage.

For maize, waterlogging (2–10 days) at various growth stages significantly impacted all growth and yield indices, with the greatest yield impact at the six-leaf stage, followed by the three-leaf stage, vegetative, and reproduction stages [133]. Adverse effects worsened with longer waterlogging durations. Another study found that grain filling and endosperm cell proliferation in summer maize hybrids DengHai605 (DH605) and ZhengDan958 (ZD958) were most affected at the three-leaf stage, with substantial reductions in the endosperm cell content, proliferation rate, grain weight, and filling rate [134]. Yield reductions were highest at the three-leaf stage, followed by the six-leaf stage and vegetative stage, with twice the impact after 6 days compared to 3 days of waterlogging.

Finally, a study on sesame varieties, BARI Til 2 and BARI Til 3 showed significant yield reductions as waterlogging duration increased, with maximum losses of 51.67% and 58.24%, respectively, after 36 h of continuous waterlogging [135].

These findings emphasize the importance of timely drainage and stage-specific management strategies to mitigate yield losses due to waterlogging.

4.3. Agricultural-Based Adaptation Strategies to Flooding

4.3.1. Plant-Based Adaptation Strategies

Flooding places plants in two main states that generate environmental or abiotic stresses. The first is waterlogging, which involves water saturation of the belowground parts of the plant, mainly the root zone [4]. Waterlogging limits the amount of oxygen in the soil available for plant roots. This is due to the low diffusion rate of oxygen in water. In response to the lack of oxygen, ethylene is produced and entrapped in the root tissues, leading to higher levels, which could be negative for the survival of the plant. Plants have developed strategies to liberate entrapped ethylene and facilitate the transport of oxygen to hypoxic tissues, which include the proliferation of adventitious roots and aerenchyma [136]. Rupngam et al. [137], in a pot experiment, also showed that the dry matter yield and P offtake of annual ryegrass (*Lolium multiflorum*) were lower under waterlogged soil compared to the soil at field capacity. The second status is submergence, which can be partial or complete. In partial submergence, the root zone and part of the shoot are submerged under water, while in complete submergence, the entire plant, including the root zone and the shoot, is submerged under water [4]. Submergence limits the amount of oxygen available to the roots but also limits the amount of light intercepted by the shoots, which is necessary for photosynthesis. The accumulation of ethylene in the roots has ripple effects on the shoots, and this is highlighted by the closure of the stomata on the leaves. Studies have shown that waterlogging and submergence are conducive to root growth inhibition, which can impact nutrient uptake and yield [138]. Enhanced antioxidant defense systems, such as superoxide dismutase and catalase, scavenge ROS and mitigate oxidative stress in flood-exposed plants [124]. Changes in hormone signaling pathways, such as ethylene and gibberellins, regulate adaptive responses to flooding stress, including elongation growth and shoot elongation [139]. Polacik et al. [140] found that photosynthesis in flooded salt cedar (Tamarix ramosissima) was reduced by non-stomatal limitations and subsequently increased due to metabolic acclimation. The authors also found that root alcohol dehydrogenase (ADH) activities were higher in flooded plants compared to drained plants, indicating oxygen stress. Understanding the adaptation strategies of plants to flooded soils is essential for breeding flood-tolerant crops and enhancing agricultural resilience to climate change-induced flooding.

4.3.2. Human-Led Mitigation and Adaptation Strategies

Mitigation and adaptation strategies are essential for managing flooding impacts on agriculture and enhancing resilience to climate change. These may include strategies, such as improved drainage and water management practices, soil amendments, and rehabilitation techniques, best management practices (BMPs), such as reduced tillage and cover crops, and the development of flood-tolerant crop varieties.

Drainage and water management practices are critical for reducing flooding impacts on agricultural productivity and soil health. Surface drainage systems, such as ditches, channels, and contour drains, facilitate excess water removal from fields and prevent waterlogging [141]. Subsurface drainage systems, such as tile drains and French drains, lower water tables and improve soil aeration in waterlogged soil. Water management practices, such as controlled drainage, irrigation scheduling, and floodplain management, optimize water use efficiency and mitigate flood risks in agricultural landscapes. Implementing drainage and water management practices is essential for enhancing agricultural resilience to flooding and sustaining soil health in flood-prone areas.

Soil amendments and rehabilitation techniques are effective for restoring soil fertility and ecosystem functions in flood-affected areas. Organic amendments, such as compost, manure, and biochar, improve soil structure, nutrient retention, and microbial activity in degraded soils. Liming materials, such as calcium carbonate and gypsum, alleviate soil acidity and improve nutrient availability in acid-sulfate soils. Soil rehabilitation techniques, such as reforestation, agroforestry, and wetland restoration, enhance ecosystem resilience and biodiversity in degraded landscapes.

