THE INTERNATIONAL SOCIETY OF PRECISION AGRICULTURE PRESENTS THE
13th INTERNATIONAL CONFERENCE ON
PRECISION AGRICULTURE
July 31-August 4, 2016 • St. Louis, Missouri USA

SITE SPECIFIC COSTS CONCERNING MACHINE PATH ORIENTATION

Mark Spekken [a], José Paulo Molin [b], Tiago Libório Romanelli [b] Marcos Nascimbem Ferraz [b]

[a] Department of R&D, SOMO solutions, Piracicaba, Brazil
[b] Department of Biosystems Engineering, University of São Paulo, Piracicaba, Brazil

A paper from the Proceedings of the
13th International Conference on Precision Agriculture
July 31 – August 4, 2016
St. Louis, Missouri, USA

Abstract. *Computer algorithms have been created to simulate in advance the orientation/pattern of a machine operation on a field. Undesired impacts were obtained and quantified for these simulations, like: maneuvering and overlap of inputs in headlands; servicing of secondary units; and soil loss by water erosion. While the efforts could minimize the overall costs, they disregard the fact that these costs aren't uniformly distributed over irregular fields. The cost of a non-productive machine process (like maneuvering) is minor when it is distributed along a lengthy working track, yet can be profit-compromising for a short track. Also, these tracks hardly follow the terrain contours perfectly, leading to regions more prompt to soil loss. Hence the path orientation affects the length and the surface grade of a track, the intensity and location of the impacts will also be altered. An application was developed to create machine tracks on irregular surfaces and estimate quantities of soil loss within segments of the tracks. Procedures were embedded into the algorithm to calculate costs of maneuvering space, length, time and overlap by the use of geometric equations. A procedure was added assign a cost to a track when its length unable a precise depletion/completion of the tank's content (of fertilizer for e.g.) when reaching the field boundaries/roads. Two case studies of distinct crops and machine properties were processed by the algorithm in a specific pattern searching minimal soil loss. In a sugarcane study, the model obtained that for the average of five harvests, 2.69% of the area presented negative turnover due to the path orientation impacts; however, this area increases tenfold when financial balance is calculated for the last two harvests of the crop. In a cotton case study, a high input cost was calculated for overlap of applied products in headland; with the adoption of a section control boom for the spraying operation, a significant reduction of costs up to US$ 50.00 per hectare was obtained. Considering the costs owed to path establishment these cannot be ignored in economic spatial studies given its role in compromising revenue in certain regions of the field.*

Keywords. *Path planning, Spatial cost distribution, Soil loss impact, Machine efficiency.*

Introduction

Diversity of agricultural practices (crop nutrition, pest control and irrigation) and crop cycles (annual or perennial) has attracted focus for site-specific management in agricultural fields. Some of these studies approached the financial aspects of the field's natural variability and, when it is the case, the respective intervention on them. (Bullock et al., 2002; Bongiovanni, R. and Lowenberg-Deboer, 2004; Boyer et al., 2010).

Among agricultural cost components, mechanization costs and machine traffic impacts are often considered as fixed cost in a production system for the total area. In such analysis, the unproductive impacts of machines and their traffic and coverage impacts are rounded up in overall percentages of inefficiency. Yet, this inefficiency does not only vary among agricultural fields (Sturrock, 1977), but often varies within each individual field.

In the recent years, the impacts of machine operations on irregular field shapes have been, more accurately retrieved and minimized. This was possible by simulating, through computer algorithms, the paths/routes of the machine operations on agricultural fields and calculating its impacts. Works were carried to minimize time of non-productive procedures, like maneuvering and replenishment of inputs (Bochtis and Vougioukas, 2008; Oksanen and Visala, 2007), searching for an accurate coverage of fields to reduce overlap (De Bruin et al., 2009; Bochtis et al., 2010), and combined aspects (Jin and Tang, 2010). Regarding surface irregularity and soil loss by water erosion, a few works searched for optimized orientation of machine tracks and crop rows to be perpendicular to slope (Jin and Tang, 2011; Spekken et al., 2016).

Still, majority of path planning efforts focused in allocating machine tracks with minimized costs for the field as a whole. Yet, as track lengths vary over fields of irregular geometries, and costs (like maneuvering) can be uniquely assigned each track; if this cost is proportionally distributed along the track, it will vary in accordance to the track length. Economic impacts derived from maneuver costs and headland overlap may present themselves to be low relative to a long track, yet economically compromising for a short one. As the length of tracks will vary for different orientations, this poses a factor of spatial cost variability over a field.

Spekken et al. (2015) pointed this issue in sugarcane operations, calculating that sugarcane rows shorter than 50 m may have their financial revenue compromised by the maneuvering costs. Spekken and Molin (2012) developed a path planning approach that identifies regions covered by short tracks for different track patterns. Case study results pointed that short tracks in field corners representing 2% of the area, responded for over 15% of the maneuvers; and, in these, the proportional overlap of inputs in headland was 3 times higher than for the whole field.

In contrast, long tracks may create a logistic problem for operations that depend on reloading of inputs or offloading of harvest produce. This procedure, here known as servicing, requires a machine to load/offload either on the field boundary before reservoir capacity is fully used (Spekken; De Bruin, 2013), or demand an auxiliary unit moving within the field to aid in this procedure. An ideal track-length allows a machine to work the field reaching the field boundary with a full use of its reservoir.

Also, a machine-track/crop-row crossing a field with irregular surface will often present variance in its altimetry. This will result in slope along segments of the track which become susceptible to soil loss by water erosion. Thus, soil loss will vary in space and intensity because of the machine/crop-row

The authors are solely responsible for the content of this paper, which is not a refereed publication.. Citation of this work should state that it is from the Proceedings of the 13th International Conference on Precision Agriculture. EXAMPLE: Lastname, A. B. & Coauthor, C. D. (2016). Title of paper. In Proceedings of the 13th International Conference on Precision Agriculture (unpaginated, online). Monticello, IL: International Society of Precision Agriculture.

orientation, presenting an additional cost to be considered.

This work proposes a path planning approach to distribute spatially, over a field-plot, financial costs related to path orientation, embodying: machine maneuvering in the in the edge of tracks, overlap of inputs in the headlands, cost for inefficient use of the tank's capacity, and soil loss derived from establishment of tracks along slope.

Methodology

The methods here described are modified and implemented after Spekken et al. (2016), where an approach for designing curved tracks and retrieving the soil loss along these was proposed. The method was enhanced for obtaining the full path planning cost by adding the unproductive operational cost (*UOC*), which includes maneuvering cost (*MC*), overlap cost (*OvC*), and cost for inadequate length of track (*CILT*).

The cost calculation method for each of the impacts is described in the following chapters, whilst methods that are derived from previous works are presented by summarized description.

Creating tracks and calculating soil loss costs

The creation of tracks on field and soil loss calculations follow the methodology proposed by Spekken et al. (2016) to create geometric virtual tracks on field-polygons by computational algorithms. Tracks are polylines composed by shorter straight line segments linked in a curved pattern, which can represent a machine path or a crop row. Terrain contours are a common data source used as reference for creating parallel tracks.

In the methodology used, tracks have to be reshaped in curved with a degree of smoothness that allows a machine to steer along.

By overlaying the created tracks on a DTM (Digital Terrain Model), altimetry can be retrieved for existing and created features.

The reference-tracks are then designed in parallel replications in an offset distance user-defined, while the altimetry is assigned to the edges of the segments, obtaining the parameters necessary for applying the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997). The model calculates a soil loss quantity for cumulative water runoff along the tracks (Foster and Wishmeyer, 1974), resulting in soil loss estimates in units of Mg ha^{-1} $year^{-1}$ for each segment. The soil loss is adjusted to Mg^{-1} $year^{-1}$ for its respective area of coverage.

The financial soil loss cost is calculated in proportion to quantity of eroded soil. A comprehensive study, carried by Telles et al. (2011), reviewed many approaches for soil loss costs considering impacts of in-field (loss of nutrients, organic matter and yield) and off-field (soil sedimentation on rivers and eutrophication of water) suggesting US$ 5.00 per Mg of soil eroded. The latter value was used as the final parameter for soil loss cost in the cases to be studied in this work.

