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Remediation measures of waterlogged soils and its distribution, categories in the world

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Abstract
Waterlogged soils represent one of the most challenging constraints to global food security and sustainable land management, affecting an estimated 640 million hectares worldwide. This comprehensive review synthesizes current knowledge on the global distribution, paedogenic characterization, and reclamation strategies of waterlogged soils. We examine the geomorphological and climatic drivers of waterlogging across major agroecological zones, analyse soil morphological, physical, chemical, and biological characteristics under prolonged saturation, and critically evaluate established and emerging reclamation technologies. Evidence from over 150 peer-reviewed studies published between 1990 and 2024 is integrated. Key findings indicate that anaerobic conditions induced by waterlogging trigger cascading redox reactions—including iron and manganese reduction, denitrification, and methanogenesis—that profoundly alter nutrient cycling, soil structure, and microbial communities. Reclamation success depends on accurate diagnosis of waterlogging cause, integration of drainage engineering with biological and chemical amendments, and long-term monitoring. Future directions include precision drainage design, climate-adaptive management, and leveraging remote sensing for large-scale waterlogging mapping. This review serves as a reference for soil scientists, agronomists, and land-use planners managing waterlogged landscapes.

Keywords: Gleysols, soil redox chemistry, subsurface drainage, land reclamation, hydric soils, anoxia, wetland management, soil classification

Introduction

The extended or permanent saturation of soil pores with water, which results in oxygen deprivation and significantly changed biogeochemical processes, is a characteristic of waterlogged soils. These soils constitute an important interface between terrestrial and aquatic ecosystems and make up a sizable portion of the Earth's terrestrial surface (Vepraskas & Craft, 2016) [60]. Between 570 and 700 million hectares of waterlogged and hydromorphic soils are thought to exist worldwide, making up 4–5% of all ice-free land surface (FAO, 2022) [25].

It is impossible to overestimate the importance of wet soils for agriculture and the environment. Waterlogging is a major biophysical limitation that causes production penalties of 20–80% in cereal crops in developing countries in South and Southeast Asia, Sub-Saharan Africa, and Latin America (Setter & Waters, 2003) [53]. In addition to acting as carbon sinks and vital reservoirs of biodiversity, these soils also control hydrological cycles. However, waterlogging is a type of land degradation that needs immediate restoration when it is caused by human activity, such as poor land grading or insufficient irrigation management (GLASOD, 1990; Ghassemi *et al*., 1995) [15].

Since the groundbreaking work of Ponnamperuma (1972) [38], who methodically detailed the electrochemical alterations accompanying soil submergence, the scientific understanding of wet soils has advanced significantly. Soil morphological diagnosis (Vepraskas, 1992) [59], hydrological modelling (Skaggs *et al*., 2012) [54], remote sensing-based mapping (Bartsch *et al*., 2016) [58], and integrated reclamation technology (Nijland *et al*., 2005; Ritzema, 2016) [34, 45] have all advanced in the decades that followed. Despite these advancements, there is still a dearth of a comprehensive worldwide synthesis that looks at distribution patterns, diagnostic characterisation, and reclamation effectiveness.

This review aims to: (1) describe the global distribution of waterlogged soils and their climatic-geomorphological drivers; (2) characterize the physical, chemical, and biological properties of waterlogged soils; (3) examine diagnostic criteria and classification systems; and (4) critically evaluate reclamation strategies and their agronomic and environmental outcomes. A total of over 150 peer-reviewed publications, FAO reports, and international soil survey data published between 1990 [16] and 2024 were reviewed. Special attention is given to integrating knowledge across soil taxonomy frameworks (WRB and USDA Soil Taxonomy) and across major global agroecological zones.

Scope and Objectives: Both naturally occurring hydromorphic soils and artificially waterlogged agricultural areas are included in this overview of mineral and organic waterlogged soils in temperate, tropical, and arid/semi-arid zones. Despite its similarities, coastal wetlands and tidal marshes are only discussed in relation to acid sulphate soils and tidal drainage. Submerged aquatic soils (below permanent water bodies) are not the main focus of the review.