The impacts of BMPs, such as reduced tillage and cover crop management, are usually assessed based on nutrient cycling, soil fertility, water quality, erosion control, soil health, and seldom on the flooding risk at the watershed. The role of BMPs in changing flow regimes and discharge may affect the frequency of downstream flood events [142]. Other agricultural BMPs, including grass waterways, wetland restoration, and riparian buffers, can provide a greater reduction in nutrient exports and other co-benefits following flooding [143]. Changes from perennials to annual row crops and increases in landscape-scale drainage contribute to the rainfall-runoff response at the watershed scale, resulting in enhanced erosive rivers agricultural landscapes [144]. The introduction of switchgrass and different crop rotations into a corn and soybean-dominated landscape resulted in a reduction in both the number of flood events and frequency of severe events at the eight-digit watershed level [145]. The establishment of BMPs, such as paralleled terraces, grassed waterways, and detention ponds, reduced peak flow at the eight-digit watershed scale [146].

Developing resilient crop varieties through breeding programs is essential for enhancing agricultural productivity and food security in flood-prone regions. Breeding for flood tolerance traits, such as submergence tolerance, waterlogging tolerance, and root aeration capacity, improves crop performance and yield stability under flooding stress. Marker-assisted selection and genomic approaches enable the rapid identification and introgression of flood tolerance genes into elite crop germplasm. Participatory breeding programs engage farmers and stakeholders in the selection of crop varieties and their evaluation, promoting the adoption of flood-tolerant crops and enhancing agricultural resilience to climate change-induced flooding [93].

5. Technological Advances in Assessing Flooding

Technological advances play a crucial role in assessing flooding dynamics and impacts on crop production in agricultural landscapes.

5.1. Remote Sensing and GIS Applications

Remote sensing and GIS applications enable the spatial and temporal monitoring of flooding extent, soil moisture, and vegetation dynamics in agricultural landscapes. Satellite imagery, such as optical and radar data, provides information on flood inundation, land cover changes, and crop growth patterns [147]. Unmanned aerial vehicles (UAVs) and drones offer high-resolution imagery for assessing flood impacts and crop damage at field scales [148]. GIS-based hydrological models integrate remote sensing data with spatially explicit information on soil properties, topography, and land use, enabling flood risk assessments and mitigation planning [149]. Implementing remote sensing and GIS applications is essential for improving flood monitoring and management in agricultural landscapes.

5.2. Sensor Technologies for Soil Monitoring

Sensor technologies for soil monitoring provide real-time data on soil moisture, temperature, and nutrient levels in agricultural fields. Soil moisture sensors, such as capacitance probes and time domain reflectometry (TDR) sensors, measure soil water content and enable irrigation scheduling and water management [150]. Soil temperature sensors monitor soil thermal regimes and facilitate phenological modeling and crop growth simulations. Nutrient sensors, such as ion-selective electrodes and nutrient analyzers, quantify nutrient concentrations in soil solutions and inform fertilizer application and nutrient management [151]. Wireless sensor networks (WSNs) and Internet of Things (IoTs) platforms enable the remote monitoring of soil conditions and facilitate data-driven decision making in precision agriculture [152]. Implementing sensor technologies for soil monitoring is essential for optimizing agricultural practices and enhancing soil health in flood-prone areas.

5.3. Numerical Modeling for Predicting Flooding and Nutrient Effects

Numerical modeling plays a crucial role in predicting flooding dynamics and nutrients, including the effects of phosphorus on water quality and ecosystem health. Hydrological models, such as SWAT and MIKE SHE, simulate rainfall-runoff processes, streamflow routing, and flood inundation mapping in agricultural watersheds [153]. Soil erosion models, such as RUSLE and WEPP, quantify sediment transport and phosphorus losses from agricultural fields to receiving water bodies [154]. Biogeochemical models, such as PnET-BGC and INCA-P, simulate phosphorus cycling, nutrient dynamics, and eutrophication processes in aquatic ecosystems [155]. Integrated modeling frameworks combine hydrological, erosion, and biogeochemical models to assess the cumulative impacts of flooding and P dynamics on water quality and ecosystem services [156]. Implementing numerical modeling for predicting flooding and P effects is essential for informing land management practices and water resource planning in agricultural landscapes.

5.4. Flood Susceptibility Assessment

Flood susceptibility analysis methods can be classified into three main categories, including (1) hydrological and hydrodynamic models, (2) multi-criteria decision analysis, and (3) machine learning models [157]. Hydrological and hydrodynamic models are time-consuming and require detailed datasets to enable flood magnitude simulations [158]. In contrast, the multi-criteria decision analysis method relies on expert opinions and encounters constraints associated with the redundancy of layer data and includes subjectivity and large calculations to simulate flood susceptibility [159]. Finally, machine learning methods such as Random Forest [160], Support Vector Machines [161], Artificial Neural Networks [24,162]), Extreme Gradient Boosting [163], and Decision Trees [164] are gaining popularity in flood susceptibility assessments. These models perform flood susceptibility analysis by establishing a point-to-point relationship of flood occurrences vs. corresponding explanatory factors. Machine learning models are able to unveil intricate relationships between variables within small samples, allowing extrapolations to large datasets [157].

6. Challenges and Gaps in Current Knowledge

Challenges and gaps in our current knowledge exist in understanding flooding dynamics, nutrient cycling, and their impacts on agriculture and the environment.

