soil systems

Review

Reshaping How We Think about Soil Security

Katsutoshi Mizuta [1,*] **and Sabine Grunwald** [2]

[1] Department of Soil, Water, and Climate, University of Minnesota, St. Paul, MN 55108, USA
[2] Department of Soil, Water, and Ecosystem Sciences, University of Florida, Gainesville, FL 32611, USA
* Correspondence: toshim@umn.edu

Abstract: The soil security framework has been conceptualized and views soil as a resource that needs to be secured to avoid or minimize adverse environmental/anthropogenic impacts and undesirable consequences for people. Our critical literature review suggests that measurements, estimations, simulations, or digital mapping of soil properties fall short in assessing soil security and health. Instead, soil security that considers soil ecosystem functionality based on regionalized and optimized relationships between targeted functions and site-specific soil environmental conditions allows for the discernment of actual and attainable efficiency levels for observation sites. We discuss the pros and cons that undergird the paradigm shift toward a pedo-econometric modeling approach. Such a multiperspectival approach to soil security allows for simultaneous interpretations from economic, pedogenic, agronomic, environmental, biotic/habitat, and other perspectives. This approach is demonstrated by modeling total nutrient efficiencies in complex multi-use soilscapes with diverging soil environmental interests and concerns.

Keywords: integral soil security; soil health; data envelopment analysis; soil functions; quantification methods

Citation: Mizuta, K.; Grunwald, S. Reshaping How We Think about Soil Security. *Soil Syst.* **2022**, *6*, 74. https://doi.org/10.3390/soilsystems6040074

Academic Editor: Matteo Spagnuolo

Received: 17 August 2022
Accepted: 20 September 2022
Published: 23 September 2022

1. Introduction

1.1. The Emergence of Soil Security

Soil security is an emerging concept that has been narrowly and broadly defined from geo-engineering, ecosystem, sustainability, health, integral, and land management perspectives. The term soil security first appeared in the journal article entitled “Soil Security Test for Water Retaining Structures” in 1985 [1,2] and was used from a geomechanical perspective to assess the security of an earthen embankment for water retention—both for short-term (flood levees) and long-term purposes (dams, canals) using a water-retention security test.

In the early 2010s, soil security was then reframed into the global political context to combat the global soil crisis [3]. The motivation was to bring soil security into line with food security, water security, and human security. Securing soil is critically important for supporting global ecosystem functionality that had been hampered by a science–policy divide. The importance of soils has often been addressed from the perspective of global environmental sustainability, global climate change, and ecosystem services, but has not yet been acknowledged as a critical factor when dealing with critical environmental problems [4]. The concept was later redefined from a broad global perspective as “being concerned with the maintenance and improvement of the world’s soil resource to produce food, fiber and freshwater, contribute to energy and climate sustainability, and maintain the biodiversity and the overall protection of the ecosystem” [5]. There are five pillars of focus in the framework: condition, capability, capital, connectivity, and codification [6,7]. Although these dimensions capture elements of the quantity, quality, and connection of people to soil resources, they are somewhat ambiguous and lacking in clarity on how the five Cs influence the totality and complexity of soil ecosystem functionality, resilience, and human security. The relatively new concept of soil security has often been limited to single soil properties/classes lacking a comprehensive indication reference system that would allow for the optimization of relations between soils and ecosystem functions [8].

Soil security has been seen as being more active than the more passive concept of soil protection in addressing a variety of soil degradation problems [4]. A normative approach undergirded the concept of soil security, arguing that soils need to be secured to maintain the security of people because otherwise there would be grave political, economic, and social consequences. Soil security is rooted in anthropocentric thinking that involved safety concerns, avoidance of risks, and people's anxiety and fear of negative societal consequences caused by soil degradation or a decline in soil quality. The point was made that soils play a critical role in addressing biodiversity loss, energy sustainability, food and water security, and global climate change. The role of soils in ecological and human development should be included in existing policy instruments for sustainable development [3]. Normative approaches are too often not embraced or met with resistance by stakeholders, farmers, and landowners that operate in highly regulatory societies, However, this approach to soil security values the close association between soil health and biotic health [9–11], arguing that the health and well-being of humanity and organisms depend on the health and functionality of soils around the globe. Although earlier concepts of soil security were soil-centric and/or anthropocentric, pluralistic soil ethics emphasizes a biocentric worldview [11].

The aim of the soil-centric concept of soil security was to reframe soil that had been previously derogatorily labeled as dirt and marginalized in scientific, political, economic, and social spheres. A Copernican paradigm shift put soil at the center of the universe surrounded by water security, biodiversity, food production, climate change abatement, energy sustainability, and delivery of ecosystem services [3,6]. This soil-centric view undergirded what soil scientists had recognized earlier—soil "is the transformer, regulator, buffer and filter of water, nutrients and other dissolved and dispersed compounds that soils are most important to humankind—a connecting link between the biogeochemical cycles of the Earth and the dynamic atmospheric system [12]".

This view of soil as an integrator is reflected in the Earth's critical zone concept, which states that soil serves as an integrator controlling various ecosystem functions [13]. The concerns about soils in order to secure and protect them have been grounded in preserving their functionality with five principal functions: (1) nutrient cycling (e.g., soil nitrogen, phosphorus), (2) water retention (available water capacity), (3) biodiversity and habitat preservation (e.g., microbiomes, vegetations), (4) storing, filtering, buffering, and transforming compounds (e.g., soil carbon), and (5) provision of physical stability and support (e.g., soil aggregate stability) [3].

These principal functions, together with the dimensions of soil security, objectify and commodify soil as a resource [7]. This view adopts an objective lens of soils and ecosystems and views humans as nodes in a system in which the use and management of soil and land are for the benefit of the people (e.g., to secure food production). However, people are more than just objects or factotums in an ecosystem model. Individuals and communities hold sometimes conflicting values, beliefs, morals, preferences, and relationships with soils, nature, and the Earth (e.g., sustainability, resilient ecosystems, profit-oriented policies, and economies). These cultural values and ethics toward soils translate into their use. This extended view of soil security gave rise to the concept of integral soil security [14].

1.2. *Integral Soil Security*

Integral soil security is a multiperspectival framework that emphasizes relationships between soil, soil ecosystems, people, communities, and cultures that are dynamically co-created. The characteristics of integral soil security are anchored in integral ecology [15] and integral theory [16,17]. The latter considers four major domains: social and systems phenomena (e.g., ecosystems, educational, technological, legal, and other systems), physical and behavioral phenomena (empirical data, e.g., soil physical and chemical data), cultural phenomena (values, beliefs, ethics, shared communication among stakeholders), and individual experiential phenomena (e.g., awareness of the soils and how they are used). Integral soil security is best suited for addressing the integration of the personal, interpersonal, and socioeconomic political aspects of soil security and soil ecosystems [14]. Farmers, stakeholders, politicians, decision makers (agencies), and citizens are viewed as active participants who co-create laws, regulations, land usage rights and more that pertain to the security of soils. For example, the European Union (EU) has placed the concept of soil health at the core of the European Green Deal and developed a new EU Soil Strategy to improve soil health in different ecosystems with targets for 2030 and 2050 to secure soils. Special soil observatories will be created to implement the relevant EU soil policies, especially in the context of the Common Agricultural Policy (CAP) and Zero Pollution Action Plan [18]. The main focus of integral soil security is to integrate various domains by giving an equal voice to people's individual and collective views as well as the assessment/quantification of soil and ecosystems.

