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# THE FRACTAL DIMENSION OF AGRICULTURAL PARCELS CONSIDERING MAIZE YIELD

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***Abstract:*** Before making any decisions, all farm managers would like to have some indication about the effectiveness of a particular investment, especially when investing in precision agriculture technologies. Usually, the best indicator should be associated with the yield geometric complexity and its spatial and temporal dynamics. The fractal dimension of corn yield in a given year was calculated for six studied parcels, considering the fractal dimension of yield buffer zones above and below average yield. The less complex geometries usually have a fractal dimension close to the unit which can reach a value close to 2 in more complex geometries. This study shows that the number of yield buffer zones, above or below average yield, changes over time, with a different pattern, from parcel to parcel, and that there is a greater change in the smaller yield buffer zones compared to the larger ones. Fractal dimension can be a very strong indicator when the spatial complexity of a particular parcel is considered, and it is therefore a strong indicator of the greater or lesser need for precision agriculture technologies. The higher the fractal dimension of a given parcel, the higher will be the economic and environmental return of that parcel, when using precision agriculture technologies.

***Key words:*** *fractal geometry, yield spatial and temporal variability, maize.*

## INTRODUCTION

Before making any decision, all farm managers would like to have some indication about the effectiveness of a particular investment. In most cases, the risk associated with a given farming investment is not fully known and most managers make decisions on the basis of intuitive guesses. When commercial yield mapping began, in the early 1990s,

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the conventional wisdom was that certain parts of a given plot of land would always have a low yield, while other parts of the same plot would always have a high yield. This principle was linked to the idea that permanent soil characteristics would always behave in the same way, year in year out. Several authors have developed different types of methods for analyzing this spatial and temporal variability [18], [34], [16,17], [25,26]. Blackmore *et al.* [1] and Marques da Silva and Silva [21] used a similar technique for identifying the sites where production is stable over time and the sites where it is unstable. They encountered great difficulty in establishing a temporal threshold between stability and instability for the studied crop. They found that spatial trends were not stable over time. Instead, the spatial trends, in all the studied fields, became less pronounced than the variability found in the individual years.

Thus, there are two questions that can be asked:

1. Which spatial and temporal variability make the acquisition of precision agriculture technology profitable?
2. Is there an index that could help assess if a particular agricultural parcel should or should not be managed with precision agriculture techniques?

Fractal theory [19] is one of the tools that can be used to investigate and quantitatively characterize spatial variability, across a large range of measurement scales [6]. Fractal theory has been used to study topographic land features [20], [5], [14], [38], [4], [35], [37], precipitation distributions [19], vegetation patterns [12], [6], [15], soil roughness [13], [11], soil aggregates [27] [31], soil tillage practices [9], [28], soil water properties [33], [30], [32], [29] and crop variability [10], as well as crop yield [7], [8].

Therefore, the aim of this paper is to determine if fractal dimension could be useful in identifying parcels with greater or lesser need for precision agriculture technologies, considering that higher fractal dimension values indicate greater geometric complexity of the parcel and consequently the need for technologies that better manage such complexity. We also intent to see if fractal dimension of corn yield in a given parcel is temporally stable or whether it varies in time.

## MATERIALS AND METHODS

### Yield data collection and analysis

This study was conducted using data collected from agricultural fields in Fronteira (Lat.: 39.09307; Long.: -7.611332), located in the Alentejo region (Southern Portugal). The studied fields were Arribana (29 ha), Azarento (62 ha), Bemposta (30 ha) and Cristalino (38 ha), which were irrigated using centre-pivot irrigation systems.

The predominant soils of these fields are classified as Vertic Luvisols and Haplic Regosols (FAO, 1998) with, sandy clay loam and sandy surface texture, respectively. The topography of this region can be characterized as undulated, with soil depths varying from 0.3 m at the higher elevation positions of the fields to more than 1 m at the lower positions of the fields.

Maize yield data were collected over six years, 2002, 2003, 2004, 2006, 2007 and 2008, using a Claas Lexion 450 combine harvester with a 4.5 m cutting head, equipped with a CEBIS information system, which makes it possible to obtain grain yield data with a 5% error. The data were analysed in accordance with [18], to eliminate identifiable errors, and the weight of collected grain was adjusted for grain moisture (140 g $kg^{-1}$).

Yield data for all the years were standardised on a 5 m × 5 m grid using a 15 m search radius. This was to ensure that each cell of the grid had data from at least three harvester tracks avoiding the existence of cells with no information or non-typical information, when adjacent values were considered.

In the six years of the study, and in all the fields, maize was sown in late April / early May and harvested in September. The producer used a reduced tillage system, composed of a small subsoiler (30 cm depth), prior to sowing. In areas with higher slopes the farmer used reservoir-tillage [36], with the objective of storing non-infiltrated water, avoiding excessive runoff from the higher field positions to the lower ones.

