Energy assessment for variable rate nitrogen application

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Abstract: Based on material flows, energy flow assessment evaluates environmental sustainability and energy use efficiency on a production system. As precision agriculture was developed to optimize agricultural production, energy assessment has become an interesting approach to analyze these systems. A method was developed to propitiate energy evaluation on site-specific data from variable rate nitrogen application on precision agriculture management. It provides maps of energy indicators (energy balance, energy return on investment and energy embodiment) from input and output energy flows. Variable and fixed nitrogen applications were evaluated on a wheat production on Paraná state, Brazil. An optical sensor was used to generate variable rate nitrogen prescriptions. Energy balance and profitability was higher on precision agriculture management because it provided nitrogen savings without compromising yield. Besides, less energy was embodied on the final product. All energy indicators pointed to the fact that variable rate technology was more sustainable than traditional management.

Keywords: precision farming, nitrogen, energy indicators, energy balance

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1 Introduction

Material and energy flows have been approached by several studies that tried to track how energy is used in agriculture, especially on food and energy crops. Energy assessment is a method frequently used in eco-engineering research and an appropriate way to study agricultural systems without considering economic aspects (Odum and Odum, 2003). Basically, it converts the material flow of a production system into an energy flow by relating energy indexes of every material (Romanelli and Milan, 2010a). So, all input and output in a given system are translated into energy values that are used to calculate energy indicators. In agriculture, these indexes allow interpretation regarding which practices are more efficient or demanding in energy terms and which are more energetically and environmentally sustainable.

Using energy assessment, Bala et al. (1992), Ozkan et al. (2004) and Tabar et al. (2010) found that fertilizers were the most energy demanding items on the agriculture of their countries, as well as irrigation. Nitrogen fertilizer was pointed out as the main component of energy input due to its highly embodied energy – a great amount of fossil energy is needed in its production – besides the high rates applied on crops (Hulsbergen et al., 2002; Ercoli et al., 1999). Considering the amount of fossil derived products used on agriculture, techniques that could reduce inputs without affecting crop yields are desirable.

In this context, precision agriculture (PA) was developed with the purpose to rationalize inputs and reduce environmental impacts (Zhang et al., 2002; Xiang

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et al., 2008). As defined by Whelan and McBratney (2000), PA is a set of techniques and procedures aim to optimize agriculture production systems based on the field spatial variability and site-specific management. One of the main tools on PA is the variable rate technology (VRT), which consists of varying input rates within a field, according to the local demands. Although it could be used for any agronomic input, it certainly has been more frequent on fertilization operations. Its adoption is encouraged by the high monetary value of this input and the chance to get more profit over the same cultivated area, ether by increasing yield or reducing costs.

Some authors have reported the effects of PA in input consumption and yield (Yang et al, 2001; Wang et al, 2003; Johnson and Richard Jr., 2010; Molin et al, 2010; Thomason et al., 2011) which indicate economic benefits. Studies also showed how site-specific operations and optimization of inputs can reduce chemical leaching and avoid environmental contamination (Wang et al, 2003; Bongiovanni and Lowenberg-Deboer, 2004). However, in energy terms, the performance of variable rate applications have not been approached or compared to traditional farming. Instead of analyzing an entire field, energy indicators could also be calculated site-specifically if energy assessment were combined to georeferenced data and geographic information system (GIS) software. This sort of analysis would provide knowledge about the energy performance of a PA system and how it could improve sustainability on an agricultural production.

This work aimed to develop a method to enable energy assessment over site-specific data from variable rate application, aside from comparing VRT on nitrogen fertilization with traditional practice in relation to their energy performance.

2 Material and methods

2.1 Variable vs. fixed rate experimental design

In Paraná state, Brazil, two wheat fields of 6.8 hm^2 (1 hm^2 = 1 ha) and 7.7 hm^2 (-24° 29' 00.07" latitude, -50° 21' 18.13" longitude), were used for this study during 2006/2007 season. Each field was divided into eight 9 m wide strips (equivalent to a combined head width). Nitrogen variable rate was carried out on 4 strips on each field intercalated with fixed rate application (Figure 1).