The awareness and capacity building of environmental competence and literacy play a pivotal role in integral soil security [19]. The understanding and communication of the idea that soils have been degraded in some way or another in a region through scientific studies or publications are informative yet are unlikely to motivate people to improve soil conditions and soil security. Rather, the adoption of explicit soil environmental ethics based on three pillars has been proposed to both encourage the care of soil and actions to secure them efficiently: (1) Soil and environmental valuation and people's moral views of soil; (2) Soil and environmental literacy and the domain of soil and environmental sciences (facts, knowledge, data, maps, models, and assessments of soil environments); (3) Soil and environmental competency and awareness (i.e., personalizing soil through experiences in nature/soil landscapes) [11].

For example, an integrated soil security approach was adopted to assess soils and ecosystem services from personal and scientific perspectives in Florida. Climate regulation, soil carbon sequestration, and nutrient cycling ecosystem services (water quality) from biophysical, ecological, and socioeconomic perspectives were investigated in the large Suwannee River Basin in Florida in the U.S. [20]. The beliefs and perspectives of local residents in the basin, identified through a questionnaire (sample size: 762), showed that nutrient cycling was the most important service and that climate regulation and carbon sequestration were the least important services, which somewhat contradicted the scientific findings based on empirical assessments and soil and water quality in the basin. Florida topsoils had acted as a net sink for carbon with the median soil organic carbon (SOC) significantly increasing from 2.69 to 3.40 kg m^{-2} over the past few decades (1965–2009) according to comprehensive machine learning modeling [21,22]. Thus, SOC stock assessments demonstrated the extraordinary importance of soils to sequester carbon and help mitigate global climate change. Soil total nitrogen (N) was assessed in Florida's topsoils (0–20 cm) under agricultural, forest, wetland, urban, and other land uses, with the total N ranging from 0.006 to 2.5 g kg^{-1} and median values of 0.22 g kg^{-1} and was modeled using a Bayesian semiparametric model [23]. These total N values in Florida's sand-rich soils are considered quite low and are unlikely to pose great risks of N leaching into the aquifer used as a drinking water supply. Only low-to-moderate impairments in terms of the total N loads and P loads in the surface waters of the large Suwannee River Basin, Florida, were found [24]. The total N loads in water ranged between 0.003 (Coastal sub-basin) and 366.7 tons a $month^{-1}$ (Lower Suwannee Basin) based on the long-term geometric means, and the total P loads varied between 0.002 (Aucilla sub-basin) and 43.8 kg $month^{-1}$ (Lower Suwannee Basin) based on long-term geometric means. From a scientific perspective, soils in the basin performed critically important functions and provided various services—specifically, carbon sequestration and climate regulation services—whereas residents cared more about water quality and nutrient regulation services. However, the results from the questionnaire (the survey of 762 residents of the Suwannee River Basin) showed that the willingness of the residents to pay for soil, water, and climate ecosystem services was extremely low (<\$2/household yr^{-1}), which is worth less than a fast-food meal [19].

Importantly, integral soil security considers not only soils but also social, cultural, and other aspects to reveal discords in opinion and engage stakeholders in the assessment process that focuses not only on soils in isolation but also takes an integrative holistic view of the totality of the human–natural ecosystem [25].

Soils cannot be assessed, predicted, or quantified in any way in isolation but only in dependence on their purpose or valuation [19,26]. Purpose can be expressed as the specific function(s) that soils perform in a given setting or through ecosystem service valuations. Land use may be considered a proxy for expressing the predominant function(s) that soil performs. For example, conventional agricultural crop production focuses predominantly on food production, whereas soil health may be considered secondary to supporting crop growth. The co-dependence of soil security on land use (i.e., purpose) suggests that a soil model is computed separately for specific land use domains.

1.3. Assessment of Soil Security

Soil security is closely related to the concept of planetary boundaries. Both share in common the idea of thresholds or boundaries to secure the common global good or ecosystem functionality that must not be transgressed because a breach of a boundary could cause unacceptable environmental changes that threaten the livelihood and well-being of humanity. The transformative concept of a safe operating space for humanity based on planetary boundaries considers biodiversity loss, biogeochemical cycles (N and phosphorus, P), climate change, ocean acidification, stratospheric ozone depletion, global freshwater use, change in land use, chemical pollution, and atmospheric aerosol loading [27]. Over the past two decades, research to identify and quantify these planetary boundaries has exploded [28–30]; however, soil has been surprisingly absent or has been given less importance in planetary boundary studies.

For example, safe operating spaces have been conceptualized in social–ecological systems by recognizing societies' values, knowledge, and decision-making fallacies in controlling the dynamics of safe operating spaces without consideration given to soils' life-sustaining value [31]. Others have argued that soil and humanity are closely connected. The flourishing of cultures and civilizations, including their health and livelihoods, depends on soil [9,32]. Soil is a living substance, as are humans and other organisms on Earth, and their health matters [33]. Soil biology plays a critical role in maintaining healthy and resilient soils capable of recovering from or adapting to stress [34]; however, an unresolved question is how to identify boundaries or thresholds that secure soils in ecosystems. Would it even be possible to identify such soil observation thresholds given the wide variety of site-specific soil conditions and temporal dynamics (e.g., in soil biology and hydrology) and competing ecosystem functions that are under pressure due to human and natural stressors such as climate change, soil pollution, and soil acidification.