Costs from headland maneuver and coverage overlap

Maneuvering costs in headland were calculated considering its time, space and length costs. The methods used for obtaining these are given after Spekken et al. (2015). The main variables that compose the maneuvering costs are: maneuvering type, machine turning radius (r), machine width (w) and angle of machine orientation towards the border (θ). The types of maneuvers considered and its participant variables are shown in Figure 1.

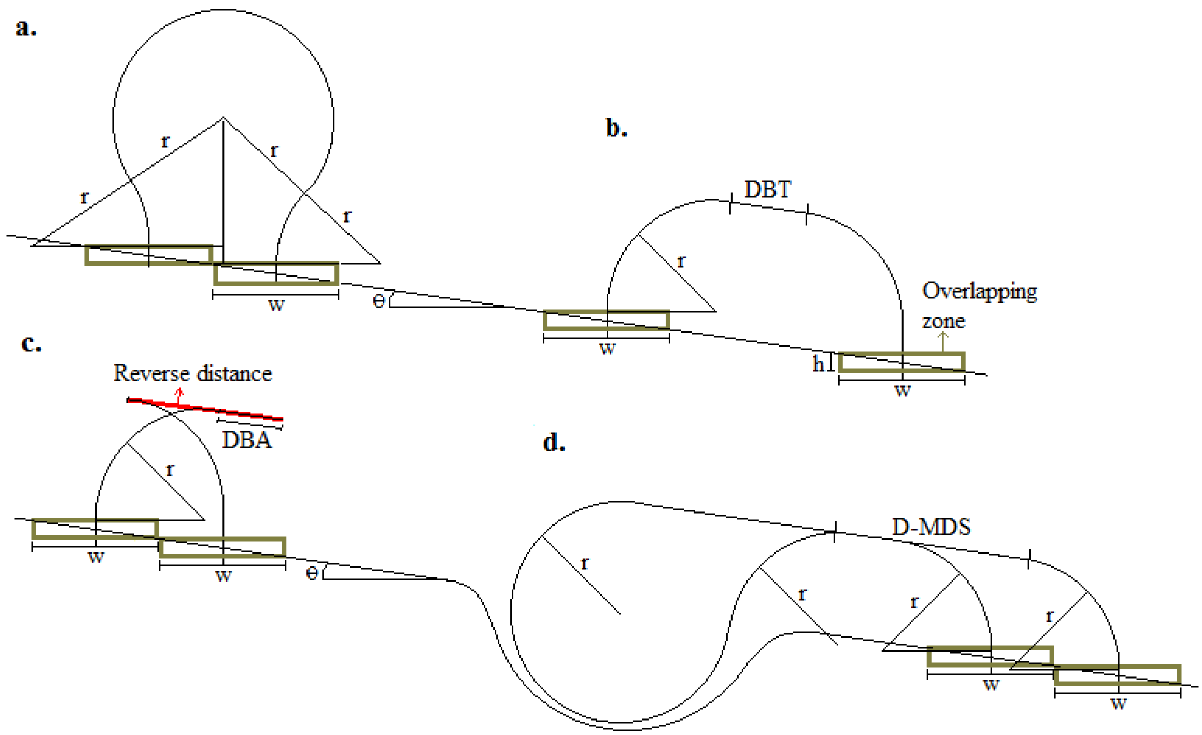

Fig 1. Composition of the types of maneuvers: Ω-turn (a), U-turn (b), T-turn (c) and P-turn (d)

In Figure 1, the variables shown *DBT*, *DBA* and *D-MDS* are respectively distance between steering in a U-turn, distance between rear and steering axles of the machine, and distance to a maneuvering dedicated space.

The time for the maneuver is given by distinct machine working speeds along it. These velocities, along with the other variables mentioned, are given as user-given model parameters. The parameters must be provided upon definition of the maneuvering type and kept constant for all maneuvers in an operation. Only two parameters are obtained by the model while creating the machine tracks: the track length and the angle θ. The latter is retrieved for the first and last segments of a curved track when these reach the field boundary. The final maneuver cost is thus obtained by:

$$TMC = MT * MC + MS * {w^2}/{\cos(\theta)} * OCA + MD * Tw * CR \tag{1}$$

Where:

TMC is the total maneuvering cost (in US$);

MT is the maneuvering time (in s);

MC is the machine cost (in US$ s^{-1});

MS is the maneuvering space (in m);

OCA is the opportunity cost of the land (in US$ m^2);

MD is the maneuvering distance;

Tw is the width of the area under the machine's tires (in m);

CR is the crop revenue or costs for compacted surface per area (in US$ m^2);

Owing that the maneuver may happen in any of the extremities of a track, the final impact cost is an average of the values calculated for both extremities.

The coverage overlap is calculated only for the headland and it is dependent on two of the variables listed, *w* and θ. Usually, in agricultural operations, the overlap exceeds the exact need for overlap length in order to achieve safe area coverage, this is shown in Figure 4.2 by the variable *ASL*, which must be given as an input parameter in the model.

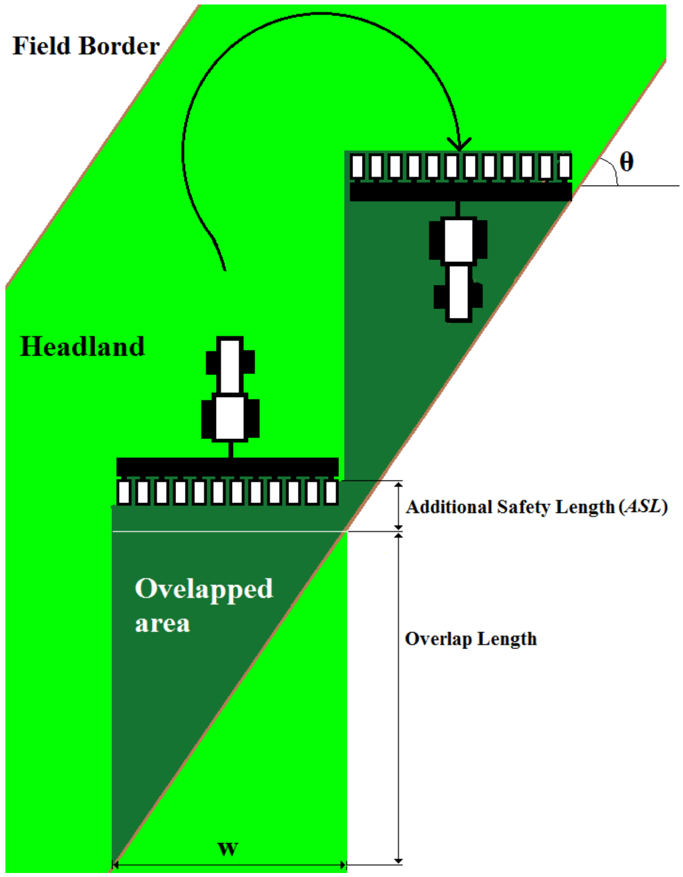

Fig 2. View of headland overlap and its related variables.

As shown in Figure 2, the overlapped area (*OvA*, in m^2) at the extremity of a track is calculated by Equation 2 and the overlapped cost (*OvC*, in US$) is given in Equation 4.3:

$$OvA = w * \left[ASL + \frac{w}{\tan(\pi/2 - \theta)} \right] \tag{2}$$

$$OvC = OvA * APC \tag{3}$$

Where *APC* is the product value applied per area (in US$ m^{-2}).

The final *OvC* is summed for both extremities of a created track.

Cost of servicing

Machine loading or offloading of agricultural goods can happen by two means: servicing with aid of auxiliary units within the field, or servicing restricted to the field boundary (headlands or roads). The first is more related to harvesting procedures, where high quantities of product must be constantly offloaded in a narrow time-window operation; while the latter is related to application of inputs (seeds, fertilizer, pesticides), in which auxiliary units on field would be either unaffordable financially or soil/crop damaging.