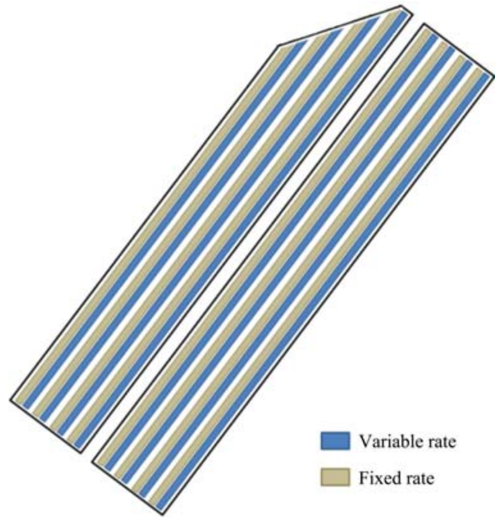

Figure 1 Design of intercalated variable and fixed rate strips on the experimental wheat field

2.2 Energy assessment for site specific data

Variable nitrogen prescription maps came from an optical sensor reading (GreenSeeker Hand Held TM). Nitrogen rates were based on canopy reflectance and the vegetation index NDVI (normalized difference vegetation index) in accordance with Raun et al. (2002) and Povh et al. (2008). The resulting rates were simplified into three doses: 20, 40 and 60 kg/hm^2. A fixed rate of 18 kg/hm^2 was previously applied on all variable rate strips. Fixed rate strips received a uniform nitrogen application of 120 kg/hm^2, which is the traditional nitrogen management for wheat in this production region.

Georeferenced yield data were collected by using a yield monitor in a combined grain harvester. They composed yield maps for variable and fixed rate strips separately. Nitrogen rates and yield data were paired in the same coordinate from the yield monitoring by using an electronic spreadsheet (Microsoft Excel 2007®) and a GIS software (SStollbox®). Descriptive statistics were carried out on these data.

After combining yield and nitrogen rate data in the same coordinate, the following energy indicators were calculated on each point: input energy, output energy, energy balance, energy return on investment (EROI) and energy embodiment.

Input energy is given as the sum of all input materials are converted into energy values through each energy index. Input materials data were gathered for wheat production in Paraná state, Brazil (AgriFNP, 2009). Factors such as labor hours, machine depreciation, diesel oil, seeds, fungicide, herbicide, insecticide and NPK fertilizer (Table 1) were all considered. Machine depreciation was determined according to the methodology from Romanelli and Milan (2010b). On top of these items, nitrogen fertilizer was also counted considering its variable and fixed rate application. The energy index for nitrogen fertilizer was 74.00 MJ/kg (Pellizzi, 1992).

Table 1 Input on Paraná state (BR) wheat production converted into energy flow

Item	Quantity	Energy index/MJ	Energy input/MJ · hm^{-2}	Reference
Labor	4.25 h · hm^{-2}	2.200	9.350	Serra et al (1979)
Machine depreciation	19.90 kg · hm^{-2}	68.900	1371.110	Ulbanere & Ferreira (1989)
Diesel oil	46.35 L · hm^{-2}	38.600	1789.110	Ulbanere & Ferreira (1989)
NPK 08-30-20	230.00 kg · hm^{-2}	11.028*	2536.440	Pellizzi (1992), Ferraro Jr. (1999)
Seed	146.00 kg · hm^{-2}	18.109**	2643.914	Pellizzi (1992)
Fungicide	1.32 L · hm^{-2}	97.130	128.212	Pimentel (1980)
Herbicide	5.60 L · hm^{-2}	254.570	1425.592	Pimentel (1980)
Insecticide	0.10 L · hm^{-2}	184.710	18.471	Pimentel (1980)

Note: * Calculated from weighing of N, P_2O_5 e K_2O energy indexes; ** Considered as 40% over the energy index of wheat grain.

The Output energy is given simply by multiplying yield to the energy index of the final product (on wheat grain, 13.93 MJ/kg) (Pellizzi, 1992). It is certainly interesting to approach the output as energy when working with food (carbohydrates) and energy crops.

Given the energy flow,(input and output energy) energy indicators were calculated. Energy balance (Equation 1) is the energy left from deducting the input energy from the output energy. The EROI (Equation 2) represent the amount of energy that was made available from each energy unit invested. It can be interpreted as the energy “profitability” of the production system. They both help explain if the system is either demanding or supplying energy.

Energy embodiment (Equation 3) refers to the energy necessary to produce each unit of wheat mass. It also represents the calculated energy index of this item.

