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A Data Fusion Method for Yield and Soil Sensor Maps

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Abstract

Utilizing yield maps to their full potential has been one of the challenges in precision agriculture. A key objective for understanding patterns of yield variation is to derive management zones, with the expectation that several years of quality yield data will delineate consistent productivity zones. The anticipated outcome is a map that shows where soil productive potentials differ. In spite of the widespread usage of yield monitors, commercial agriculture has found it difficult to collect and assemble yield data effectively for this purpose. A soil-topography-yield analysis approach has been developed and tested on several fields across the US. It uses soil and topography data that share the dense spatial scale of yield maps. These soil maps are fused into zones delineating the key soil properties that affect yield such as nutrient and water-holding capacity. Yield datasets are then queried to identify the significant yield drivers on each field. From those relationships the methodology identifies areas that could benefit from soil-specific management and suggests appropriate strategies. Whereas most yield analysis efforts attempt to create soil productivity polygons around yield map patterns, the approach presented here precisely delineates the soil boundaries first and then mines yield data to quantify and explain the actual difference in productive potential. The objective of this study is to evaluate the fusion results on several US fields. Results show the output can be useful for decision support on drainage and irrigation investments, establishing an appropriate rationale for variable yield goals, and uncovering hidden areas of lost yield potential.

Keywords: yield, soil sensing, EC, pH, organic matter, topography, zones, fusion, variable.

Introduction

The invention of yield monitors in the mid 1990's and the yield variations they displayed sparked growers' interest in site-specific agriculture. As yield maps began to be generated from the monitor data, it quickly became evident that the monitors were reading differences that resulted from many factors: soil, weather, management, as well as monitor anomalies such as calibration and sensor issues. Monitor and software technology has progressed in the past two decades reducing monitor-related distortions and leading to improved yield mapping. Some anomalies remain however, and there are a myriad of complex and interacting factors which cause actual yield differences within a field and between fields within a farm. For example, cultivar and planting date differences often exist within a field, causing sudden shifts in the patterns shown on yield maps. A soil type in one area of a field may yield significantly more or less than similar soil in an area of the field planted on a different date or to a different cultivar. Yet both soils may have equal potential. When differences of this nature are few and growers have maintained accurate records of all fieldwork, it's theoretically possible to filter, shift, and reprocess yield records to address these differences. In reality, the differences are too many, too unexplainable, and growers too busy to properly account for all management-induced and yield monitor related variances.

When the goal of yield mapping and yield map analysis is to delineate soil productive potential, using yield maps that exhibit the issues described above seriously hamper the effort to extract accurate zones of varying yield potential. Zone boundaries are not clearly defined, actual yields and recorded yields are inconsistent, and management effects confound the results (Figure 1). Additionally, yield data alone does not provide any information about possible causes of poor yields and remedy options. Assuming a low yielding area has low potential may be a faulty assumption and lead to reduced profit potential.

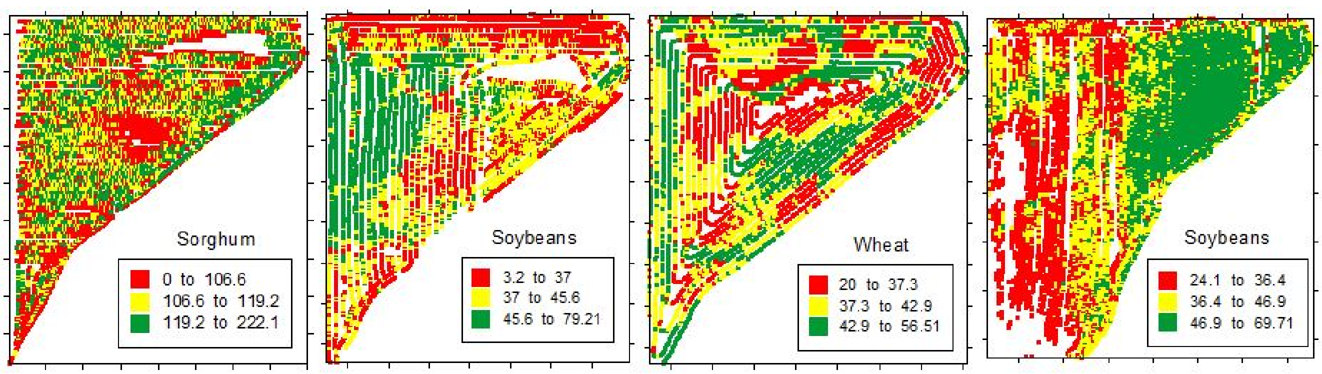

Figure 1. Four years of yield data from Kansas field.

To develop reliable maps of productive potential, what is needed are precise maps of the soil properties that typically impact yield, primarily water and nutrient-holding capacity, soil depth, and topography, as well as a method of combining those layers with available yield data to establish historical production differences for each soil zone. It is important that such methodology be only minimally affected by the inherent limitations of yield data. Properly executed, the results from such an approach could provide the rationale for varying seed populations, yield goals, and fertilizer rates. It would identify underperforming areas where yields might be improved and quantify the potential benefit of those increased yields. An important distinction between this approach and most yield analysis efforts is that typical yield map analyses attempt to create soil productivity polygons using yield patterns. The approach presented here precisely delineates the soil boundaries first and then mines yield data to quantify and explain the actual difference in productive potential.

