Developing a multi-factor crop production environmental risk index

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Abstract
The production of crops is not always done without soil degradation or damage to the environment. Many indexes have been developed to define the productivity of soils but fewer are designed to integrate many soil and landscape factors to describe the potential hazards of crop production. The objective of this work is to report on a method of quantifying the environmental risk that may occur to the soil resource and the environment as a result of crop production. The risk of erosion by water and wind, compaction, acidification, salinization, denitrification, surface and subsurface water contamination, and organic matter loss are examined using the soil interpretations module of the National Soil Information System. This system allows the magnitude of soil properties to be evaluated in terms of their degree contribution to a risk factor and also permits weighting of the importance of each risk factor. Productivity index and the environmental risk ratings are mapped for Mason County, Illinois, USA. The result of combining the risk and productivity indices has clear implications for biofuels and other land uses.

Key Words
Soil productivity, soil degradation, dynamic soil properties, sustainable land use.

Introduction
Many models have been developed to quantify the relative inherent productivity of soils. These include the Storie Index (Storie 1978), and the National Commodity Crop Productivity Index (Dobos *et al.* 2008), among many others. Similarly, many models have been developed to quantify or index the degree of environmental hazard inherent in land use due to one factor, such as soil erodibility, pesticide leaching, or phosphorus indexes. Lal *et al.* (2004) list several ways in which soil can be degraded during use. Soil erosion by water and wind are major types of degradation. Soil can also be degraded due to salinization and mining (Lal *et al.* 2004). In the Soil Atlas of Europe (2005), several key threats to soil are recognized in addition to erosion and salinization. These include loss of organic matter, compaction, soil sealing, decline in biodiversity, and hydrogeological risks (European Commission 2005). Long-term application of anhydrous ammonia can cause soils to acidify (Bouman *et al.* 1995), which has implications for micronutrient bioavailability and pesticide efficacy. Crop production can have effects that are not necessarily manifested in the soil, but rather are shown to be detrimental to surface or subsurface waters. The materials added to the soil during pesticide or fertilizer application can have one of several fates. They can remain immobilized in the soil, they can contaminate surface water due to runoff, or they can move through the soil and contaminate ground water. A method of integrating the level of risk associated with many different hazards to the environment or impacts on the soil resource is needed. Having both a risk index and a productivity index will allow a degree of quantification of the potential harm that can be done to the soil or environment associated with the agricultural use of a state, county, landscape, or parcel of ground. This paper describes such a system.

Methods
The "Environmental Risk Index" is being developed using the National Soil Information System (NASIS) database. This database contains soil property, climate, and landscape data for nearly 3000 soil survey areas in the United States. The geographic extent includes the continental United States, Alaska, Hawaii, Puerto Rico, and the U.S. territories of the Pacific Basin. Data can be readily retrieved and manipulated using the NASIS-based Calculation/Validation, Interpretation and Reporting (CVIR) scripting language (Soil Survey Staff 2002). The interpretations module of the soil survey database system uses fuzzy logic to allow soils to be considered in terms of their degree of membership in the set of soils that are limited for a particular land use. A statement can be made such as: "A soil that has a given set of characteristics is a non-member, partial member, or a full member of the set of soils that are prone to environmental risk". The degree of truthfulness ranges from zero (absolutely false) to one (absolutely true). The actual linkage between a soil characteristic and the degree of membership in the set of soils that may pose an environmental risk is based on a graphed

function that describes the fuzzy set. The shape of the relationship can be specified to reflect the effect of an independent variable on a dependent variable, whether it is linear, sigmoidal, bell-shaped, or any other shape based on empirical evidence. One of the challenges in fuzzy systems modeling is determining the relationship between the variables being modeled (Cox 1994). In the Environmental Risk Index (ERI), this task was handled by assuming a linear relationship between the critical values, since there is not much hard data on the impact of the variables studied on the nationwide scale of the model.