All calculations were made on each georeferenced point from the yield monitoring.

$$E_B = E_{OF} - E_{IF} \tag{1}$$

$$E_{ROI} = E_{OF} / E_{IF} \tag{2}$$

$$E_E = E_{IF} / Y \tag{3}$$

where, E_B, energy balance, MJ/hm^2; E_{IF}, energy input flow, MJ/hm^2; E_{OF}, energy output flow, MJ/hm^2; E_{ROI}, energy return on investment, non-dimensional; E_E, energy embodiment, MJ/hm^2; Y, wheat yield, kg/hm^2.

3 Results and discussion

Descriptive statistical analyses for yield and nitrogen rates data were shown in Table 2. Yield averages and the coefficient of variation (CV) were similar between variable and fixed rate nitrogen fertilization. Slightly lower variation occurred on variable rate nitrogen strips.

Table 2 Descriptive statistics of yield and nitrogen rates

Field	Item	Nitrogen rate	Average /kg · hm^{-2}	Max. /kg · hm^{-2}	Min. /kg · hm^{-2}	CV/%
1	Yield	Variable	3025.9	5239.0	1530.0	16.3
		Fixed	3053.6	4808.0	1327.0	17.7
	Nitrogen	Variable	49.2	78.4	38.4	25.4
		Fixed	120.0	120.0	120.0	0
2	Yield	Variable	3546.3	5237.0	1411.0	16.9
		Fixed	3568.0	5436.0	1541.0	18.7
	Nitrogen	Variable	89.7	112.4	72.4	15.4
		Fixed	120.0	120.0	120.0	0

Nitrogen savings around 59% on field 1 and 25% on field 2 occurred on variable rate application (Table 2), compared to fixed application. If the same method of sampling and prescription is adopted by variable and uniform application, fertilizer savings should not be expected, unless traditional application tends to over apply or the equipment used on traditional farming is not properly calibrated. Nitrogen savings on this study are explained since the VRT prescription was based on a sensor reading contrary to traditional sampling and prescription practices. Besides, the sensor calibration method, based on Raun et al. (2002) and Povh et al (2008), did not intend the yield increase, but the nitrogen used reduction without compromising yield. Studies that tried to measure economic benefits of VRT over traditional management normally test one out of two hypotheses: the assertion that VRT would provide inputs savings without compromising yield or that using the same amount of input would increase yield (Adrian et al. 2005). The two would both increase profit.

Maps of energy indicators showed the spatial variability of energy performance and the results from variable (right strip in every pair) and uniform nitrogen application (left strip in every pair) (Figure 2). Regions of low energy balance (yellow and red points) were found more often on fixed rate strips. Some of these values are negative, which mean that the input energy flow was greater than the output energy flow.

EROI maps also address the input and output energy relationship, representing energy profitability. Areas of similar performance between variable and fixed rate can be found on both fields, but frequently there were regions where higher values were observed on variable nitrogen strips. These areas showed that more energy was provided by VRT for each unit of input energy than on fixed rate fertilization. Maps from energy embodiment reveled regions of lower values on variable rate strips. Less input energy was required when using VRT to produce the same quantity of wheat on these areas.