Materials and Methods

Soil Sensors

Developing a set of maps that precisely delineate key soil properties requires densely collected soil data. Soil sensors using GPS have the dense coverage needed to improve the delineation of soil boundaries (Adamchuk et al., 2004). The first commercialized on-the-go soil mapping system was for mapping soil electrical conductivity. Soil EC measurements correlate with soil properties that affect crop productivity, including soil texture, cation exchange capacity, drainage conditions, salinity and subsoil characteristics (Kitchen et al., 1999; Grisso et al., 2009). On-the-go soil pH sensing was commercialized nearly a decade ago with the introduction of the Veris Mobile Sensor Platform (Adamchuk et al., 2005). Soil pH is an important factor in crop production. Nutrient usage, crop growth, legume nodulation, and herbicide activity are all affected by the pH of the soil. Recently, on-the-go soil optical mapping became commercially available with the Veris OpticMapper which correlates soil reflectance with organic matter. (Kweon et al, 2012). Soil OM affects the chemical and physical properties of the soil and its overall health. It is a key component of productivity, affecting moisture holding capacity and nitrogen availability. Veris Technologies produces two multi-sensor platforms that record soil EC, Optical, and pH along with topography data (Figure 2). The MSP3 and U3 systems generate highly detailed soil maps of these critical soil properties and the sensor readings are typically calibrated with lab-analyzed organic matter and cation exchange capacity (Figure 3). In a six-state study, the accuracy of Veris OM and CEC sensing and calibrations were compared to lab analyzed samples. Results for OM showed an average .86 R^2 with an RMSE of .31% and for CEC .82 R^2 with an RMSE of .86 meq/100g (Kweon, et al., 2013).

Figure 2. Veris MSP3 and U3 models that map soil EC, OM, and pH.

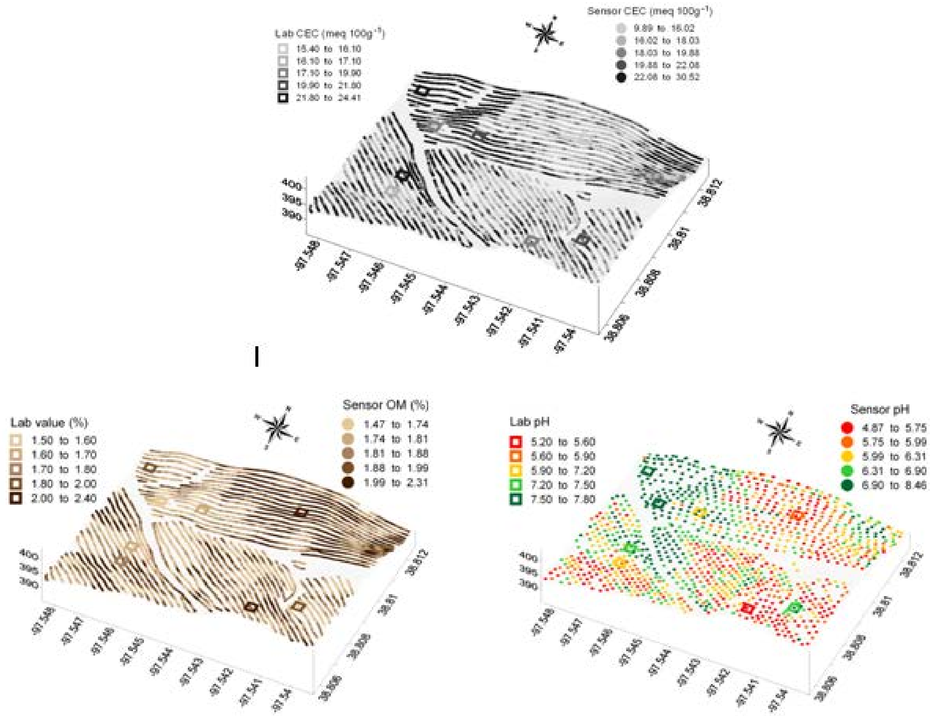

Figure 3. Transect maps of each sensed soil property with calibration samples overlaid.

Soil Data Fusion

As the number of layers of soil information increases, a methodology is needed to deal with the increased complexity and number of maps. For example, precise maps of sensor-based CEC and OM can be generated (Figure 4). Closer inspection of the two maps reveals areas of high CEC with high organic matter, but also areas of high CEC with low organic matter, along with areas of low CEC with both low and high organic matter. These soil properties are precisely delineated with soil sensors and both maps show important soil properties. Merging these into one map may be helpful for yield analysis and subsequent action. Data fusion techniques have the potential to address this challenge (Adamchuk, et al., 2011).

