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A technical opportunity index adapted to zone-specific management

Pierre Roudier[*,†,‡], Bruno Tisseyre[§], Hervé Poilvé[‡] and Jean-Michel Roger[†]

Abstract Ten years after the introduction of zone-based management to take into account within-field phenomena in agronomic practices, several methodological developments have progressed to the operational level. However, this raises a new scientific question: how can the relevance of this type of management be evaluated? This paper adapts the concept of a technical opportunity index to zone-specific management. Based on the characteristics of machinery, zoning opportunity is introduced through a new index (*ZOI*) adapted specifically to zone-based management. This index takes into account the operational conditions in which zoning is applied, together with its associated risks. The results obtained on simulated and real field data highlight the relevance of this index.

Keywords Opportunity index · Management zones · Precision agriculture · Decision support tools

[*] Corresponding author.
E: p.roudier@usyd.edu.au
P: +61(0)2 9351 2947
F: +61(0)2 9351 3706
[†] Cemagref, 361 rue J.F. Breton, BP 5095,34196 Montpellier Cedex 05, France
[‡] Infoterra France, Parc Technologique du Canal, 15 Avenue de l'Europe, 31520 Ramonville Saint-Agne, France
[§] Montpellier SupAgro, 2 place Pierre Viala, 34060 Montpellier Cedex 01, France

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Introduction

Within-field delineation of zones aims at simplifying the spatial representation of within-field variability. Its principle is to divide a field into a small number of regions. Those regions must be contiguous (a region is a set of connected points), homogeneous (intra-zone variability is low) and distinct (inter-zone variability is high). This process allows the farmer to adapt field management to allow for differences between the main zones that can exist within a field. Ten years after the introduction of this concept (McCann et al.; 1996, Stafford et al. 1998), several methods of zoning have been published (Vrindts *et al.* 2005) and are now implemented into commercially available management solutions (Roudier *et al.* 2008; Douche *et al.* 2008).

The availability and diffusion of such tools introduced a new technical choice for the manager. It is now possible to apply a given recommendation according to different management options: classical uniform management (reference management option) and zone-based management (alternative management option). Such a decision is case-specific, and depends on a combination of several factors: field, type of recommendation, date of recommendation, proposed treatments and machinery used to apply the treatments, etc.

With the development of within-field management tools comes the need to characterize the potential for a given field to be treated using zone-specific treatments. As a consequence, Whelan and McBratney (2000) proposed a method to quantify the relevance of a site-specific treatment compared to a classical uniform one taken as a reference (or null hypothesis). Several criteria are taken into account and analysed:

- Economic criterion *Ec*: ability of a treatment to maximize economic profitability of the farm
- Environmental criterion *En*: quantifying environmental impacts of cropping practices
- Technical criterion *T*: ability of a treatment to maximize the agronomic performance of

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a field

While economic and environmental criteria *Ec* and *En* have been discussed already in the literature (Wu *et al.* 2005; Rider *et al.* 2006; Tozer and Isbister 2007; Delgado *et al.* 2008), the technical criterion *T* has been studied much less (Tisseyre and McBratney 2008). Its study is an important requirement in the application of within-field management tools. A major step in the adoption of these technologies is to decide whether or not the degree of variation of a given field is important and spatially structured enough to justify the application of a site-specific treatment. The concept of technical opportunity describes the technical aptitude of a field for a site-specific treatment (Tisseyre and McBratney 2008). This aptitude depends on the within-field variability of the recommendations to be applied and of the capability of machinery used to apply it.

The concept of technical opportunity is relatively new in the literature, and few estimators of *T* have been proposed. Two kinds of methods exist at present. The first is based on the use of geostatistical tools to compare the average area within which data are autocorrelated with the spatial footprint of the machinery (Pringle *et al.* 2003). However, the steps required to model the autocorrelation are computationally demanding and difficult to automate. Despite recent efforts to simplify this formalism (de Oliveira *et al.* 2007), estimation of the average extent of autocorrelation is not compatible with the processing of a large amount of data. The second method makes use of morphological operators to simulate the path of the machinery through the field (Tisseyre and McBratney 2008). The potential to apply a treatment site-specifically using a given machine is estimated using morphological filtering of an application map. The index obtained from this method is, however, limited to the study of two different treatments and does not take into account the magnitude of within-field variability. Neither method is

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adequate to evaluate zone-specific management. The first method focuses on the combined study of the magnitude and spatial structure of within-field variation, but does not assess the performance of the zone-based model. The second method evaluates the technical opportunity in part only.

There is a marked absence in the literature of a method to estimate the technical opportunity in relation to the various risk factors, under operational conditions and without expert or manual intervention. This study introduces an opportunity index adapted to the specific case of zoning. The aims of this index are (i) to help the end-user to decide between a uniform treatment and its zone-specific alternative and (ii) to be implemented into an operational precision agriculture solution (i.e. matching strong industrial constraints such as automation, robustness and simplicity of analysis).

Theory

Decision support systems for precision agriculture can be represented by a wheel with four successive steps organized around a central process, i.e. spatial referencing (Fig. 1, McBratney and Taylor 2000). This study focuses on the application step. The recommended rate, $z(x,y)$, with its associated uncertainty, is produced from the preconisation step. The recommended rate is adapted to be applied technically: this is the prescribed rate, $h(x,y)$, that goes into the applicator.

FIGURE 1 HERE

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Quantifying the performance of a zoning model

The zoning opportunity index (*ZOI*) proposed in this study quantifies the relevance of applying a given zone-based treatment instead of the reference treatment. On a given field, *P*, two ways to apply a given recommendation *z* exist:

- (H_0): Null hypothesis. Zone-based application is rejected, and the reference treatment is applied.
- (H_1): Alternative hypothesis. Zone-based application is accepted in preference to the reference treatment.

Management options H_0 (reference management option) and H_1 (zone-based management option) are represented by their prescribed rates, h_0 and h_1, which are two different ways to model a recommendation $z(x,y)$ on *P* with regard to its application. The zoning opportunity index aims to compare the performances of prescribed rates h_0 and h_1 on field *P*, where h_0 is the rate that is applied if the zone-based management hypothesis is rejected. The most common example is uniform management, e.g. using the mean recommendation on the field $(h_0(x,y) = \overline{z})$. The alternative treatment, $h_1(x,y)$, is a piecewise constant function on *P* resulting from a given zoning method (either automated or manual, empirical or expert).