Irrigation management practices were essentially the same for the studied period. Yield data were normalized, before being analyzed, considering equation (1):

$$s_{ti} = \frac{x_{ti} - x_t}{\sigma_t} \tag{1}$$

where:

$s_{ti}$ [-] - normalized productivity of year $t$ and cell $i$
$x_{ti}$ [t ha$^{-1}$] - productivity of year $t$ and cell $i$
$x_t$ [t ha$^{-1}$] - average yield productivity of year $t$
$\sigma_t$ [t ha$^{-1}$] - yield standard deviation in year $t$.

### Fractal attributes

For each parcel and for each analyzed year, the normalized productivity was divided into two classes of polygon buffer zones:

a) polygons with productivities below average and
b) polygons with productivities above average.

For all polygon buffer zones, the area (A), the perimeter (P) and the P/A ratio average, minimum and maximum were calculated.

The fractal dimension of corn yield in a given year was then calculated for all parcels considering the fractal dimension of polygon buffer zones with:

1. below average yield (FUA),
2. above average yield (FAA) and
3. both together (FT).

For this calculation, only polygon buffer zones with a value above 100 m$^2$ were considered. The methodology, well described in [36], uses a linear regression between $\log_{10}$ (P/4) and $\log_{10}$ (A) for all polygon buffer zones considered. The slope of this linear relation is commonly regarded as a measure of fractal dimension. The less complex geometries usually have a fractal dimension close to the unit while a value close to 2 can be reached in more complex geometries.

## RESULTS AND DISCUSSION

The fractal dimension of a particular yield buffer zone within an agricultural parcel indicates the geometric complexity associated with that particular yield buffer zone in that particular parcel. A parcel which has a fractal dimension greater than another, in a particular yield buffer zone, is geometrically more complex and can consequently provide a better economic return when using precision agriculture technologies.

## Buffer zones

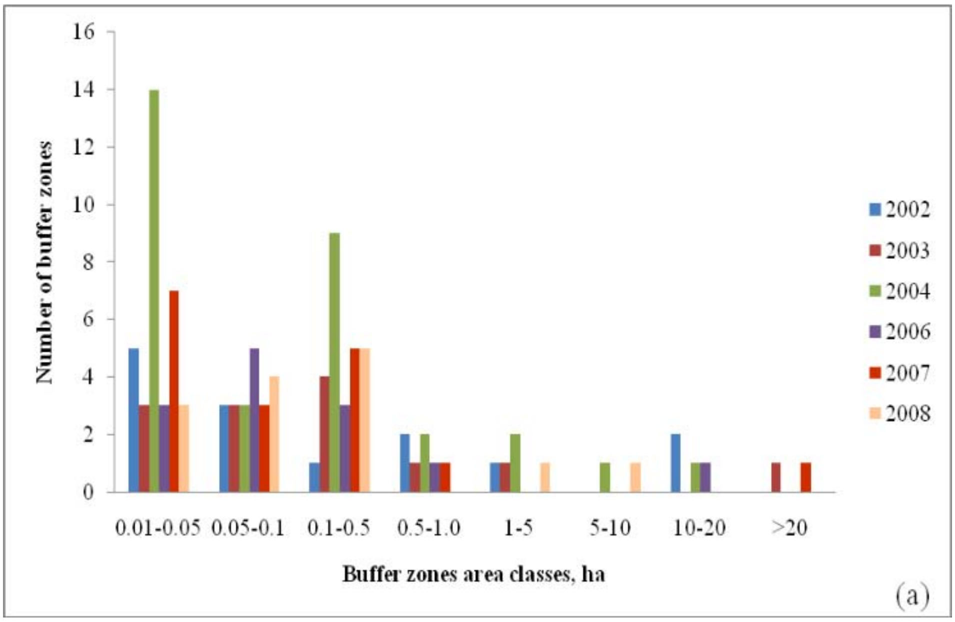
Considering the Azarento parcel (Table 1) in 2004, it is possible to see that the number of buffer zones with yields below average, 32, is greater than the number of buffer zones with yields above average, 17; however, in 2007 this pattern is reversed, with 17 and 33 buffer zones, respectively. Also, the geometric characteristics of these buffer areas change from year to year, a fact that can be observed in the mean, minimum and maximum P/A ratio (Tab. 1).