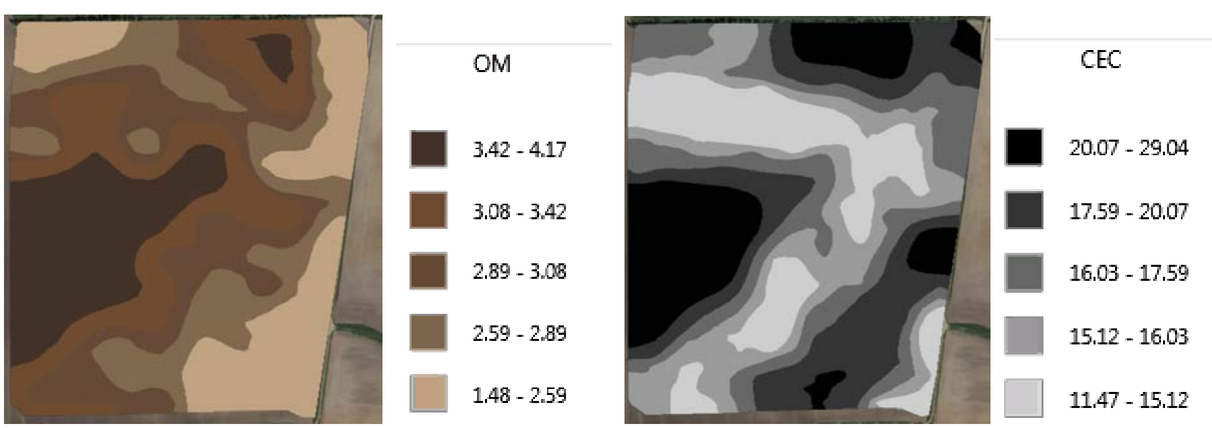

Figure 4. Illinois field with OM zones (left) and CEC zones (right).

A proprietary discriminating data modeling technique derived from a fuzzy clustering approach has been developed (Kweon, 2012). When this method is applied to the two maps in Figure 4, a single map delineating the soil property combinations is generated (Figure 5).

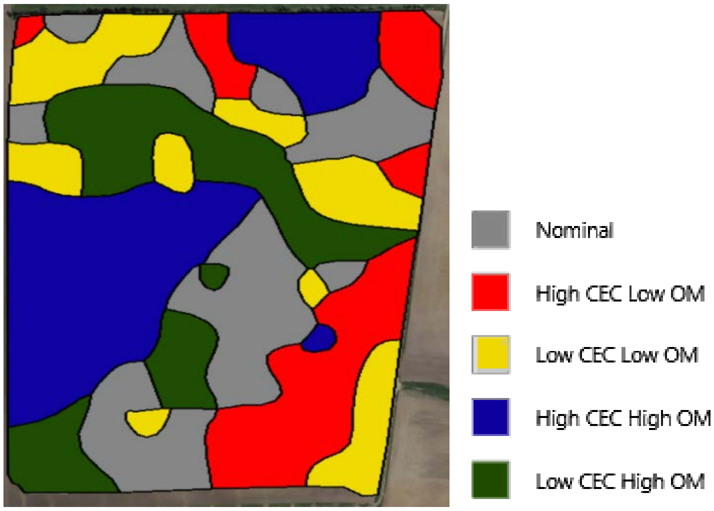

Figure 5. Illinois field with data fusion technique applied, resulting in single map based on two soil properties.

In addition to the basic CEC-OM fusion shown in Figure 5, topographical information can be fused as well (Figure 6). Delineating zones with similar soil texture and organic matter but with unique drainage characteristics provides additional insights into yield variations and productive potential. For example, the light blue zones on the map in Figure 6 have the highest CEC and have convex topography. The dark blue zones have similar CEC's but are depressional. Those differences may be especially relevant in understanding yield patterns from years when rainfall has been excessive. Each fused map zone has a table containing the relevant soil information for the zone as it relates to the soil properties within the field (Table 1).

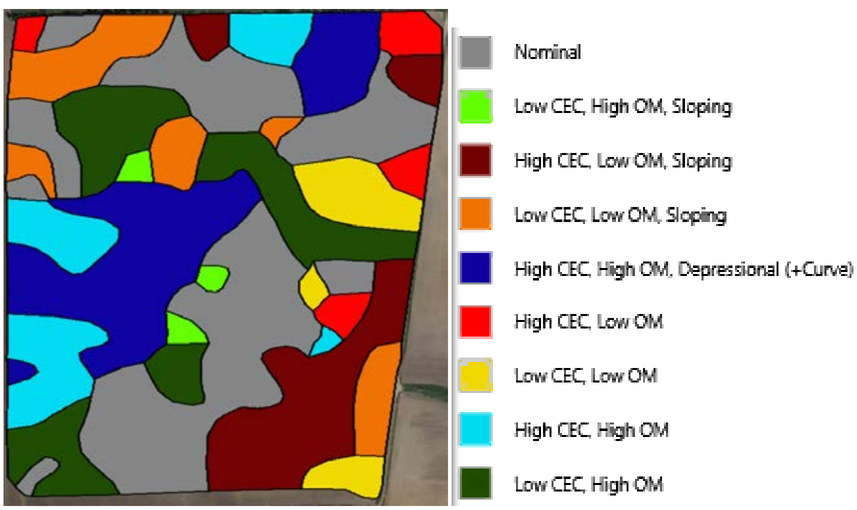

Figure 6. Zones in Illinois field created by fusing proximal sensed soil readings and topography.

Table 1. Soil properties for an Illinois field and its fused zones.

	Field ave.	High CEC, OM	High CEC, OM, depr.	low CEC, OM	low CEC, OM, sloping	High CEC, low OM	High CEC, low OM, sloping	Low CEC, High OM	Low CEC, High OM, sloping
OM	2.96	3.66	3.64	2.58	2.47	2.39	2.3	3.31	3.28
CEC	17.36	22.67	21.68	14.22	14.57	19.22	19.62	13.97	13.94
Slope	0.79	0.55	0.66	0.46	1.31	0.49	1.25	0.49	1.07
Curvature	0	-0.04	0.04	-0.02	-0.01	-0.02	0	0.01	-0.01

Yield Data Pre-processing

For this study, yield data was processed through a simple standard deviation filter which removed data points outside three times the standard deviation, plus or minus the mean. After filtering, each soil sensor point was matched to yield data near the recorded sensor location by interpolating the yield using a Gaussian kernel weighting structure. Yield points were weighted relative to a 3m nominal radius around the each sensor point.