FIGURE 2 HERE

Figure 2 illustrates for a part of *P* the estimation and comparison of the respective performances of management options H_0 and H_1 for application of the recommendation *z*. This one-dimensional example is around a boundary, *f*, between two zones *A* and *B* proposed by a

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zoning model h_1 so that $h_1(x \in A) = a$ and $h_1(x \in B) = b$. Reference management option H_0 is a uniform treatment over the field, and is described by a uniform rate $h_0 = \bar{z}$. The less the difference there is between the recommendation (z) and its model (h), the better a given management option H is. This difference corresponds to the modelling error of z by h, which shown in Fig. 2 by the area I_0 for management option H_0, and by the area I_1 for management option H_1. In practice, those areas can be estimated by the sum of the squared error (SSE) between recommendation z and each prescribed rate h:

$$I_0 = \sum_{x,y \in P} (h_0 - z(x,y))^2 \ , \qquad (1)$$

$$I_1 = \sum_{x,y \in P} (h_1(x,y) - z(x,y))^2 \ . \qquad (2)$$

The I_0 and I_1 enable the model performance of a recommendation, z, by each treatment h_0 and h_1 to be estimated. To characterize a zoning model, we propose to compare its performance with the reference treatment. To formulate an index in which the order depends on the relevance of applying the zone-based treatment, the zoning opportunity index *ZOI* is computed as:

$$ZOI(h_1 \mid h_0) = 1 - \frac{I_1}{I_0}, ZOI \in \left]-\infty, 1\right], \qquad (3)$$

where h_1 is a zone-based application model of recommendation z and h_0 is the reference treatment. The decision as to whether or not to apply the proposed zoning model can be determined by a simple decision rule:

- If $ZOI(h_1 \mid h_0) > 0, I_1 < I_0$. The alternative hypothesis H_1 is accepted.
- If $ZOI(h_1 \mid h_0) \approx 0, I_1 \approx I_0$. H_1 could be accepted, but in most cases it will be rejected as it

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does not bring significant advantages to justify setting it up.

- If $ZOI(h_1 \mid h_0) < 0, I_1 > I_0$. Alternative hypothesis H_1 is rejected.

Integration of the zoning application risks

The application of a recommendation z by a prescribed rate h can be affected by errors that generate a difference between the treatment's prescribed rate $h(x,y)$ and the rate that is actually applied *in situ*. Such errors affect the modelling of z by h and are related to the technical characteristics of the machinery. Two sources of error can be identified:

- Spatial errors, related to the spatial footprint of the machinery (and associated uncertainties).
- Discretization errors, related to the differences between prescribed rate and fixed increments in application rates that the machinery can achieve (and associated uncertainties).

Risks related to the spatial footprint of the machinery

The spatial footprint, ε, of the machinery represents the maximum spatial resolution of a within-field treatment (Pringle *et al.* 2003; Tisseyre and McBratney 2008). It is defined by characteristics of the machinery, i.e. the width of application (β) and the distance required to alter the input control (given by the product of the cruising speed v and the time τ required to alter the command, Fig. 3):

$$\varepsilon = \beta v \tau. \tag{4}$$

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The uncertainty of the positioning system (δ_{geo}) can also be integrated into Eq. 4:

$$\varepsilon = (\beta+\delta_{geo})(v\tau+\delta_{geo})\,. \qquad (5)$$

The spatial footprint of the machinery used to apply a zone-based treatment h_1 defines a risk of error in the application of this treatment. This risk expresses itself in the neighbourhood of a boundary, i.e. a change in the prescribed rate. While passing from one rate, *a*, to another, *b*, the spatial footprint of the machinery represents the area below it where the actual amount of input applied is unknown. The convolution of this spatial footprint on the zone boundaries of treatment $h_1(x,y)$ defines the set of points in *P* for which the amount of input that is actually applied is uncertain. This set defines the risk area of treatment h_1 and is known as *r* (Fig. 3b).

FIGURE 3 HERE

For each boundary between two management zones *A* and *B* with respective rates *a* and *b*, the risk of applying a zone-based management model h_1 expresses itself by an error in the rate that is actually applied inside the risk area *r* that exists between two adjacent zones (Fig. 5). In the example in Fig. 4, field *P* can be decomposed as follows:

$$P=A+B\,, \qquad (6)$$

$$A= n_A+ r_A\,, \qquad (7)$$

$$B= n_B+ r_B\,, \qquad (8)$$

$$r= r_A+ r_B\,, \qquad (9)$$

where r_A and r_B are the areas of zone *A* and *B*, respectively, where a technical risk of application exists, and n_A and n_B are the areas of zone *A* and *B*, respectively, without any

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technical risk of application. The risk of applying zone-based model h_1 is given by an uncertainty on the rate applied in r:

$$h_1(x, y \in r_A) \in [a, b]. \qquad (10)$$

$$h_1(x, y \in r_B) \in [a, b]. \qquad (11)$$

FIGURE 4 HERE

The formulation of this risk can be used to take into account the machinery effects in *ZOI*. There are several ways of integrating this uncertainty, for example an applicator response function to a change in rate. In this study, we decided to consider the maximum risk systematically. Thus, for the first possible error (Eq. 10), the risk area r_A is treated with the rate b, whereas it has been prescribed the rate a. A symmetrical reasoning in relation 11 allows us to formulate the two possible risks in the neighbourhood of a given boundary:

$$h_1\left(x, y \in r_A\right) = b. \quad \text{(Fig. 5b)} \qquad (12)$$

$$h_1\left(x, y \in r_B\right) = a. \quad \text{(Fig. 5c)} \qquad (13)$$

FIGURE 5 HERE

Consequently, it is necessary to correct the value of I_1 in Eq. 2 for *ZOI*. The I_1 must be replaced by a corrected SSE I_{1c} that takes into account the two application errors that can occur around a given boundary (Eqs. 12 and 13, Figs. 5b and 5c). In practice, only one of the two errors can occur at one time. If the application error occurs in the risk area r_A, then the application is correct in n_A ($h_1(x, y \in n_A) = a$) and incorrect in r_A ($h_1(x, y \in r_A) = b$). Moreover, there is no application error in r_B as the same rate is applied to the risk area ($h_1\left(x, y \in \{r_A, r_B\}\right) = b$). As for n_A, the application is always correct in n_B, and consequently the treatment in B is correct ($h_1\left(x, y \in n_B\right) = b$).

