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Development of a Soil Carbon Index for Iowa Mineral Soils

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A carbon index (CI) is one of many soil quality indicators that depends on organic carbon concentration. One of the values of a soil carbon index is in determining the impact of agriculture practices (i.e., tillage, crop rotation, N management, etc.) on soil organic matter status of mineral soils. Interactions of climate, parent material, topography, time, and organisms including human activities influence soil organic carbon (SOC). This study developed a soil carbon index for mineral soil map units in Iowa using data collected by the Iowa Cooperative Soil Survey Laboratory and the USDA Soil Survey Laboratory for over 2,300 soil map units across the state in the past 20–30 years. The results show that the soil CI is highly influenced by soil forming factors. The highest soil carbon index was associated with soil map units of soils that are poorly drained, have moderately fine textures, and are on relatively flat topography as in the Clarion-Nicollet-Webster soils association area in north-central Iowa. Additionally, there was a negative correlation between the number of hectares of soils formed under deciduous forest vegetation and CI values within a county. The CI is also related to soil productivity in the state. Fifty five percent of the variability of the corn suitability ratings was explained by the CI. The CI is a valuable tool in evaluating soil organic matter status, productivity of Iowa soils, and land value.

INDEX DESCRIPTORS: SOC, C index, organic matter.

INTRODUCTION

A carbon index (CI) is one of many soil quality indicators that depends on soil organic carbon (SOC) concentration as affected by various ecosystems and climate factors. One of the values of a soil CI (a ratio of soil carbon mass of a certain soil to a reference value of soil carbon mass) is in determining the impact of agriculture practices (i.e., tillage, crop rotation, N management, etc.) on soil organic matter status of mineral soils. The interaction of climate, parent material, topography, time, and organisms including human activities can influence SOC (Jenny 1980). The importance of SOC to soil quality, environmental quality, and crop production (Bauer and Black 1994, Doran and Parkin 1994, Robinson et al. 1994, and Fenton et al. 1999), makes the CI a useful tool in evaluating present soil carbon stocks and the factors that have influenced those stocks. This study developed a soil carbon index for each mineral soil map unit in Iowa using data collected by the Iowa Cooperative Soil Survey Laboratory and the USDA Soil Survey Laboratory for over 2,300 soil map units across the state in the past 20–30 years (USDA-NRCS STAFF 1998). Each soil map unit varies by soil series as influenced by slope percent and level of erosion. The use of this indicator will be of practical interest to land managers and policy makers to evaluate different land values and necessary management decisions at the field level for their relative carbon contents. Although marketing carbon credits has not yet proven successful (Young 2003), there is still great interest in improving soil carbon to sustain soil productivity and environmental quality (Lal et al. 1998, Kimble et al. 2002, and Sanchez et al. 2004). The CI provides a more detailed, field scale evaluation of current carbon levels for individual soil series and map units and provides valuable information for land managers.

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Iowa soils have the characteristics that have enabled them to sequester large amounts of carbon in the past resulting in relatively high organic matter contents. Iowa has seven landform regions within its borders (Fig. 1). Each landform region has dominant soil associations developed under different soil forming conditions. For example, the soils on the Des Moines Lobe (Clarion-Nicollet-Webster soil association area) are on relatively undissected landscapes and include deep, fertile soils formed in glacial drift under tall grass prairie (Prior 1991). In contrast, the Southern Iowa Drift Plain consists of a dissected landscape with loess-mantled uplands and outcroppings of weathered glacial drift on slopes. Native vegetation under which Iowa's soils formed ranged from prairie grasses to forests. In general, tall grass prairie dominated all but the southeastern and northeastern corners of the state and major waterways where deciduous forest (oak and hickory) was the dominant vegetation. Prairie plants are efficient cation recyclers, which contribute to significant accumulations of organic matter in soil (Jenny 1980 and Brady and Weil 2002). Mollisols are the principal soil order found in areas covered by prairie in Iowa (over 68% of the land area) (Miller et al. 2010). In parts of the state where forest was the dominant native vegetation, Alfisols are the dominant soil order. Alfisols formed under deciduous vegetation and have lower levels of organic matter.