The popularization of soil security came at a time of pernicious and persistent global soil and land degradation, desertification, topsoil losses, decarbonization of soils, and salinization as global climate change, population growth, and demands for increased food production intensified under unsustainable management practices. Global assessments have demonstrated the substantial variability of soils' responses to stressors. For example, the effects of global warming on soils are contingent on site-specific conditions (i.e., the size of initial soil carbon stocks), with considerable C losses from soils occurring in high-latitude areas [35]. In this study, it was estimated that the global soil C stocks in the upper soil horizon (0–15 cm depth) would fall by 30 ± 30 Pg of C to 203 ± 161 Pg of C under 1 °C of global warming. Importantly, the effects of global warming have been negligible in areas with small initial C stocks, but C losses have occurred beyond a threshold of 2–5 kg C m^{-2} and have been substantial in soils with ≥ 7 kg C m^{-2}. Despite the monumental uncertainties in the assessment of global C stocks and losses from 49 field experiments on a global scale, this study demonstrates that site-specific conditions modulate C losses, or in other words, soil C sequestration functionality. Most importantly, there is no distinct soil C loss threshold associated with a specific soil that would allow for the categorization of the soil itself as 'secure' or 'not secure'. A soil C loss of 5% in a C-poor Entisol due to respiration losses would substantially deplete its functionality (e.g., nutrient holding capacity), and the impact of carbon loss would vary depending on the soil types and environmental factors. Therefore, soil security assessment is ideally tied to its spatially explicit site-specific conditions in the ecosystem (e.g., climatic, pedogenic, lithologic, and biotic conditions such as land use) that control its effects on the resilience and fragility of ecosystem functions. The reframing of soil security defined by its site-specific soil properties toward soil security conceptualized as an attainable capacity allows us to go beyond threshold considerations (i.e., secure vs. insecure soils) in the optimization of soil security and soil health. A guiding question for assessing soil capacity has become "How efficient is a given soil to achieve one or more specific ecosystem functions?". The actual ($\mathrm{TerrC}_{\mathrm{actual}}$) and attainable ($\mathrm{TerrC}_{\mathrm{attain}}$) terrestrial carbon pools in a large watershed in the southeastern US were assessed using site-specific soil and environmental variables [24]. Random Forest machine learning combined with simulated annealing computed $\mathrm{TerrC}_{\mathrm{actual}}$ and the lower and upper bounds of $\mathrm{TerrC}_{\mathrm{attain}}$. The latter indicates the capacity of below- and above-ground carbon in a region. Another study assessed soil capacity by modeling long-term attainable soil organic carbon (SOC) sequestration using the Roth-C model and land management scenarios in Ethiopia [36]. Estimations of the SOC sequestration potential have also been investigated using the SOC saturation concept [37,38].

The soil carbon sequestration efficiency function using the STEP-AWBH modeling framework [39] and the Data Envelopment Analysis (DEA) has been performed to provide results of attainable soil carbon in the southeastern U.S. [40]. When assessing a specific soil or ecosystem function (soil C sequestration), the DEA is used to optimize the input and output variables by either reducing the levels of the inputs while achieving the same levels of the outputs or maximizing the levels of the outputs while maintaining the same levels of the inputs. An approach that vets the specific functionality of an individual soil relative to the overall functionality of all soils in a regional domain is best suited to provide inferences on soil health and security [41]. In a study in Florida, soil with an available water capacity (AWC) of 3 cm showed substantially less capacity for soil C stocks (<2 kg m^{-1} in the topsoil) than a soil with high AWC of 10 cm that showed a high capacity for soil C stocks (30 kg m^{-2} in the topsoil). Here, the site-specific conditions primed the individual soil functions (e.g., soil C stocks or soil C sequestration); however, these individual functions can only be interpreted meaningfully in the context of the broader functionality of regionalized soilscapes to sequester carbon in soils.

1.4. Soil Security Assessment from a Soil Function Perspective

A quantitative modeling approach that can be linked to specific soil functions and land uses provides an ideal framework for soil security assessment. Such an approach relies on reproducible expressions for the first 3 Cs of soil security—soil capability, condition, and capital—as critical contributions to both effective interdisciplinary research and communication with the general public on a large scale [42]. The global initiative "4 per 1000" is one example of the practical relevance of soil security, which was launched at the 2015 UNCCC conference (United Nations Climate Change Conference) in Paris, France (www.4p1000.org; accessed on 16 August 2022). The aim of the 4 per 1000 initiative was to achieve an annual growth rate of 0.4% in soil carbon stocks (SCS) in the first 30–40 cm depth of agricultural land. The simplified target of "4 per 1000" serves to communicate to policymakers a strong commitment rather than an aspirational goal (e.g., achieving a specific threshold of soil carbon to secure soils) [43]. The critiques regarding the initiative emphasized four aspects, including (1) biophysical limits, (2) trade-off effects, (3) climate change effects, and (4) socioeconomic implications for the agricultural sector.

Some factors that invite criticism seem to be driven by ambiguity in discussions about the targets and calculation methods that have not resulted in a consensus. The initiative was also a major opportunity to reaffirm the scientific and social relevance of soil science research without considering soil's complexity and vulnerability [44]. This criticism can be applied to the implementation of soil security. The quantitative evaluation of soil functions based on measurable soil properties is a formidable research challenge [45], yet from the perspective of decision makers, it is desirable to monitor positive/negative changes in soil functions, which require a reference system to compare values.

Such a quantitative reference system requires the user to (1) consider a relationship between a target soil ecosystem function and relevant input variables; (2) compare the actual site-specific functionality to the outer bounds of the highest achievable efficiency of a given target function ("frontier") within a study domain; and (3) identify attainable improvements for a target function by either minimizing inputs while maintaining given output variables or changing management to increase outputs while keeping the levels of inputs. A method that possesses such ideal axiomatic expectations is provided through a new approach, called pedo-econometrics [41,46]. This new research paradigm applies the DEA, or other econometric methods, to assess soil health and soil security. The DEA is a useful method that advances soil security beyond simply measuring/estimating/predicting/simulating/mapping site-specific soil properties. This goal is accomplished by calculating the attainable efficiency of soil functions. Another asset of the DEA as an assessment framework for soil security is the data-driven reference (base) that enables the user to compare the efficiency of soil functions or metric scores to distinguish between inefficient and efficient sites. For any selected soil function, the distance of a site-specific efficiency score from the level of the highest attainable efficiency scores within a study domain expresses the level of inefficiency. Thus, inefficient sites can be targeted by management to improve their efficiency level to attain a specific soil ecosystem function (e.g., nutrient regulation, soil carbon sequestration, or net ecosystem productivity). The usefulness of the DEA algorithm has been recognized as a quantitative evaluation method for soil quality [47,48] and ecosystem services assessment [49,50].

The terms efficiency and capacity of functions have been used interchangeably in the soil health and soil security literature [46]. Thus, the efficient approach of the DEA to assess soil security is aligned with recent conceptions of soil health. Soil health defined as "the vitality of a soil in sustaining the socio-ecological functions of its enfolding land", argues that the health of soils is not limited to reflecting the elemental composition of soil but rather its capacity to promote ecosystem functions [51]. The capacity approach allows us to pursue a soil health metaphor that stresses relational mechanisms between soil and socio-ecological systems that inform site-specific management. Such broad efficiency-based concepts of soil health emphasize the valuation of soils relative to the specific functions they perform in the socio-ecological sphere rather than the identification of an absolute target soil measurement or threshold to be ideally achieved. Although site-specific efficiencies that take ecosystem conditions explicitly into consideration can be computed by the DEA, it would be highly controversial to find a consensus on an ideal absolute soil content or stock (e.g., SOC stock value) that works for all soils, land uses, and regions. Next, we present a brief case study that demonstrates how soil efficiencies (e.g., soil nutrient efficiency) adopting pedo-econometrics can be assessed.