$$\begin{aligned} I_{1c}\left(A\right) &= \sum_P \left(h_1 - z\right)^2 \\ &= \sum_{n_A} \left(h_1 - z\right)^2 + \sum_{r_A} \left(h_1 - z\right)^2 + \sum_{r_B} \left(h_1 - z\right)^2 + \sum_{n_B} \left(h_1 - z\right)^2 \\ &= \sum_{n_A} \left(a - z\right)^2 + \sum_{r_A} \left(b - z\right)^2 + \sum_{B} \left(b - z\right)^2 \end{aligned} \tag{14}$$

A similar reasoning allows us to define $I_{1c}(B)$:

$$I_{1c}(B) = \sum_A \left(a - z\right)^2 + \sum_{r_B} \left(a - z\right)^2 + \sum_{n_B} \left(b - z\right)^2 \tag{15}$$

As we have decided to consider the maximum risk, the less favourable case is chosen to compute I_{1c}:

$$I_{1c} = max\left(I_{1c}\left(A\right), I_{1c}\left(B\right)\right) . \tag{16}$$

The zoning opportunity index then takes into account the operational conditions of the application of the zoning (Eq. 17):

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$$ZOI(h_1 \mid h_0) = 1 - \frac{I_{1c}}{I_0}. \tag{17}$$

Risks related to the discretization of input rates by the machinery

The application constraints that can be taken into account are not limited to the spatial footprint of the machinery and uncertainties that can affect the positioning system. In addition, errors related to the discretization of the prescribed rates by the applicator can be integrated using the same formalism.

A discretization of the prescribed rates by the controller of the applicator is necessary for the technical implementation of a zone-based treatment h_1. Thus, errors can occur between the prescribed rates h_1 and the rates that are actually handled by the controller:

- Most of the time, controllers have a discrete and finite range of rates (e.g. steps of 10 units in the case of a nitrogen spreader). Thus it is necessary to adapt the prescribed rate h_1 so that every prescribed value can be handled by the controller.
- There are always uncertainties between the prescribed rate and the rate actually applied that are related to the accuracy of the application system.

Uncertainties also affect the recommendation z through the errors of predicting the crop's needs. However, the aim of this study is the integration of operational constraints during the application step in Fig. 1. Integration of the uncertainties on z are considered in the Discussion.

FIGURE 6 HERE

To take into account these risks there is a need to correct the prescribed rate h_1 by a prescribed rate h'_1 so that (i) h'_1 values are in the range of the applicator and (ii) the uncertainties on the applied rate are taken into account (Fig. 6). Once the prescribed rate is corrected, the computation is the same as the one described above.

Material and methods

Theoretical data

To characterize the behaviour of the zoning opportunity index, three theoretical fields simulated by Tisseyre and McBratney (2008) to provide values at a resolution of 1m in a 1ha field plot were tested. These fields were derived from a Gaussian distribution. The values for fields *r*27, *r*36 and *r*45 were simulated with variogram models with increasing ranges of spatial dependence, 27, 36 and 45 m, respectively. As a consequence, the spatial organisation of the data increases from field *r*27 to field *r*45. The fields tested were obtained after elimination of the white noise that affected the initial simulated fields using the *GREYCstoration* algorithm (Tschumperlé 2006, Fig. 7). The aim of this was to eliminate the high frequency noise resulting from the nugget effect in the variogram models, while retaining the differences in spatial organisation of the data.

FIGURE 7 HERE

To test the behaviour of the zoning opportunity index in relation to the spatial structure in each of the three theoretical fields, an agronomist delineated zones based on expertise. Prescribed rates were determined using the mean value in each zone. To test the behaviour of the index when the number (and therefore the area) of the zones varies, an increasing number of zones (from 2 to 6 zones) were delineated in field *r36* (Fig. 8a) as shown in Fig. 8b–f.

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FIGURE 8 HERE

For each zoning, the *ZOI* was computed using a circular spatial footprint. The radius of the spatial footprint r_ε ranged from 0 to 5 m.

Real data

To ensure the relevance of our approach in an operational context, nitrogen recommendation data for wheat from the Farmstar service (Douche *et al.* 2008) were also considered. Two fields on commercial farms in Northern and Central France were studied. Figure 9a-b shows the maps of recommendations, and Table 1 summarizes the characteristics of each field tested.

FIGURE 9 HERE

TABLE 1 HERE

A zoning of each of the agricultural fields was generated by the method proposed by Roudier *et al.* (2008): an initial segmentation step is followed by a hierarchical fusion of the zones obtained, until constraints related to the size and morphology of the zones are satisfied. The zoned maps are shown in Fig. 9c-d. To compute the *ZOI* for these fields, the spatial footprint of the machinery was modelled by a 12 m-radius disc (ε=452.4 m^2), corresponding to the average width of a nitrogen spreader on the farms where the fields are located. We have also considered that the controller can accept only a limited set of commands, corresponding to the

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rates that can be accepted by the fertilizer spreaders. This set of values was determined by the Farmstar agronomist as 0, 30, 40, 50, 60, 70, 80 and 100. Thus, values of the prescribed rates in each zone have been modified and given the nearest value in the spreader's range.

Implementation

Risk areas were determined by morphological dilation of the zone boundaries (Serra 1982). The morphological dilation is an operator whose effect is to enlarge the width of the boundaries to the detriment of the neighbouring pixels. This neighbourhood used in the dilation process is defined on the basis of the spatial footprint of the machinery used to apply inputs to the zones, i.e. a disc with a radius $r_\varepsilon = \max(\beta+\delta_{geo};\ \nu\tau+\delta_{geo})$. The methods described in this paper were implemented in the IDL language (Research Systems, Inc. 2005), on a PC-platform.

Results

Characterisation of the index

Spatial structure of the within-field variability

The first experiment aims to study the sensitivity of the proposed zoning opportunity index in relation to the characteristics of the machinery. To do so, the *ZOI* was computed for each theoretical field (Fig. 7) for a circular spatial footprint of radius r_ε varying from 0 to 10 m.

FIGURE 10 HERE

Figure 10 presents the results of these experiments graphically. Figure 10a shows the evolution of areas of risk with the change in spatial footprint of the machine. For each of the three simulated fields, the risk area increases with the size of the machine's footprint. Figure 10 also shows that whatever the size of the footprint, the risk area decreases with increasing spatial structure (i.e. variogram range) of the data. Figure 10b shows the evolution of the zoning opportunity index with the size of machine's footprint, for each of the three simulated fields. Zoning opportunity is affected by the increase in the footprint because this increase implies a bigger uncertainty in the rate that is really applied by the applicator. Similarly, for a given spatial footprint, zoning opportunity increases with greater spatial structure in the data. These results are consistent with the definition of opportunity in the PA context.