Soil and Yield Fusion

Growers have at least two possible objectives and site-specific management options for their soil and yield map analyses: 1) setting variable yield goals, i.e. challenging field areas with high yield potential to produce more, while possibly reducing inputs on areas with lower yield potential; and 2) improving production in areas that are currently lower yielding. The methodology presented here first identifies and delineates soil into zones of possible productivity difference: soil is zoned by soil texture, organic matter, slope, and curvature. These properties affect water and nutrient holding capacity and have been shown to frequently correlate with yield (Kitchen et al., 2003). The second step is to evaluate the relationship between each soil property and yield using both regression of the entire data set along with boundary line analysis techniques to identify top yields for each soil property (Schnug et al., 1995; Lund et al.,1999; Shatar and McBratney, 2004;). Once the main yield drivers of each dataset are identified, along with the highest yields for several ranges of that property as defined by the available yield data, production differences can be calculated and geo-referenced areas delineated on a map of the field. While there are many possible variations of this approach, the methodology presented here is a four-step process:

1. Identify key drivers of crop yield,

2. Identify areas where variable yield goals may be appropriate and establish a rationale for setting soil-specific yield goals,

3. Identify currently low yielding soil areas where the yield environment may be upgraded with investment in irrigation, drainage, soil amendments, or other action. Quantify possible yield gains from improving yield environment.

4. Identify soil zones containing highly productive soils that are currently underperforming. Create scouting map for additional investigations.

Results

Four fields representing a wide range of crops and soils were analyzed using this approach: a Kansas wheat field, a California vineyard, and two Illinois corn fields.

Kansas

The process used on all four fields is explained in greater detail on this 18.2 ha field. First, the soil-yield relationships were examined. Five years of normalized wheat yield were regressed against EC, OM, and topographic features. Scatter plots displaying bivariate regression and boundary lines were created and visually inspected for significant relationships along with a table reporting and ranking the correlations (Figure 7, Table 2).

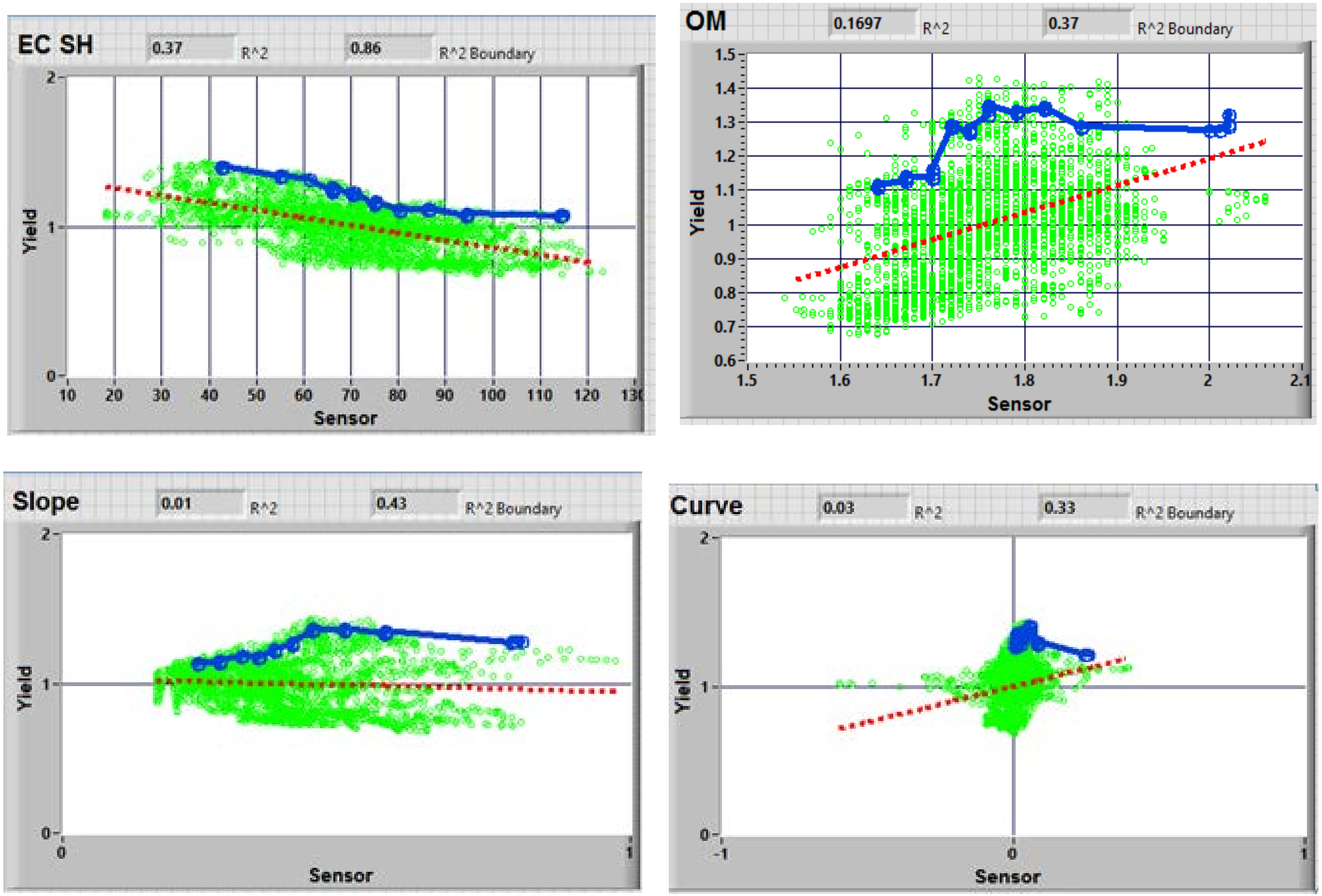

Figure 7. Five years of normalized wheat yield with regression and boundary lines.