2. Case Study

2.1. Purpose

We exemplify the usefulness of a pedo-econometric approach using the DEA to optimize the total nutrient efficiency (TNE) in soil, which represents the target soil ecosystem function in this case study. The efficiency level of sites expresses the efficiency of soils to store total nitrogen (TN) and total phosphorus (TP), which has multiple significance—an ecological function to support specific vegetation types and habitats, nutrient regulation, and an agricultural function linked to crop growth and yield.

2.2. Data and Methods

Samples were retrieved from the Florida Soil Carbon Project (FLSCP) database that contains the lab-measured biochemical and physical properties of soil samples that were collected in the topsoil (0–20 cm depth) at 914 sites (Table 1). The study area has various land use/land cover (LULC) types covering a wide range of soil and environmental characteristics. The optimization problem using the DEA can be approached mainly in two ways: input orientation (minimizing the levels of input variables while maintaining the same levels of output variables) and output orientation (maximizing the levels of output variables while maintaining the same levels of input variables). Growers may have an interest in both orientation approaches focused on cost reduction by minimizing excessive fertilizer applications or an increase in output values (here: TN and TP) by improving management without changing the site-specific input variables, which may lead to increased profits and incentives. From an environmental perspective, the input orientation of the TNE focuses on the preservation of the output variables (here: TN and TP) by minimizing the levels of site-specific soil environmental variables, whereas the output orientation aims to maximize the levels of the output variables with the given site-specific soil environmental conditions.

Table 1. Input and output variables used in the Data Envelopment Analysis.

Variables	Unit	Use for DEA	Data Sources [2]	Year
Soil organic carbon [1]	kg C m^{-2}	Input	FLSCP	2008–2009
pHw [1]	-	Input	FLSCP	2008–2009
Normalized Difference Vegetation Index [2]	-	Input	MODIS	2008–2009
Enhanced Vegetation Index [2]	-	Input	MODIS	2008–2009
Sand [1]	%	Input	gNATSGO	2020
Soil total nitrogen [1]	kg m^{-2}	Output	FLSCP	2008–2009
Soil total phosphorus [1]	kg m^{-2}	Output	FLSCP	2008–2009

[1] Soil variables in the topsoil (0–20 cm). [2] Averaged means within the time period. <Abbreviation/Acronym> FLSCP, Florida Soil Carbon Project database; gNATSGO, Gridded National Soil Survey Geographic; MODIS, Moderate Resolution Imaging Spectroradiometer; w, water extracted.

To demonstrate the DEA optimization approach to assessing soil security, we chose TN and TP rather than the available nutrient forms that are highly dynamic and can widely fluctuate temporally and spatially. Inversed values of TN and TP in soil were considered as the output variables to be optimized, whereas the site-specific input variables (pH_w, SOC, Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), and sand content) relevant to the output variables were selected. The remote sensing-derived vegetation indices served as proxies to characterize the vegetation conditions at the sampling sites. This setting allows users to identify areas with the same levels of the input variables but with lower levels of the output variables. A wide variety of different returns-to-scale (RTS) and orientation settings (input and output orientation) using the DEA approach was simulated to assess the sensitivity of soil carbon sequestration efficiency and above-ground net ecosystem productivity [8,40]. These studies found the highest discriminatory ability with different levels of conservativeness in the computed efficiencies for the following options—output orientation with three conservative levels of RTS as the DEA settings: free-disposable hull (FHD), variable RTS (VRS), and constant RTS (CRS). We adopted these settings in this case study. The DEA scores and statistics were calculated using the statistical software R (3.5.3) with two packages “Benchmarking” and “agricolae”. The map with the DEA scores that averaged the FDH, VRS, and CRS scores by the LU/LC type was produced using ArcGIS 10.6.1.

2.3. Results and Discussion

The closer the DEA scores are to the value of one, the more efficient the sites are in terms of total nutrients (TN and TP) in the soil. The scores calculated by the different types of RTS indicated that the FDH scores are statistically more conservative and closest to the value of one (efficient), which was the opposite of the CRS scores (Figure 1). These results are consistent with the findings from previous studies that assessed various ecosystem functions [2,41,46].

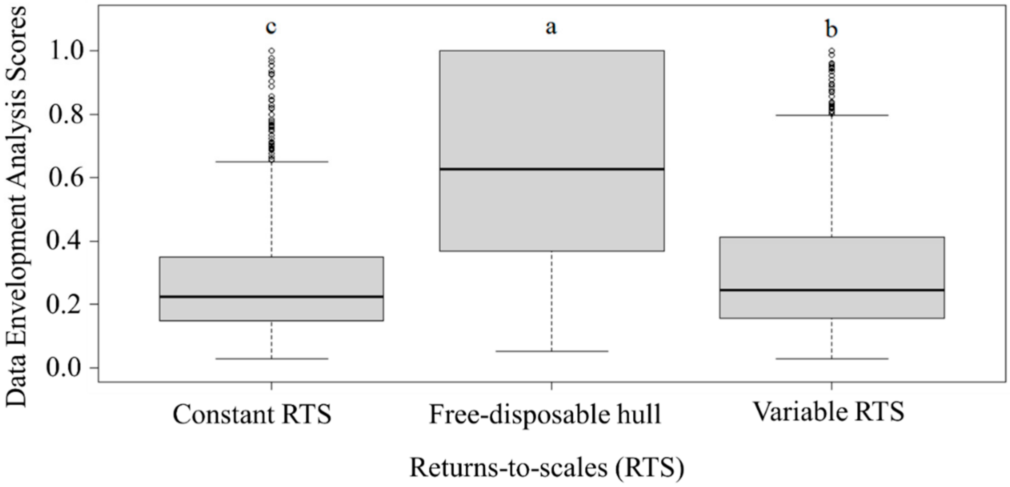

Figure 1. Data Envelopment Analysis scores by different types of returns-to-scale (RTS). Note that letters denote significant differences in means between the variables based on the analysis of variance test with Tukey's distance approximation ($p < 0.05$).

The combined DEA scores calculated by the different RTS showed that improved pasture soil had the lowest DEA scores among the LULC types, followed by soils in urban and citrus (Figure 2). On the other hand, soils in the xeric upland forest and shrub swamp had the highest scores in the TNE. Similar trends in the computed DEA efficiency scores were found for FDH, VRS, and CRS (Figure 1). The averaged DEA scores for the xeric upland forest (i.e., 0.70) and improved pastures (i.e., 0.19) indicated that the efficiency could be improved by approximately 30% ($= (1 - 0.70) \times 100$) for the former and 81% ($= (1 - 0.19) \times 100$) for the latter (Figure 2a). Therefore, the results suggest to policymakers and landowners in Florida that improving soils in three of the LULC types (improved pasture, urban, and citrus) rather than soils in other LULC types would be the most efficient strategy for reducing excessive nutrients by enhancing the storing function of soils.

