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Land fragmentation index for drip-irrigated field systems in the Mediterranean: A case study from Ricote (Murcia, SE Spain)

Katharina Heider[a,*], Juan Miguel Rodriguez Lopez[a], José María García Avilés[b], Andrea L. Balbo[c]

[a] Research Group Climate Change and Security (CLISEC), Institute of Geography and CliSAP/CEN, University of Hamburg, Grindelberg 5, 20144 Hamburg, Germany
[b] University Library, University of Alicante, Campus de San Vicente del Raspeig, Carretera de San Vicente del Raspeig s/n, 03690 San Vicente del Raspeig, Alicante, Spain
[c] Alexander von Humboldt Stiftung/Foundation Research Fellow assigned to Research Group Climate Change and Security (CLISEC), Institute of Geography and CliSAP/CEN, University of Hamburg, Grindelberg 5, 20144 Hamburg, Germany

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ABSTRACT

Land fragmentation is widespread in traditional field systems of the Mediterranean region. A typical case for high fragmented properties is the Valley of Ricote. It is dominated by smallholder agriculture. To promote smart sustainable development in rural areas it is important to address the specific needs of these small agricultural producers; especially considering that agriculture is the most important consumer of water worldwide and that the great majority of farms are small production units extending over < 2 ha. Indeed, high land fragmentation, resulting from traditional land inheritance and transmission systems, may cause loss of water and productive land, entropic governance and superfluous emissions. In particular, drip-irrigated systems suffer from higher costs for irrigation due to high land fragmentation.

In this study, we develop a Fragmentation Index for Drip Irrigation and Distance Assessment (FIDIDA) using Geographic Information Systems. FIDIDA quantifies farms considering their transaction costs. Based on these costs, FIDIDA brings together mean plot size, degree of separation and degree of dispersion of land parcels on farm level. The index can be used to compare the individual fragmentation of farms or the land fragmentation between different study areas. The definition of FIDIDA aims at supporting the management of reasonable land fragmentation thresholds in the context of communities made of traditional small farms, while suggesting possible pathways for a gradual inversion of high land fragmentation trends through agreed plot fusion where necessary.

1. Introduction

Irrigated agriculture is fundamental to address current and future alimentary needs (Cárdenas et al., 2017) because it provides 40% of the global food production using only 20% of the global agricultural land (Anderies, 2017). Irrigated agriculture obviously plays a key role for global food supply in times of increased population pressure. At the same time, within the global agro-alimentary industry, 90% of farms can be defined as small producers, with < 2 ha, and often < 1 ha (Anderies, 2017; Cárdenas et al., 2017). These small producers provide food to 40% of the poorest population globally (Anderies, 2017). In consequence, to promote smart sustainable agriculture on a global scale, it is important to address the needs of small producers.

One of the major issues affecting efficiency in communities of small farmers is the high fragmentation of agricultural land properties, which has been observed in many parts of the world (Tan et al., 2006). The valley of Ricote is a typical case for smallholder farming in highly fragmented traditional field systems in the Mediterranean region.

Considering the need to assess land fragmentation in the specific context of drip-irrigated agriculture, our main research question is: *How to assess agricultural land properties considering the influence of land fragmentation in traditional Mediterranean agro-ecosystems predominantly made of small farmers?* To answer this question, we developed a Fragmentation Index for Drip Irrigation and Distance Assessment (FIDIDA).

We use Geographic Information Systems (GIS) to calculate FIDIDA on farm-level. FIDIDA quantifies farms considering transaction costs, i.e. costs for drip irrigation systems, plot size as well as emissions and travel time due to transportation. The quantification would then inform policies oriented to reduce land fragmentation, as well as highlight priority interventions for a gradual inversion of land fragmentation trends through agreed plot exchange and fusion among farmers with a

* Corresponding author.
E-mail address: katharina.heider@uni-hamburg.de (K. Heider).

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high fragmentation index. The index can be used to compare the fragmentation of individual farms or, on a broader level, the land fragmentation between different study areas. FIDIDA aims at informing reasonable management of land fragmentation thresholds in traditional drip-irrigated field systems.

While several fragmentation indices can be found in the literature (Gonzalez et al., 2004; King and Burton, 1982; Tan et al., 2006; van Dijk, 2003; Vijulie et al., 2012), there is no land fragmentation index adapted to drip-irrigated agriculture of traditional field systems. Additionally, most of them fail to include the relative distance of plots in a combined index that also considers plot sizes and their *degree of separation*. When mentioned, distance is only considered as a separate and arbitrary (inconsistently used) parameter (Tan et al., 2008; Vijulie et al., 2012).