The ERI model is a system that calculates an index of the degree of hazard of environmental or soil degradation due to crop production. The model has three parts (subrules): Surface Water Contamination (SWC), Groundwater Contamination (GC), and Soil Degradation (SD). SWC examines the relationships between the soil and site properties that contribute to rapid runoff (saturated hydraulic conductivity, slope, and landform shape) and the availability of enough precipitation to create runoff under normal circumstances. Also considered is if the soil is artificially drained, since nutrients can move quickly into surface water through the drainage network. Finally, the possibility of removal of nutrients or crop residue by floodwaters is considered. The GC section of the model examines the permeability of the soil profile, the availability of water for leaching, and the adsorptive capacity of the soil. Soils having moderate permeability and adequate adsorptive capacity can attenuate nutrients or pesticides to prevent or at least slow their deposition into the aquifer. SD considers dynamic soil properties that can be degraded by some crop and soil management systems (Tugel *et al.* 2005). A risk of denitrification losses is indicated when saturation is at or near the soil surface during the growing season. Organic matter loss sensitivity is indexed by observing the current organic matter level and estimating a loss rate from the mean annual soil temperature with modification due to seasonal wetness. Water erosion risk is indexed using the water erodibility factor and slope of the soil. Soil compaction hazard is rated from the difference between the observed bulk density and a maximum bulk density dampened using the structure grade and organic carbon content of the surface layer. Wind erosion hazard is indexed using a calculation used in the interpretations generator. Salinization risk is indicated for soils that are in groundwater discharge areas that already have some salts and a non-leaching moisture regime. Acidification risk is based on the cation exchange capacity and the existing pH of the surface layer. Balancing or weighting the various risk factors in terms of their degree of limitation on the use of the soil is an ongoing process. Factors that are irreversible or only slowly reversible, such as erosion and groundwater contamination are weighted more heavily than those factors, such as pH, which can be changed in a short term time scale. Illustrating the actual mechanisms involved in the derivation of the index, while of great interest, is unfortunately beyond the scope of this paper.

The productivity aspect of the paper is provided by the NCCPI, which is described by Dobos *et al.* (2008). The NCCPI, briefly, is a fuzzy system model that ranks the impact of soil, landscape, and climatic properties on relative commodity crop yield. Being fuzzy systems models, both the ERI and NCCPI return values from 0 to1.

Soil attribute data contained in the Soil Survey Geographic (SSURGO) Database were used to develop thematic maps showing the National Commodity Crop Productivity Index and the Environmental Risk Index as unitless index values. The NCCPI and ERI values were originally prepared in NASIS for soil survey areas in Illinois. The NASIS text output was converted to Dbase IV format and then joined to SSURGO feature classes for mapping using ArcGIS version 9.3 (Soil Data Mart source dated 8/2009). The study area for this paper is Mason County, Illinois USA. This area is chosen because it is highly agricultural and has a diversity of soil parent materials, ranging from deep loess to outwash sands (USDA-NRCS 2009)

Results and discussion

Figures 1 and 2 are plots of NCCPI and ERI, respectively, for Mason County, Illinois. Figure 1 shows that much of Mason County is comprised of soils that are highly productive, having the NCCPI greater than 0.6 (dark green and blue). The Environmental Risk Index, mapped in Figure 2, on the other hand, indicates a significant proportion of soils that are potentially risky to farm, in terms of the potential for environmental degradation, having the ERI greater than 0.6 (orange and red). Figure 3 illustrates some selected combinations of NCCPI and ERI. The dark blue areas in Figure 3 are soil map units that are both highly

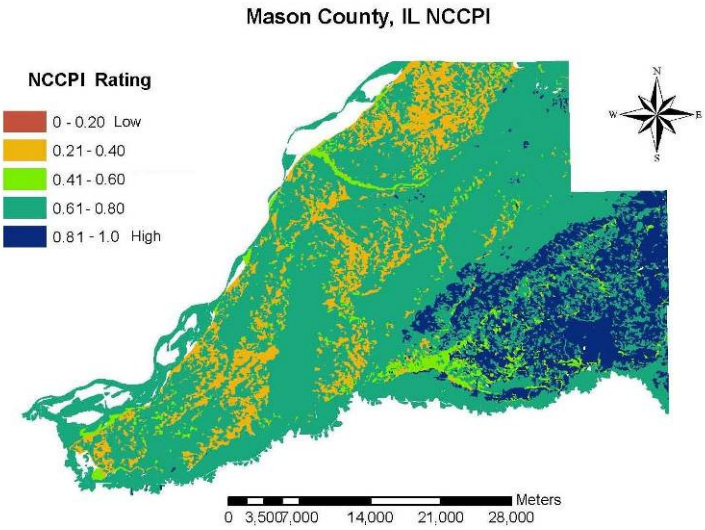

Figure 1. Mason County, IL National Commodity Crop Productivity ratings

productive and not typically an environmental hazard to farm. These areas are composed mostly of Tama and similar soils (Fine-silty, mixed, superactive, mesic Typic Argiudolls) that formed in deep loess. The red areas in Figure 3 denote highly productive soils that are predicted by the model to be prone to increasing environmental degradation when farmed. Thorp (Fine-silty, mixed, superactive, mesic Argiaquic Argialbolls) and