The Iowa carbon index (ICI) is an important tool that can be utilized to evaluate the long-term impact of agricultural management practices on soil carbon stocks across the diverse soil associations in Iowa in particular and the Midwest in general. Soil organic C content plays a crucial role in sustaining soil quality, crop production, and environmental quality (Bauer and Black 1994, Doran and Parkin 1994, and Robinson et al. 1994) due to its effects on soil physical, chemical and biological properties such as soil water retention, nutrient cycling, erosion control, gas flux, plant root growth as well as water and air quality (Carter 2002 and USDA-NRCS Staff 2003). Therefore,

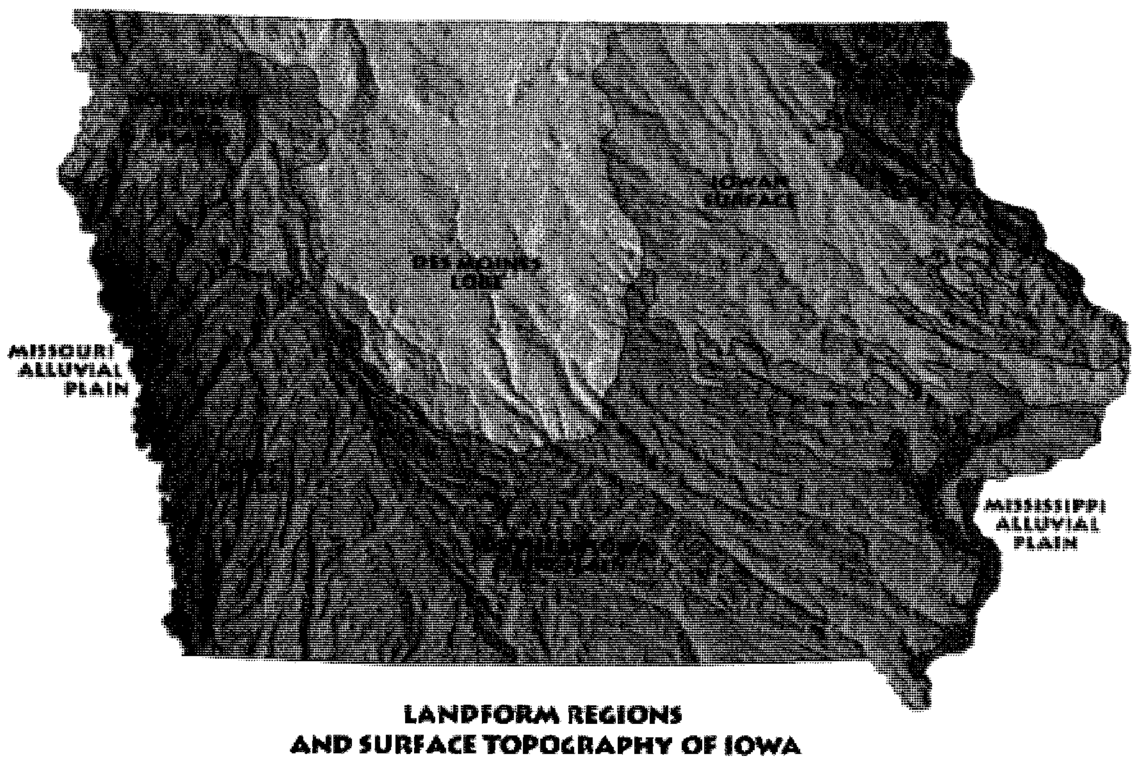

Fig. 1. Landform Regions and Surface Topography of Iowa. (Adopted from Iowa Department of Natural Resources 2011).

the implications and applications of the ICI are very important in developing best management practices for managing soil C stocks. The application of this tool will be significant in understanding soil suitability and the role of SOC in evaluating land use.

The objective of this study was to develop a CI for different soil map units across the mineral soil landscape. Absolute values were calculated for modal soil profiles, but when ranges in properties of soil map units are considered, an index is a preferred method of showing relative differences.