Soil colour map of India (Different coloures of soil in India)

Training of EF & Awareness to HCL Consultency for soil testing by SMS, Soil Science Dr. Trilok Nath Rai at KVK, Hardoi-II

Global Distribution of Waterlogged Soils

1. **Extent and Geographic Patterns:** The equilibrium between water inputs (precipitation, irrigation, groundwater recharge) and outputs (evapotranspiration, surface runoff, deep drainage) essentially governs the distribution of wet soils. According to FAO's 2022 [25] projection, 640 million hectares of soils worldwide suffer from periodic or persistent waterlogging, with the tropics and subtropics accounting for about 350 million of these hectares. Strong continental and latitudinal gradients can be seen in the spatial pattern of occurrence, with irrigated river basins, boreal peatlands, and humid tropical lowlands having the largest populations (Kottek *et al*., 2006) [28].

2. **Factors Controlling Waterlogging:** Several interacting factors govern the distribution and intensity of soil waterlogging. These can be broadly classified into climatic, geomorphological, paedogenic, and anthropogenic drivers (Rengasamy, 2002) [44].

Climatic Drivers: The primary climatic factor is the precipitation regime. Seasonal saturation can occur for three to six months a year in soils in monsoonal climates, especially in the Indo-Gangetic Plains, Mekong Delta, and West African lowlands (Sahrawat, 2004) [48]. Waterlogging occurs in temperate oceanic regions (such as northwest Europe) when low-intensity rainfall persists and wintertime evapotranspiration is decreased. Snowmelt and the limited permeability of frozen or permafrost-affected subsoils are the main causes of waterlogging in boreal regions (Vitt *et al*., 2000) [62].

Characterization of Waterlogged Soils: Characterization of waterlogged soils spans morphological, physical, chemical, and biological dimensions. The transformations induced by waterlogging represent a cascade of interlinked processes that collectively define the diagnostic properties recognized in modern soil classification systems (Fiedler & Sommer, 2004) [13].

Morphological Characteristics: The visual and tactile properties of waterlogged soils provide valuable diagnostic information accessible through field examination. The most distinctive morphological features include gleying, mottles (redoximorphic features), and organic matter accumulation (Vepraskas, 1992) [59].

Gleying: The term "gleying" describes the blue-grey or greenish hue of soil that results from the anaerobic conversion of ferric iron (Fe^{3+}) to ferrous iron (Fe^{2+}). Ferrous iron is mobilized in soil solution and has characteristic Munsell color values of 5Y, 5BG, or 5GY with low chroma (<2). Under extended saturation, it may precipitate as vivianite ($Fe_3(PO_4)_2 \cdot 8H_2O$) or siderite ($FeCO_3$). According to USDA Soil Taxonomy, Gleying is a required diagnostic characteristic for Gleysols in the WRB and Aquic suborders (IUSS Working Group WRB, 2022) [25]. The average water table position throughout decadal periods is inferred from the depth at which gleying starts.

Redoximorphic Features (Mottles): Zones of localized oxidation (orange to reddish-brown) and reduction (grey) within the soil matrix are represented by mottles, which can indicate shifting water tables or the preferred flow of oxygen along root channels and macropores. Formally known as redoximorphic concentrations and depletions, these characteristics develop over years to decades and continue to exist even when drainage is improved (Vepraskas & Faulkner, 2001) [61]. In order to reconstruct past water table dynamics and guide drainage design, their color, quantity, and vertical distribution are utilized.

Physical Characteristics: Prolonged waterlogging alters soil physical properties through aggregate disruption, pore clogging, and altered bulk density. The major physical changes are summarized alongside chemical changes in Table 1.

Table 1: Comparative physicochemical properties of well-drained versus waterlogged soils and their agronomic/ecological consequences. Values represent typical ranges; actual values vary by soil type and duration of saturation (Ponnamperuma, 1972; Reddy & DeLaune, 2008).