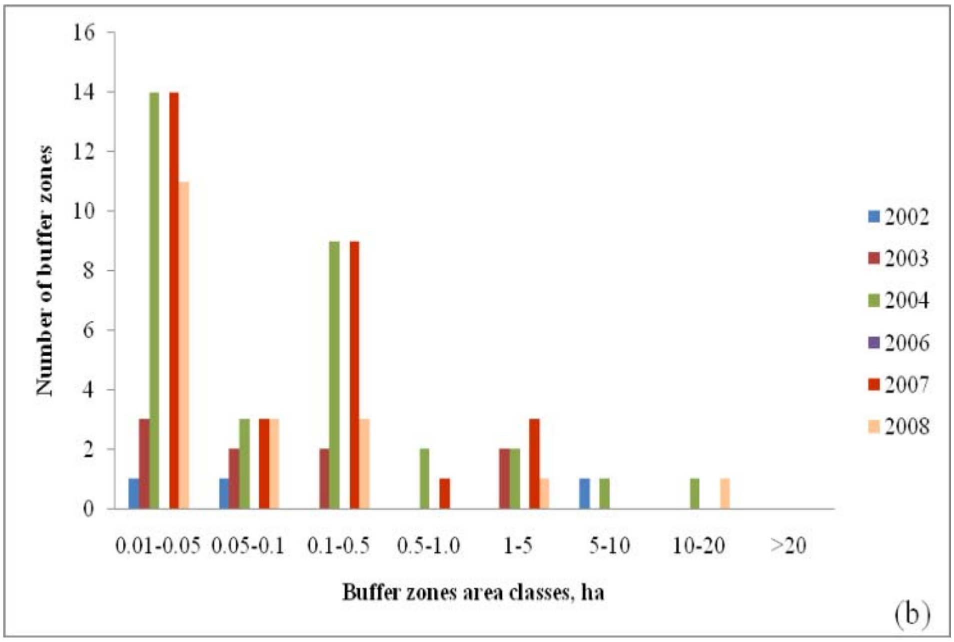
Looking at Figures 1 and 2, it can be noted that the number of buffer zones, above or below average, change over time, and this change has a different pattern from parcel to parcel, being greater in the smaller buffer zones, when compared with the larger ones. Smaller buffer zones change rapidly in number and size, from year to year, usually moving to the superior or inferior buffer zone class. This phenomenon is also observed in the larger buffer zone classes; however, the migration to adjacent classes is less evident.

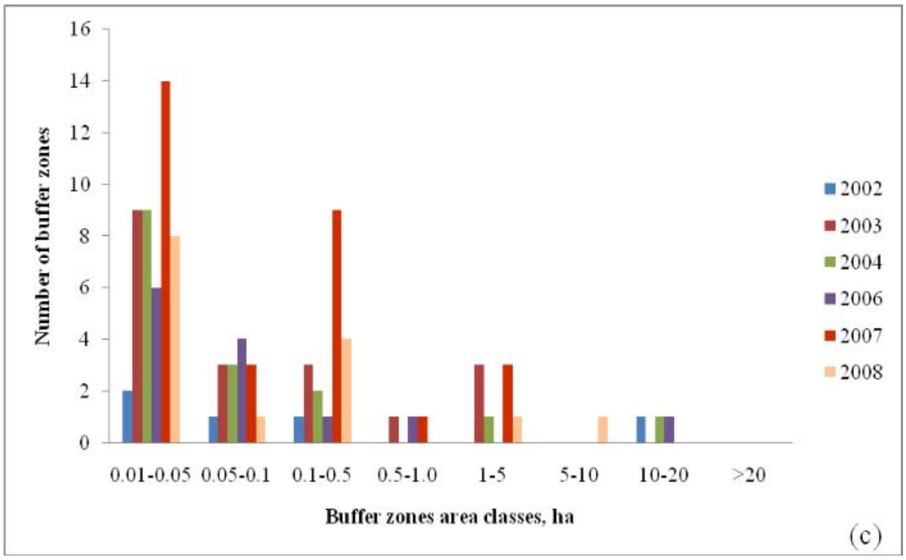
*Table 1. Geometric characteristics of the parcels, considering average, minimum and maximum Perimeter/Area (P/A) ratio and the number of polygon buffer zones, within the parcel, above and below average yield*