The ideal length to attend the capacity of a machine (*IdL*, in m) is given by:

$$IdL = \frac{Tank}{Rate * w} \tag{4}$$

Where *Rate* is the application rate or product harvested along the followed track (units m^{-2}); and *Tank* is the capacity the reservoir (units).

When a track presents the same length as *IdL*, the *CILT* is nil, assuming that there are no costs to the servicing procedure. In the same way, when auxiliary units can follow the primary unit without stopping the latter for offloading (like for grain discharge of harvesters unto wagons in motion), unproductive time is inexistent and the *CILT* is also nil.

Unproductive use of a machine is found in harvesting operations when there is need of constant presence of an auxiliary unit, like for silage or sugarcane harvesting as in Figure 3a.

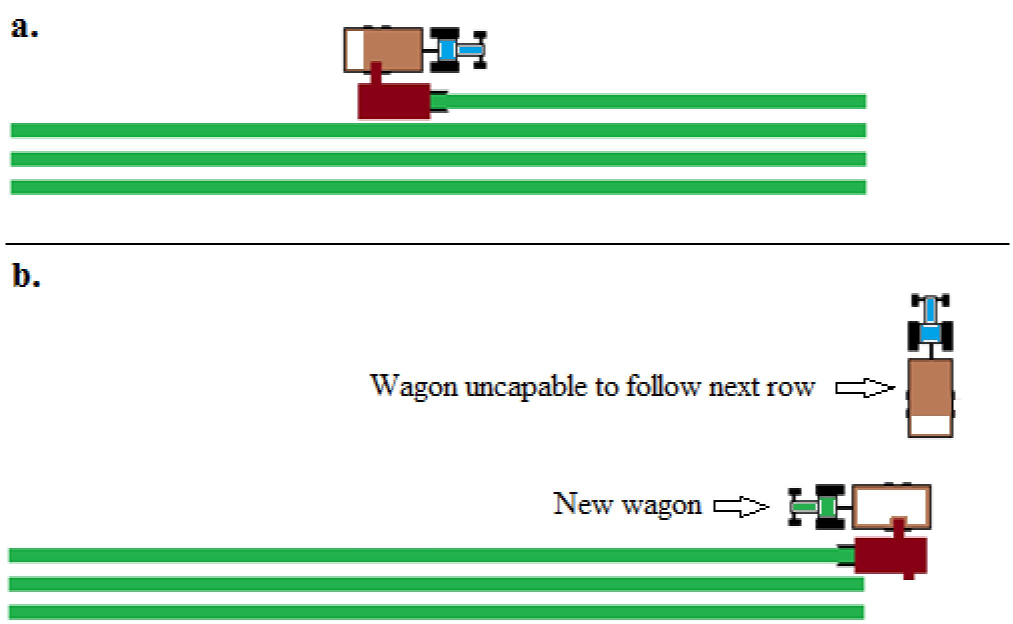

Fig 3. Harvesting operation with primary and secondary units (in 'a'), and switch of wagon carriers at the edge of a row-track (in 'b')

The replaced wagon in Figure 3b is leaving the field with underused capacity. Therefore, the transportation cost for the incomplete cargo is added to the track, which is the proportional fraction to the transport of a full wagon.

For harvested product, a tolerance value (*Slack*, in %) is considered to transport an additional weight for tracks a minimally longer than *IdL*. The real length of a track (*RLen*, in m) is given by the created tracks on the field by the model. *RLen* is obtained by the number of passes (*NP*) capable to approximate to *IdL*, i.e. when more passes of a certain track are needed to complete the ideal length. *NP* and *RLen* are given by equations 4.5 and 4.6 respectively;

$$NP = int\ [(IdL+IdL*Slack) / TrackL] \tag{5}$$

$$RLen = NP*TrackL \tag{6}$$

The lacking load of the reservoir at the edge of a track (*LLoad*, in units) is given by:

$$LLoad = Tank - \left(\frac{Tank * RLen}{IdL} \right) \tag{7}$$

If *LLoad* is negative, meaning that the carrier is using the tolerance capacity to finish the track, and the machine managed to fully use the track length and *LLoad* is then equalled to zero.

The cost of the lacking cargo is calculated by multiplying *LLoad* by the cost of unit-weight transported, which is based in an hourly auxiliary-unit time cost (*ATC*, in US\$ s^{-1}) and an average trip time (*ATT*, in s) to offload the cargo. The final *CILT* for this operation is obtained by equation 8:

$$CILT = \frac{ATC * Load}{ATT * Tank * NP} \tag{8}$$

When the *Lload* is excessively high, the carrier may continue with the harvester and be replaced in the middle of the field to complete its loading, and an empty carrier will replace it when the cargo becomes critical. In this case, the replacing time interruption is for the whole operation (primary and auxiliary units) and for a fixed time-cost value (in US$). When this cost is lower than the *CILT*, as calculated by equation 4.8, it overrules the equation and becomes the new *CILT* (i.e. cost of in-field swap of carriers is lower than cost for transporting incomplete cargo).

In other field operations, where application of product on field is involved, auxiliary units are absent or attending the primary units only on the boundaries of the fields. These operations have no additional tolerance for its capacity (no *Slack*), and when tracks do not meet the *IdL* criteria, a machine-time cost is computed to refill the reservoir. *CILT* is then proportional to the length that is not covered by the remaining capacity, calculated by equation 4.9.

$$CILT = \frac{(IdL - RLen) * TCM}{IdL * NP}$$

(9)

The values of *MC*, *OvC* and *CILT* compose the unproductive operational cost (*OUC*), and are unique for each track. When this cost is divided by the track-length, it becomes a relative cost per distance (US$ m^{-1}). This relative cost is assigned to each of the segments composing the track.

Model implementation

The methods were applied on the model originally developed by Spekken et al. (2016). An algorithm was embedded to the existing model within the Lazarus free-pascal environment. Figure 4 provides a view of the developed model with a practical case being evaluated.

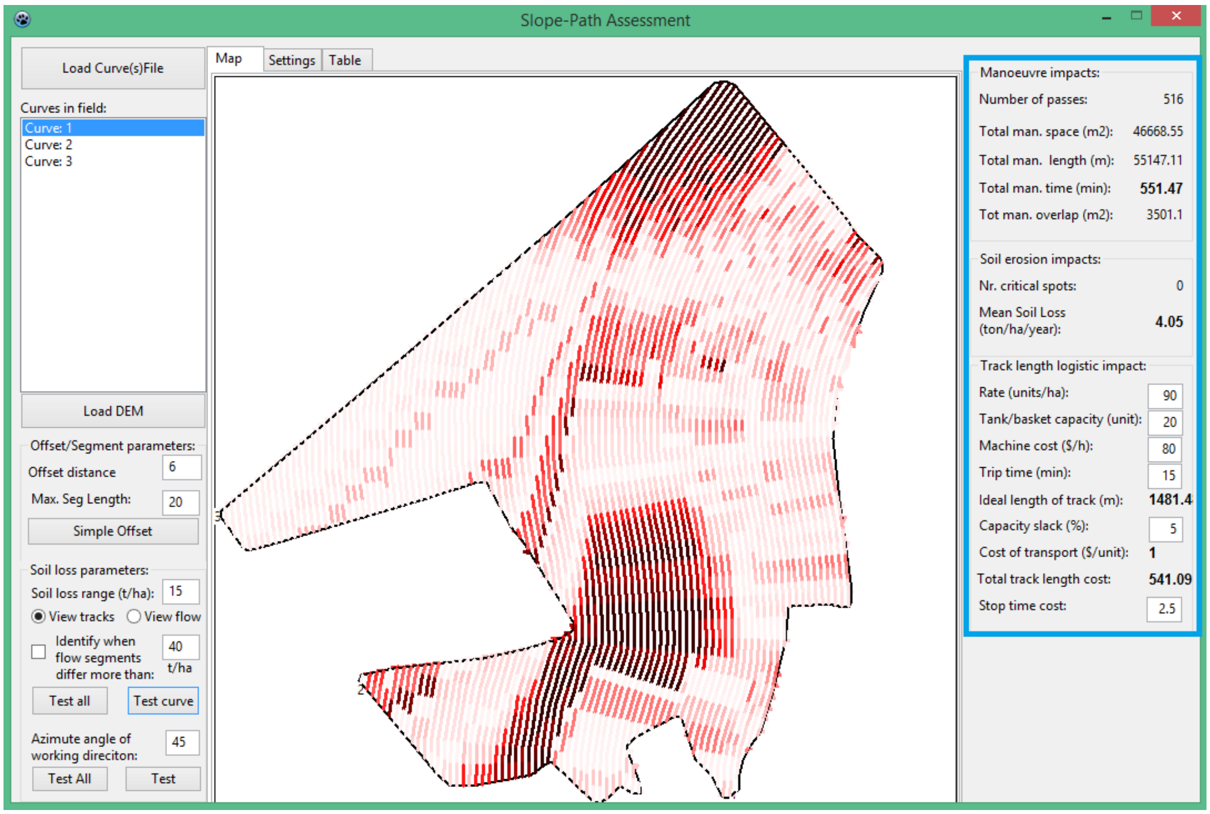

Fig 4. View of the implemented model showing an output of track coverage where red coloured intensity in the field-map is proportional to the local soil loss intensity.