Property	Well-Drained Soil	Waterlogged Soil	Ecological/Agronomic Impact
Soil Eh (mV)	+200 to +700	-200 to +200	Controls redox reactions; Fe/Mn reduction
Soil pH	5.5–7.5	6.5–7.5 (neutralization)	Nutrient availability shifts
O2 diffusion rate	>40 μg cm^{-2} min^{-1}	<10 μg cm^{-2} min^{-1}	Root anoxia, aerobic microbial death
CO2 concentration	0.03–0.3%	5–20%	Root respiration inhibition
Methane (CH4)	Absent/trace	High (0.1–5 μmol/L)	Greenhouse gas emission
Available N (NO_3^-)	Moderate–high	Low (denitrification)	Nitrogen loss, crop yield reduction
Available Fe2+	Negligible	Very high (toxic)	Iron toxicity in crops
Available Mn2+	Low	High	Manganese toxicity
Bulk Density (g/cm^3)	1.2–1.6	0.8–1.3	Compaction and structure loss
Hydraulic conductivity	Moderate–high	Very low	Poor drainage perpetuates flooding

Waterlogging causes a 15–40% reduction in macroporosity due to swelling of clay particles, microbial gas production (CO2, CH4), and dispersal of colloids upon wetting (Horn & Smucker, 2005) [20]. Hydraulic conductivity may decrease by 1–3 orders of magnitude compared to drained states. Surface soil compaction, paradoxically common in waterlogged arable soils due to machinery traffic on wet ground, further reduces infiltration rates, creating self-reinforcing waterlogging cycles.

Chemical Characteristics and Redox Biogeochemistry: The most profound transformations in waterlogged soils are chemical. When soil pores are water-saturated, diffusion of oxygen (O_2) into soil drops to approximately 10^{-4} times its rate in air (Greenwood, 1961) [17]. Microbial respiration rapidly depletes residual O_2 within hours to days, establishing anaerobic conditions. The soil redox potential (Eh) then falls progressively as successive terminal electron acceptors are reduced in a thermodynamically predictable sequence (Ponnamperuma, 1972; Reddy & DeLaune, 2008) [38, 43]:

O_2 reduction (+600 to +400 mV) → NO_3^- denitrification (+400 to +200 mV) → MnO_2 reduction (+400 to +200 mV) → $Fe(OH)_3$ reduction (+200 to -100 mV) → SO_4^{2-} reduction (-100 to -200 mV) → CH_4 production (-200 to -300 mV)

Each of these reductive steps has significant consequences for nutrient availability, toxicity, and greenhouse gas emissions. Denitrification leads to substantial losses of soil nitrogen (N_2O and N_2 gas), compromising fertilizer use efficiency. Iron and manganese reduction release soluble Fe^{2+} and Mn^{2+} into the rhizosphere at concentrations potentially toxic to crops; submergence injury in rice, for example, is often exacerbated by high Fe^{2+} (Sahrawat, 2004) [48]. Sulfate reduction generates hydrogen sulfide (H_2S), which is directly phytotoxic and contributes to 'bronzing' disease in lowland rice (IRRI, 2015) [24]. Methanogenesis under prolonged saturation makes rice paddies and peatlands significant sources of atmospheric methane, contributing approximately 10–15% of global CH_4 emissions (Kirschke *et al*., 2013) [27].

Biological Characteristics: Soil microbial populations are significantly altered by waterlogging, which inhibits aerobic decomposers and promotes anaerobic fermenters, iron/sulfate reducers, and methanogens. Soil enzyme activity is drastically decreased, especially oxidase enzymes (laccase, peroxidase), which slows the breakdown of organic matter and leads to the buildup of partially decomposed organic molecules (peat formation in systems that are continuously wet) (Freeman *et al*., 2001) [14]. The soil food web changes: anaerobic protozoans and nematode populations change into functional guilds adapted to low-oxygen circumstances, whereas earthworm activity drastically decreases within 24 to 48 hours of saturation (McLaughlin & Kinzel, 1999) [31].

Root responses to waterlogging include the formation of aerenchyma (gas-filled cortical tissue), adventitious roots, and hypertrophied lenticels, enabling oxygen transport from shoot to root tip in tolerant species (Armstrong *et al*., 1994) [1]. Intolerant crops exhibit ethylene-mediated stomatal closure, leaf epinasty, root death, and ultimately whole-plant senescence when anaerobiosis persists beyond species-specific thresholds.