| | | *Below average yield* | | | | *Above average yield* | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *Year* | *(1)* | *(2)* | *(3)* | *(4)* | *(1)* | *(2)* | *(3)* | *(4)* |
| | *2002* | *14* | *0.158* | *0.032* | *0.374* | *11* | *0.245* | *0.030* | *0.400* |
| | *2003* | *13* | *0.122* | *0.035* | *0.222* | *8* | *0.158* | *0.030* | *0.397* |
| *Azarento* | *2004* | *32* | *0.179* | *0.036* | *0.480* | *17* | *0.253* | *0.036* | *0.500* |
| | *2006** | *13* | *0.186* | *0.056* | *0.374* | *8* | *0.409* | *0.043* | *1.171* |
| | *2007* | *17* | *0.205* | *0.045* | *0.446* | *33* | *0.233* | *0.030* | *0.500* |
| | *2008** | *14* | *0.154* | *0.061* | *0.374* | *12* | *0.219* | *0.025* | *0.461* |
| | *2002** | *3* | *0.185* | *0.061* | *0.318* | *15* | *0.232* | *0.040* | *0.500* |
| | *2003** | *9* | *0.158* | *0.057* | *0.333* | *6* | *0.196* | *0.026* | *0.425* |
| *Arribana* | *2004** | *12* | *0.190* | *0.069* | *0.405* | *5* | *0.230* | *0.032* | *0.331* |
| | *2006* | - | - | - | - | - | - | - | - |
| | *2007* | *30* | *0.208* | *0.048* | *0.405* | *3* | *0.144* | *0.032* | *0.231* |
| | *2008* | *19* | *0.219* | *0.057* | *0.333* | *7* | *0.216* | *0.035* | *0.437* |
| | *2002* | *5* | *0.181* | *0.050* | *0.320* | *12* | *0.237* | *0.039* | *0.416* |
| | *2003* | *19* | *0.212* | *0.052* | *0.461* | *7* | *0.179* | *0.037* | *0.374* |
| *Bemposta* | *2004* | *16* | *0.217* | *0.057* | *0.398* | *21* | *0.229* | *0.034* | *0.500* |
| | *2006* | *13* | *0.215* | *0.065* | *0.374* | *11* | *0.250* | *0.042* | *0.500* |
| | *2007* | *9* | *0.167* | *0.046* | *0.349* | *9* | *0.212* | *0.034* | *0.374* |
| | *2008* | *15* | *0.222* | *0.069* | *0.450* | *7* | *0.255* | *0.034* | *0.396* |
| | *2002* | *19* | *0.262* | *0.055* | *0.405* | *4* | *0.233* | *0.036* | *0.398* |
| | *2003* | *23* | *0.199* | *0.072* | *0.405* | *4* | *0.165* | *0.028* | *0.332* |
| *Cristalino* | *2004* | *33* | *0.288* | *0.058* | *0.388* | *4* | *0.158* | *0.022* | *0.500* |
| | *2006* | *26* | *0.242* | *0.057* | *0.403* | *15* | *0.235* | *0.035* | *0.399* |
| | *2007* | *18* | *0.143* | *0.069* | *0.388* | *2* | *0.152* | *0.024* | *0.280* |
| | *2008** | *9* | *0.248* | *0.067* | *0.500* | *4* | *0.119* | *0.023* | *0.210* |

(1) Polygon buffer zone number; (2) Average P/A ratio; (3) Minimum P/A ratio; (4) Maximum P/A ratio.
* Particular year when only half of the parcel area was cultivated.


16
14
12
10
8
6
4
2
0
Number of buffer zones
2002
2003
2004
2006
2007
2008
0.01-0.05
0.05-0.1
0.1-0.5
0.5-1.0
1-5
5-10
10-20
>20
Buffer zones area classes, ha
(a)


16
14
12
10
8
6
4
2
0
Number of buffer zones
2002
2003
2004
2006
2007
2008
0.01-0.05
0.05-0.1
0.1-0.5
0.5-1.0
1-5
5-10
10-20
>20
Buffer zones area classes, ha
(b)