The fragmentation index we propose is adapted to drip-irrigated agriculture and uses a standardised measure for distance to include the costs of the irrigation system in terms of travel time and associated emissions. This measure for distance is integrated in the proposed fragmentation index, which has been conceived considering the need for mitigation strategies in agriculture within the context of climate change (IPCC, 2012).

1.1. Land fragmentation, property rights and transaction costs

Some of the disadvantages associated with high land fragmentation include inefficiencies such as the loss of productive land due to the presence of fences, ditches or hedgerows, hindering of mechanisation, higher production costs, incremental use of pipes and electrical wiring for automated drip irrigation, and the loss of time. Consequently, the net income per farm is affected. This can lead to the abandonment of farms and land use changes. Furthermore, land fragmentation fosters additional emissions due to the distance one has to travel between parcels (King and Burton, 1982; Tan et al., 2006; Tan et al., 2008; van Dijk, 2003).

Although the clear definition of property rights is one of the most prominent solutions to the tragedy of commons (Hardin, 1968, 1989), high property partition is problematic for overall efficiency. Yet, it has to be mentioned that more recent studies of common properties on a local level suggest that self-management is a promising solution to prevent the tragedy of commons (Dietz et al., 2003; Ostrom et al., 1999; Ostrom, 2009).

Higher fragmentation leads to increased transaction costs (Williamson, 1981), e.g. in the form of needed infrastructure or distances to be travelled. In other words, if unchecked, the property rights solution for the tragedy of commons could generate a *tragedy of property*, also known as the "tragedy of the anticommons" (Heller, 1998). Williamson (1981) argued that transaction costs are additional costs in mechanical production; for example, the transfer of a product between two machines produces the transaction cost of changing from one machine to another, and the longer and the more difficult the change is, the higher are the additional costs. For the decision process of small farmers, the cost of transactions between various fields is increased by high land fragmentation similarly to the additional costs in the industrial production. High transaction costs produce difficulties in decision-making. Assuming the existence of these difficulties, small farmers compare information to take rational decisions in a bounded form (Simon, 1991) while assessing the possibility of making profits (opportunism). Hence, farmers should try to avoid fragmentation because of the high transaction costs and the associated difficulties in decision-making. Otherwise the net income per farm decreases contributing to the abandonment of food production activities.

1.2. Definition of terms

The term *parcel* is used here for cadastral land subdivisions. The term *plot* indicates a single parcel with drip irrigation or a cluster of neighbouring parcels that belong to the same owner and are served by a single counter. A *counter* is a distribution point and measuring device for water used for one plot. i.e. the number of counters in Ricote equals the number of plots. Counters (and plots), rather than cadastral parcels, are therefore used as indicator for the *degree of separation* within *farms*. A *farm* describes all plots belonging to one *owner* or *farmer*. Distances between plots are used as indicator for the *degree of dispersion*.

1.3. Co-design in Ricote

This paper should be read as a result of co-design of researchers with local stakeholders in order to understand the needs of the community, exchange knowledge, integrate local expertise, cooperate, and create acceptance for place-based sustainable solutions (Levidow et al., 2014; Reynolds et al., 2014; Scheffran and Stoll-Kleemann, 2003). A science and stakeholders meeting took place in June 2017 in Ricote as a part of the stakeholder dialogue on which we have relied on since the beginning of our research in this area in 2010. After defining the priorities and possible pathways for sustainable development with local stakeholders, we introduced a GIS platform as an interactive map for the community of Ricote (Murcia, Southeast Spain). The GIS platform was then used at community level as the basis to explore possible pathways to reach an efficient configuration in terms of land fragmentation. One of the needs highlighted by the local community was that of reducing land fragmentation, to minimise the *degree of separation* (i.e. number of counters used for drip irrigation), thus promoting monetary savings (deployment and maintenance) and management simplification (irrigation schedule complexity), without weakening the stability of the system.

2. Study area

The study area is the orchard (Spanish *huerta*) of Ricote, located in the region of Murcia in Southeast Spain (Fig. 1). Climate is semi-arid with strong seasonality. Total annual rainfall lies between 200 and 350 mm with more than twice the amount of evapotranspiration creating arid conditions. Average summer temperature is between 31 and 34 °C and in winter between 1 and 5 °C (Lopéz Bermúdez, 1973; Puy and Balbo, 2013).

The huerta in Ricote was established by Amazigh-Berber populations > 1000 years ago (Puy and Balbo, 2013; Puy et al., 2016) and as one of the oldest known irrigation systems in Europe, Ricote has a long history of water shortages and water conflicts (García Avilés, 2000). Today, it counts about 1.330 inhabitants (Instituto Nacional de Estadística, 2017). Its urban area is located to the north of the huerta, and both are surrounded by mountains. The orchard contains > 2000 parcels distributed among approx. 620 farmers. Most plots are cultivated on terraces, shaped by stonewalls. The primary crop is lemon, followed by olives and other fruits. An overview of the huerta is given in Figs. 1 and 2.