As shown by Fig. 10a and b, the ratio of the area of risk to the total area of the field is a good indicator of zoning opportunity. However, this notion is not sufficient to assess zoning opportunity because it does not take into account the differences in the rates required on both sides of a boundary. The greater the difference between two adjacent zones, the greater is the risk of application error, which diminishes zoning opportunity.

The results of Fig. 10b allow us to estimate explicitly the opportunity for zone-based treatment according to the spatial footprint of the machinery. Zone-specific treatment for a field will be opportune if *ZOI>0*. This means having a spatial footprint smaller than a limiting value, $\varepsilon_{lim} = \pi \times R^2$, where R is the radius of the machinery footprint. This value is $\varepsilon_{lim} = \pi \times 4^2 \approx 50.3m^2$, $\varepsilon_{lim} \approx 28.3m^2$ and $\varepsilon_{lim} \approx 7.1m^2$ for fields *r*47, *r*36 and *r*27, respectively. These results highlight the relevance of our approach for the theoretical fields. They show logically that the more the field is spatially structured, the more suitable it is for zone-based treatment.

Number and area of zones

The second experiment tests the behaviour of the zoning opportunity index when the number (and area) of management zones varies. The number and area of the zones depend both on the spatial structure of the data and on the operational constraints. They can also be affected by the zoning method that has been used. Five different zonings of theoretical field *r*36 were generated manually by an expert (Fig. 8). The relation between the *ZOI* for each possible zoning of field *r*36 to the size of the machine's spatial footprint is given in Fig. 11.

FIGURE 11 HERE

The results show that zoning opportunity decreases systematically when the spatial footprint of the machinery increases. The change in zoning opportunity with the number of zones also varies according to the spatial footprint of the machinery. An increase in the number of management zones improves the modelling performance of a zone-based treatment because it reduces the difference between the recommendation rates and the prescribed rates in each zone. However, this advantage can be offset by the presence of risk areas, for which there is a risk of applying an inappropriate rate. The areas at risk increase with the number of zones. Therefore, when the spatial footprint of the machinery is small (from ε =0 m^2 to ε =12.57 m^2), zoning opportunity increases with the number of zones because the ratio of risk areas to total field area remains low. On the contrary, when the spatial footprint becomes more important (ε =78.54 m^2), increasing the number of zones systematically penalizes the zoning opportunity. Between those two categories (ε =28.27 m^2 and ε =50.27 m^2), an optimal number of zones exists.

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Application example

The application of the zoning opportunity index in an operational context was tested for nitrogen recommendations on two wheat fields (Fig. 9a-b). For each field, the decision-maker must choose between an application following either a zoned or a uniform application map.

FIGURE 12 HERE

The zoning proposed for field Fort (Fig. 9c) results in a large *ZOI* of 0.935 in relation to the machinery constraints considered. As Fig. 12 shows, the nitrogen recommendations are significantly different for each delineated zone; as a consequence, the modelling of the recommendation by the prescribed rate is significantly better for zone-based treatment than with the uniform recommendation. Figure 9a also shows that the within-zone variation is also small. Moreover, the total length of zone boundaries is not important, which reduces the areas of risk. Therefore, zone-based treatment of nitrogen would be applied in this field. By contrast, the zoning proposed for field Mont (Fig. 9d) and for the machinery constraints considered, the *ZOI* is low (*ZOI*=0.099≈0). The boxplot in Fig. 12 shows that the two zones proposed by the zoning model are not significantly different, and Fig. 9b shows that both have considerable within-zone variation. As a result, there is no significant advantage of applying zoned-based treatment in this field; a uniform nitrogen application would be made in field *Mont*.

Discussion

This study has aimed to apply within-field modulation tools in a commercial service. The context implies taking into account some specific constraints (e.g. computing efficiency, automation), while integrating knowledge about the operational conditions for zoning. The method that has been proposed answers those requirements, since computing of the proposed index is based on operations that are simple from a computing point of view (sum of squares, morphological dilation). Computing *ZOI* takes <0.005 s on a standard desktop computer for a field of 100 × 100 pixels. Moreover, the ZOI can be computed for any continuous variable. The only requirements are, in addition to machinery-based information, that both the recommendations and the zoned data are on a regular grid. Finally, when the spatial footprint of the machinery can be specified, computation of the *ZOI* is fully automated. Opportunity can be computed by defining a standard spatial footprint for the machinery, i.e. an area defined by the radius of influence of the machinery. If the working direction is specified, an oriented spatial footprint of the machinery can be defined.

The proposed *ZOI* gives a means of comparing the performance of two concurrent treatments by taking into account the technical conditions of application. The index can support the choice of a treatment for applying a given recommendation and can determine an optimal number of management zones. We think that, if the zoning is regarded as a means of simplifying the spatial representation of within-field variation, several other uses are possible, *e*.g. it could guide the choice of zoning method to maximize the resulting opportunity.

Several improvements to the methodology presented in this paper are suggested. As mentioned above, there is always an uncertainty on the recommendation *z* the farm manager has to apply. We propose two different approaches to integrate the uncertainty. The first uses a Bayesian approach that requires the distribution of the recommendation *z* to be modelled. The second approach is based on possibility theory (Zadeh 1978), which can model different sources of uncertainty using the same formalism. The approach we have proposed in this study is a first step towards an index that could be more exhaustive, for example using fuzzy formalism to define the spatial footprint of the machinery (Paoli 2009). The latter is more flexible than our Boolean representation of the risk areas and closer to technical reality.

Finally, it would also be of interest to consider the notion of zoning opportunity beyond its

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technical component by integrating environmental and economic risks of a treatment through cost functions. However, this raises the question of the aggregation of different types of data, which might be possible with methods based on fuzzy logic.

Conclusion

Computation of the opportunity of a given zoning takes into account the technical characteristics of the machinery that is used to apply the recommendations zone-specifically, and estimates the relevance of its application by modelling the effects of several risks (positioning errors, errors in the rates that are actually applied). Experiments enabled us to highlight the main characteristics of the zoning opportunity index proposed in this paper as follows:

- it can be computed whatever zoning operator has been used (automated or manual, empirical or expert),
- it integrates the technical risks of zone-specific applications by determining the risks related to uncertainties in the rates applied and through the notion of spatial footprint of the machinery,
- it depends on the number of zones proposed by the zoning method.

The proposed method addresses the different requirements of use within the framework of a commercial PA service (computing efficiency, automation, robustness).

Finally, a major aim of this study was to propose a method that can integrate the technical conditions of applications by zone. The method enables the integration of different kinds of expert knowledge:

Knowledge on data: The expert can give knowledge on the zoned data (range of rates specific to a particular machine, uncertainty on the applied rates) to correct the rate value for each zone.

