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Cropland Reference Ecological Unit: A land classification unit for comparative soil studies

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ABSTRACT

There is a growing consensus on a need for measuring the dynamic soil properties of croplands and even comparisons with a reference state or native land. These measurements and paired comparisons will create the capacity to determine soil health management effects and targets. However, the complex soil heterogeneity and climate variations make soil health potential variable and confound the effects of land-use and management practices and comparisons between soils from different sites. Identifying a discrete landmass unit where all soils have similar health potential will be critical in conducting meaningful comparative studies and measuring the impact of conservation practices. This methodological paper proposes and discusses a land unit, Cropland Reference Ecological Unit (CREU), that accounts for soil genoform and climate variabilities and covers an area with a presumably similar soil health potential. An example CREU has been developed, for one Major Land Resource Area (MLRA) in Nebraska, which is an area delineated based on the standard United States Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS) hierarchical land classification system. This example portrays an actual difference in soil health for different land use and agronomic management practices can be determined by comparing sites under the framework of CREU. Evaluation of management effects on soil health indicators in a CREU will adequately illustrate the beneficial impact of such practices without being confounded by agroecological variations. This proposed framework addresses researchers' current interest in comparing soil health parameters among croplands and reference sites to benchmark soil health measurements, set soil health targets, and determine the effects of different management practices.

1. Introduction

Concerns over the sustainability of the soil ecosystem being hampered in its ability to produce food, fiber, and fuel for the growing world population have helped coalesce efforts around soil health. Currently, soil bio-physicochemical properties are measured as indicators of soil health in croplands to identify management practices that can maintain or improve those properties. In addition, there is a growing consensus that soil health in cropland needs to be compared to a reference state to understand its status and soil health management target (Morgan and Cappellazzi, 2021).

Maharjan et al. (2020) proposed the "Soil Health Gap" concept that compares soil health in cropland and in native undisturbed land, providing a measure of soil health decline in croplands since cultivation began and simultaneously setting potential soil health targets. However, comparing croplands with reference native sites or among themselves can be confounded with agroecological variations, including the heterogeneity in soil and climate.

Significant changes in soil properties can be observed across different soils (Caudle, 2019). Climate, especially precipitation, significantly affects soil biological functions, nutrient cycling, and native vegetation. Precipitation gradient and soil series based on pedogenetic differences or soil genoform (Rossiter and Bouma, 2018) can create differences in soil health potential. For that reason, the soil health response to different management practices is site-specific (Nunes et al., 2021; Wills et al., 2017). Therefore, when comparing soils, they should belong to an ecologically discrete unit that accounts for soil heterogeneity and climate variability. This paper proposes such landmass classification unit, Cropland Reference Ecological Unit (CREU), using the existing hierarchical framework.

1.1. Definition of Cropland Reference Ecological Unit

A Cropland Reference Ecological Unit (CREU) is a land area with

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presumably uniform pedogenetic and climatic properties and where sites can be compared unconfounded by extenuating agroecological variation. The CREU will provide a leveled platform for comparative studies where soil health can be assessed and compared for a group of sites with presumably similar soil health potential. If measured in the same CREU, soil health at different sites will provide actual differences due to land use or management practices. Thus, the CREU provides a geographically universal framework for comparative studies between parcels of land by accounting for the different native potential based on the soil and climate.

The CREU can be created to achieve the desired resolution by adjusting boundary conditions of pedogenetic and climatic factors. The methodology to determine a CREU is illustrated with an example in the US, where there is a USDA-NRCS Land Resource Hierarchy or Hierarchical Land Classification System (HLCS) (Fig. 1a).

In the USDA-NRCS HLCS, a Major Land Resource Area (MLRA) is a broad classification of geographically associated land considering the geology (parental material), climate (precipitation, temperature), water source, soils (dominant soil orders), biological resources (plants and animals), and land-use types (USDA NRCS, 2022a). The MLRA is further divided into ecological sites (ES), which are distinctive lands with specific soil and physical characteristics that produce distinct kinds of vegetation and respond to management practices and natural disturbance USDA NRCS, 2022b). Benchmark ES are selected for their potential to yield data and information about ecological functions, processes, and climate change, which are essential to characterize an area or critical ecological zones based on NRCS definition and descriptions (Ypsilantis et al., 2009). Thus, the NRCS Hierarchical system presents the framework vital for the delineation of CREU.

In the region outside the US and where organized land classification based on soil, ecological functions, and vegetation characterization data is lacking, a critical zone of regional agroecological significance (CZAS) needs to be determined within the Region of Interest (ROI) before identifying the CREU (Fig. 1b). The ROI will be analogous to MLRA, a distinct area with dominant physical and climate characteristics and important in regional agricultural planning. The CZAS will share similarities with ES in the USDA-NRCS classification, which can be distinguished by soil groups, hydrologic units, topography, landscape features, vegetation, resource use and resource concerns.