Table 2. Correlation coefficients for soil properties and five-year normalized average yield.

Sensor/property	Regression R^2	Boundary Line R^2
EC shallow	0.37	0.86
EC deep	0.34	0.91
OM	0.17	0.37
Slope	0.01	0.43
Curvature	0.03	0.33

From the initial review of the soil-yield relationships, it was evident that yields are highest in the lower EC/less clay and higher OM soils, while the high clay, low OM soils are lower yielding. Topographic features did not exhibit a consistent relationship to yield on this field. Soil data was then fused into combinations of soil texture and OM (Figure 8).

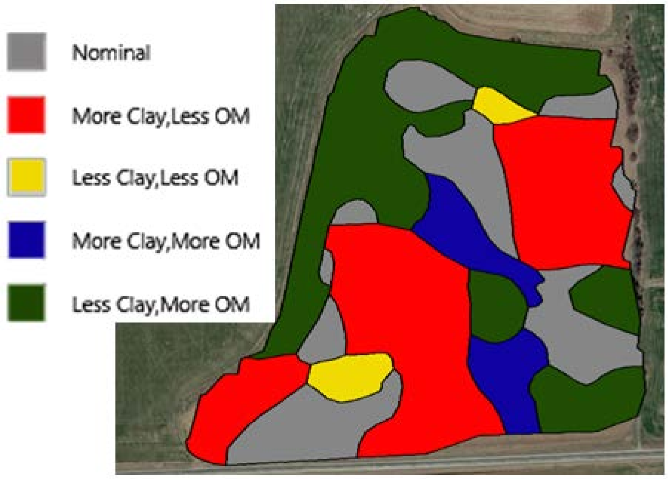

Figure 8. Soil texture and OM maps are fused into one map.

Variable Yield Goal

Considering the consistent and quantifiable soil-yield relationships on this field, and that these production differences are reasonable for upland Kansas wheat fields where eroded slopes have higher clay and lower OM than silty depositional areas of the field, a variable yield goal can be established. The yield goals shown in Table 3 are derived directly from the five-year normalized average yields for each of the mapped soil areas in Figure 8.

Table 3. Five-year normalized average yield by soil zone.

Soil Description	Map Color	Yield goal % of avg.
>OM, <clay	Green	111%
<OM, <clay	Yellow	103%
>OM, >clay	Blue	97%
<OM, >clay	Red	88%
Avg soils	Gray	100%

Yield Environment Upgrade

Soil and yield data can be used to consider possible management strategies to improve the soil properties in low yielding areas with the expectation of increasing yields. Strategies that have been shown to improve the quality of low OM, heavy clay soils are the adoption of no-till, usage of cover crops, addition of amendments such as gypsum, or manure and other organic amendments which could increase plant available water holding capacity (Hanza and Anderson, 2002; Hoorman et al., 2009). A strategy that could be deployed site-specifically on this field is the application of manure to the areas where the soil quality is the poorest and where yields are most reduced. The soil and yield data are mined by identifying the lowest yields in the red zone in Figure 8 to reveal the areas where the yields are most limited by the low OM/high clay condition (Figure 9). This 2.5 ha area has historical yields 23% under the five-year average. Considering the average gross revenue on this field is ~$500/ha, if the yields on this portion of the field could be brought up to the field average, the gross annual return on improving the soil in this zone would be nearly $300. Cost/benefit analyses such as this can provide the rationale for deciding whether to pursue upgrading the yield environment or a variable yield goal strategy.

Figure 9. Lowest yielding area of low productivity soil.

Productive Soil Scouting

There are areas on most fields that have high-yield capability as defined by the soil-yield boundary line but are not yielding as well as other areas in that field with the same soil properties. These areas may be yielding above the field average, but well below average for that soil's ability to produce. Because their yields are above field average, these zones' under-performance is hidden when using traditional yield map analyses. A map of these areas can be generated and used to scout for possible nutrient deficiencies or other yield-limiting factors. On this field the soil zone with high OM and less clay is yielding 11% above the field average, yet there are areas within that soil combination that have less than 50% of the yield average for that soil (Figure 10).

Figure 10. Scouting map of under-performing high capability soil.

California

Mechanical grape harvesters were outfitted with yield monitors and collected high quality yield data from a 60 ha block, which can be compared visually with soil EC data (Figure 11).