The input parameters are given to the model as setting variables that can be altered for each simulation and/or case study. The blue square in the right side of the window shows the overall calculated impacts for the chosen pattern.

The algorithm calculates soil loss and operational parameters in real time, storing the coordinates of the segments in the form of an array-list along with the relative cost per distance of the calculated soil loss, *MC*, *OvC* and *CILT* for each segment. The list can be exported in comma separated value (.CSV) files for analysis.

Case studies and results

Two case studies were applied as scenarios into the model-algorithm to assess its performance and outputs on distinct environments and crops. The crops analysed were sugarcane (*Saccharum spp.*) and cotton (*Gossypium hirsutum*) grown in Brazilian representative regions (São Paulo and Mato Grosso states respectively); both crops are established as row crops with prohibitive traffic across them. Sugarcane has an intense mechanization cost concentrated in its harvest operation, which can encompass up to 30% of the total production costs (Coelho, 2009) and over 80% the total mechanization costs (Spekken et al., 2015); thus the operational cost calculation and its distribution for this case study is confined to harvesting. Cotton crop, on the other hand, has an intense cost related to use of inputs (seeds, fertilizer and pesticides), which makes overlap a higher issue among unproductive costs. In the latter case, four field operations (sowing, fertilizer spreading, spraying and harvesting) were considered to calculate the path planning cost. The field study areas are displayed in Figure 5 identifying the case study I (sugarcane) and II (cotton), their respective properties are displayed in Table 1.

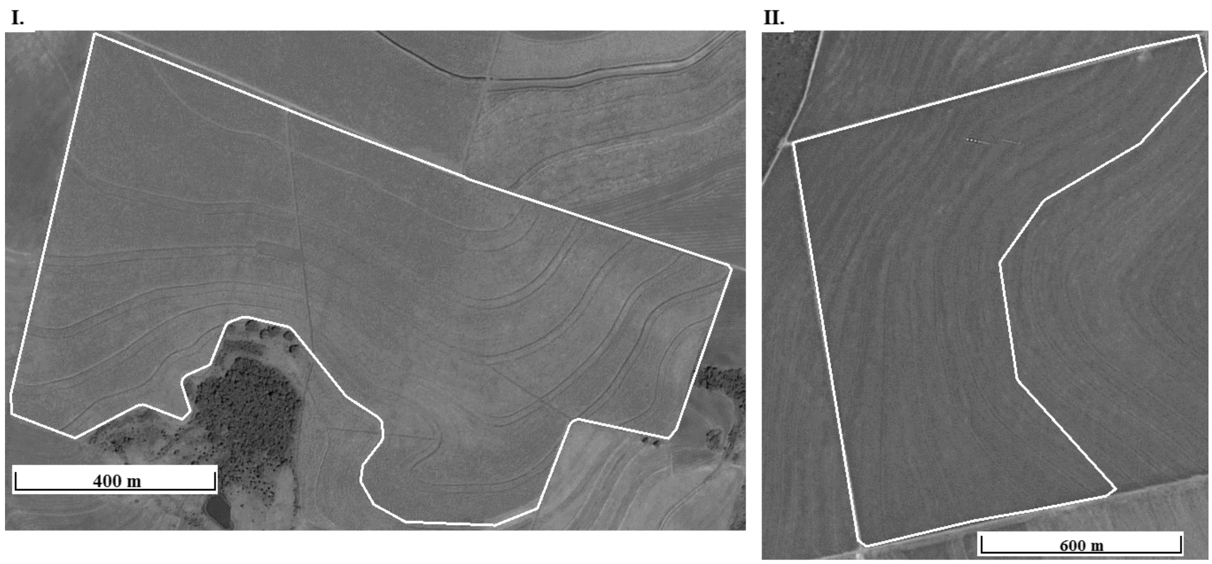

Fig 5. View of the two case study areas (I and II)

For case study I, altimetry data was available from logged RTK (Real Time Kinematic) measurements, retrieved from the auto-guidance system during the planting operation. A cotton harvest operation logging data (GNSS L1 receiver) was the altimetry source for case study II. The data was interpolated to a 5 m regular-grid by ordinary kriging using VESPER 1.62 (Minasny et al., 2005). The extraction of the surface contours was done in the GIS software Quantum GIS 2.4.0 Chugiak (Quantum GIS Development Team, 2014), which was also used for sorting and viewing the data of the spatial cost distribution.

In case study I, the average slope steepness is 6.6%, varying from 2.7 to 12.7%, and the surface contours were used as reference to find the least erosive option (model obtained). For case study II, the slope steepness average is 2.9%, varying from 0.4 to 5.6%; the lower steepness of this case study is counter balanced by a higher erosion susceptibility of the soil (factor K in Table 1). The least erosive option in case study II was a hybrid line obtained from two surface contours (see Spekken et al., 2016 for hybridization of lines). The source references used for creating parallel tracks are identified by a green line within the field-maps in Figure 6.

Table 1. Description of the case study environmental properties

	Case study I	Case study II
Location	Latitude 21º 27'42'' Longitude 47º59'03''	Latitude: 14º56'56'' Longitude: 54º56'25''
Land use	Agriculture - Sugarcane	Agriculture – Cotton
Area size (ha)	77.56	91.65
Soil classification (ISRIC[a])	Ferrasol Udox	Ferrasol Udox
Soil type	Sandy clay	Sandy loam
RUSLE R factor [b]	1785.0	1087.4
RUSLE K factor [c]	0.012	0.057
RUSLE C factor [d]	0.307	0.58
RUSLE P factor [e]	1	1
Average soil loss for the whole surface using the least erosive reference (Mg ha^{-1} year^{-1})	7.93	6.35

[a] ISRIC - International Soil Reference and Information Centre, 1998.

[b] R factor calculated after Lombardi Neto & Moldenhauer (1992), for monthly and annual rainfall of 250 and 1350 for 'i'; and of 200 and 1500 for 'ii'.

[c] K factor calculated after Lobardi Neto & Bertoni (1975), for a clay-silt-sand particle fraction of 45-10-45 for 'i'; and 15-12-73 for 'ii'.

[d] C factor obtained after Machado et al. (1982) for 'i' and Murphree & Mutchler (1980) for 'ii'.

[e] P factor suggested after Spekken et al. (2016) for water running along crop row without obstacle.