Traditional irrigation techniques have mostly been substituted by drip irrigation in Ricote over the past 10 years, to make water management more efficient. Today, about 75% of all parcels in the orchard rely on drip irrigation (Puy et al., 2016). Thus, the community is in a transition between traditional and modern irrigation. While significantly reducing farmers' workload, the drip irrigation system in Ricote suffers from high management and infrastructural costs relative to the overall land surface of the huerta, mostly due to high land fragmentation. Specifically, due to the local traditional system of land heritage and transmission, by which land is split and inherited in equal parts among all siblings, land tenure is highly fragmented. Ricote's farmers own, on average, 3.63 parcels (standard deviation 3.92), and the mean size of a parcel is 1073 m^2 (standard deviation 1951 m^2), of which 884 m^2 (standard deviation 1317 m^2) is cultivated on average. The smallest parcel is as small as 20 m^2 and the largest is 30,344 m^2 (i.e. c. 3 ha). The mean land per farm is 3895 m^2, of which 3209 m^2 are

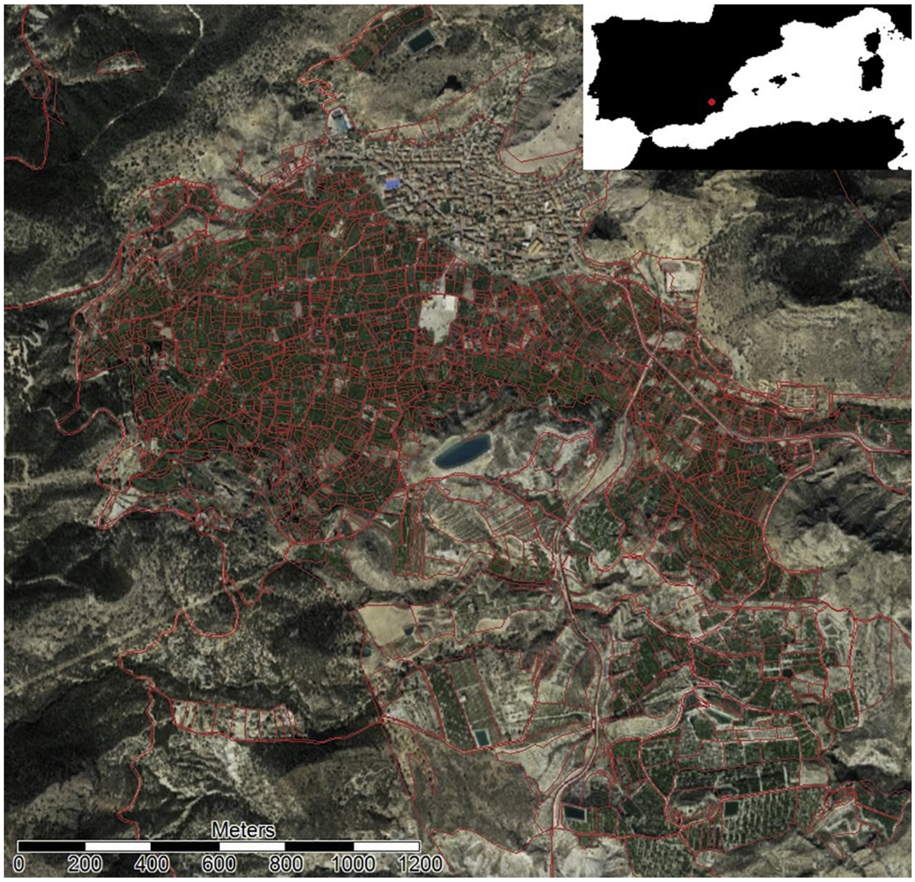

Fig. 1. Overview of the study region of Ricote based on satellite imagery (GoogleSatellite, 2015) overlaid with a cadastre map (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cultivated on average. Thus, Ricote is characterised by small farm sizes. Almost 70% of the farms in Ricote consist of more than one parcel. About one quarter of the farms comprise more than four parcels and a single farm can consist of > 30 parcels distributed around the huerta. A high number of electronic counters were deployed in Ricote for the drip irrigation system to adapt to the existing distribution of land; generally one counter per parcel or cluster of contiguous parcels belonging to the same farmer. While allowing for the maintenance of pre-existing property patterns, the drip irrigation system in Ricote is associated with high deployment and maintenance costs, i.e. high transaction costs. Additionally, the high number of counters increases the execution time of the irrigation as well as the likelihood of technical problems.