The TNE scores for the different LULC types across Florida are shown in Figure 3. Low-efficiency sites have the potential to achieve higher TNE scores through management (e.g., best management practices, conservation management) or land use conversions to more appropriate uses in terms of nutrient regulation functionality. From an agricultural perspective, the DEA score calculation that considers the balance between the target nutrient function and relevant input variables to be optimized is useful for evaluating the appropriateness of management practices for improved functional performance (i.e., store TN and TP). The data-driven scores were sensitive enough to detect the differences in the performance levels of the target function by the different LULC types. From an ecological perspective, some land use types, such as natural xeric upland forest, support vegetation species that have adapted to xeric hydrologic conditions and support habitats suitable for endangered species (e.g., gopher tortoise) of biodiversity bound to relatively low TN and TP in soils and biodiversity. Importantly, the TNE efficiency scores that bundle multiple ecosystem properties (here TN and TP) are valuable for simultaneous agronomic, environmental, biotic/habitat, and economic interpretations.

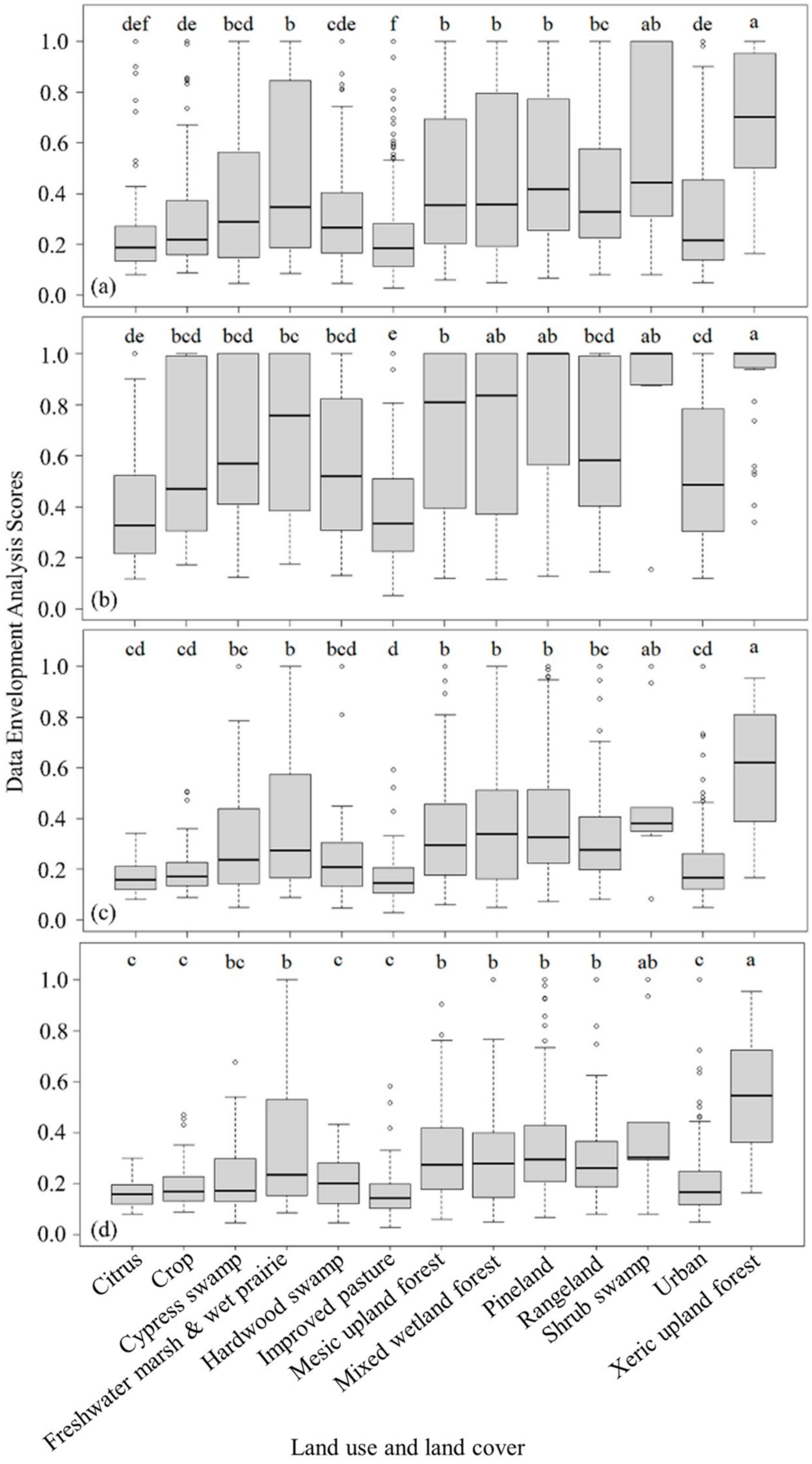

Figure 2. Data Envelopment Analysis scores by land use/land cover type. Letters in parenthesis in the lower left corners of the figure show the scores (**a**) altogether with three types of returns-to-scale (RTS); (**b**) free-disposable hull, (**c**) variable RTS, and (**d**) constant RTS. Note that letters denote significant differences in means between the variables based on the analysis of variance test with Tukey's distance approximation ($p < 0.05$).