MATERIALS AND METHODS

The concept of the Iowa carbon index (ICI) was based on three major components, including: soil organic carbon concentration, soil bulk density (BD), and horizon thickness (HT) of mineral soils that have been cultivated for at least 20 years. Land surfaces covered by lakes, ponds, rivers, dams, pits, Orthents, organic based soils, marshes, quarries, urban land, man-made land, sewage lagoons, and sanitary landfills are excluded from the analysis. The study includes approximately 410 soil series and 2,300 soil map units across the state. The soil organic carbon mass per unit area for each map unit was calculated using the equation:

$$\mathrm{SOCM} = \sum_{\mathrm{HT}=i}^{\mathrm{HT}=i+n} \{(\mathrm{SOC}_i * \mathrm{BD}_i * \mathrm{HT}_i) + (\mathrm{SOC}_{i+1} * \mathrm{BD}_{i+1} * \mathrm{HT}_{i+1}) + ..(\mathrm{SOC}_{i+n} * \mathrm{BD}_{i+n} * \mathrm{HT}_{i+n})\}$$

Where, SOCM is soil organic carbon mass (kg ha^{-1}); HT is horizon thickness in cm, i is soil A-horizon thickness, i+n is thickness up to 100 cm, SOC is soil organic carbon concentration (g kg^{-1}), and BD is bulk density (g cm^{-3}) at 1/3 bar moisture content. The soil C mass was calculated for each soil map unit within each county by summing the carbon mass of all horizons up to 100 cm soil depth.

Data collected by the Iowa Cooperative Soil Survey Laboratory and the USDA Soil Survey Laboratory for over 2,300 soil map units across the state were used in this study (USDA-NRCS STAFF 1998). The database contains soils bulk density, SOC concentration, horizons thickness, soil texture, drainage class, slope, and erosion class. Soil organic carbon concentration and particle size data were available for all soils. However, for soil series horizons with missing bulk density data, a model obtained from Soil Water Characteristics, "Hydraulic Properties Calculator" (USDA-ARS and Washington State University, 2009) was used to calculate the 1/3 bar bulk density for those soils. This model allowed adjustments for particle size, coarse fragments, and compaction. For soils with 2:1 expanding clay minerals, the 1/3 bar bulk density is the most reproducible and the best measurement (Miller et al. 2010). It is the volume that is measured at 1/3 bar moisture and then the sample is oven dried. The compaction variable was calibrated for parent material difference by using data from similar soils developed from loess, till and alluvium. Adjustments were also made based on soil consistence as given in the soil profile description. For other soils for which there were limited data available, indexes were estimated based on the similarity of their physical, chemical, and morphological properties to an appropriate benchmark soil. Classification criteria at the family level (i.e. Fine-silty, mixed,

Table 1. Average Iowa CI, average corn suitability ratings, total hectares by county, forest hectares and forest % values based on the 1832–1859 original land survey notes for all Iowa counties. Standard deviation is given in parentheses. Corn suitability ratings and total county hectares obtained from Iowa Soil Properties and Interpretations Database (ISPAID; 2010).