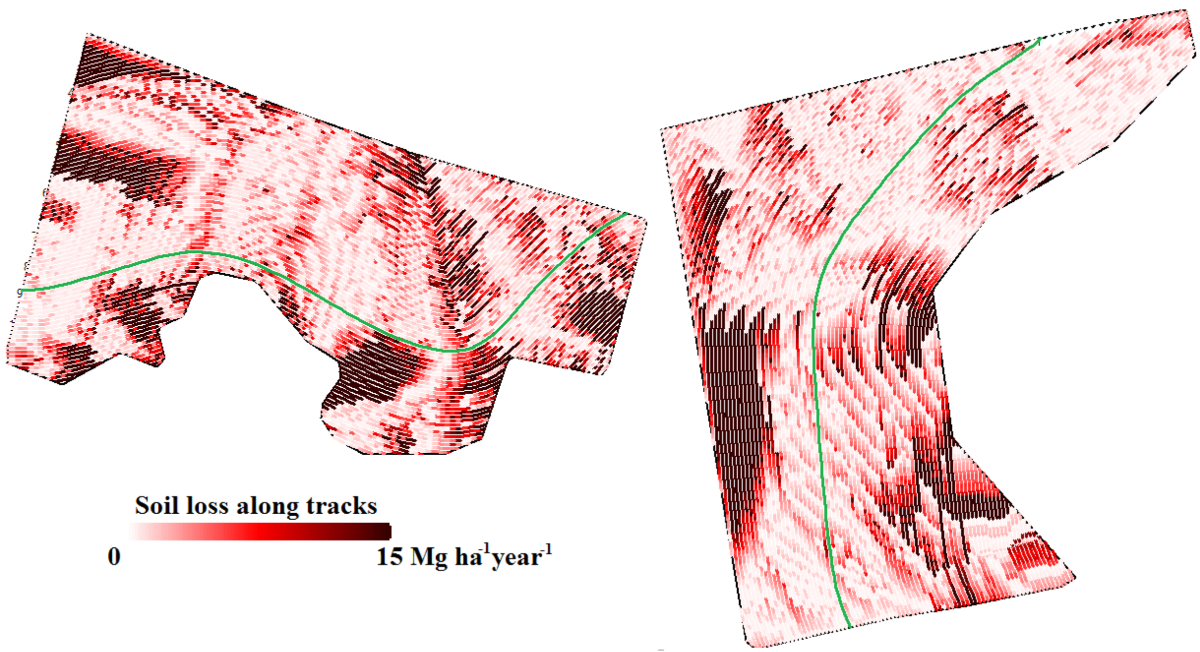

Fig 6. Algorithm-suggested pattern for field coverage for minimal soil loss impact.

The tracks created by the algorithm were fractured (if necessary) in shorter line segments of 15 m. Figure 6 displays parallel tracks offset in 9 m for the purpose of viewing the orientation, yet the studied data was processed to create offsets of 3 m for sugarcane (2 sugarcane rows) and 4.5m for cotton (5 cotton rows, to match harvester width). A total of 24204 and 19181 track-segments were generated for the cases I and II respectively.

The segments carrying its relative soil loss and unproductive operational costs had the coordinates of the edges averaged to a point-location, and exported for analysis.

Case study I

The parameters used for the harvesting operation are described as follows: turning radius (r) of 10.5 m (for wagon-carriers); operation width (*w*) of 1.5 m; maneuvering type as *P-turn*; distance to maneuvering dedicated space (*D-MDS*) of 20 m; turning speed of 1.5 $m.s^{-1}$ and road speed of 2.5 m s^{-1}. In sugarcane operations headland is inexistent, and all the maneuvers are done in roads around the fields; therefore, no costs apply for crop overrunning, soil compaction or overlap. Hence, the cost for maneuvering is limited to space (*road width*) and time. The time cost of the harvest operation was US$ 170.00 h^{-1} and the area lease cost (to calculate maneuvering area) was US$ 410 ha-1. The *CILT* was calculated for a harvesting rate of 78 Mg ha^{-1}, basket capacity of 17 Mg, slack capacity of 10%, time cost for carrier of US$ 30.00 and a round-trip time for offloading of 15 min.

The algorithm retrieved a total maneuvering time and space of 20.36 h and 3.18 ha with respective costs of US$ 3481.15 and US$ 1313.34. The *CILT* cost was of US$ 500.99. The final *UOC* regarding the working orientation is US$ 5295.48 or US$ 68.27 ha^{-1}. The total soil loss cost was of US$ 3075.25 or US$ 39.65 ha^{-1}.

A financial balance of the crop was calculated using the total costs of each segment-location subtracted from a revenue per length. The average revenue of five harvests (US$ 400.00 ha^{-1}) has its value adjusted to US$ 0.12 m^{-1} (for a width of 3 m between tracks). Also the balance for the last two harvests was studied (revenue of US$ 107.00 ha^{-1} or US$ 0.032 m^{-1}). The revenue values were obtained from FNP Consultoria e Comércio (2012).

The spatial distribution for the operational unproductive cost and soil loss cost are given in Figure 7.

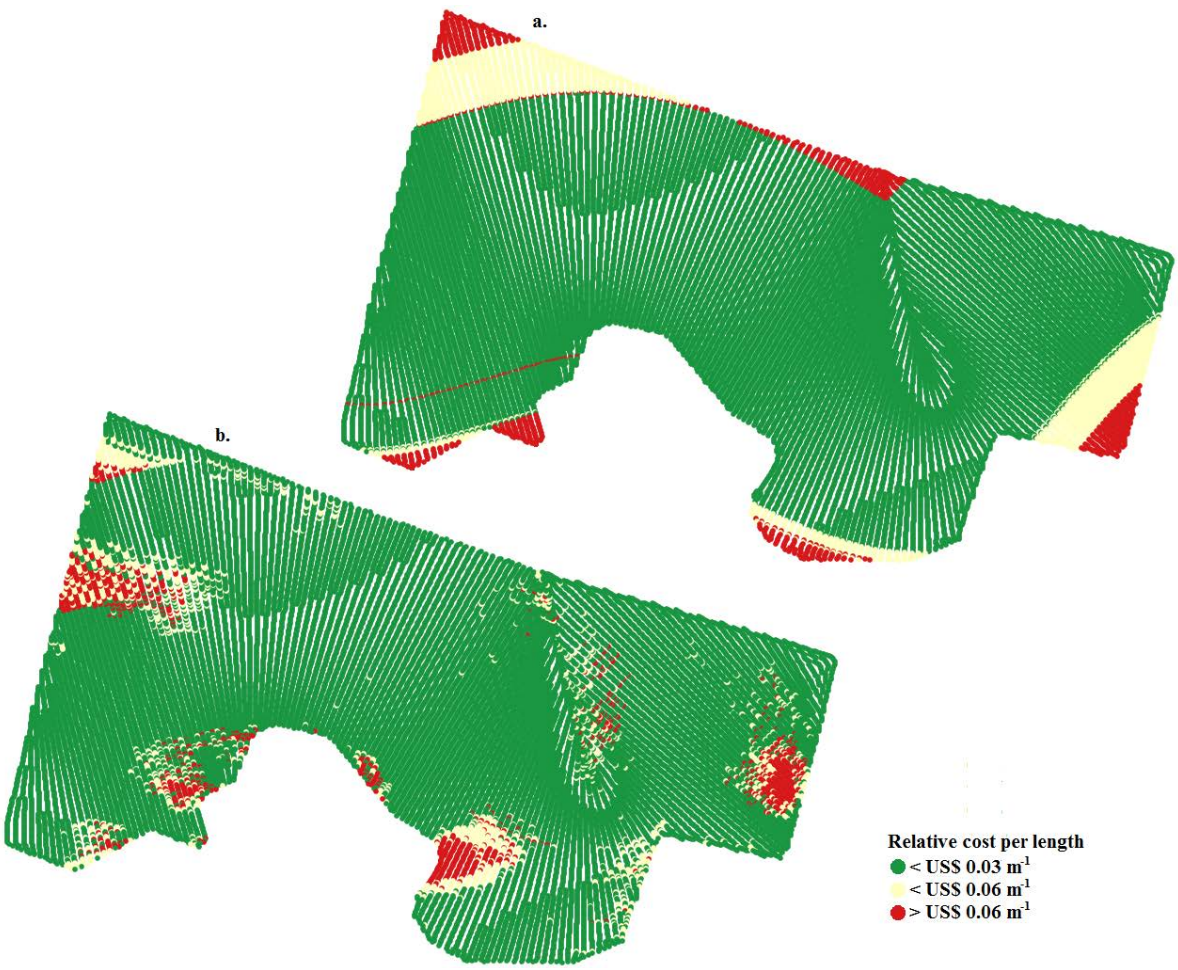

Fig 7. Spatial distribution of the unproductive operational costs in ‘a’ and soil loss cost in ‘b’.