Knowledge on operational constraints: The definition and use of the spatial footprint of the machinery used to apply the recommendations zone-specifically enables the real risks of application by a given zoning to be determined.

Knowledge and automation: Finally, the methods make it possible to integrate detailed information on operational zoning constraints, without making concessions on automation.

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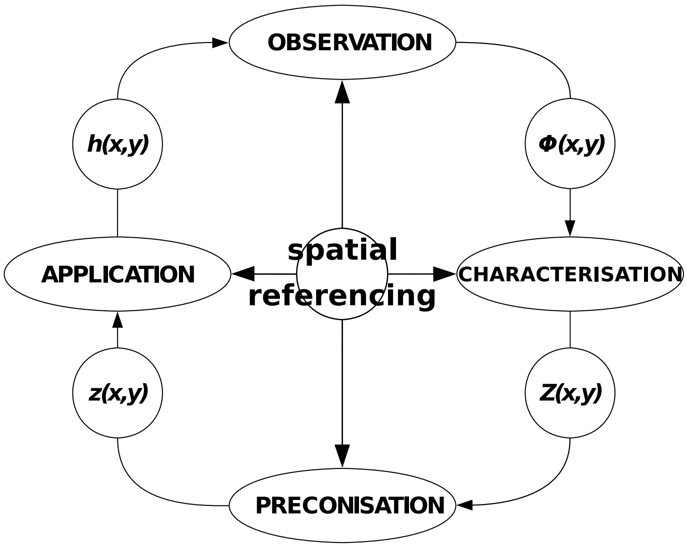

Fig. 1. The 'PA wheel' representation of decision support systems for precision agriculture (after McBratney and Taylor, 2000), where Φ is the physical quantity recorded by the sensor (*observation*), Z is a variable describing the characteristics of the observed crop and or soil (*characterization*), z is the recommendation proposed by the decision support system given Z (*recommendation*) and h is the way recommendation z is applied on the field (*application*).

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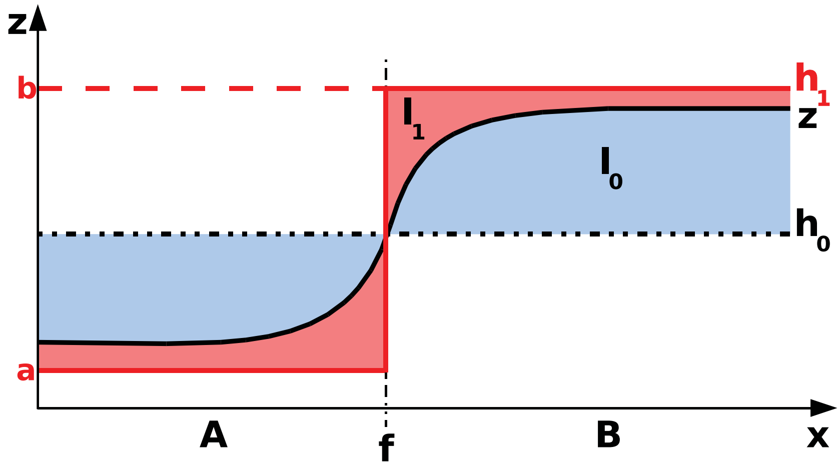

Fig. 2. One-dimensional illustration of the situation around a boundary, *f*, between two zones *A* and *B*. Two treatments h_0 and h_1 can be considered to apply a recommendation *z*. In this example h_0 is a uniform treatment, whereas h_1 is a zone-based treatment with prescribed rates *a* and *b* for zone *A* and *B*, respectively. The relative performance of those treatments for modelling recommendation *z* is estimated by comparing areas I_0 and I_1.

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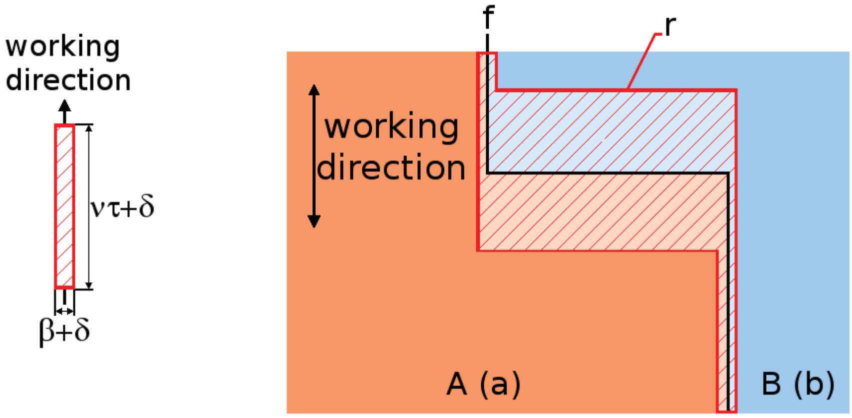

(a) (b)

Fig. 3. Spatial footprint of the machinery and area of risk on a field plot *P*: (a) spatial footprint of the machinery and (b) risk area *r* corresponding to the convolution of the spatial footprint (a) on the boundary *f* between zones *A* and *B*, according to a working direction given by the black arrow.