County	CI*	CSR±	Total County Area (Hectare)	Total Forest Area≠ (Hectare)	Forest (%)
Adair	33 (15)	57 (29)	147,370	13,259	9
Adams	33 (16)	55 (32)	110,358	14,628	13.3
Allamakee	18 (10)	42 (29)	170,858	152,249	89.1
Appanoose	24 (13)	41 (23)	135,456	54,130	40
Audubon	33 (16)	61 (31)	116,031	5,470	4.7
Benton	34 (10)	73 (32)	185,960	25,982	14
Blackhawk	33 (17)	72 (27)	148,357	19,943	13.4
Boone	34 (23)	72 (38)	148,341	25,123	16.9
Bremer	35 (17)	73 (29)	113,757	19,166	16.8
Buchanan	34 (20)	71 (29)	147,370	26,024	17.7
Buena Vista	39 (18)	72 (31)	148,258	486	0.3
Butler	34 (17)	73 (27)	150,737	16,058	10.7
Calhoun	40 (20)	77 (32)	148,147	1,214	0.8
Carroll	34 (20)	68 (32)	148,639	4,176	2.8
Cass	36 (17)	62 (33)	144,780	12,432	8.6
Cedar	32 (16)	78 (33)	150,826	30,756	20.4
Cerro Gordo	34 (16)	71 (25)	148,976	8,806	5.9
Cherokee	39 (19)	63 (32)	148,406	2,315	1.6
Chickasaw	34 (18)	69 (27)	130,835	34,600	26.4
Clarke	27 (12)	40 (26)	111,085	22,484	20.2
Clay	39 (15)	68 (29)	148,276	1,335	0.9
Clayton	18 (16)	48 (32)	201,837	148,250	73.5
Clinton	26 (10)	62 (29)	180,003	32,737	18.2
Crawford	30 (13)	59 (23)	185,021	4,375	2.4
Dallas	33 (16)	74 (31)	154,622	26,159	16.9
Davis	23 (10)	40 (32)	132,089	81,195	61.5
Decatur	23 (17)	35 (27)	138,655	50,990	36.8
Delaware	28 (23)	63 (38)	148,406	45,168	30.4
Des Moines	26 (17)	63 (29)	105,931	50,723	47.9
Dickinson	38 (20)	66 (29)	98,290	801	0.8
Dubuque	18 (18)	51 (31)	161,097	81,675	50.7
Emmet	37 (17)	67 (27)	104,004	1,619	1.6
Fayette	28 (20)	64 (32)	188,550	51,301	27.2
Floyd	34 (20)	76 (32)	129,823	25,414	19.6
Franklin	37 (17)	77 (33)	151,773	6,475	4.3
Fremont	36 (17)	65 (28)	135,663	23,123	17
Greene	37 (20)	76 (35)	147,344	10,295	7
Grundy	40 (15)	85 (24)	129,758	259	0.2
Guthrie	31 (16)	56 (33)	154,363	17,819	11.5
Hamilton	36 (23)	76 (26)	149,556	7,899	5.3
Hancock	38 (22)	71 (30)	148,147	3,626	2.4
Hardin	36 (19)	76 (27)	148,587	17,612	11.9
Harrison	30 (16)	54 (26)	180,210	26,053	14.5
Henry	26 (12)	60 (30)	113,960	46,536	40.8
Howard	32 (16)	69 (26)	121,988	21,011	17.2
Humboldt	38 (20)	75 (28)	113,069	1,942	1.7
Ida	36 (17)	60 (26)	111,855	259	0.2
Iowa	27 (15)	61 (31)	152,202	36,549	24
Jackson	16 (9)	47 (29)	166,743	114,290	68.5
Jasper	31 (16)	64 (35)	189,327	27,842	14.7
Jefferson	24 (11)	57 (29)	113,838	57,970	50.9
Johnson	28 (15)	68 (28)	160,594	43,926	27.4
Jones	26 (14)	61 (28)	151,514	55,322	36.5
Keokuk	26 (15)	59 (35)	150,259	47,158	31.4
Kossuth	40 (23)	70 (30)	253,558	1,554	0.6
Lee	21 (12)	48 (27)	135,197	24,522	18.1

Table 1. Continued.