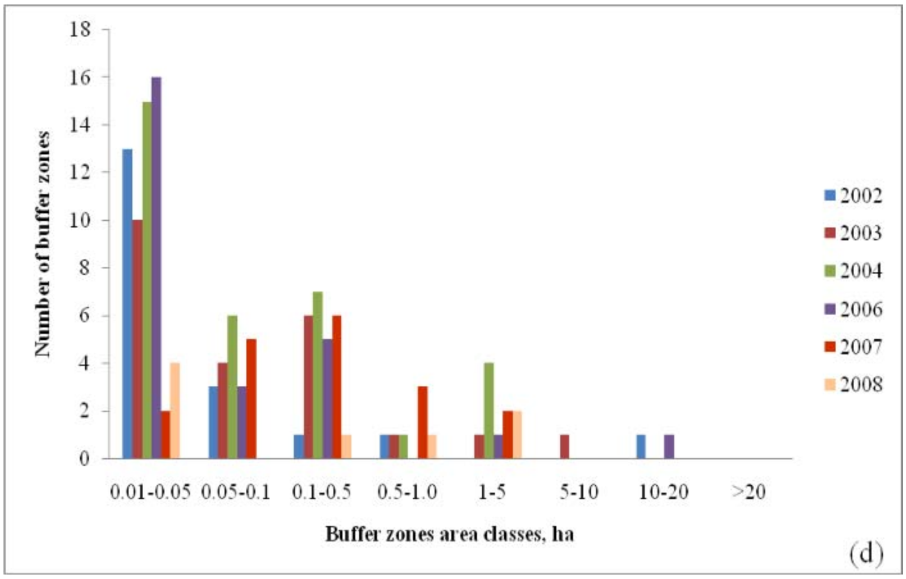
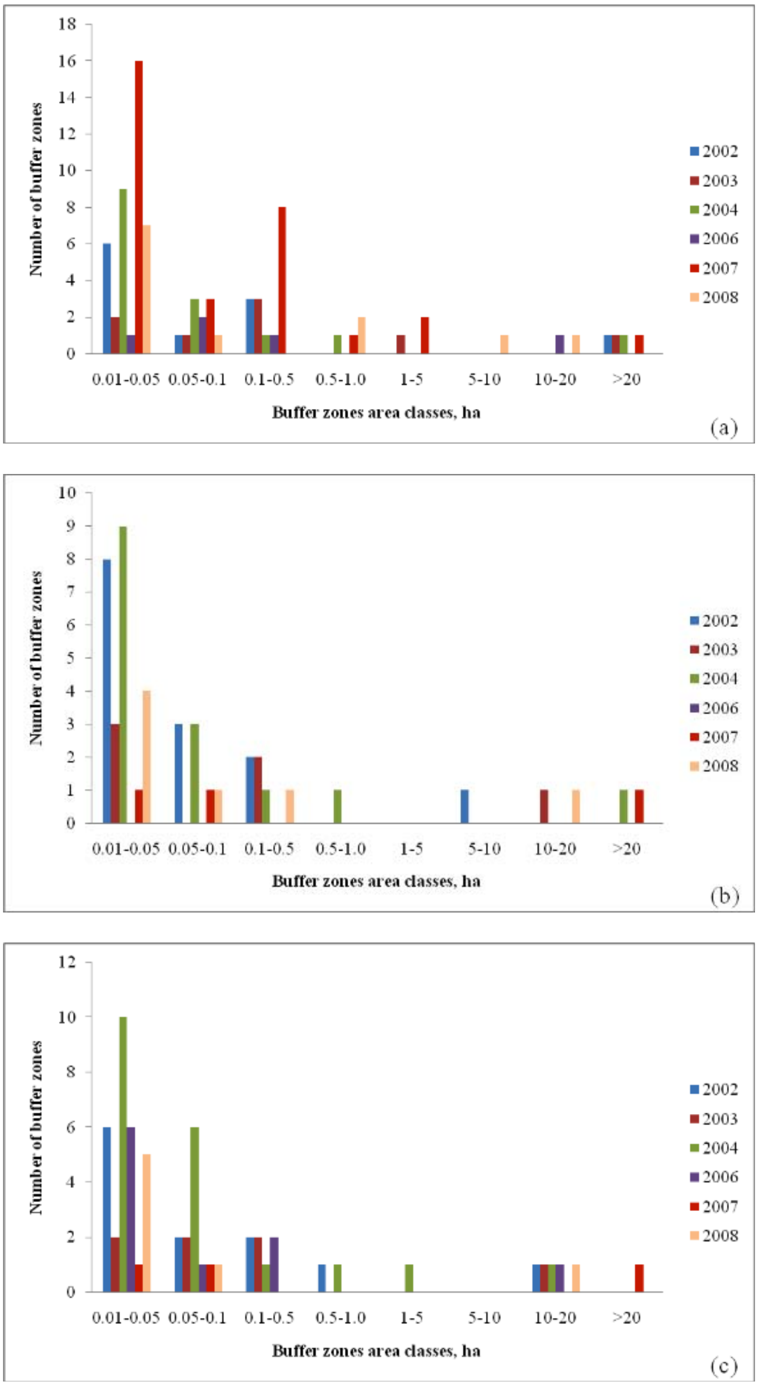




*Figure 1. Polygon buffer zones below average yield: (a) Azarento; (b) Arribana; (c) Bemposta; (d) Cristalino*

We can conclude that the buffer zones' geometric characteristics, in each parcel, change over time, and this change is faster in the smaller buffer zones, when compared with the larger ones. The point that needs to be considered is if these changes in the buffer zones' geometry affect the fractal dimension of corn yield in each parcel, each year.


Number of buffer zones
Buffer zones area classes, ha
0.01-0.05
0.05-0.1
0.1-0.5
0.5-1.0
1-5
5-10
10-20
>20
2002
2003
2004
2006
2007
2008
(a)
(b)
(c)

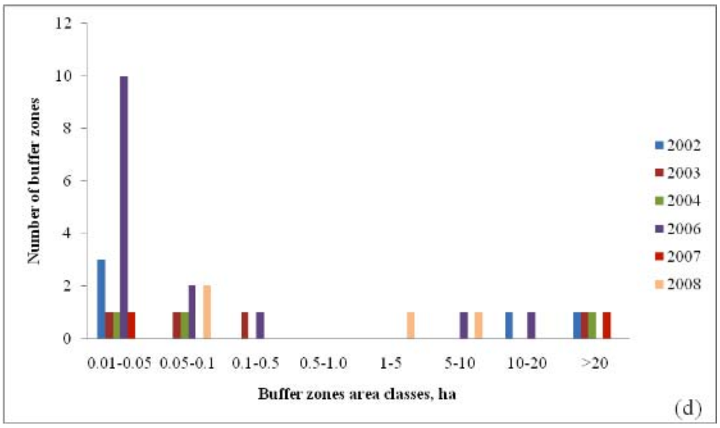



*Figure 2. Polygon buffer zones above average yield: (a) Azarento; (b) Arribana; (c) Bemposta; (d) Cristalino*