In Figure 7, the range of the three cost categories (green, yellow and red) was defined in steps of US$ 0.03 m^{-1}, which represent a quarter of an expected crop revenue (US$ 0.12 m^{-1}). This implies that the cost in the regions covered by red dots consumes over 50% of the expected profit. Also, the total *UOC* for the red area in 'a' (13.7 ha) was of US$ 1604.35, which represents 30.3% of the *UOC* of the whole field.

As expected, the distributed *UOC* were higher for segments of short tracks, with maneuvering as the leading cost. Soil loss costs are more scattered, with some major clusters concentrated in regions where tracks are in higher off-grade regarding the surface.

The spatial financial balances calculated for the two proposed revenues are shown in Figure 8.

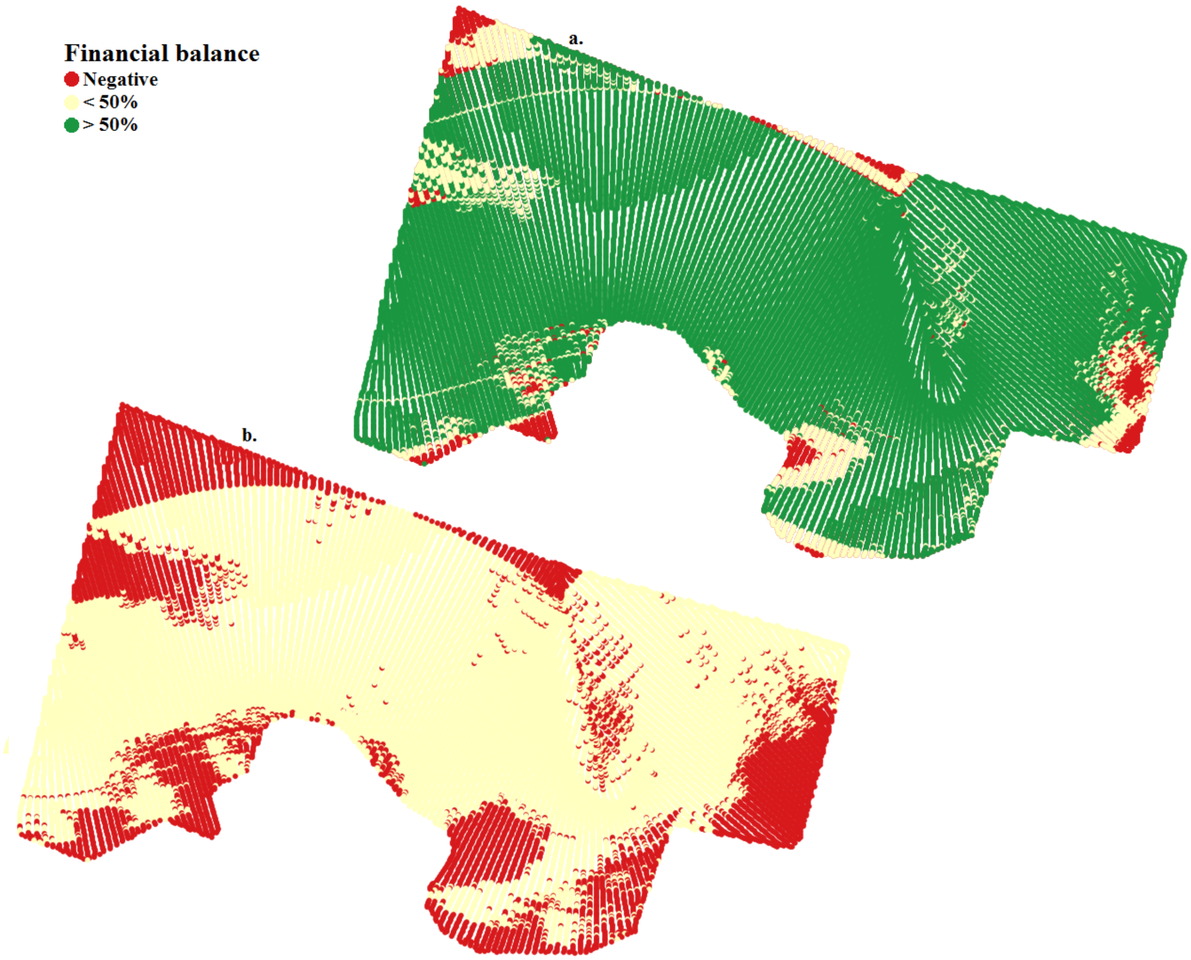

Fig 8. Localized financial balance in sugarcane for the path planning impact for a fixed income expected per meter. In 'a' the balance considers an income averaged by all five harvests and in 'b' the balance considers the average of the last two harvests.

The area of negative turnover in Figure 4.8a is 2.08 ha (2.69% of the field) and the area with financial margins below 50% is 7.04 ha (9.07% of the field); these areas increase to 20.36 ha and 57.23 ha respectively, in Figure 4.8b. Tracks with length shorter than 50 m showed no revenue.

Case study II

In this case study, four operations were simulated by the algorithm using width multiple of the cotton harvester (4.5 m). The highest costs among *UOC* is the overlap of fertilizer and pesticides (over 50%

of *UOC*), for which the latter counts over 20 spraying applications during the growing of the crop for the local conditions. Table 2 displays the operational properties used as parameters and the total costs retrieved by the algorithm.

Table 2. Operational and machine cost values used as parameters in the model

	Sowing	Fertilizer spreading	Spraying	Harvesting
	Operational parameters			
Operation width (m)	9	27	27 [a]	4.5
Machine turning radius (m)	6	6	5	6
Composition of maneuvering cost	Time	Time + Length [b]	Time + Length [b]	Time
Maneuver type	Ω-turn	U-turn	U-turn	T-turn
Application overlap	Yes	Yes	Yes	No
Rate of product loaded/offloaded (units ha^{-1})	400 kg Fertilizer [c]	200 kg Fertilizer	100 L water + prod.	3750 kg cotton
Reservoir/basket capacity (units)	2700 kg	5000 kg	2700 l	2700 kg
Sum of the value of products applied (US$ ha^{-1})	153	321	695.5	0
Machine cost (US$ h^{-1})	191	131.66	41.01	272.25
Replenishment time of reservoir/basket (min)	15	60	10	4
	Operational cost of the path planning calculated by the algorithm			
Total maneuvering costs (US$)	146.73	163.53	524.83	855.06
Total overlap costs (US$)	239.64	1439.9	3119.78	0
Total *CILT* costs (US$)	60.00	24.87	33.08	262.13
Total unproductive operational costs (US$)	446.38	1628.30	3678.50	1117.20

a. Sprayer boom without section-control.
b. Length of the maneuver calculated for crop overrun in the after-implanted crop in the headland. The calculated length was multiplied by a track width of 1 m and the overrun area was multiplied by an expected crop revenue of US$ 400 ha^{-1}.
c. Fertilization and seeding are simultaneous operations in the local sowing procedures. However, fertilizer reservoir has higher frequency of replenishment, and the re-loading of seeds happens during these events.

The calculated *UOC* summed US$ 6870.38 (US$ 75.96 ha^{-1}), and the soil loss cost was US$ 2909.88 (US$ 31.75 ha^{-1}). Figure 9 displays the spatial distribution of these costs where the *UOC* (in 'a') of the red spots sums US$ 4372.73 (US$ 259.29 ha^{-1}) and the soil loss cost (in 'b') of the red spots sums US$ 1614.51 (US$ 213.04 ha^{-1}). Similarly to case study I, the three categories of costs in Figure 9 are separated in ranges (of US$ 0.045 m^{-1} in this case), identifying the local *UOC* or soil loss costs when these surpassed 25% (yellow dots) or 50% (red dots) of a suggested revenue. This revenue was set on US$ 400.00 ha^{-1} (or US$ 0.18m^{-1} for tracks offset in 4.5m).