County	CI*	CSR±	Total County Area (Hectare)	Total Forest Area≠ (Hectare)	Forest (%)
Linn	28 (24)	66 (28)	185,649	62,159	33.5
Louisa	26 (15)	63 (29)	108,262	40,899	37.8
Lucas	25 (12)	40 (25)	112,624	26,159	23.2
Lyon	34 (15)	60 (24)	152,291	405	0.3
Madison	30 (16)	54 (35)	146,334	29,461	20.1
Mahaska	30 (16)	68 (44)	148,147	45,065	30.4
Marion	25 (12)	56 (25)	143,489	53,037	37
Marshall	35 (18)	76 (32)	148,665	13,079	8.8
Mills	34 (17)	64 (25)	115,643	20,554	17.8
Mitchell	32 (14)	78 (25)	120,926	26,853	22.2
Monona	31 (15)	50 (22)	181,015	19,882	11
Monroe	24 (15)	41 (26)	112,665	34,964	31
Montgomery	35 (14)	64 (29)	109,298	14,918	13.6
Muscatine	27 (15)	65 (28)	114,607	36,753	32.1
O'Brien	43 (20)	72 (33)	148,898	607	0.4
Osceola	38 (17)	68 (22)	103,082	259	0.3
Page	38 (15)	63 (28)	138,564	20,720	15
Palo Alto	37 (24)	69 (29)	145,298	2,266	1.6
Plymouth	31 (17)	56 (26)	223,514	1,473	0.7
Pocahontas	41 (24)	74 (32)	150,737	890	0.6
Polk	34 (18)	74 (27)	153,294	27,194	17.7
Pottawattamie	33 (16)	61 (26)	249,466	20,968	8.4
Poweshiek	31 (14)	65 (32)	152,550	13,597	8.9
Ringgold	29 (13)	46 (24)	139,341	20,246	14.5
Sac	39 (19)	71 (27)	149,701	890	0.6
Scott	31 (16)	74 (32)	121,365	17,401	14.3
Shelby	28 (17)	66 (35)	153,092	6,754	4.4
Sioux	37 (21)	65 (25)	198,392	283	0.1
Story	36 (20)	78 (31)	147,111	15,151	10.3
Tama	34 (21)	71 (38)	187,085	32,245	17.2
Taylor	29 (12)	53 (26)	139,171	23,081	16.6
Union	33 (13)	55 (29)	110,075	11,655	10.6
Van Buren	20 (11)	41 (24)	126,586	81,636	64.5
Wapello	24 (11)	47 (28)	113,053	58,792	52
Warren	30 (15)	55 (32)	148,106	33,443	22.6
Washington	27 (16)	67 (35)	147,111	38,207	26
Wayne	27 (13)	43 (23)	137,787	22,840	16.6
Webster	38 (19)	74 (30)	185,993	18,648	10
Winnebago	37 (24)	68 (25)	103,885	2,072	2
Winneshiek	20 (11)	58 (29)	178,666	61,827	34.6
Woodbury	25 (14)	50 (27)	227,229	8,037	3.5
Worth	34 (16)	74 (24)	103,626	3,731	3.6
Wright	37 (21)	73 (25)	149,338	3,496	2.3

*CI, Iowa carbon index
±CSR, Corn Suitability Rating
≠Estimated forest area per county in hectares according to 1832–1859 GLO survey notes

superactive, mesic Typic Hapludolls) together with parent material were used to group similar soils. Most of the moderately-well and well drained soils have erosion phases and again the assumption is that the index is for the modal member of that soil map unit, where soils range in properties and the model or typical properties were used rather than the extremes of the properties.

A weighted average soil C mass for each county was determined by multiplying the number of hectares of each mineral soil map unit by the soil C mass for that map unit. To normalize the CI, the amount of carbon contained in the Iowa mineral soil having the greatest soil organic carbon content (Okoboji mucky silty clay loam, 45.5 kg/m^2 to a depth of 1m) was divided into 100 to derive a conversion factor (2.2). The soil organic carbon mass of each soil map unit to a depth of 1m was multiplied by the conversion factor (2.2) to calculate the CI.

Corn Suitability Rating

Soil organic matter is one of the properties considered in the CSR rating. Weighted county CSR averages were used to investigate the relationship between CI and this widely used soil