Classification and Diagnostic Criteria: Major soil classification systems handle waterlogged soils through specific diagnostic horizons and properties. Table 3 presents the principal diagnostic features used to identify waterlogged soils under both the World Reference Base (WRB) and USDA Soil Taxonomy frameworks.

Table 2: Diagnostic morphological features of waterlogged soils and their equivalents in the WRB (IUSS Working Group, 2022) and USDA Soil Taxonomy (Soil Survey Staff, 2022)

Diagnostic Feature	Observation	Soil Depth (cm)	Classification	WRB/USDA Equivalent
Gleying (blue-grey)	Ferrous iron reduction	0–100 cm	Gleysols	Aquents/Aquepts
Mottles (orange)	Fe/Mn oxidation zones	20–80 cm	Stagnosols	Fragiaquults
Plinthite	Hard iron concretions	40–100 cm	Plinthosols	Plinthaquults
Peat/Muck layer	Organic accumulation	0–40 cm	Histosols	Histosols (USDA)
Albic horizon	Bleached sandy layer	5–30 cm	Planosols	Argiaquolls
Sulfidic material	Sulfide smell (H2S)	20–80 cm	Thionic Gleysols	Sulfaquents

Under WRB 2022, Gleysols are the primary reference soil group for waterlogged soils, with qualifiers such as Thionic (sulfidic), Folic (peat-rich), and Stagnic (perched water table) modifying the base group. Histosols, defined by the presence of an histic horizon (>12–18% organic C, depending on clay content) deeper than 40 cm in the upper

80 cm, constitute a separate major group. In USDA Soil Taxonomy, waterlogged soils are distributed across multiple orders including Histosols, Inceptisols (Aquepts), Entisols (Aquents), Mollisols (Aquolls), Alfisols (Aqualfs), and Ultisols (Aquults), with the 'Aquic' modifier denoting periodic saturation and reducing conditions (Soil Survey Staff, 2022) [55].

Processes and Interactions in Waterlogged Soils Understanding waterlogged soils requires appreciation of how physical, chemical, and biological processes interact across temporal scales from minutes (gas exchange) to millennia (peat formation).

1. **Green House Emissions:** Waterlogged soils are major global sources of CO2, CH4, and N2O. The low decomposition rates under anaerobia (compared to aerobic decomposition) limit CO2 emissions, but CH_4 emissions can be very significant, especially from northern peatlands (Blodau, 2002) and rice paddies (Neue, 1993) [4, 33]. N2O emissions, which are mostly linked to nitrification-denitrification interfaces at the oxic-anoxic boundary, vary significantly depending on nitrogen inputs and drainage status (Saggar *et al*., 2013) [47]. Global estimates indicate that natural and managed waterlogged soils collectively contribute about 20–25% of total atmospheric CH_4. Particularly concerning are the climate-carbon feedbacks of tropical peat drainage: draining 1 ha of peat forest releases an estimated 50–100 Mg C over the next ten years due to rapid oxidation (Page *et al*., 2011) [35].

2. **Nutrient Cycling:** The nitrogen cycle is particularly disrupted by waterlogging. Nitrification ($NH_4^+ \rightarrow NO_3^-$) is an aerobic process that ceases under anaerobia, allowing ammonium to accumulate. Simultaneously, denitrification converts NO_3^- to N_2 and N_2O gases, creating a net nitrogen sink. This has important agronomic implications: urea-based fertilizers applied to waterlogged soils can experience >50% N loss through volatilization and denitrification (Sahrawat, 2008) [49]. Phosphorus availability initially increases under anaerobic conditions due to reductive dissolution of Fe-P complexes (Reddy & DeLaune, 2008) [43], potentially causing eutrophication of adjacent water bodies through P release from saturated sediments.

Reclamation of Waterlogged Soils: Reclamation aims to restore waterlogged soils to productive or ecologically functional states by removing excess water, improving soil aeration, and rehabilitating soil biological and chemical properties. A spectrum of approaches exists, ranging from engineering-intensive drainage to low-input biological methods. Effective reclamation requires accurate diagnosis of waterlogging cause and type, followed by selection of context-appropriate strategies (Ritzema, 2016) [45].