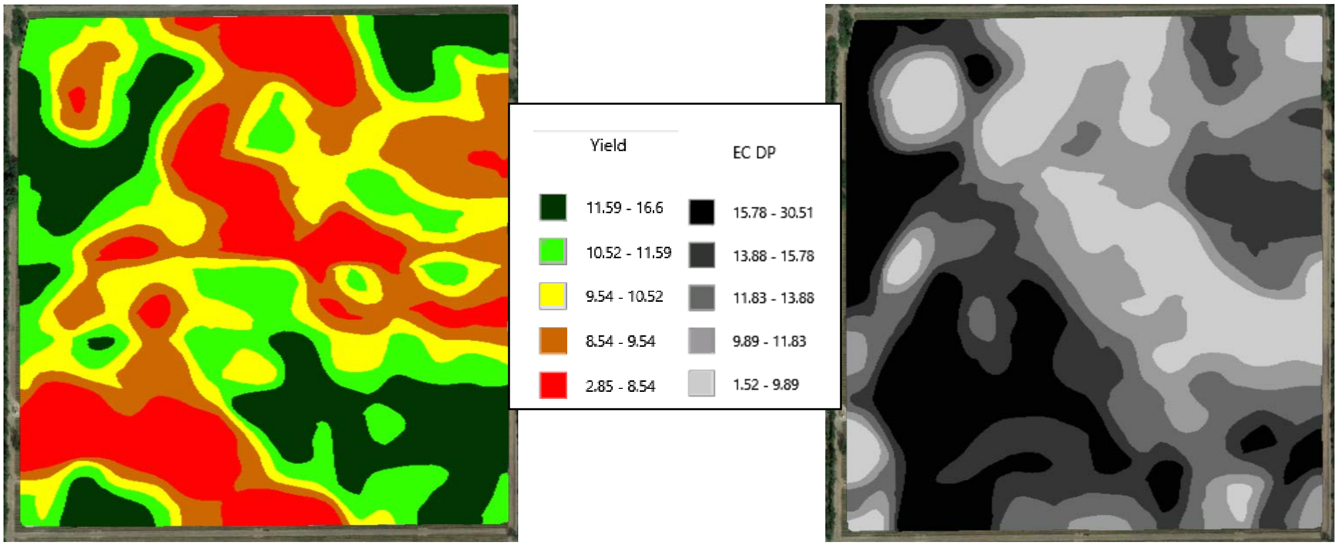

Figure 11. Grape yield (tons/ac) and soil EC (mS/m) from a central California vineyard.

Regression and boundary line analysis revealed the fundamental soil-yield relationship on this block, which is that the highest yields tended to occur on high soil EC while lower yields were typically found on coarser, low EC soils (Figure 12). This irrigated block is in an arid region and is not equipped with any variable irrigation capability. Initial review of the data set suggests that the areas of the block with lowest water-holding capacity are not receiving adequate water to optimize yields.

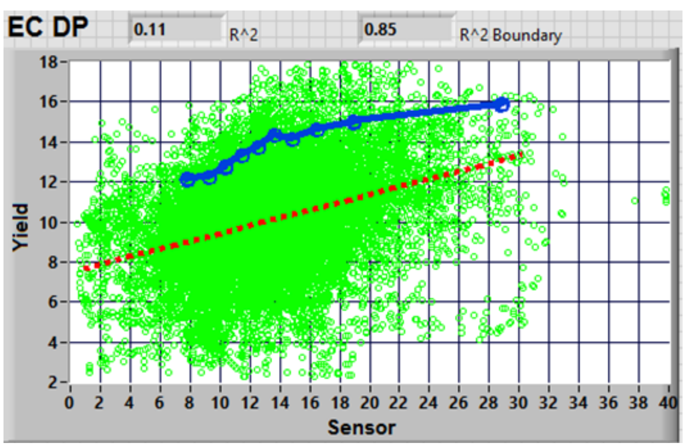

Figure 12. Soil EC and yield relationship from a California vineyard.

Yield Environment Upgrade

In order to evaluate the cost/benefit of renovating this block with variable irrigation, the yield and EC data were analyzed to delineate the area of greatest yield reduction due to under-watering and to quantify the yield reduction in this area of the block. The bottom 50% of yields from the lowest 20% of the EC values was extracted and the area delineated (Figure 13). This approach focused on the area with the specific challenge of low yields in coarse soil. The 3.7 ha represented by the area shown in Figure 13 has a yield of 17.3 ton/ha while the block average is 24.9 ton/ha. If improving the irrigation on this area raised its yield to the block average, the additional annual production would represent 28.1 tons of grapes. This cost-benefit information provides decision support for the irrigation investment decision.

Figure 13. 3.7 ha area of a 63 ha vineyard block with coarse soil and very low yields.

Productive Soil Scouting

The areas on this block with high-yield capability as defined by the soil-yield boundary line but are underperforming are shown as green zones in Figure 14. These 3.9 ha contain the higher EC, finer-textured soils which on average are yielding 30.7 tons/ha, however the soils delineated are only producing 22.8 tons/ha. While the cause of the reduced yield may not be readily evident, this map serves as a reconnaissance map for additional investigations.

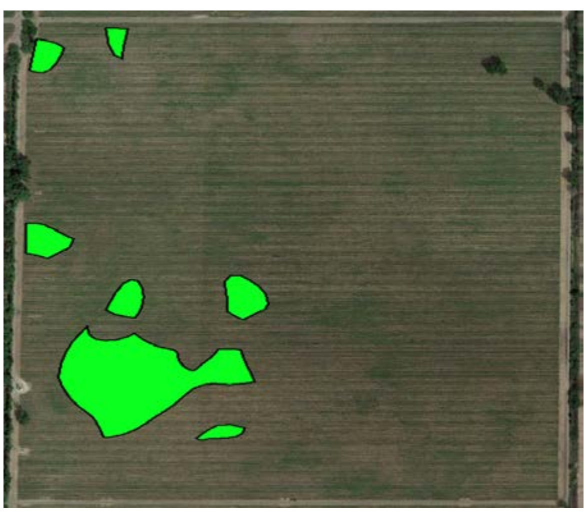

Figure 14. Scouting map of under-performing high capability soil.