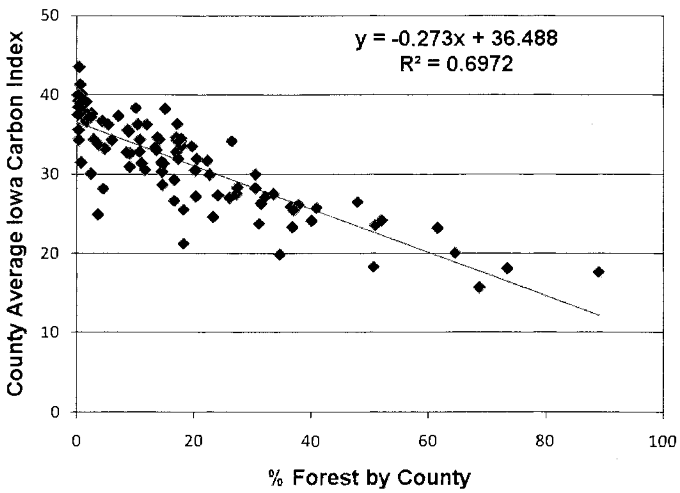

Fig. 2. Relationship between soil carbon index and percent of forest hectares based on the 1832–1859 original land survey notes in each county of Iowa.

productivity measure for each county. The CSR system was developed by comparing long-term yield averages of major soils in Iowa and then assigning these soils a CSR value, with a value of 100 indicating the best soil for corn production. Soils with less available yield data were also assigned a CSR value by comparing them to a benchmark soil which has similar soil properties and also considering differences in weather trends for different parts of Iowa. In this way, CSR values can be calculated for any soil in Iowa without an extensive set of yield data, as long as the soil properties are known. Soil properties such as slope class, erosion class, texture class, drainage conditions, solum thickness, and precipitation are all used when calculating CSR values and comparing to a benchmark soil. Although corn yields may vary dramatically between years for a given soil, the CSR index provides a consistent system for ranking soils by row-crop productivity without extensive yield data (Fenton et al. 1971 and Miller 2005).

Statistical Analysis and Data Interpolation

All statistical analyses were done using ArcGIS software (ESRI 2011). The CI means and their associated standard deviation were determined for each county. Additionally, an inverse distance weighted (IDW) average using the mean values from the nearest five counties were used to interpolate CI values across the state.

RESULTS AND DISCUSSION

Soil Carbon Index

Carbon index values for each Iowa County are summarized in Table 1. The average CI values for each county ranged between 16 and 43. The distribution of CI across the state is highly affected by the different factors of soil formation, which include native vegetation, climate, topography, parent material, and time. Man has also been a major influence due to cropping systems, accelerated soil erosion, artificial drainage, and other agricultural practices over the past 100+ years. The variable most highly correlated with the CI is the amount of forest hectares based on the 1832–1859 General Land Office (GLO) survey notes and reported on a county basis (Table 1). As forested hectares increase within a county, CI value decreases. Approximately 70% of the variation in the CI is related to the hectares of forest land as recorded in the GLO surveys (Fig. 2).

Northwest Iowa and parts of the Clarion-Nicollet-Webster soil association area in north-central Iowa had the highest soil CI values (35–40) in the state. This reflects the deep, fertile soils formed in glacial drift under tall grass prairie in this low-relief landscape under poor soil drainage conditions. These conditions contribute to a slow organic matter mineralization rate and lower soil temperatures which lead to greater organic matter accumulation (Al-Kaisi and Licht 2005). Several of the counties in this region had less than 2,000 hectares of forest land as reported in the GLO survey.