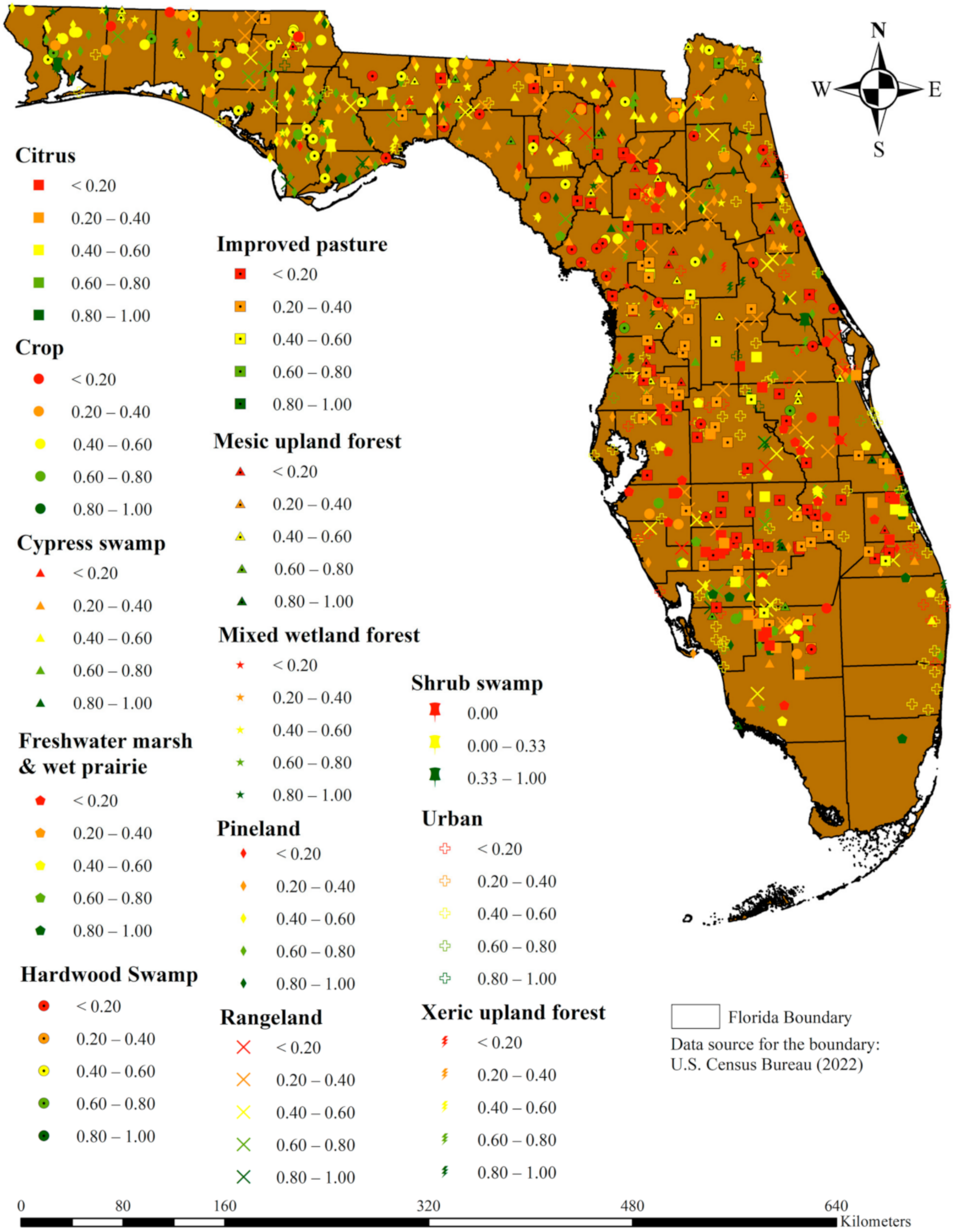

Figure 3. Data Envelopment Analysis scores for total nutrient efficiency (TNE) ensembled by the scores with a free-disposable hull, variable returns-to-scale, and constant returns-to-scale. Note that the red, yellow, and green colors of each symbol indicate the low/medium/high efficiencies, respectively.

The DEA approach does not predict/estimate/simulate soil nutrients but provides a metric reference system for evaluating the efficiency of the total soil nutrient provision. Thus, the approach facilitates the assessment of soil ecosystem services. This case study showed the TNE with a given level of site-specific input variables and output variables that were optimized at the lowest levels of TN and TP. Florida soils are sand-rich with low levels of TN [23], but soil TP levels vary more widely due to natural geologically rich P materials in which soils form and fertilization occurs that have led to P enrichment in various land uses, specifically wetlands [52–54]. The computed efficiency scores can be used to identify the TNE inefficient soils under the specific LULC types that need attention with strategic soil management (e.g., urban soil). Citrus producers, for example, typically attempt to apply more fertilizers to avoid yield loss. However, the results show the possibility of lowering fertilizer application for N and P in soils while keeping the same level of input variables to support citrus tree growth. The better optimization of resource allocation has the potential to improve agronomic, economic, and environmental benefits.

This case study employed the DEA for the entire dataset at once to identify efficient sites where the minimum levels of soil TN and TP were produced while maintaining the same levels of input variables. The calculation of the DEA scores can also be conducted for each LULC type separately by producing designated frontiers (references or basis) because each ecosystem has unique environmental conditions that might or might not be suitable for a specific function. In other words, the efforts required to increase the efficiency of a target function by 1% can be different depending on the LULC type. Our approach has the capability of providing quantitative metrics that evaluate and suggest attainable goals for better functional performance for a specific soil, LULC type, or area, depending on the environmental conditions and users' objectives for securing soil resources. Other future research opportunities using the DEA or other econometric techniques to quantify soil security are available such as the validation of the DEA scores [25,55].

3. Conclusions: Prospects for Achieving Soil Security

The presented pedo-econometrics soil security approach is ideally suited to assessing soil security. DEA-based soil security assessment focuses on the efficiencies of specific soil ecosystem functions, such as nutrient provisions and regulations of given site-specific soil environmental conditions. The DEA approach goes beyond the mapping or modeling of soil properties/classes and the associated uncertainties, the latter falling short of discerning the security levels of soils. One of the profound benefits of the DEA approach is that it links the security levels to ecosystem functionality. This is accomplished through the simultaneous incorporation of both the input and output variables in the modeling process, which links site-specific soil environmental conditions and unique or multiple soil ecosystem function(s). We presented a case study in which the selected function was the TNE in soils calculated for different LULC types as well as conservative and progressive RTS assumptions.

The DEA soil security approach can be applied to other soil ecosystem functions (e.g., biodiversity, water regulation, soil carbon sequestration, net primary productivity) and in other regions with different soils. Our pedo-econometrics approach is scalable to national, continental, and global scales. It holds great potential for identifying sites or regions that are inefficient in terms of specific soil ecosystem functions that can be targeted with management practices or interventions to make soils more efficient and secure. Specifically, those soils at risk of losing functionality that are valued by people and communities (e.g., soil carbon sequestration efficiency, nutrient regulation capacity, or water-holding efficiency) can address soil degradation and soil quality problems more elegantly than traditional digital soil-mapping approaches that focus on the modeling of soil properties. Reframing soil property assessments toward soil ecosystem efficiency modeling allows for more direct inferences about the security levels of soils.