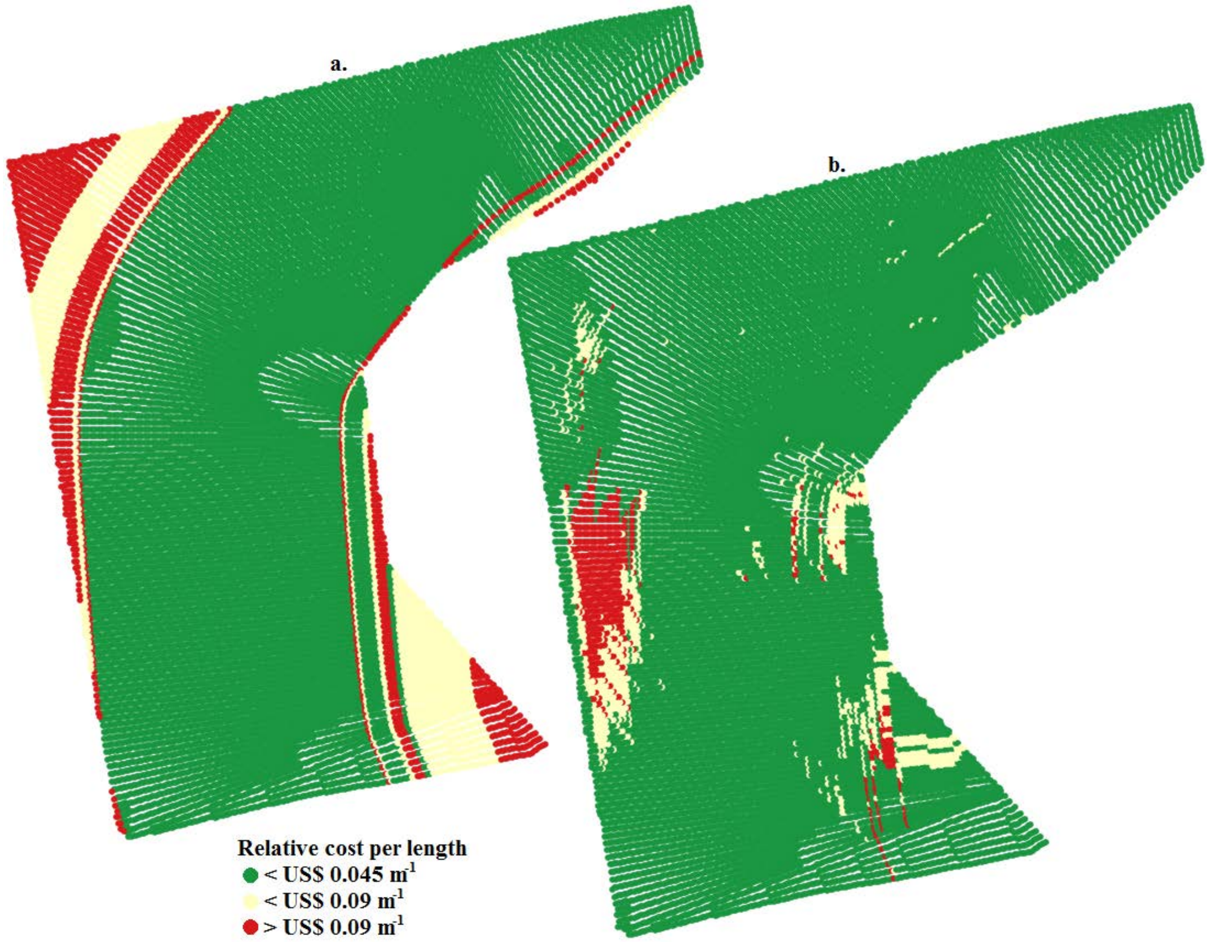

Fig 9. Spatial distribution of the unproductive operational costs in 'a' and soil loss cost in 'b'.

The high overlap cost in Table 2 can also be seen in the maps of Figure 9a, where tracks reaching borders with a large angle θ. increases overlap and the relative cost per length. Such costs make the use of sprayer with section control along the boom a suitable acquisition. The standard financial balance of the crop for the path planning costs was thus compared to a similar setting yet dividing the sprayer boom in four equidistant sections. Figure 10 shows the spatial distribution of the balance for both scenarios.

The overlap area of the spraying coverage decreased from 9.1 ha (9.9% of the field area) to 2.43 ha (2.65% of the field area) with the section control, proposing an expense savings of US$ 4638.98 (US$ 50.61 ha^{-1}) of product that would be applied twofold. Similar results were found in path planning for one case study in Bochtis et al. (2010), where the overlapped area of the sprayer was the key-factor for defining a more financially affordable working orientation on the field.

The area correspondent to a negative turnover in Figure 10a is 2.82 ha (3.08 % of field area), and the area with revenue below 50% than expected because of path planning costs was of 12.5 ha (13.67% of field area). These areas decrease respectively to 1.53 ha and 7.12 ha (1.67% and 7.77% of the field area) with adoption of the section control in the sprayer boom as shown in Figure 10b.

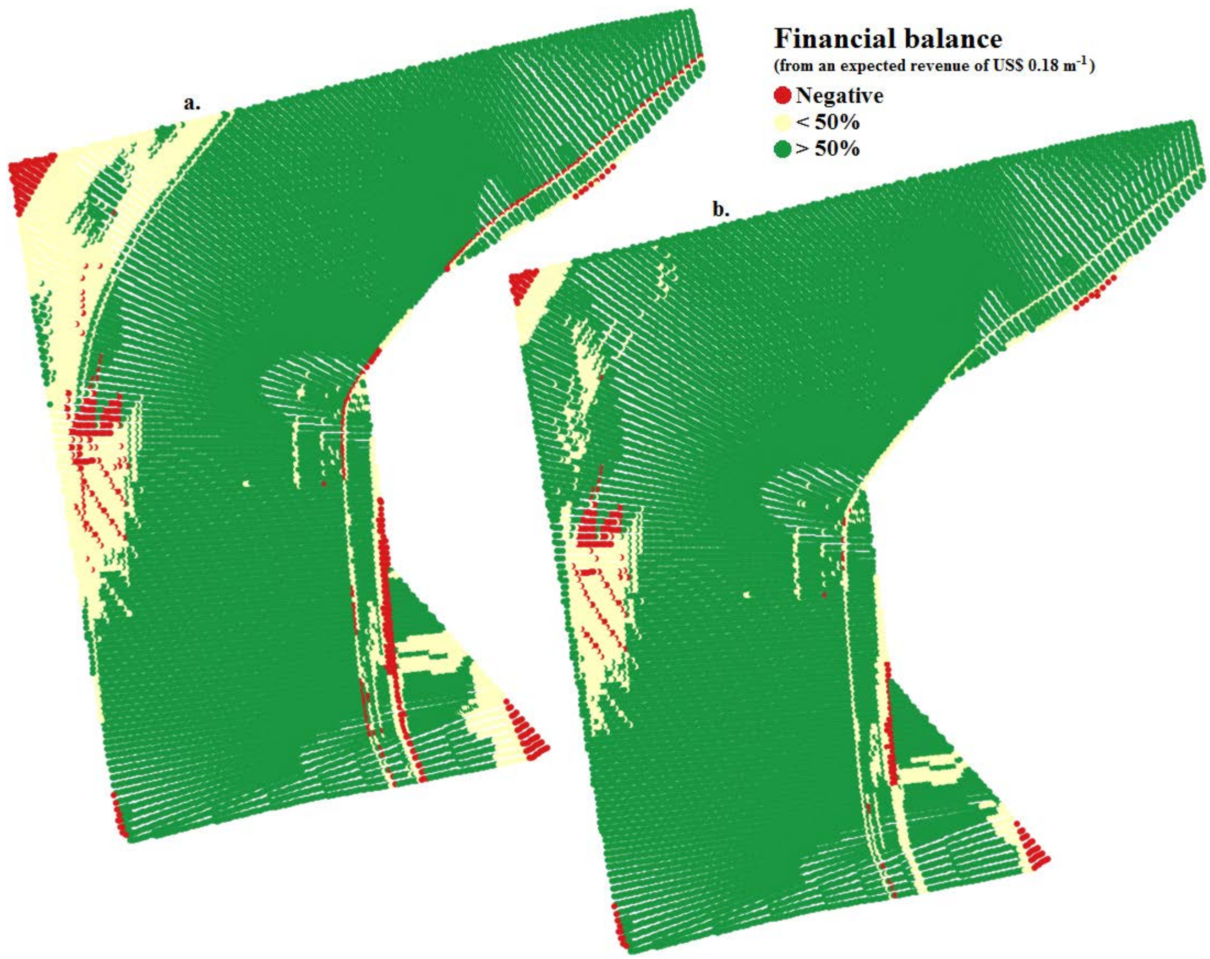

Fig 10. Localized financial balance for the path planning impact for a fixed income expected per meter. In 'a' the balance with a standard operational setting and in 'b' the balance for a modified sprayer.