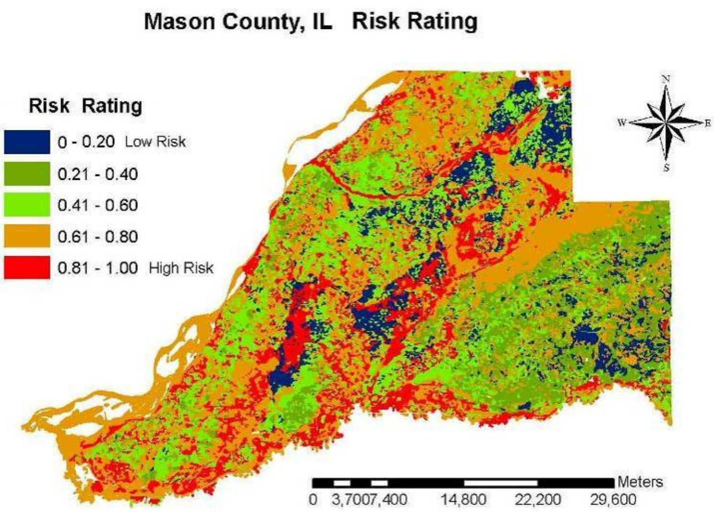

Figure 2. Environmental Risk Index map for Mason County, IL.

Edgington (Fine-silty, mixed, superactive, mesic Argiaquic Argialbolls) and similar soils are found in the red areas of Figure 3. These soils have been drained in order to produce crops and the drain tiles and ditches can provide a ready conduit for transmitting nutrients and agricultural chemicals to streams. The gold areas in Figure 3 are soils that are of low to moderate productivity and are somewhat risky to farm. The soil found in this area is almost exclusively Plainfield (Mixed, mesic Typic Udipsamments). These very permeable soils having low cation exchange capacity formed in sandy parent materials.

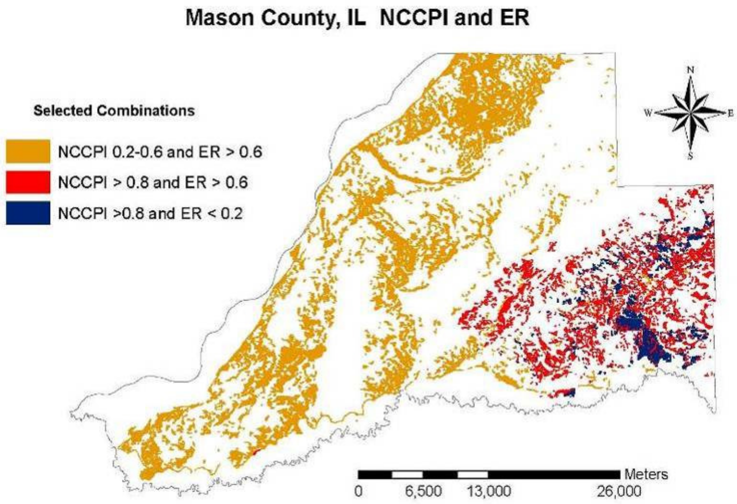

Figure 3. Selected combinations of NCCPI and ERI for Mason County, IL.

Groundwater contamination is a serious concern when these soils are farmed. Moderate to low productivity soils may be targeted for production of biofuels, but producers must be cognizant of the potential for environmental damage that exists when these soils are cropped.

The ERI can provide information for better land use decisions. A future experiment with the ERI will be to intersect the risk level with the spatial distribution of lands in the Conservation Reserve Program (CRP). This would allow a way to judge the benefits and risks of returning parcels of this land into crop production. This process may be especially valuable in terms of locating and selecting soils for biofuels production. This index is relatively new and thus is subject to improvement and enhancement. The authors welcome suggestions for improvement.

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