1. **Surface Drainage:** Surface drainage involves reshaping land to direct excess water into surface channels. Land smoothing and grading to achieve slopes of 0.1–0.3% are standard practices in lowland rice cultivation areas and subsistence farming systems in sub-Saharan Africa (Zhu *et al*., 2012) [65]. Open drains at 0.5–1.5 m depth can handle peak discharge events but require regular maintenance to remain effective. In paddy systems, controlled surface drainage is combined with bund management to regulate ponding depth for weed suppression while avoiding prolonged anoxia detrimental to non-rice crops.

2. **Subsurface Drainage:** Subsurface pipe drainage, using perforated PVC or clay tile pipes installed at 0.6–1.5 m depth and 10–80 m spacing, is the most effective method for controlling water table depth in agricultural soils. Design follows Hooghoudt's equation or the Ernst formula for steady-state drainage (Skaggs *et al*., 2012) [54]. In the Netherlands, the United States Corn Belt, and Punjab (India/Pakistan), large-scale subsurface drainage programs have converted millions of hectares of hydromorphic soils to highly productive arable land. However, subsurface drainage is capital-intensive (USD 800–2000/ha) and may accelerate nitrate leaching to groundwater if not managed with controlled drainage structures (Skaggs *et al*., 2012) [54].

3. **Chemical Amendments:** Chemical approaches to reclamation target soil structural improvement, pH adjustment, or remediation of specific toxic compounds. Gypsum ($CaSO_4{\cdot}2H_2O$) applied at 2–10 t/ha is the primary amendment for sodic-waterlogged soils, where Na^+ dispersion of clay particles suppresses hydraulic conductivity. Calcium ions from gypsum displace sodium on cation exchange sites, flocculating clays and restoring macroporosity (Qadir *et al*., 2001) [41]. Lime application ($CaCO_3$ or CaO) corrects soil acidity in acid sulfate soils, where pyrite oxidation upon drainage releases sulfuric acid, dropping pH to <3.5 and mobilizing toxic Al^{3+} and Fe^{2+} (Dent & Pons, 1995) [6]. Organic matter amendments (compost, biochar) have also shown promise in improving soil water regulation and microbial rehabilitation.

4. **Biological and Agroecological Methods:** Biological reclamation exploits plant and microbial processes to improve soil conditions. Deep-rooted trees such as Eucalyptus camaldulensis and Populus spp. can lower shallow water tables through high transpiration rates (biological drainage), achieving water table reductions of 0.5–1.5 m in suitable conditions (Heuperman, 1999) [18]. This approach is particularly relevant in peri-urban areas and for saline-waterlogged lands in South Asia. In Pakistan's Indus Basin, agroforestry with Eucalyptus achieved water table control comparable to tube-well drainage at 10–20% of the cost.

Phytoremediation using wetland macrophytes (Phragmites australis, Typha latifolia, Scirpus spp.) is employed on waterlogged soils contaminated with heavy metals or persistent organic pollutants. These plants accumulate contaminants in root and shoot biomass and, through root-mediated oxidation, create oxidized rhizosphere zones that immobilize Fe, Zn, and Pb (Vymazal, 2014) [63]. Constructed wetland systems based on this principle are now widely used for treatment of agricultural runoff.
Green manuring with flood-tolerant legumes (Sesbania, Astragalus) improves nitrogen supply and organic matter

content in waterlogged paddy soils between rice cycles (Ponnamperuma, 1984) [39]. The Azolla-Anabaena symbiosis, a pteridophyte-cyanobacteria N_2 fixation system, provides additional biological nitrogen in flooded rice systems, reducing fertilizer requirements by 25–40 kg N/ha (Liu *et al*., 2008) [30].