**Fractal dimension**

Table 2 shows that fractal dimension of corn yield varies from parcel to parcel, and within the same parcel, from year to year. This variation is more noticeable when the fractal dimension of corn yield above and below yield average is considered independently. If the fractal dimension of buffer zones with yields above and below the average yield are considered as a whole (Tab. 2, above and below average yield), the differences in fractal dimension are found to be in hundredths, with the Azarento parcel having the largest fractal dimension and the Bemposta parcel the lowest one. If the fractal dimension of buffer zones with yields below average yield (Tab. 2, Below average yield), are considered, it can be noted that Cristalino parcel has the highest fractal dimension and the Bemposta parcel continues to be the one with the lowest fractal dimension. If the fractal dimension of buffer zones with yields above average yield (Table 2, Above average yield) are considered, it is noted that Cristalino parcel and the Bemposta parcel continue to be the parcels with the highest and lowest fractal dimension, respectively.

The yields from buffer zones with yields below average fractal dimension are typically 0.1 fractal dimension units lower when compared with the yields from buffer zones with yields above average fractal dimension (Fig. 3). This evidence shows that the former have a less complex geometry than the latter, and the pattern holds, in general, for all the analyzed parcels. Why is this? And what are the reasons that can explain higher complex geometries in the yield buffer zones with yields below average? Marques da Silva and Silva [21-24] have shown that in undulated areas the higher yield zones are generally associated with the concave topographies and/or with the flow lines' border areas and the low productivity zones are generally associated with the convex topographies, usually the hill tops. Topographically it is easier to find a complex geometry associated with the hill tops when compared to the concave and flow lines' border areas. This can be confirmed by the fractal dimension presented in this study. The differential geometry associated with yield level, is detected by fractal dimension, however, will this remain true when a different topographic pattern, with different soils and a different crop are considered? The answer to this question falls outside the scope of this article, however, it is important to understand two aspects:

1. Is the fractal dimension of corn yield of a given parcel dependent on soil type, crop or the type of technology used?
2. Does the fractal dimension of corn yield in a given parcel represent the fingerprint of that parcel independent of the above mentioned factors?

*Table 2. Fractal dimension of the parcel for: Above and below average yield polygon buffer classes; below average yield polygon buffer classes and above average yield polygon buffer classes*

| | *Above and below average yield* | | | |
|---|---|---|---|---|
| *Year* | *Azarento* | *Arribana* | *Bemposta* | *Cristalino* |
| *2002* | *1.52* | *1.43** | *1.44* | *1.43* |
| *2003* | *1.48* | *1.51** | *1.46* | *1.43* |
| *2004* | *1.50* | *1.49** | *1.49* | *1.52* |
| *2006* | *1.48** | - | *1.38* | *1.42* |
| *2007* | *1.51* | *1.48* | *1.44* | *1.43* |
| *2008* | *1.48** | *1.44* | *1.43* | *1.57** |
| *Average* | *1.49* | *1.47* | *1.44* | *1.47* |
| *Sd*** | *0.02* | *0.04* | *0.04* | *0.06* |
| *Cv**** | *1.21* | *2.41* | *2.69* | *4.12* |
| | *Below average yield* | | | |
| *Year* | *Azarento* | *Arribana* | *Bemposta* | *Cristalino* |
| *2002* | *1.51* | *1.32** | *1.33* | *1.43* |
| *2003* | *1.37* | *1.40** | *1.48* | *1.41* |
| *2004* | *1.50* | *1.45** | *1.40* | *1.48* |
| *2006* | *1.36** | - | *1.32* | *1.39* |
| *2007* | *1.42* | *1.51* | *1.40* | *1.37* |
| *2008* | *1.30** | *1.44* | *1.39* | *1.47** |
| *Average* | *1.41* | *1.42* | *1.39* | *1.43* |
| *Sd*** | *0.08* | *0.07* | *0.06* | *0.04* |
| *Cv**** | *5.79* | *4.74* | *4.09* | *3.10* |
| | *Above average yield* | | | |
| *Year* | *Azarento* | *Arribana* | *Bemposta* | *Cristalino* |
| *2002* | *1.50* | *1.54** | *1.52* | *1.45* |
| *2003* | *1.47* | *1.65** | *1.43* | *1.49* |
| *2004* | *1.48* | *1.55** | *1.59* | *1.60* |
| *2006* | *1.55** | - | *1.44* | *1.45* |
| *2007* | *1.56* | *1.42* | *1.49* | *1.54* |
| *2008* | *1.63** | *1.46* | *1.49* | *1.70** |
| *Average* | *1.53* | *1.52* | *1.49* | *1.54* |
| *Sd*** | *0.06* | *0.09* | *0.06* | *0.10* |
| *Cv**** | *3.97* | *5.82* | *3.92* | *6.40* |

*Particular year when only half of the parcel was cultivated.
**Standard deviation
***Coefficient of Variation (%)

Through observing Fig. 4 it can be seen that there is no dependence between the fractal dimension and corn yield so, it can be assumed, that the fractal dimension can be a very strong indicator of the spatial complexity of a particular parcel and therefore a strong indicator of the greater or lesser need for precision agriculture technologies. The higher a fractal dimension of a given parcel, the higher the economic and environmental return when using precision agriculture technologies.