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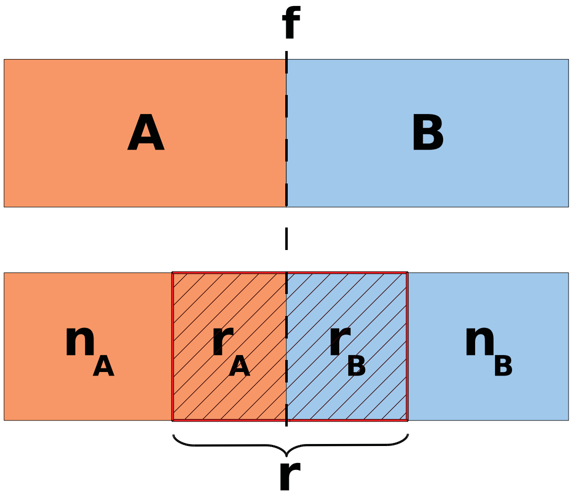
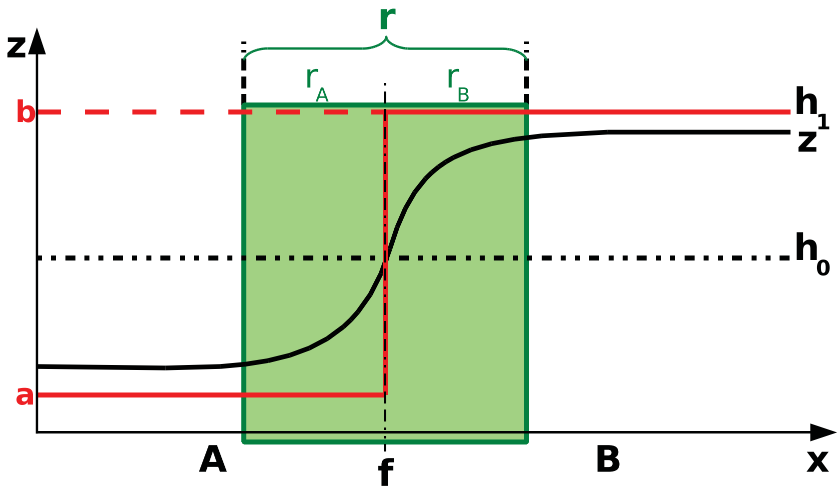
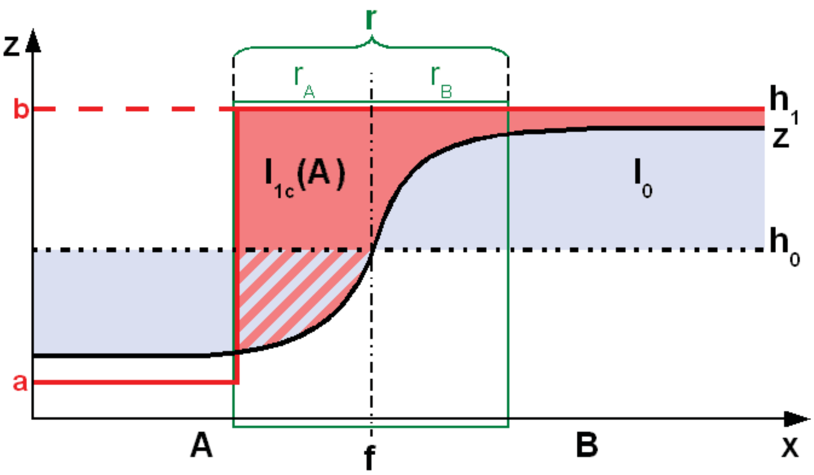


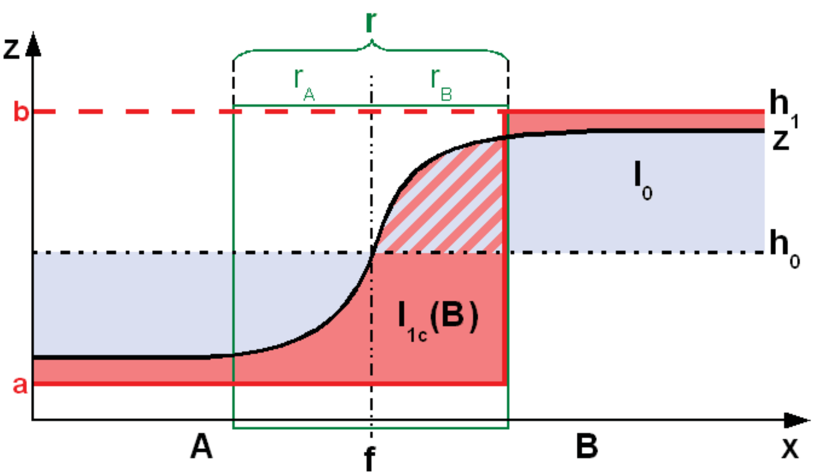
Fig. 4. Decomposition of a field according to the existence of a risk of application error (r_A and r_B) or not (n_A and n_B).



(a)



(b)



(c)

Fig. 5. Consideration of the errors related to the footprint of the machinery when computing the technical risk of application by zones in the neighbourhood of a boundary *f*: (a) risk area *r* is a transition zone between two different management zones (two errors are possible within *r*), (b) the control applies the rate *b* in r_A or (c) the control applies the rate *a* in r_B. The SSE of the zone-based model (I_1) must be corrected by $I_{1c}(A)$ or $I_{1c}(B)$ that take those risks into

account.

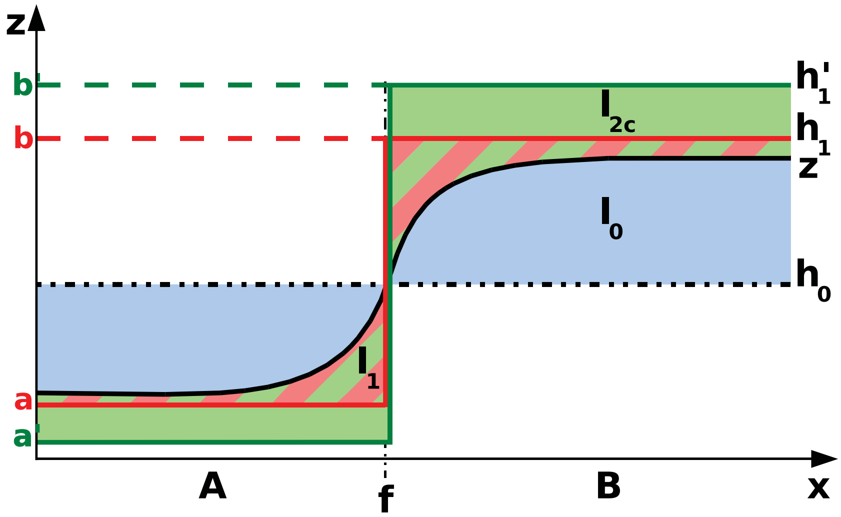
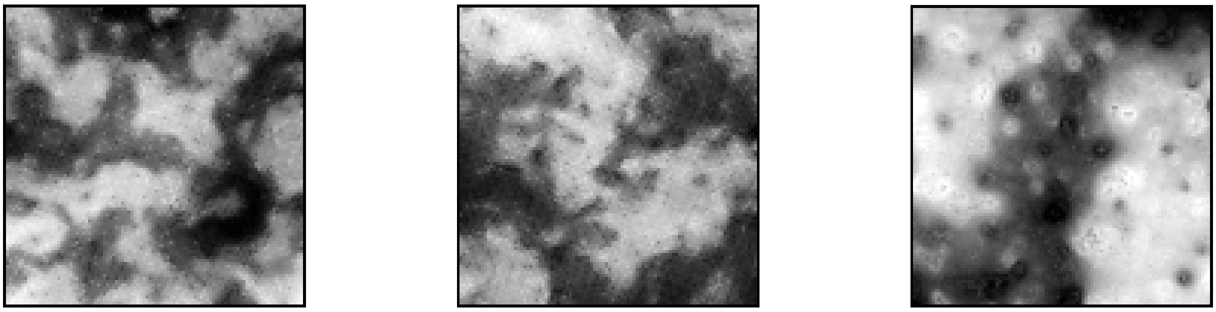
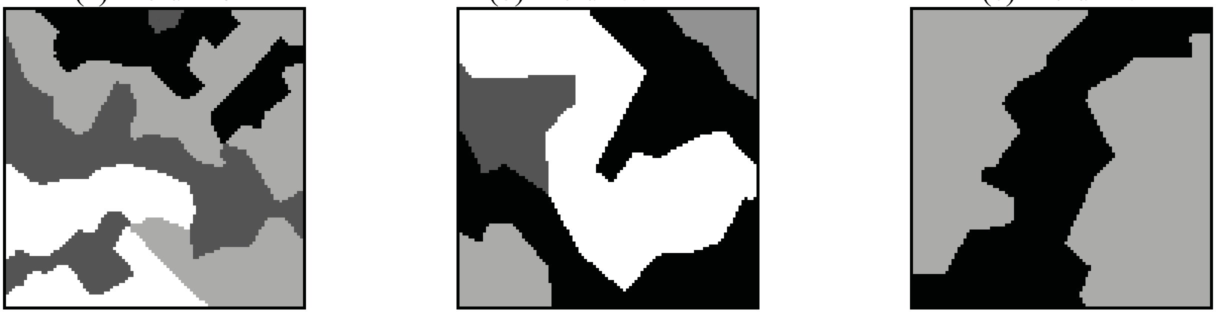