Regional Case Studies -South Asia: Waterlogging in the Indo-Gangetic Plains: The Indo-Gangetic Plains spanning India, Pakistan, Bangladesh, and Nepal represent perhaps the world's most extensively waterlogged agricultural region. An estimated 8.5 million hectares in Pakistan alone suffer from waterlogging and secondary salinity, primarily in the Indus Irrigation System (Qureshi *et al*., 2008) [42]. The SCARP (Salinity Control and Reclamation Project) program, implemented between 1959 and 2002, installed over 13,000 public tube-wells and 50,000 km of surface drains, reclaiming approximately 3.8 million hectares. However, unsustainable groundwater pumping, inadequate maintenance, and political economy challenges have limited long-term success. Lessons include the need for farmer participation, integration of biological and engineering approaches, and cost recovery mechanisms (Sarfraz *et al*., 2010) [50].

Conclusion

Several overarching conclusions emerge:

- Waterlogged soils are globally significant, covering ~640 million hectares across tropical, temperate, and boreal zones, with distribution controlled by the interplay of climate, geomorphology, pedology, and human land management.
- Waterlogging induces cascading chemical transformations following the thermodynamic sequence of electron acceptor reduction: from O_2 to CH_4, with major consequences for nutrient cycling, toxicity, and greenhouse gas emissions.
- Diagnostic characterization using redoximorphic features, soil Eh measurements, and classification systems (WRB, USDA Soil Taxonomy) provides a robust framework for identifying and mapping waterlogged soils.
- Reclamation success requires accurate diagnosis of waterlogging cause followed by selection of appropriate measures from a spectrum ranging from subsurface pipe drainage to biological methods, with integrated approaches showing the highest long-term sustainability.
- Regional case studies from South Asia, West Africa, Europe, and Southeast Asia demonstrate both the transformative potential of drainage-based reclamation and its ecological risks, particularly in peatland contexts.
- Future advances in remote sensing, smart drainage technology, and paludiculture offer new paradigms for managing waterlogged soils in the context of climate change and sustainable development goals.

Waterlogged soil management is at the nexus of ecosystem protection, climate change mitigation, and food security. It will take interdisciplinary cooperation between soil scientists, hydrologists, ecologists, economists, and policymakers to resolve the conflicts between agricultural productivity, carbon storage, and biodiversity in wet landscapes. In addition to identifying priority areas for future study and funding, this analysis lays the groundwork for such collaboration.

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References

1. Armstrong W, Brändle R, Jackson MB. Mechanisms of flood tolerance in plants. Acta Botanica Neerlandica,1994:43(4):307–358.
2. Arrouays D, Grundy MG, Hartemink AE, *et al*. GlobalSoilMap: Toward a fine-resolution global grid of soil properties. Advances in Agronomy,2014:125:93–134.
3. Bartsch A, Trofaier AM, Hayman G, *et al*. Detection of open water dynamics with ENVISAT ASAR in support of land surface modelling at high latitudes. Biogeosciences,2016:9:703–714.
4. Blodau C. Carbon cycling in peatlands: A review of processes and controls. Environmental Reviews,2002:10(2):111–134.
5. Boelter DH. Physical properties of peats as related to degree of decomposition. Soil Science Society of America Journal,1969:33(4):606–609.
6. Dent DL, Pons LJ. A world perspective on acid sulphate soils. Geoderma,1995:67(3–4):263–276.
7. El-Sadek A. Upscaling field scale hydrology and water quality modelling to catchment scale. Water Resources Management,2007:21(1):149–169.
8. Evans RO, Skaggs RW, Gilliam JW. Controlled drainage management guidelines for improving drainage water quality. North Carolina Cooperative Extension Service AG, 2009, 25p.
9. FAO. World Reference Base for Soil Resources. World Soil Resources Reports No. 103. FAO, Rome, 2006.
10. FAO. AQUASTAT Database. Food and Agriculture Organization, Rome. Accessed 2024, 2014.
11. FAO. The Future of Food and Agriculture – Trends and Challenges. FAO, Rome, 2017.
12. FAO. Soils for Nutrition: State of the Art. FAO, Rome, 2022.
13. Fiedler S, Sommer M. Water and redox conditions in wetland soils–Their influence on pedogenic oxides and morphology. Soil Science Society of America Journal,2004:68(1):326–335.
14. Freeman C, Ostle N, Kang H. An enzymatic 'latch' on a global carbon store. Nature,2001:409:149.
15. Ghassemi F, Jakeman AJ, Nix HA. Salinisation of Land and Water Resources: Human Causes, Extent, Management and Case Studies. CABI, Wallingford, 1995.
16. GLASOD. Global Assessment of Soil Degradation. UNEP/ISRIC, Nairobi, 1990.
17. Greenwood DJ. The effect of oxygen concentration on the decomposition of organic materials in soil. Plant and Soil,1961:14(4):360–376.