6.1. Limitations in Existing Research

Existing research on flooding dynamics and nutrient cycling, including N and P, often lacks spatial and temporal resolution, hindering the accurate assessment of flood risks and nutrient losses in agricultural landscapes. Limited long-term monitoring data and inconsistent methodologies make it challenging to quantify the cumulative impacts of flooding on soil health, water quality, and ecosystem resilience. There is limited knowledge of how different crop species and varieties respond to varying durations and intensities of flooding, particularly at different growth stages. There is also a lack of detailed studies on how flooding affects soil microbial communities and their role in nutrient transformation and plant health. Knowledge gaps also exist in understanding the interactions between flooding, climate change, land use, and nutrient dynamics, requiring interdisciplinary research approaches and collaborative efforts to address complex environmental challenges.

6.2. Critical Gaps in Understanding Flooding and Nutrient Impacts

Critical gaps exist in understanding flooding and nutrients impact dynamics on agriculture and the environment. Uncertainties in predicting flood frequencies, magnitudes, and durations complicate flood risk assessment and mitigation planning in agricultural watersheds [165]. Inadequate knowledge of nutrient sources, transport pathways, and transformation processes limits the effective management of N and P pollution and eutrophication in freshwater ecosystems [166]. Understanding the interactions between flooding, nutrient dynamics, and ecosystem responses requires integrated research approaches and interdisciplinary collaborations across natural and social sciences.

6.3. Methodological Challenges and Areas for Improvement

Methodological challenges exist in assessing flooding dynamics, nutrient cycling, and their impacts on agriculture and the environment. Standardized protocols and guidelines for data collection, analysis, and reporting are needed to ensure consistency and comparability across studies. Integrating field observations, laboratory experiments, remote sensing data, and numerical modeling approaches can provide holistic insights into flooding processes and nutrients, including N and P dynamics, in agricultural landscapes [167]. Developing innovative methodologies, such as sensor networks, high-throughput sequencing, and machine learning algorithms, can enhance our understanding of complex environmental systems and inform evidence-based decision making [168]. Addressing methodological challenges and advancing research methodologies are essential for improving our understanding of flooding and nutrient impact dynamics and supporting sustainable land and water management practices.

7. Future Perspectives and Research Directions

Future perspectives and research directions should focus on emerging technologies, climate change projections, interdisciplinary approaches, and capacity building to address pressing environmental challenges. Emerging technologies offer new opportunities for assessing flooding dynamics and nutrient impacts, including N and P, on agriculture and the environment. This review provides an overview of remote sensing and GIS applications, sensor technologies for soil monitoring, and numerical modeling for predicting flooding and its effects, followed by discussions on the challenges in current knowledge and future research directions. Integrating climate change projections into research is essential for understanding future trends in flooding, nutrient dynamics, and their impacts on agriculture and the environment. Interdisciplinary approaches are also crucial for gaining a comprehensive understanding of flooding dynamics, nutrient cycling, and their impacts on agriculture and the environment. In conclusion, flooding events and nutrient dynamics have significant implications for agriculture, soil health, water quality, and ecosystem sustainability. Addressing these challenges requires interdisciplinary research efforts, innovative technologies, and collaborative approaches to inform evidence-based decision making and support sustainable land and water management practices.

8. Conclusions

Flooding represents one of the most significant hazards worldwide. Human activities, including changes in land cover, the alterations of drainage systems, and deforestation, have also exacerbated flooding risks in recent years. From 2010 to 2013, the majority of flooding events were influenced by climate change, amplifying occurrences in some regions while suppressing them in others. Flooding impacts both human communities and ecosystems. According to the FAO [1], between 2008 and 2018, farmers worldwide lost approximately USD 21 billion in crops and livestock as a result of floods. The sensitivity of different crops to waterlogging varies significantly across growth stages. Flooding events have significant impacts on soil's physical, chemical, and biological properties. Flooding impacts soil structure and aggregation by altering its resistance to slaking. Flooding also affects SOM and nutrient cycling, including N and P. Anaerobic conditions are the driving factors controlling the dynamics and cycling of nutrients in flooded conditions. The availability of nutrients, including macro- and micro-nutrients, in flooded soils is lower than that in well-oxygenated soils. The assessment of flooding dynamics and impacts on crop production in agricultural landscapes can be improved using advanced technology. Remote sensing and GIS applications can be used to monitor flooding, while sensor technologies are essential for optimizing agricultural practices and enhancing our understanding of soil health in flood-prone areas. Machine learning models, with their ability to unveil intricate relationships between variables, are also excellent tools to enhance our understanding and monitoring of flooding in agricultural areas. Knowledge gaps exist in the interactions between the flooding duration, climate change, land use, plant growth stages, and nutrient dynamics. Addressing these gaps requires interdisciplinary research approaches and collaborative efforts. This gap in understanding impedes the development of precise, targeted agricultural management strategies to mitigate the adverse effects of waterlogging. Raising awareness, particularly among the young generation, is crucial for understanding and addressing our impact on climate change, flooding events, and agroecosystems. Future research should focus on developing innovative approaches to manage flooding in agricultural landscapes, incorporating advanced technologies, and promoting sustainable practices to enhance resilience against waterlogging.

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