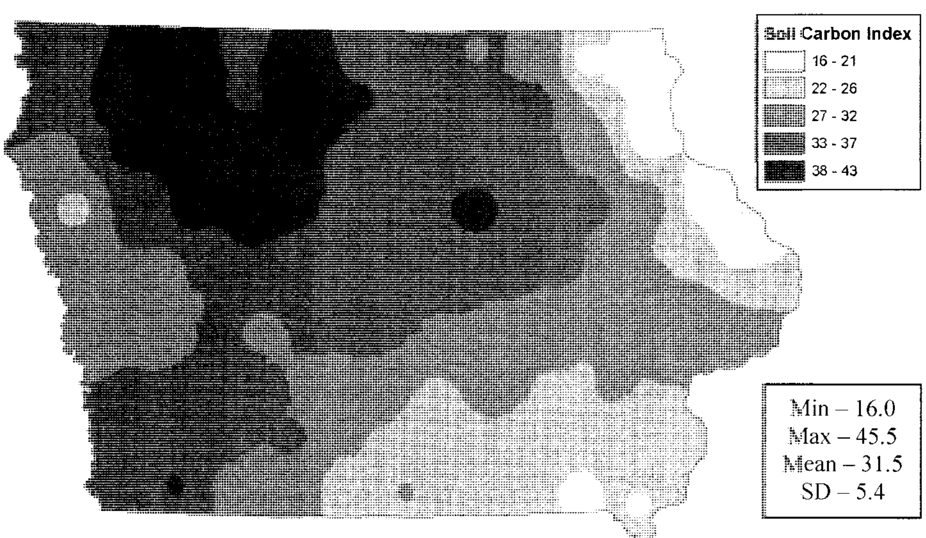

Fig. 3. Distribution of Iowa Carbon Index interpolated using ArcGIS software. County weighted average Iowa Carbon Index values were calculated from hectares listed in Iowa Soil Properties and Interpretation Database (ISPAID) for mineral soils.

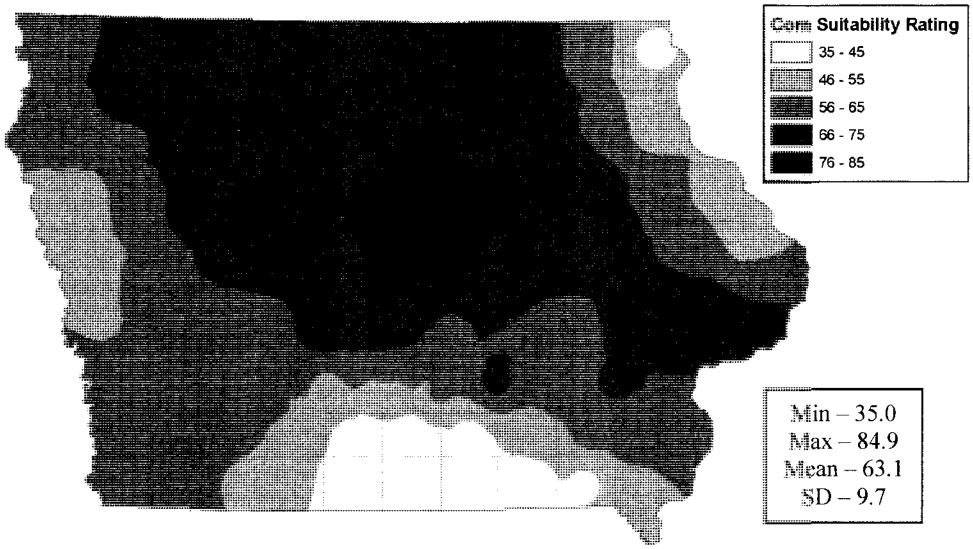

Fig. 4. Distribution of corn suitability rating (CSR) for Iowa soils interpolated using ArcGIS software.

The majority of the east-central region of the state, in areas where the tall grass prairie was dominant, had the next highest soil CI, ranging from 26–34. Similar ranges in the CI were observed in the western region of the state, where well-drained loess derived soils formed under tall grass prairie are dominant. The southern Iowa drift plain had a similar range of CI to the east and west part of the state, except for a few counties at the extreme southern part of the state with CI values of 20–24. Lower CI values were also observed for counties in the southeastern part of the state, where the original vegetation was a mixture of tall grass prairie and deciduous forest; the CI for most of the counties in this area ranges from 20–26. Four counties in the northeastern part of the state have the lowest soil CI (<20). These counties had the greatest numbers of hectares of soils formed under deciduous forest, Allamakee, Clayton, Dubuque, and Jackson had 152,249 ; 148,250 ; 81,675 and 114,290 hectares, respectively, of forest in the original land survey (Table 1). The Fayette series, an Alfisol, is the dominant soil on this landscape. The high number of hectares of well drained soils formed under deciduous forest vegetation and the potential of high organic matter mineralization contribute to the low CI in this area.