Discussion

The case studies already searched for optimized track establishment with minimal soil loss. Still, the parallel behaviour of machines is limited by the non-parallel conditions of the slope. This will unavoidably result in off-grade condition of the rows and machine paths in varying intensities. An alternative for more reduction of soil loss through path planning would then require divisions in the pattern of orientation of the tracks within the field to increase perpendicularity to slope; yet such option would likely increase the unproductive operational costs. Other alternatives like establishment of wide base ridges (in which machines can move across) following the surface contours can reduce runoff within the tracks; also, to adopt minimal soil mobilization would also be an option.

The simplified assumption of assigning a fixed cost-value for a quantity of soil eroded is not fully accurate. Aspects like re-sedimentation has to be taken into account (which is not computed in the RUSLE), and calculation for across-track runoff must be considered. Other aspects of soil erosion cost should be studied further, especially to consider the concentration of water on spots within the field, which may lead to the formation of gullies. Such drastic outcomes have no specific way to calculate its costs, because its consequences can harm from the soil morphology to the very traffic of machines across the field.

Nevertheless, the approximation for assigning costs to soil loss (drawing back from Jin and Tang, 2011) can direct decision makers to search for long-term sustainable soil use.

Land use issues arise for areas in field corners, where operational costs are unprofitable. Such areas must also require attention from the decision makers that may find alternatives, like compliance with legislation for establishment of natural reserves (Brazilian Federal Law 4771/1965), or assigning these for transhipment areas (offload from sugarcane carriers onto trucks in case study I) for logistic purposes.

Summary and Conclusion

This work makes use of an existing model-algorithm for simulating virtual tracks and retrieving their respective soil erosion impact. In this model, methods were embedded for obtaining machine unproductive operational impacts like maneuvering, overlap of inputs applied in headlands, and cost of inadequate length of tracks due to underutilization of the machine's reservoir-capacity.

The model-algorithm was subject to assessment by case studies applied for covering a field with an erosion-minimized set of tracks. These tracks had soil loss and unproductive operational costs assigned to each of the track-segments. In a sugarcane case study, the top cost issue was maneuvering, which identified a range of unprofitable short tracks and showed that 17.65% of the inefficient area comprises for almost a third of the unproductive operational costs. Also the results suggest that, for the last two years of harvest, the low revenue margins increase significantly the financial prohibitive area. For the cotton case study, overlap of applied inputs were the top cost issue for which the angle between field boundary and machine orientation is the most costly factor. The *UOC* of the high cost areas were 3.4 times higher than the field average; and the adoption of a section controlled sprayer boom decreased the overlap area in 3.74 times and halved the non-profitable and low profitable areas.

In conclusion, in irregular shaped fields the operational costs are not equally distributed; likewise for soil loss costs in irregular surfaces. These issues need to be accounted as an in-field variability because of its potential to compromise the income of certain regions, particularly when studies of robust financial balance are aimed. Also suggests better planning and destination for the areas with limited operability.

Acknowledgements

This paper is derived from a subset of a doctoral thesis defended in July 2015. We acknowledge with gratitude the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) that provided a doctoral scholarship to the first author (Project number 2012/07958-2) and continues to sponsor this research for its applicability and innovation (Project number 2015/01071-4).

REFERENCES

Bochtis, D. D., Sørensen, C. G., Busato, P., Hameed, I. A., Rodias, E., Green, O., Papadakis, G. (2010). Tramline establishment in controlled traffic farming based on operational machinery cost. Biosystems Engineering, 107(3), 221-231.

Bongiovanni, R., Lowenberg-DeBoer, J. (2004). Precision agriculture and sustainability. Precision agriculture, 5(4), 359-387.

Boyer, C. N., Brorsen, B. W., Solie, J. B., Raun, W. R. (2011). Profitability of variable rate nitrogen application in wheat production. Precision Agriculture, 12(4), 473-487.

Brasil. Laws, decrees, etc. (2012). Brazilian Forest Code: Lawi nº 12.651, 25 of May of 2012. Brasília. Available in: <http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/L12651compilado.htm>. Accessed in: 31 may. 2016.

Coelho, M.F. (2009). Planejamento da qualidade no processo de colheita mecanizada da cana-de-açúcar. 74 p. Master Thesis– Escola Superior de Agricultura "Luiz de Queiroz", São Paulo University.

FNP Consultoria e Comércio. AGRIANUAL 2012: anuário da agricultura brasileira. São Paulo, (2012). 482 p.

Foster, G.R., Wischmeier, W.H. Evaluating irregular slopes for soil loss prediction. (1974). Transactions of the ASAE, St Joseph, v. 17, n. 1, p. 305–309.

Jin, J., Tang, L. (2010). Optimal coverage path planning for arable farming on 2D surfaces. Transactions of the ASABE, 53(1), 283-295.

Jin, J., Tang, L. (2011). Coverage path planning on three-dimensional terrain for arable farming. Journal of Field Robotics, 28(3), 424-440.

Machado, E. C., Pereira, A. R., Fahl, J. I., Arruda, H. V., Cione, J. (1982). Índices biométricos de duas variedades de cana-de-açúcar. Pesquisa Agropecuária Brasileira, 17(9), 1323-1329.

Minasny, B., McBratney, A. B., Whelan, B. M. (2005). VESPER version 1.62. Australian Centre for Precision Agriculture, McMillan Building A, 5.

Murphree, C. E., & Mutchler, C. K. (1980). Cover and management factors for cotton. Transactions of the ASAE, 23(3), 585-0588.

Oksanen, T., Visala, A. (2007). Path planning algorithms for agricultural machines. 112 p. Thesis (PhD) - Automation Technology Laboratory, Helsinki University of Technology, Helsinki, 2007. (Series A: Research Reports, 31).

Renard, K.G., Foster, G.R., Weesies, D.K., Toder, D.C. (1997). Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE). Washington: USDA, 1997. 407 p. (Agriculture Handbook, 703).

Spekken, M., de Bruin, S. (2013). Optimized routing on agricultural fields by minimizing maneuvering and servicing time. Precision agriculture, 14(2), 224-244.

Spekken, M., Molin, J. P. (2012). Optimizing path planning by avoiding short corner tracks. In: Proceedings of the International conference on precision agriculture. International Society in Precision Agriculture, 11, p. 314-328 2012, Monticello-IL.

Spekken, M., Molin, J. P., Romanelli, T. L. (2015). Cost of boundary manoeuvres in sugarcane production. Biosystems Engineering, 129, 112-126.

Spekken, M., de Bruin, S., Molin, J. P., Sparovek, G. (2016). Planning machine paths and row crop patterns on steep surfaces to minimize soil erosion. Computers and Electronics in Agriculture, 124, 194-210.

Sturrock, F.G.; Cathie, J.; Payne, T.A. (1977). Economies of scale in farm mechanization**.** Cambridge: Cambridge University, Department of Land Economy. 15 p. (Ocas. Papers,. 22, Economics Unit).

Telles, T. S., Guimarães, M. D. F., Dechen, S. C. F. (2011). The costs of soil erosion. Revista Brasileira de Ciência do Solo, 35(2), 287-298.