2. Methodology to determine Cropland Reference Ecological Unit

Each geographic region of interest should be first categorized into CZAS based on known dominant agroecological conditions and local natural resources. In the case of the US, the benchmark ES is the smallest unit in the current NRCS land classification system. In each MLRA, only the top-ranked benchmark ES cumulatively representing > 90 % of cropland is considered in determining CREU and is referred to as dominant ES for crop production (Fig. 1a). Depending on application and purpose, a generalized CREU can be created from ES. Since our effort here is to benchmark soil health in croplands, we narrowed ES into dominant ES accounting for > 90 % of crop cover. Thus, selecting the dominant ES allows comparing sites of greater relevance within the region of interest and serving the objective. Individual dominant ES or CZAS are then divided into discrete landmass units as a function of soil association, topography, and precipitation range to determine the CREU.

The soil series is the smallest category in the six-level US taxonomy classification of soil and is intended to have similar pedogenesis and properties. However, mapping an area with a single taxonomic unit is rare and cannot define the morphological behavior of a natural heterogenic landscape. A soil association reflects the reality where a soil map unit comprises two or more primarily noncontrasting components (USDA NRCS, 2022b). For the illustration in this paper, we used the generalized soil map for Nebraska which divides the state into 80 soil associations using the Soil Survey Geographic Database (SSURGO) (UNL SNR, 2022). For example, Tripp – Mitchell – Alice (TMA) in Fig. 2 is association of the Tripp, Mitchell, and Alice soil series. The resolution of the CREU can be adjusted based on the scale of available soil map and applicability.

The selection of precipitation range used for delineation should be adjusted between regions since the effects of the same change in precipitation on vegetation may differ from hydric to mesic to arid regions due to varying potential evapotranspiration (PET) (Altieri et al., 2015; Robinson and Nielsen, 2015). In a semi-arid region where precipitation makes 20–35 % of PET and dryland farming is practiced, a smaller precipitation range should be selected than in the regions where rainfed farming is practiced (precipitation > 35 % of PET). The precipitation range selected for CREU determination should be such that the resultant soil and vegetation in that range in the given agroecological region are presumably uniform.

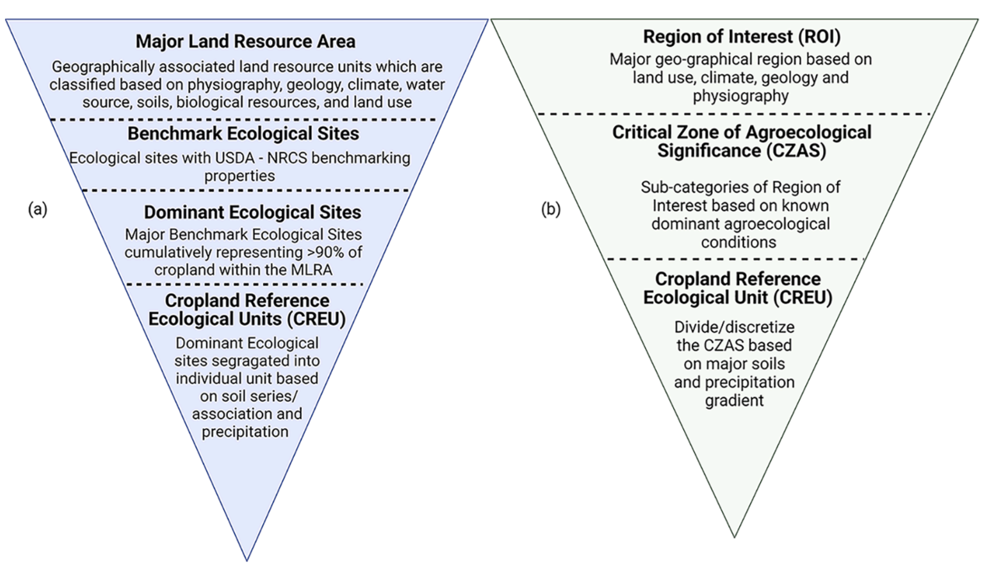

Fig. 1. A flow chart showing the development of Reference Ecological Units (a) using the USDA-NRCS hierarchical land classification system (USDA NRCS, 2021) and (b) when organized and hierarchical land classification is absent.