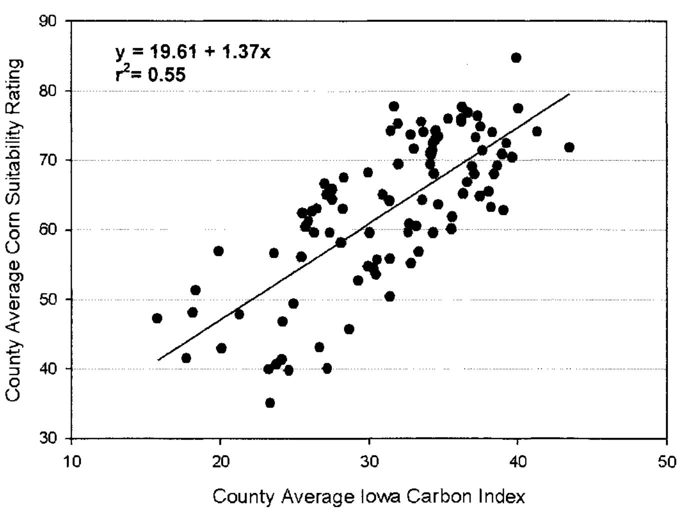

Fig. 5. Relationship between corn suitability rating and soil carbon index.

The low CI values in the northeast, west-central and southern regions in Iowa are primarily due to landscape characteristics impacted by initial soil formation conditions (i.e., vegetation and moisture), greater slope, and past and current row cropping systems leading to significant soil erosion. The comparison of the CI values across landscape regions shows significant differences. These differences reflect the influence vegetation and other soil forming factors have on the distribution of CI across Iowa.

The soil organic matter content of Iowa soils over the past 50+ years has been significantly influenced by the establishment of agro-ecosystems that are predominantly in corn and soybean rotation, where a significant amount of conventional tillage is taking place. These practices have led to significant soil carbon loss (Al-Kaisi and Yin 2005). These management practices played a significant role in increasing soil erosion and consequently reducing soil organic carbon (Fenton et al. 2005).

Soil Carbon Index and Soil Productivity

One of the potential applications of the CI is its relationship to corn suitability ratings (CSR); average CSR values for each county are listed in Table 1. Corn suitability rating is an index developed to evaluate soil productivity (Fenton et al. 1971 and Miller 2005). ArcGIS software (ESRI 2011) was used to interpolate county average CSR values and develop a state-wide distribution of CSR for Iowa (Fig. 4). An inverse distance weighted average using the average values from the nearest five counties was used to interpolate CSR values across the state. The county average soil CI was correlated with county-average CSR (Fig. 5). The CSR as a dependent variable shows that CI as a single predictor explains 55% of soil suitability for row crop production in Iowa. Similar trends are observed in the spatial distribution of these two indices across the state. The high soil CI in central Iowa (Fig. 3) matches the high values of CSR where corn and soybean productivity is among the highest in the state. The high values of CI in central Iowa are primarily influenced by the native prairie vegetation, landscape topography, and low rates of soil erosion. The major soils of this area are characterized as poorly and somewhat poorly drained with slope gradients of less than 5%. In spite of the intensity of tillage in this part of the state over the past many decades, the soil organic matter still is the highest due to the conditions cited above. The lower values of CSR generally follow the trend of CI in a few counties in the northeastern part of the state as well as in a significant number of the counties in the southern part of the state. In the northeastern counties, sloping landscapes and forest-derived soils contribute to the lower ratings. In southern Iowa, mixed prairie-forest vegetation is the major reason for lower CI and CSR ratings.

CONCLUSIONS

The CI for soils shows great variability in soil organic carbon distribution across the state. This variability was influenced by soil forming factors, primarily native vegetation, climate, and topography by affecting natural drainage, and soil erosion. However, cropping systems and management practices are also important factors contributing to variability we observed in CI values across 2,300 soil map units. The correlation between productivity as defined by corn suitability rating and soil CI showed that 55% of soil productivity is influenced by soil organic matter. The CI values are highly influenced by the type of vegetation under which soils were formed which mainly consists of grassland prairies and deciduous forest in Iowa. There is a significant decline in the average CI of soils formed under deciduous forest land as the number of hectares increases in a county. The soil CI is a useful tool that can have significant applications not only in determining carbon amounts, but also yield potential and the resulting effects on land value.

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