18. Heuperman AF. Hydraulic gradient reversal by trees in shallow water-table areas and repercussions for the sustainability of tree-growing systems. Agricultural Water Management,1999:39(2–3):153–167.
19. Hooijer A, Page S, Jauhiainen J, *et al*. Subsidence and carbon loss in drained tropical peatlands. Biogeosciences,2012:9(3):1053–1071.
20. Horn R, Smucker A. Structure formation and its consequences for gas and water transport in unsaturated arable and forest soils. Soil and Tillage Research,2005:82(1):5–14.
21. Huijnen V, Wooster MJ, Kaiser JW, *et al*. Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997. Scientific Reports,2016:6:26886.
22. IGBP-DIS. SoilData v.0: A Program for Creating Global Soil Property Databases. IGBP Global Soils Data Task CD-ROM, 1999.
23. IPCC. Climate Change The Physical Science Basis. Cambridge University Press, 2021.
24. IRRI. Iron Toxicity in Lowland Rice. International Rice Research Institute, Los Baños, 2015.
25. IUSS Working Group WRB. World Reference Base for Soil Resources. International Union of Soil Sciences, Vienna, 2022.
26. Kiepe P. No runoff, no soil loss: soil and water conservation in hedgerow barrier systems. Tropical Resource Management Papers, Wageningen University, 1995.
27. Kirschke S, Bousquet P, Ciais P, *et al*. Three decades of global methane sources and sinks. Nature Geoscience,2013:6:813–823.
28. Kottek M, Grieser J, Beck C, *et al*. World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift,2006:15(3):259–263.
29. Lehner B, Döll P. Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology,2004:296(1–4):1–22.
30. Liu CC, Shao HB, Gu JD, *et al*. Contribution of biological nitrogen fixation to nitrogen budget in rice paddy in China. Pedosphere,2008:18(4):530–537.
31. McLaughlin DB, Kinzel PJ. Effects of flooding on soil communities of bur oak floodplain forests. Wetlands,1999:19(1):196–208.
32. Mulla DJ. Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. Biosystems Engineering,2013:114(4):358–371.
33. Neue HU. Methane emission from rice fields. BioScience,1993:43(7):466–474.
34. Nijland HJ, Croon FW, Ritzema HP. Subsurface Drainage Practices: Guidelines for the Implementation, Operation and Maintenance of Subsurface Pipe Drainage Systems. ILRI Publication 60, Wageningen, 2005.
35. Page SE, Rieley JO, Banks CJ. Global and regional importance of the tropical peatland carbon pool. Global Change Biology,2011:17(2):798–818.
36. Patel N, Srivastava PK. Improved classification of waterlogged areas using machine learning and Landsat-8 imagery. Remote Sensing Letters,2020:11(2):112–121.
37. Pekel JF, Cottam A, Gorelick N, Belward AS. High-resolution mapping of global surface water. Nature,2016:540:418–422.
38. Ponnamperuma FN. The chemistry of submerged soils. Advances in Agronomy,1972:24:29–96.
39. Ponnamperuma FN. Effects of flooding on soils. In T.T. Kozlowski (Ed.), Flooding and Plant Growth. Academic Press, New York, 1984.
40. Prigent C, Papa F, Aires F, *et al*. Global inundation dynamics inferred from multiple satellite observations. Journal of Geophysical Research,2007:112:D12107.
41. Qadir M, Noble AD, Schubert S, *et al*. Sodicity-induced land degradation and its sustainable management: Problems and prospects. Land Degradation & Development,2001:17(6):661–676.
42. Qureshi AS, McCornick PG, Sarwar A, Sharma BR. Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan. Water Resources Management,2008:24(6):1551–1569.
43. Reddy KR, DeLaune RD. Biogeochemistry of Wetlands: Science and Applications. CRC Press, Boca Raton, 2008.
44. Rengasamy P. Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: An overview. Australian Journal of Experimental Agriculture,2002:42(3):351–361.
45. Ritzema HP. Drain for gain: Managing salinity in irrigated lands—A review. Agricultural Water Management,2016:175:18–28.
46. Robinson M, Rohde J. Mole drainage. In A.S. Smedema, W.F. Vlotman, & D.W. Rycroft (Eds.), Modern Land Drainage. Balkema, Lisse, 2002.
47. Saggar S, Jha N, Deslippe J, *et al*. Denitrification and N_2O: N_2 production in temperate grasslands: Processes, measurements, modelling and mitigating negative impacts. Science of the Total Environment,2013:465:173–195.
48. Sahrawat KL. Iron toxicity in wetland rice and the role of other nutrients. Journal of Plant Nutrition,2004:27(8):1471–1504.
49. Sahrawat KL. Factors affecting nitrification in soils. Communications in Soil Science and Plant Analysis,2008:39(9–10):1436–1446.
50. Sarfraz M, Mehdi SM, Qadir M, Sahito A. Amelioration of a saline-sodic soil through raised bed cropping systems and chemical amendments under semi-arid conditions. Agricultural Water Management,2010:97(12):1946–1954.
51. Schroeder R, McDonald KC, Chapman BD, *et al*. Detection and evaluation of wetland inundation using the JERS-1 synthetic aperture radar. Remote Sensing of Environment,2010:114(9):2100–2116.
52. Schuur EAG, McGuire AD, Schädel C, *et al*. Climate change and the permafrost carbon feedback. Nature,2015:520:171–179.
53. Setter TL, Waters I. Review of prospects for germplasm improvement for waterlogging tolerance in wheat, barley and oats. Plant and Soil,2003:253(1):1–34.
54. Skaggs RW, Brevé MA, Gilliam JW. Hydrologic and water quality impacts of agricultural drainage. Critical Reviews in Environmental Science and Technology,2012:24(1):1–32.
55. Soil Survey Staff. Keys to Soil Taxonomy, 13th ed. USDA-NRCS, Washington D.C, 2022.
56. Tanneberger F, Schröder C, Hohlbein M, *et al*. Paludiculture on wetter land use: Reducing greenhouse