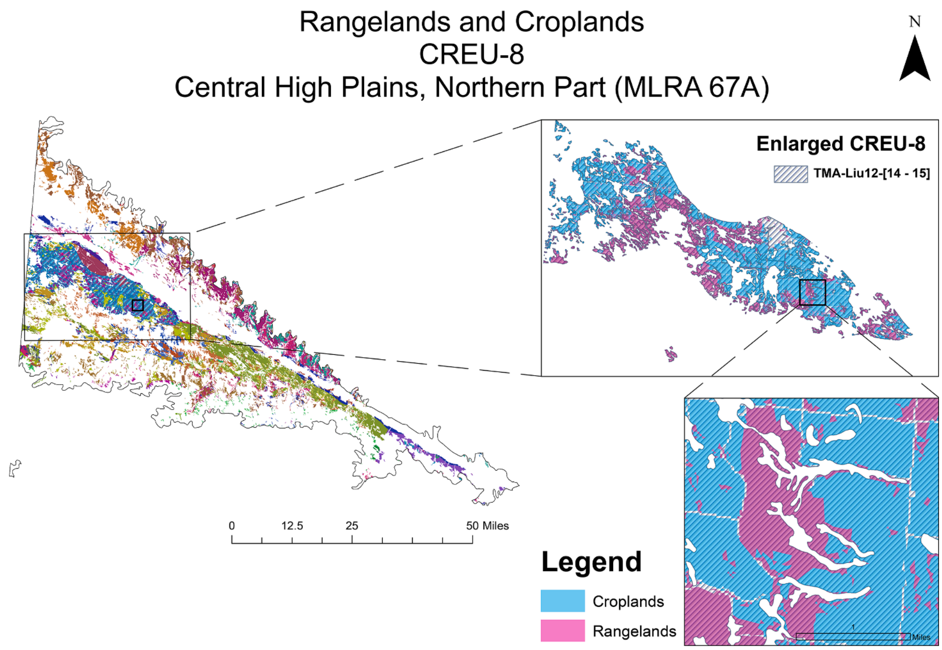

Fig. 2. Major Land Resource Area 67A with one of 45 identified Cropland Reference Ecological Units (CREU-8; in box) in Nebraska Panhandle (left). Right Top: CREU-8 enlarged and divided into cropland and rangeland. The CREU consists of soil association- Trip-Mitchell-Alice (TMA), Liu12; Limy upland, and [14 – 15]; 14–15-inch precipitation zone. Right Bottom: Enlarged section of CREU-8 showing cropland and rangeland.

Theoretically, CREU would represent uniformity from perspectives of soil genesis (geology), biotic community (plant community), physical properties (topography and hydrology), and climate (precipitation). For each CREU, croplands or rangelands associated with the specific ES designation within the same MLRA, can be paired and compared against each other. One can use an Ecological Site Description (ESD) that includes the reference plant community to inform the reference site selection (NRCS - USDA, 2022a; Salley et al., 2016). The concept of CREU is based on current and available soil pedogenetic and climate data; a collaborative effort of the soil scientific community is warranted to cross-validate the extent of applicability of CREU.

In order to develop a working example in Nebraska, geospatial analysis was conducted in ArcGIS 10.8 (Esri, CA) to determine multiple CREU. The USA Contiguous Albers Equal Area Conic was used as a reference projection model for geospatial analysis and methodology development. Available shapefiles and layer files such as MLRA, Land Cover, and Land Use were downloaded from the USDA - Geospatial Data Gateway (USDA – GDG) by generating a request form from the website (https://datagateway.nrcs.usda.gov/). All the source and reference information for the GIS shapefiles, data source, and acronyms used are described in the supplementary file S1. The CREU selection methodology involves:

)i. *Creating the geospatial layers*: where shapefiles of MLRA, cropland cover, benchmark ES, soil associations, and precipitation are created using public data sources such as the National Agricultural Statistics Service (NASS) and High Plains Regional Climate Center,
)ii. *Geospatial analysis*: which involves the geospatial intersection of above-mentioned shapefiles to determine the dominant ES for crop production that encompasses top-ranked benchmark ES representing > 90 % of cropland in an MLRA, and.
)iii. *Determination of CREU*: segregation of dominant ES as a function of selected precipitation range and soil associations in an MLRA.

A detailed method of CREU determination using USDA HLCS is given in Supplemental file S2.

2.1. Current approaches, limitations, and opportunities

There are other land classification systems used for resource planning and management. The Food and Agricultural Organization of the United Nations uses its Global Agro-Ecological Zoning Framework which characterizes climate, soil, and terrain conditions to inform cropland management decisions. Along the same line, the agro-ecological regions were created on a national level in India to create the near homogenous soil-climatic zones used to guide resource management there (Mandal et al., 2014). However, such Agro-ecological Zones or Regions can have a scale as high as 1:5,000,000 and cover very broad territories, yet still be intended for crop planning (Mandal et al., 2014). There is a constant attempt to refine these zoning frameworks by adding other important parameters and updating maps and data sets. More work is warranted to achieve uniform zoning for effective resource planning and management. It is even more imperative to achieve uniformity in zoning when two sites are being compared to determine the effects of land use or management practices.