Variable Yield Goal

Because grape vines are considered a ‘permanent’ crop rather than an annual crop, and because most of the nutrients are applied via irrigation, many of the soil-specific options for improving annual yield and profitability by challenging high producing soils to produce more are not as available as they are for annual field cropping.

Illinois (Field 1)

Variable yield goals and variable seed populations are precision practices being considered and adopted by corn growers especially in the US corn belt. This 20 ha Illinois field has soils ranging from 1.5 to 3.6 % OM and CEC varies from 7.1 to 16 meq/100g. With this wide range of soils and varying yields, this field is a strong candidate for variable population, but the questions that need to be answered are: 'where and how much to change rates?'.

Variable Yield Goal

Yields on this field correlated with soil OM and with clay/CEC, with top yields coming from areas of high CEC and high OM. Poorer yields were found in areas of low OM and high CEC. Yields by soil zone ranged from just over 14.5 to nearly 16.5 tons/ha (Figure 15).

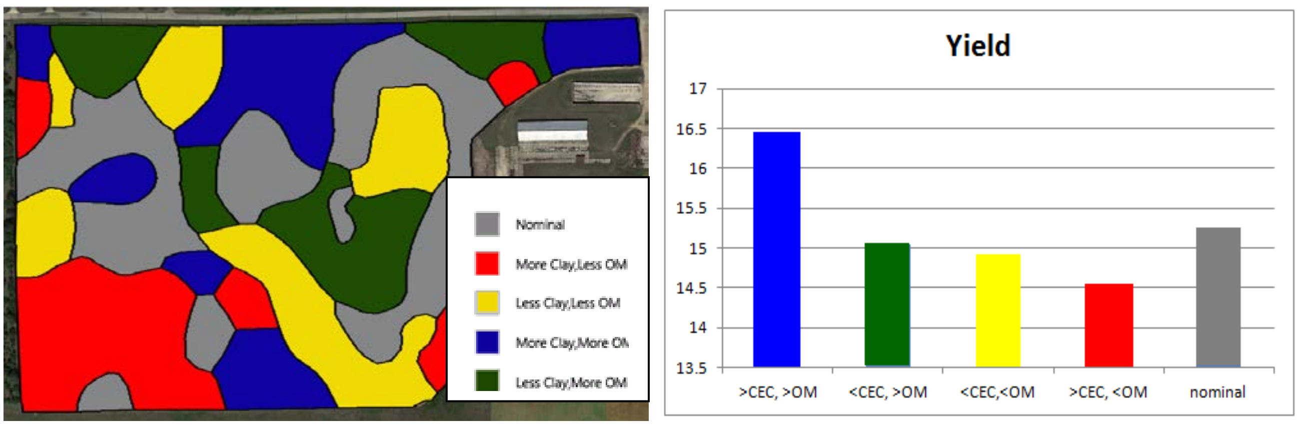

Figure 15. Fused soil OM and texture zones (left) and yields in tons/ha for each zone.

Based on these variations in yield and given that they follow a reasonable pattern for productivity in a well-drained Illinois field, the results suggest a yield goal increase of 8-10% in the blue zones and reducing yield goals by 5% in the red zones.

Yield Environment Upgrade and Productive Soil Scouting

Options for improving the yield environment on this field include site-specific amendments to increase water-holding capacity in the lower OM soils. There are also opportunities to investigate high productive potential soils not performing to their capability (Figure 16).

Figure 16. Lowest yielding, low OM soils (left) and lowest yielding, high OM soils (right).

Illinois (Field 2)

Unless properly drained, heavy clay soil and depressional areas of a field can exhibit lower yields. This 32 ha field showed soil and topography-related yield reductions when corn yields from both an abnormally wet year and a year with average rainfall were normalized and correlated with soil EC and curvature (Figure 17).

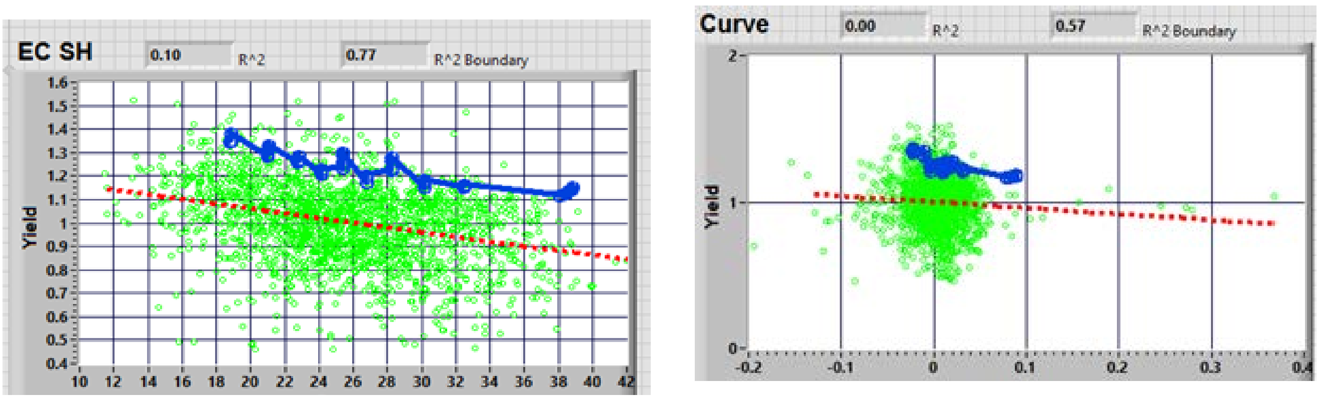

Figure 17. Key drivers of yield on Illinois Field 2 were clay/EC and curvature/concavity.