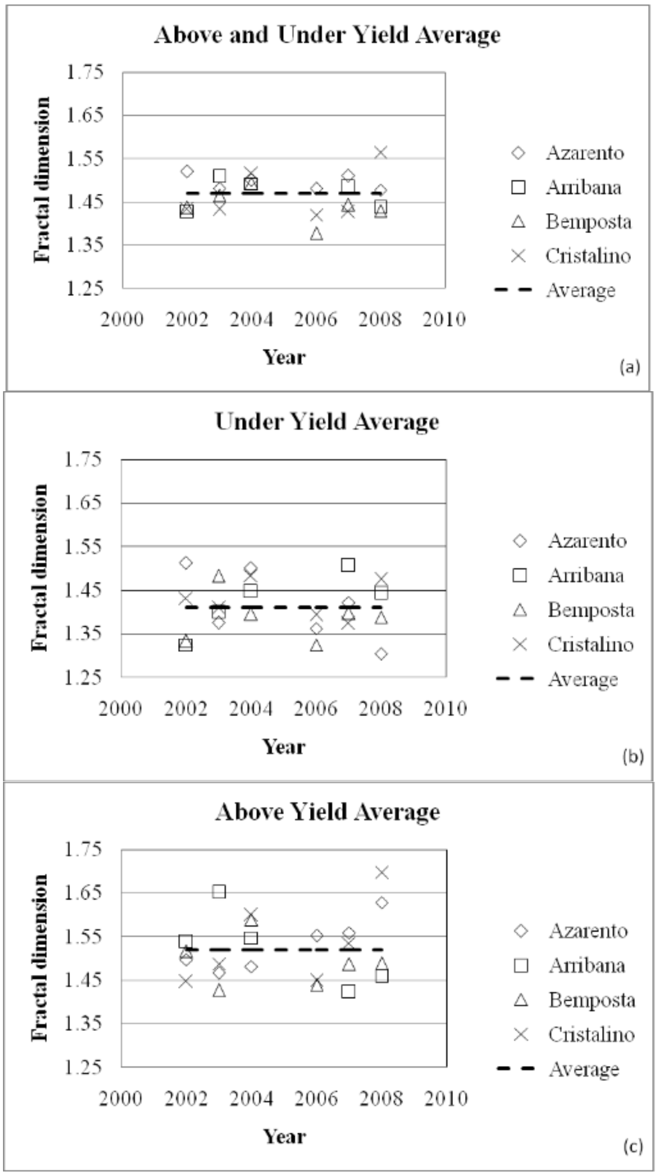
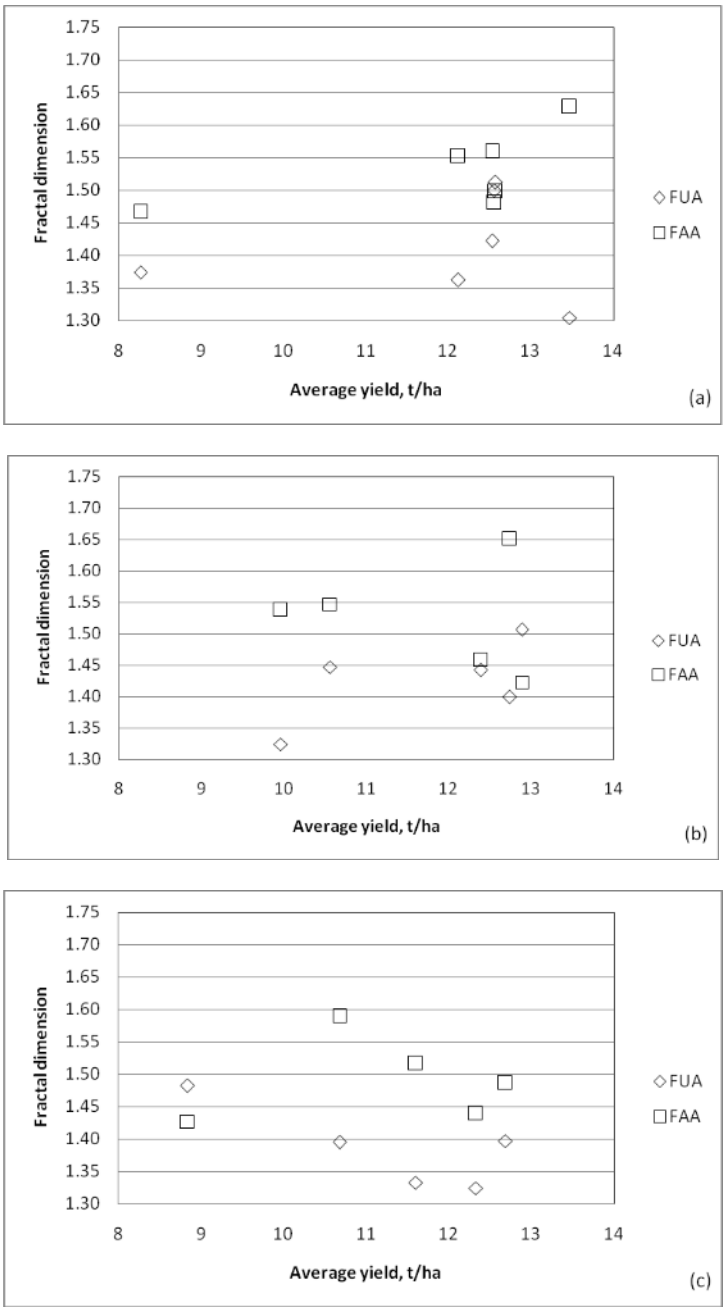