There are several past and current ongoing efforts in paired comparisons of sites to measure the success of management practices (Burke et al., 1995; Ihori et al., 1995; Norton et al., 2012). However, it is very unlikely to always find a reference site near croplands for paired comparison. The CREU Framework builds on the existing and tested NRCS land classification system and its ecological sites (ES) and sets the land boundary within which croplands and reference sites can be matched and compared. The CREU utilizes the ES concept based on the fundamental assumptions that landscapes can be grouped with sufficient precision to increase the probability of success in site-specific predictions, decisions, and management recommendations. The CREU inherits a level of homogeneity covered by the MLRA and ES. Ecological site descriptions (ESD) characterize physiographic, climatic, and soil features, potential plant communities, and vegetation dynamics (Twidwell et al., 2013). The ESD considers the best-adapted key plant species or potential native species or changes in vegetation community composition as an indicator of change resulting from differences in land use, management, and the potential capacity of the land (Brischke et al., 2018; NRCS - USDA, 2022c). However, the ESD does not provide information on inherent soil bio-physicochemical properties; soil variability that exists within an ecological site (Bestelmeyer et al., 2016). There are recent efforts from the USDA NRCS under the Dynamic Soil Properties for Soil Health (DSP4SH) program to update the ESDs with soil health metrics (USDA NRCS, 2022d). Developmental ESD was primarily to support the rangeland health assessment, not cropland. Therefore, the ES irrelevant to croplands are cropped out in the outlined process before dividing them by soil associations and precipitation ranges accounting for regional PET. Such delineation of the CREU would enhance uniformity allowing for site comparison within a such unit.

Establishing the CREU framework is a logical next step to establish and utilize a Soil Health Gap concept since it allows accurate comparisons of soil health in croplands and corresponding native reference sites to estimate the soil health gap of the various croplands. Similarly, measuring and documenting the inherent soil properties in ES that support and develop native plant and animal communities will be essential to informing land resource planning and management (Nauman et al., 2022). The plants and the soil synergistically support resilient ecosystem services. Thus, the CREU framework allows us to connect rangeland and cropland soil health, and by comparing them, we can determine the Soil Health Gap.

The CREU framework is dynamic and can be modified and updated as and when required with the updated land-use, soil mapping, and climate data. Improvement in modern technologies such as remote sensing will be critical in generating high-resolution soil maps and developing the dynamic boundaries of precipitation as a function of vegetation index and potential evapotranspiration.

2.2. CREU for comparative soil (health) studies

Croplands under different management or paired cropland and reference sites should be selected for soil health comparative studies as done in the DSP4SH Project (USDA NRCS, 2022d). Selecting sites within the CREU framework would eliminate any possible confounding effects of extenuating agroecological variations. As an example of a comparative study, in Fig. 2, the shaded background in the enlarged section is the CREU-8, and the blue and pink shaded areas represent the croplands and rangelands, respectively. Croplands in the CREU-8 can be compared against a rangeland reference site therein to determine the Soil Health Gap. On the other hand, two sites in the cropland area should be comparable to assess soil health differences due to management practices. As mentioned above, there are several reports on paired site comparisons. However, a reference site can be sometimes hard to locate. In such cases, a site of interest can be compared to sites from higher categories in suitability groups to estimate soil health decline and potential soil health targets. A list of land suitability groups is provided in supplementary file S3.

3. Summary

The CREU is constructed based on the existing USDA-NRCS Hierarchical Land Classification System and inherits a homogeneity in the topological, geological, and pedological properties from MLRA and ecological sites. The CREU further defines those landmass delineations into a more homogenous land mass unit that otherwise would be combined with areas with different dynamic soil pedogenetic properties and climatic variability. As most soil health researchers attempt to understand and determine management effects on soil health properties and the degree of gain in soil health over time, it is essential to compare cropland soil health to the soil in a prime health state or a reference state at its native potential. It is equally important to categorize comparison sites from the same CREU with similar soil health potential. Otherwise, the differences in pedology and climate among comparison sites can create confounding effects observed when interpreting soil health indicators. The CREU will be critical for future soil (health) research for its following functional attributes.

- It provides a site-specific leveled platform for comparing and understanding the soil health statuses under different land use or management practices.
- Differences in soil health properties affected by varying management practices, if measured in a CREU, will help assess the actual effect of such practices, unconfounded by agroecological variations.
- The development of CREU will allow for the creation of a comprehensive, correlative, understanding of soil health properties in different agroecological regions. More work is needed to model or determine relationships among CREUs within each MLRA and between different MLRAs.

CRediT authorship contribution statement

Saurav Das: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Bijesh Maharjan:** Conceptualization, Methodology, Software, Validation, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.109468.

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