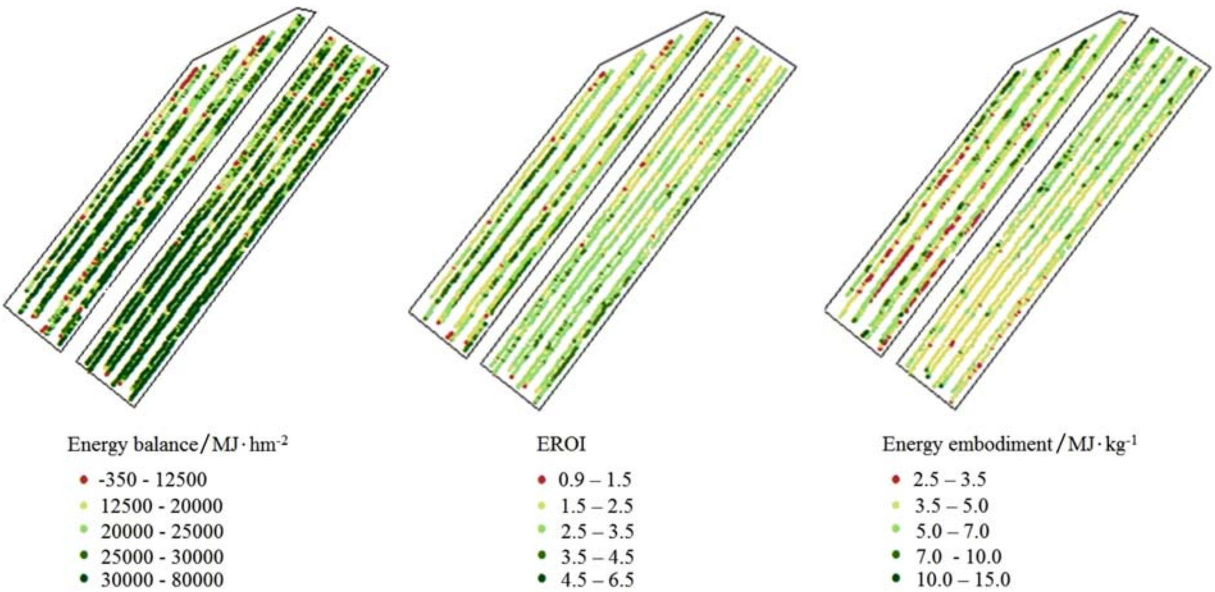

Figure 2 Maps of energy indicators on variable and fixed nitrogen fertilization intercalated strips

All three maps presented spatial variability of energy indicator once significant amplitude of values and range of colors are visualized (from red to dark green), highlighting the importance of site-specific energy assessment.

The descriptive statistical analyses from energy assessment showed the averages and coefficient of variation of energy values that reflect the energy performance of each production systems (Table 3). Reduction on input energy occurred on variable treatment once it consumed less nitrogen fertilizer. Also, the average energy contained on nitrogen fertilizer represented 47.1% of the total input energy on fixed rate application. Using VRT, it was reduced to 26.8% and 40.0% on field 1 and 2, respectively. The average output energy remained similar between treatments.

Energy balance was greater on variable rate fertilization (Table 3). At the same time, it was less variable in the field than uniform application. This is probably due to imbalance between nitrogen demand and the applied rate, which normally happens on fixed rate fertilization. It results in greater variability on yield and consequently on the output energy flow and energy balance.

Table 3 Energy indicators from variable and fixed rate nitrogen fertilization on wheat

Item	Nitrogen rate	Field 1				Field 2			
		Average	Max.	Min.	CV/%	Average	Max.	Min.	CV/%
Nitrogen /MJ • hm^{-2}	Variable	3641.1	5801.6	2841.6	25.4	6643.1	8317.6	5357.6	15.4
	Fixed	8880.0	8880.0	8880.0	0	8880.0	8880.0	8880.0	0
E_{IF} /MJ hm^{-2}	Variable	13582.7	15743.2	12783.2	6.8	16584.8	18259.2	15299.2	6.1
	Fixed	18821.6	18821.6	18821.6	0	18821.6	18821.6	18821.6	0
E_{OF} /MJ • hm^{-2}	Variable	42151.0	72979.2	21312.9	16.3	49400.6	72951.4	19655.2	16.9
	Fixed	42537.7	66975.4	18485.1	17.7	49703.3	75723.4	21466.1	18.7
E_B /MJ • hm^{-2}	Variable	28568.2	60196.0	7049.6	24.4	32815.8	55893.5	2398.9	24.5
	Fixed	23716.1	48153.8	-336.5	31.7	30881.7	56901.8	2644.5	30.2
E_{ROI}	Variable	3.1	5.7	1.4	17.9	2.9	4.3	1.1	15.7
	Fixed	2.2	3.5	0.9	17.7	2.6	4.0	1.1	18.7
E_E /MJ • kg^{-1}	Variable	4.6	9.3	2.4	18.7	4.8	12.3	3.2	17.9
	Fixed	6.4	14.1	3.9	22.1	5.4	12.2	3.4	22.2

The energy "profitability" (EROI) was also higher on variable rate application. It indicates that VRT is more efficient energetically because it makes more energy available (energy on grain mass) with each energy unit invested. On average, less energy was embodied on the output product when using the site-specific management. Energy embodiment was also more uniform on this treatment.

4 Conclusions

Energy assessment is an important tool to evaluate production systems that use PA technology, because it can provide subsidies for monitoring the energy potential of food and energy crops. The suggested method of energy assessment for site-specific data was successful in analyzing the energy performance of a PA system and reveling spatial variability of energy indicators.

VRT applied to nitrogen fertilization performed better in terms of energy use efficiency than traditional practices. All energy indicators pointed to the fact that PA improved energy sustainability on a production system.

For further studies one suggests that energy assessment is incorporated into data gathering during PA operation like fertilization and yield monitoring. These systems could automatically determine energy indicators on the go during each operation and later provide reports about the energy performance of the production system.

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