Author Contributions: Conceptualization, K.M. and S.G.; methodology, K.M. and S.G.; software, K.M.; validation, K.M. and S.G.; formal analysis, K.M.; investigation, K.M. and S.G.; resources, K.M. and S.G.; data curation, K.M.; writing—original draft preparation, S.G. and K.M.; writing—review and editing, S.G. and K.M.; visualization, K.M.; supervision, S.G.; project administration, S.G. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge accessing the database of the Florida Soil Carbon Project funded by USDA-CSREES-NRI grant award 2007-35107-18368 'Rapid Assessment and Trajectory Modeling of Changes in Soil Carbon across a Southeastern Landscape' (National Institute of Food and Agriculture (NIFA) Agriculture and Food Research Initiative (AFRI)).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The soil data are geo-referenced and were collected on privately and publicly owned land. Due to individual privacy restrictions, the x and y coordinates and soil laboratory data cannot be shared publicly. The processed data in the form of maps, graphs, or figures have been previously described and published in Xiong et al. (2014) [21]. The MODIS remote sensing data are freely available from the National Aeronautics and Space Administration (NASA) website.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tadanier, R.; Ingles, O.G. Soil Security Test for Water Retaining Structures. *J. Geotech. Eng.* **1985**, *111*, 289–301. [CrossRef]
2. Mizuta, K.; Grunwald, S.; Cropper, W.P., Jr.; Bacon, A.R. Developmental History of Soil Concepts from a Scien-tific Perspective. *Appl. Sci. J.* **2021**, *11*, 4275. [CrossRef]
3. Koch, A.; McBratney, A.; Adams, M.; Field, D.; Hill, R.; Crawford, J.; Minasny, B.; Lal, R.; Abbott, L.; O'Donnell, A.; et al. Soil Security: Solving the Global Soil Crisis. *Glob. Policy* **2013**, *4*, 434–441. [CrossRef]
4. Bouma, J.; McBratney, A. Framing soils as an actor when dealing with wicked environmental problems. *Geoderma* **2013**, *200–201*, 130–139. [CrossRef]
5. McBratney, A.B.; Minasny, B.; Wheeler, I.; Malone, B.P. Frameworks for Digital Soil Assessment. In *Digital Soil Assessment and Beyond*; Minasny, B., Malone, B.P., McBratney, A.B., Eds.; Taylor and Francis: London, UK, 2012; pp. 9–14.
6. McBratney, A.; Field, D.J.; Koch, A. The dimensions of soil security. *Geoderma* **2014**, *213*, 203–213. [CrossRef]
7. Field, D.J. Soil Security: Dimensions. In *Global Soil Security*; Field, D.J., Morgan, C.L.S., McBratney, A.B., Eds.; Springer: Cham, Switzerland, 2017; pp. 15–23.
8. Mizuta, K.; Grunwald, S.; Phillips, M.A.; Cropper, W.C., Jr.; Lee, W.S.; Vasques, G.M. New Indication Method Using Pedo-Econometric Approach. *Data Envel. Anal. J.* **2019**, *4*, 207–241. [CrossRef]
9. Minami, K. Soil and humanity: Culture, civilization, livelihood and health. *Soil Sci. Plant Nutr.* **2009**, *55*, 603–615. [CrossRef]
10. Thompson, P.B. *The Spirit of the Soil: Agriculture and Environmental Ethics*; Routledge: New York, NY, USA, 2017.
11. Grunwald, S. Take Care of Soils: Toward a Pluralistic Integral Soil Ethics. In *Cultural Understanding of Soils*; Patzel, N., Grunwald, S., Brevik, E.C., Feller, C., Eds.; Springer: New York, NY, USA, 2022.
12. Yaalon, D.H. Down to earth. *Nature* **2000**, *407*, 301. [CrossRef] [PubMed]
13. Guo, L.; Lin, H. Critical Zone Research and Observatories: Current Status and Future Perspectives. *Vadose Zone J.* **2016**, *15*, 1–14. [CrossRef]
14. Grunwald, S.; Clingensmith, C.M.; Gavilan, C.P.; Mizuta, K.; Wilcox, R.K.K.; Pinheiro, F.M.; Ceddia, M.B.; Ross, C.W. Integrating New Perspectives to Address Global Soil Security: Ideas from Integral Ecology. In *Global Soil Security*; Field, D.J., Morgan, C.L.S., McBratney, A.B., Eds.; Springer Nature: Cham, Switzerland, 2017; pp. 319–330. [CrossRef]
15. Esbjörn-Hargens, S.; Zimmerman, M.E. *Integral Ecology: Uniting Multiple Perspectives on the Natural World*; In-tegral Books: Boston, MA, USA, 2009.
16. Wilber, K. *A Theory of Everything: An Integral Vision for Business, Politics, Science and Spirituality*; Shambhala: Boston, MA, USA, 2000.
17. Wilber, K. *Sex, Ecology, Spirituality: The Spirit of Evolution*; Shambhala: Boston, MA, USA, 2000.
18. Panagos, P.; Montanarella, L.; Barbero, M.; Schneegans, A.; Aguglia, L.; Jones, A. Soil priorities in the European Union. *Geoderma Reg.* **2022**, *29*, e00510. [CrossRef]
19. Grunwald, S.; Mizuta, K.; Ceddia, M.B.; Pinheiro, F.M.; Wilcox, R.K.K.; Gavilan, C.P.; Ross, C.W.; Clingensmith, C.M. The Meta Soil Model: An Integrative Multi-model Framework for Soil Security. In *Global Soil Security*; Field, D.J., Morgan, C.L.S., McBratney, A.B., Eds.; Springer Nature: Cham, Switzerland, 2017; pp. 305–318. [CrossRef]
20. Chaikaew, P.; Hodges, A.W.; Grunwald, S. Estimating the value of ecosystem services in a mixed-use watershed: A choice experiment approach. *Ecosyst. Serv.* **2017**, *23*, 228–237. [CrossRef]
21. Xiong, X.; Grunwald, S.; Myers, D.B.; Kim, J.; Harris, W.G.; Comerford, N.B. Holistic environmental soil-landscape modeling of soil organic carbon. *Environ. Model. Softw.* **2014**, *57*, 202–215. [CrossRef]
22. Xiong, X.; Grunwald, S.; Myers, D.B.; Ross, C.W.; Harris, W.G.; Comerford, N.B. Interaction effects of climate and land use/land cover change on soil organic carbon sequestration. *Sci. Total Environ.* **2014**, *493*, 974–982. [CrossRef] [PubMed]
23. Merrill, H.R.; Grunwald, S.; Bliznyuk, N. Semiparametric regression models for spatial prediction and uncertainty quantification of soil attributes. *Stoch. Hydrol. Hydraul.* **2016**, *31*, 2691–2703. [CrossRef]
24. Chaikaew, P.; Grunwald, S.; Xiong, X. Estimation of the Actual and Attainable Terrestrial Carbon Budget. In *Digital Soil Mapping Across Paradigms, Scales and Boundaries*; Springer: Singapore, 2016; pp. 153–164. [CrossRef]
25. Friedrichsen, C.N.; Mizuta, K.; Wulfhorst, J. Advancing the intersection of soil and well-being systems science. *Soil Secur.* **2022**, *6*, 100036. [CrossRef]
26. Grunwald, S. Part I-Conceptualization of a Meta Soil Model. In *Global Soil Map*; Arrouays, D., McKenzie, N., Hempel, J., Richer de Forges, A.C., McBratney, A., Eds.; CRC Press: New York, NY, USA, 2014; pp. 233–238. ISBN 978-1-138-00119-0.
27. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S., III; Lambin, E.F.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. A safe operating space for humanity. *Nature* **2009**, *461*, 472–475. [CrossRef]