gas emissions while preserving peatland biodiversity. Frontiers in Ecology and Evolution,2021:9:673097.
57. Tiner RW. Wetland Indicators: A Guide to Wetland Formation, Identification, Delineation, Classification, and Mapping, 2nd ed. CRC Press, 2016.
58. Twele A, Cao W, Plank S, Martinis S. Sentinel-1-based flood mapping: A fully automated processing chain. International Journal of Remote Sensing,2016:37(13):2990–3004.
59. Vepraskas MJ. Redoximorphic Features for Identifying Aquic Conditions. Technical Bulletin 301, North Carolina Agricultural Research Service, 1992.
60. Vepraskas MJ, Craft CB. Wetland Soils: Genesis, Hydrology, Landscapes, and Classification, 2nd ed. CRC Press, 2016.
61. Vepraskas MJ, Faulkner SP. Redox chemistry of hydric soils. In J.L. Richardson & M.J. Vepraskas (Eds.), Wetland Soils. CRC Press, 2001.
62. Vitt DH, Halsey LA, Bauer IE, Campbell C. Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Canadian Journal of Earth Sciences,2000:37(5):683–693.
63. Vymazal J. Constructed wetlands for treatment of industrial wastewaters: A review. Ecological Engineering,2014:73:724–751.
64. Windmeijer PN, Andriesse W. Inland Valleys in West Africa: An Agro-ecological Characterization of Rice-growing Environments. ILRI Publication 52, Wageningen, 1993.
65. Zhu Y, Fox RH, Toth JD. Leachate collection efficiency of zero-tension pan and tension lysimeters. Soil Science Society of America Journal,2012:66(1):37–43.