*Figure 3. Fractal dimension: (a) Above and below average yield; (b) Below average yield; (c) Above average yield*



Fractal dimension
Average yield, t/ha
FUA
FAA
(a)
(b)
(c)

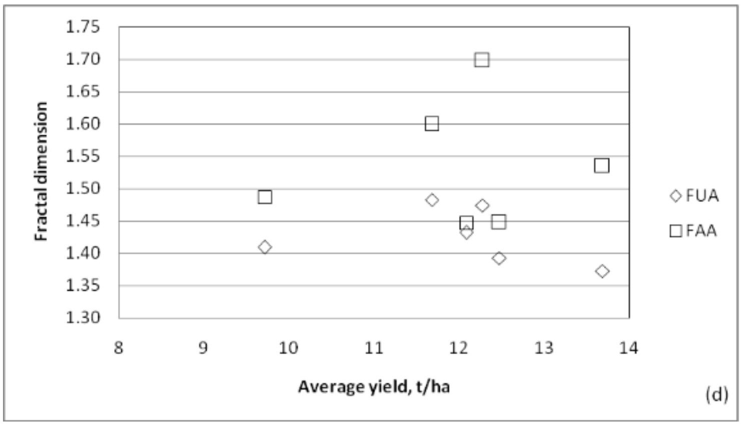



*Figure 4. Relation of fractal dimension with average yield: (a) Azarento; (b) Arribana; (c) Bemposta; (d) Cristalino; (◇FUA) Fractal dimension below average yield classes; (□FAA) Fractal dimension above average yield classes*

## CONCLUSIONS

This study shows that the number of yield buffer zones, above or below average, changes over time, and this change has a different pattern from parcel to parcel, being greater in the smaller yield buffer zones when compared with the larger ones.

Fractal dimension can be a very strong indicator when spatial complexity of a particular parcel is considered, and is therefore a strong indicator of the greater or lesser need for precision agriculture technologies. The higher the fractal dimension of a given parcel, the higher the economic and environmental return of that parcel, when using precision agriculture technologies.

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## FRAKTALNA DIMENZIJA POLJOPRIVREDNIH PARCELA PREMA PRINOSU KUKURUZA

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***Sažetak:*** Pre donošenja bilo kakvih odluka, menadžeri farmi bi hteli da imaju neka predviđanja efikasnosti pojedinih investicija, posebno kada ulažu u tehnologije precizne poljoprivrede. Obično, najbolji indikator se može povezati sa geometrijskom složenošću prinosa i njegovom prostornom i vremenskom dinamikom. Fraktalna dimenzija prinosa kukuruza u datoj godini bila je izračunata za šest ispitivanih parcela, uzimajući u razmatranje fraktalne dimenzije dodatnih opsega prinosa iznad i ispod njegove prosečne vrednosti. Manje kompleksne geometrije obično imaju fraktalnu dimenziju blisku jedinici koja može da postigne vrednost blisku 2 u kompleksnijim geometrijama. Ovo istraživanje pokazuje da se broj dodatnih opsega prinosa, iznad ili ispod srednje vrednosti prinosa, menja tokom vremena, na različite načine na pojedinim parcelama, kao i da značajnije promene postoje kod manjih dodatnih opsega prinosa u poređenju sa većim. Fraktalna dimenzija može da bude veoma čvrst indikator kad se razmatra prostorna kompleksnost pojedine parcele, pa je time i značajan indikator veće ili manje potrebe za tehnologijama precizne poljoprivrede. Što je veća fraktalna dimenzija jedne parcele, veći će bit ekonomski i ekološki rezultat na toj parceli, pri primeni postupaka precizne poljoprivrede.

***Ključne reči:*** *fraktalna geometrija, prostorna i vremenska promenljivost prinosa, kukuruz.*

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