A fusion of EC and curvature was used to create a set of soil-topo zones. The two-year yield database was then fused with that data to reveal the average normalized yields for each zone (Figure 18).

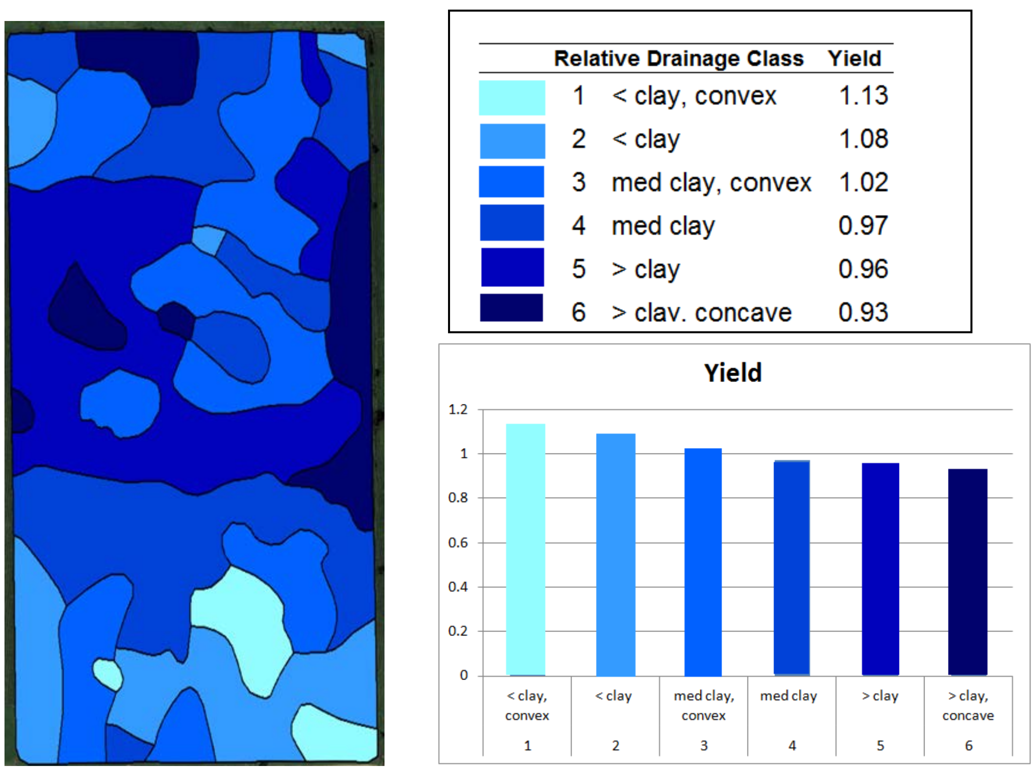

Figure 18. Two years of normalized corn yield data fused with soil-topo zones show pronounced drainage effects in poorly drained areas.

Yield Environment Upgrade

These results suggest that an investment in subsurface drainage needs to be considered. To provide decision support for determining the area to be drained, crop value by soil-topo-yield zones is calculated. This analysis shows that the most poorly drained area contains 3.2 ha and its gross returns are $124/ha less than the rest of the field. A drainage investment of up to $1900 is warranted for this 3.2 ha, assuming a five-year payout.

Variable Yield Goal

Based on data computations alone, the consistently lower yields in the heavy clay soils could be interpreted as a candidate for lowering yield goals in those zones. However, considering the water-holding capacity of the heavier soils, that isn't necessarily a reasonable strategy for this region, crops, and soil. Denitrification and plant stand reductions in heavier clay soils may be contributing to the lower yields. If so, the possible action step of reducing nitrogen and seed populations would not be appropriate and in fact could lead to even greater yield reductions. In addition to the drainage investment proposed above, more appropriate strategies may include applying test strips of increased seed population and nitrogen to evaluate the effectiveness of those options in managing the lower-yielding heavy clay soils.

Productive Soil Scouting

There are well-drained, high yield potential areas of this field which are not performing at their capability. Those can be identified and displayed on a map for additional investigations.

Conclusion

Soil, topography, and yield data from four fields were fused together in order to reveal areas of each field that could respond favorably to various management approaches. The three primary options presented for improving productivity and profit were: adopting variable yield goals on fields where inherent soil productivity capabilities can be exploited, investing to increase productivity through site-specific upgrades of yield environment, and identifying underperforming areas of high productive potential. While all three of these options can be generated for each field, not all are equally valid on every field. For example, drainage and irrigation are not viable options for some fields, and additional yield data is sometimes needed to develop the rationale for variable yield goals. In every case, grower or consultant input is valuable and a consideration of local crop and soil attributes needs to be considered in interpreting soil-topography-yield fusions and management options. Nevertheless, the approach applied here shows a unique and inventive methodology for compiling densely collected field-sensed data and providing useful insights and decision support.

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