Fig. 6. Implementation of the errors related to discretization of the prescribed rates by the applicator in computing the technical risk of application of zone-based treatment around a boundary *f*. In this example, h_1 is the prescribed rate, whereas h'_1 is the rate actually applied. The controller applies the rate $a' \neq a$ in zone *A* and the rate $b' \neq b$ in zone *B*. The SSE of the zone-based treatment (I_1) must be corrected by the SSE I_{2c}, which takes into account the discretization effect.



(a) Field *r*27 (b) Field *r*36 (c) Field *r*45



(d) Expert zoning of field *r*27 (e) Expert zoning of field *r*36 (f) Expert zoning of field *r*45

Fig. 7. Study of the relations between zoning opportunity and spatial organization of the within-field variation. (a-c) Theoretical fields showing increasing spatial organisation and (d-f) corresponding zoning models.

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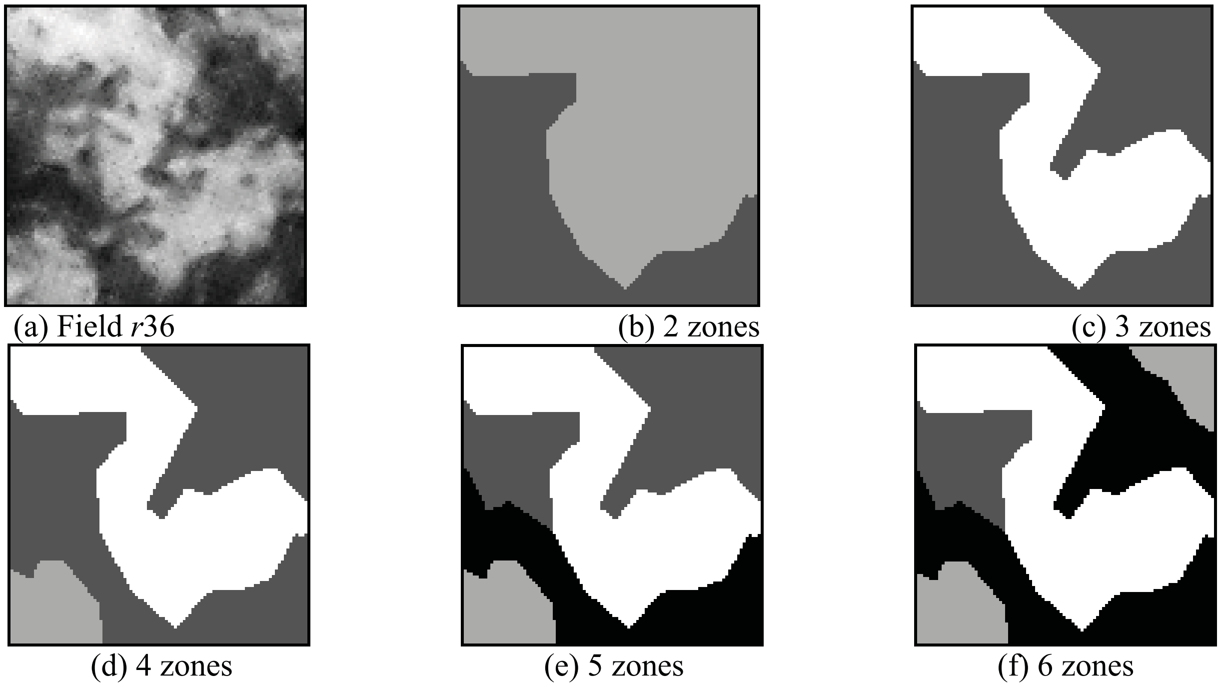
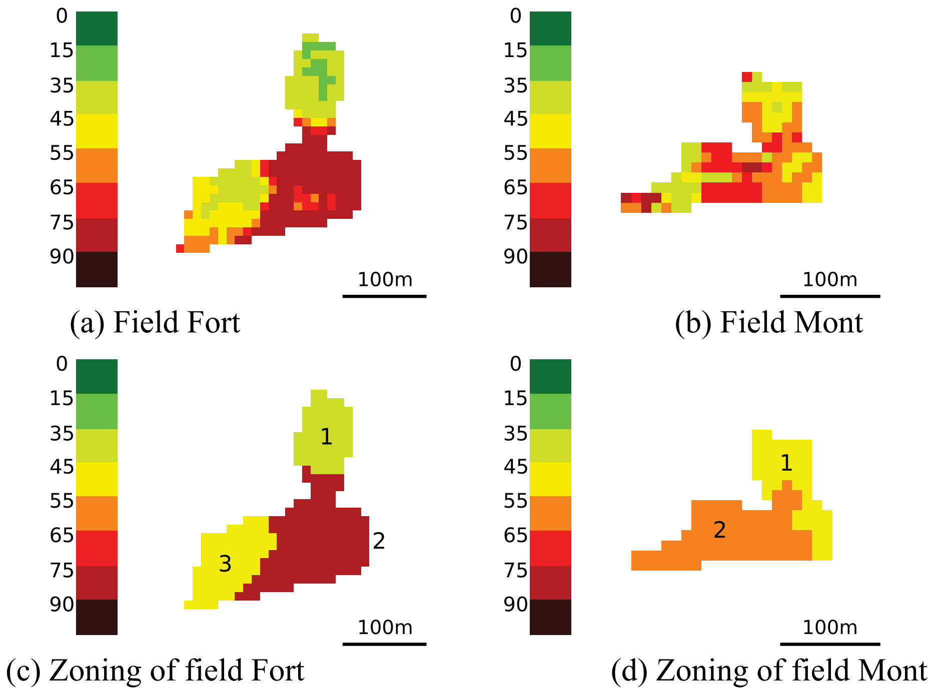