28. Biermann, F.; Kim, R.E. *The Boundaries of the Planetary Boundary Framework: A Critical Appraisal of Approaches to Define a "Safe Operating Space" for Humanity*; Social Science Research Network: Rochester, NY, USA, 2020.
29. Bunsen, J.; Berger, M.; Finkbeiner, M. Planetary Boundaries for Water—A Review. *Ecol. Indic.* **2021**, *121*, 107022. [CrossRef]
30. McAlpine, C.A.; Seabrook, L.M.; Ryan, J.G.; Feeney, B.J.; Ripple, W.J.; Ehrlich, A.H.; Ehrlich, P.R. Transformational change: Creating a safe operating space for humanity. *Ecol. Soc.* **2015**, *20*, 200156. [CrossRef]
31. Anderies, J.M.; Mathias, J.-D.; Janssen, M.A. Knowledge infrastructure and safe operating spaces in social–ecological systems. *Proc. Natl. Acad. Sci. USA* **2018**, *116*, 5277–5284. [CrossRef]
32. Diamond, J. *Collapse: How Societies Choose to Fail or Succeed*; Penguin Books: New York, NY, USA, 2011.
33. Minami, K. Soil is a living substance. *Soil Sci. Plant Nutr.* **2020**, *67*, 26–30. [CrossRef]
34. Lehman, M.; Acosta-Martinez, V.; Buyer, J.S.; Cambardella, C.A.; Collins, H.P.; Ducey, T.; Halvorson, J.J.; Jin, V.L.; Johnson, J.M.; Kremer, R.J.; et al. Soil biology for resilient, healthy soil. *J. Soil Water Conserv.* **2015**, *70*, 12A–18A. [CrossRef]
35. Crowther, T.W.; Todd-Brown, K.E.O.; Rowe, C.W.; Wieder, W.R.; Carey, J.C.; Machmuller, M.B.; Snoek, B.L.; Fang, S.; Zhou, G.; Allison, S.D.; et al. Quantifying global soil carbon losses in response to warming. *Nature* **2016**, *540*, 104–108. [CrossRef] [PubMed]
36. Abegaz, A.; Ali, A.; Tamene, L.; Abera, W.; Smith, J.U. Modeling long-term attainable soil organic carbon sequestration across the highlands of Ethiopia. *Environ. Dev. Sustain.* **2021**, *24*, 5131–5162. [CrossRef]
37. Chen, S.; Martin, M.P.; Saby, N.P.; Walter, C.; Angers, D.A.; Arrouays, D. Fine resolution map of top- and subsoil carbon sequestration potential in France. *Sci. Total Environ.* **2018**, *630*, 389–400. [CrossRef] [PubMed]
38. Georgiou, K.; Jackson, R.B.; Vindušková, O.; Abramoff, R.Z.; Ahlström, A.; Feng, W.; Harden, J.W.; Pellegrini, A.F.A.; Polley, H.W.; Soong, J.L.; et al. Global stocks and capacity of mineral-associated soil organic carbon. *Nat. Commun.* **2022**, *13*, 3797. [CrossRef]
39. Grunwald, S. Grand Challenges in Pedometrics-AI Research. *Front. Soil Sci.* **2021**, *1*, 714323. [CrossRef]
40. Mizuta, K.; Grunwald, S.; Phillips, M.A.; Moss, C.B.; Bacon, A.R.; Cropper, W.P. Sensitivity assessment of metafrontier data envelopment analysis for soil carbon sequestration efficiency. *Ecol. Indic.* **2021**, *125*, 107602. [CrossRef]
41. Mizuta, K.; Grunwald, S.; Phillips, M.A.; Bacon, A.R.; Cropper, W.P.J.; Moss, C.B. Emergence of the Pedo-Econometric Approach. *Front. Soil Sci.* **2021**, *1*, 656591. [CrossRef]
42. Bouma, J. Soil security as a roadmap focusing soil contributions on sustainable development agendas. *Soil Secur.* **2020**, *1*, 100001. [CrossRef]
43. Rumpel, C.; Amiraslani, F.; Chenu, C.; Garcia Cardenas, M.; Kaonga, M.; Koutika, L.-S.; Ladha, J.; Madari, B.; Shirato, Y.; Smith, P.; et al. The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. *Ambio* **2020**, *49*, 350–360. [CrossRef]
44. King, J.K.K.; Granjou, C.; Fournil, J.; Cecillon, L. Soil sciences and the French 4 per 1000 Initiative—The promises of underground carbon. *Energy Res. Soc. Sci.* **2018**, *45*, 144–152. [CrossRef]
45. Vogel, H.-J.; Eberhardt, E.; Franko, U.; Lang, B.; Ließ, M.; Weller, U.; Wiesmeier, M.; Wollschläger, U. Quantita-tive Evaluation of Soil Functions: Potential and State. *Front. Environ. Sci.* **2019**, *7*, 164. [CrossRef]
46. Mizuta, K.; Grunwald, S.; Phillips, M.A. New Soil Index Development and Integration with Econometric Theory. *Soil Sci. Soc. Am. J.* **2018**, *82*, 1017–1032. [CrossRef]
47. Jaenicke, E.C.; Lengnick, L.L. A Soil-Quality Index and Its Relationship to Efficiency and Productivity Growth Measures: Two Decompositions. *Am. J. Agric. Econ.* **1999**, *81*, 881–893. [CrossRef]
48. Pieralli, S. Introducing a new non-monotonic economic measure of soil quality. *Soil Tillage Res.* **2017**, *169*, 92–98. [CrossRef]
49. Susaeta, A.; Adams, D.C.; Carter, D.R.; Dwivedi, P. Climate Change and Ecosystem Services Output Efficiency in Southern Loblolly Pine Forests. *Environ. Manag.* **2016**, *58*, 417–430. [CrossRef]
50. Susaeta, A.; Adams, D.C.; Carter, D.R.; Gonzalez-Benecke, C.; Dwivedi, P. Technical, allocative, and total profit efficiency of loblolly pine forests under changing climatic conditions. *For. Policy Econ.* **2016**, *72*, 106–114. [CrossRef]
51. Janzen, H.H.; Janzen, D.W.; Gregorich, E.G. The 'soil health' metaphor: Illuminating or illusory? *Soil Biol. Biochem.* **2021**, *159*, 108167. [CrossRef]
52. Grunwald, S.; Vasques, G.M.; Comerford, N.B.; Bruland, G.L.; Bliss, C.M. Regional Modelling of Carbon, Ni-trogen and Phosphorus Geospatial Patterns. In *Modeling of Pollutants in Complex Environmental Systems*; Hanrahan, G., Ed.; ILM Publ: Herfordshire, UK, 2010; pp. 293–310.
53. Hong, J.; Grunwald, S.; Vasques, G.M. Soil Phosphorus Landscape Models for Precision Soil Conservation. *J. Environ. Qual.* **2015**, *44*, 739–753. [CrossRef]
54. Kim, J.; Grunwald, S.; Rivero, R.G. Soil Phosphorus and Nitrogen Predictions Across Spatial Escalating Scales in an Aquatic Ecosystem Using Remote Sensing Images. *IEEE Trans. Geosci. Remote Sens.* **2014**, *52*, 6724–6737. [CrossRef]
55. Mizuta, K.; Grunwald, S.; Bacon, A.R.; Cropper, W.P.; Phillips, M.A.; Moss, C.B.; Gonzalez-Benecke, C.A.; Markewitz, D.; Clingensmith, C.M.; Xiong, X. Holistic aboveground ecological productivity efficiency modeling using data envelopment analysis in the southeastern U.S. *Sci. Total Environ.* **2022**, *824*, 153802. [CrossRef] [PubMed]