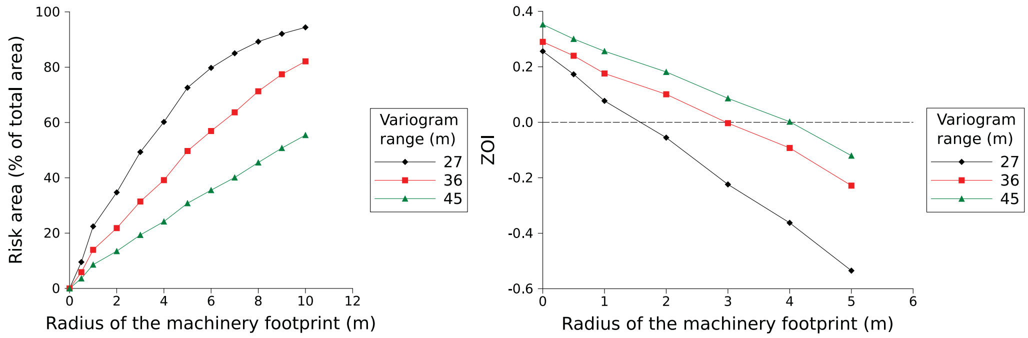
Fig. 8. Zoning of field *r*36 with an increasing number of zones.



(a) Field Fort (b) Field Mont

(c) Zoning of field Fort (d) Zoning of field Mont

Fig. 9 Use of the zoning opportunity index to estimate the relevance of zone-specific applications: (a, b) nitrogen recommendation for wheat in fields Fort and Mont and (c, d) corresponding zonings.



(a) (b)

Fig. 10. Effect of spatial structure of within-field variation on zoning opportunity: (a) Area of risk related to the spatial structure of within-field variation and the machine's spatial footprint and (b) zoning opportunity index (*ZOI*) in relation to the spatial structure of within-field variation and the machine's spatial footprint.

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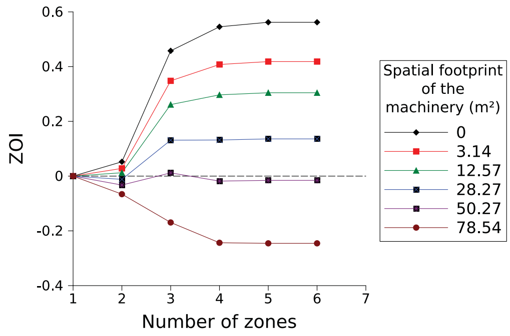

Fig. 11. Relationship between the zoning opportunity index (*ZOI*), the number of zones and spatial footprint of the machinery (ε) on field *r*36.

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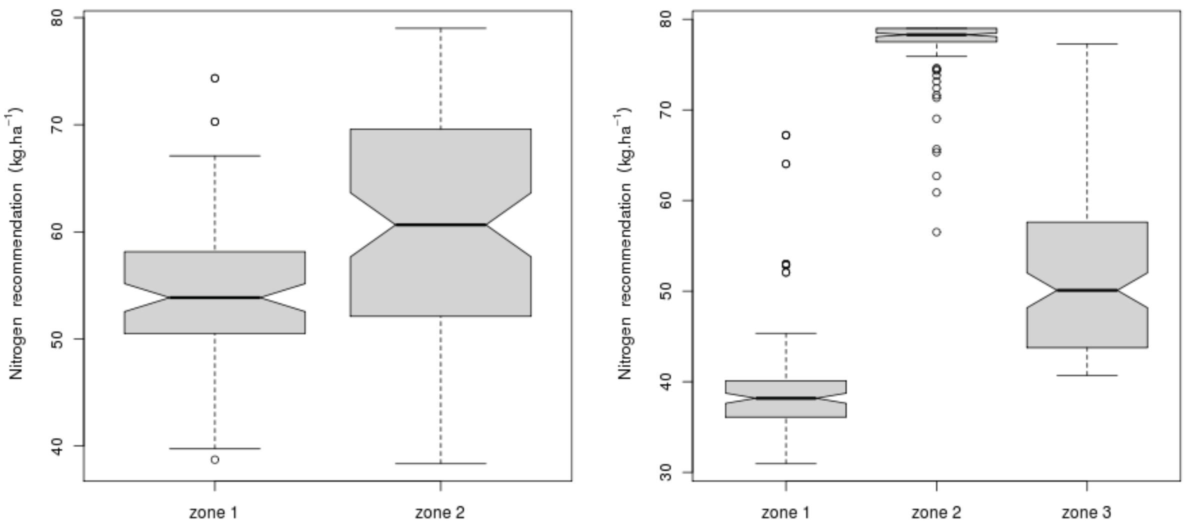

(a) (b)

Fig. 12. Nitrogen recommendation in each zone for fields (a) Mont and (b) Fort.

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Table 1: Details of the fields studied. The area of the zone, and the means and variances of the nitrogen recommendations are shown for each delineated zone. The mean recommendation can be compared to the rate that is entered to the spreader controller.

Field			**Nitrogen rate (kg.ha^{-1})**				**Zones**				
Name	Area (ha)	Variety	Min.	Max.	Mean	SD.	Id	Area (ha)	Nitrogen rate (kg.ha^{-1})		
									Mean	Rate	SD.
Fort	10.19	Hysun	26.18	79	60.60	17.44	1	2.20	39.55	40	6.89
							2	5.16	56.51	60	3.53
							3	2.84	52.17	50	9.82
Mont	5.29	Sankara	38.35	79	56.48	12.70	1	3.40	60.34	60	11.82
							2	1.92	53.44	50	7.46