3. Data and methods

3.1. The GIS platform

The GIS platform has been conceived as a tool to: (a) enable the

Fig. 2. The huerta of Ricote.

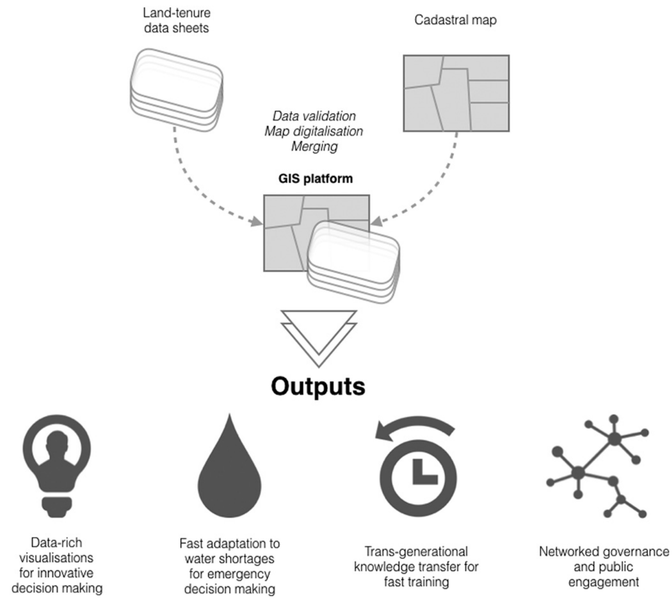

Fig. 3. The concept of the GIS platform (icon credits: the noun project).

visualisation of data, (b) promote participative decision-making processes, (c) support the design of climate adaptation strategies and (d) facilitate the training of new staff (Fig. 3). The GIS platform consists of an interactive map based on the integration of two datasets: the land tenure database of the irrigators' community in Ricote and the cadastral map from the Ministry of Agriculture in Spain (FEGA). For each parcel contained in the cadastral map, the database of the irrigators' community in Ricote contains information relative to the cadastral number, farmer's identification number, type of crop, irrigation system used, affiliation to cooperatives, counter number, counter reading, traditional name of the area in which the parcel is located, size of parcels according to cadastre and size of parcel which is actually used for cultivation (the cultivated area is based on the irrigated surface authorised by the Confederación Hidrográfica del Segura). Both datasets were processed, connected and synchronised in SAGA-GIS, which is a free and open source software (Conrad, 2006). The GIS platform was then installed on the computers of the irrigators' community in Ricote in June 2017. Employees charged with the management of the irrigation system were trained to use the GIS platform during two courses, introducing its concept, applications and relevant functions. The community also uses the GIS platform to correct errors in the administration database.

Overall, the database of the irrigators' community in Ricote includes 2105 parcels and 622 farmers. After an initial examination, parcels that have been urbanised as well as a number of parcels and farmers lacking updated information were identified, reducing the dataset to 1588 parcels and 437 farmers retained for analysis.

3.2. The assessment of land fragmentation

A fragmentation index is a widely used empirical tool to assess agricultural fragmentation (King and Burton, 1982; Latruffe and Piet, 2014; van Dijk, 2003). Here, we aim at proposing a compact fragmentation index adapted to drip-irrigated agriculture that includes the number of plots of each farm, their location and relative distance, as well as their mean size (Latruffe and Piet, 2014). A crucial factor while working on land fragmentation is the differentiation between owners and users (van Dijk, 2003). However, this differentiation is not necessary in Ricote (and generally in small farm contexts), where owners cultivate their own land and subletting is virtually non-existent. Several fragmentation indices and measurement units can be found in the literature (King and Burton, 1982; Latruffe and Piet, 2014; van Dijk, 2003; Vijulie et al., 2012). An extensively used measurement of fragmentation is based on area per landowner (van Dijk, 2003). While providing an assessment of the farm size, this index fails to provide information on the *degree of separation* of parcels within one farm, i.e. the number of counters per farm. Another simple measurement of fragmentation is parcels per farm, but the *degree of dispersion*, i.e. the location and relative distance of the parcels, is still not considered (King and Burton, 1982).

Other common fragmentation indices addressing farm size and *degree of separation* we referred to are Simmon's index, Januszewski's consolidation index, Simpson's index (King and Burton, 1982; Tan et al., 2008; Vijulie et al., 2012) and the combined size and shape index (Gonzalez et al., 2004). Regarding the *degree of dispersion* of plots we referred to specific indices, mainly Igbozurike's index, Schmook's index, the average distance of a hectare index, the grouping index, the structural index (Janus and Markuszewska, 2017; King and Burton, 1982; Latruffe and Piet, 2014). However, such indices were considered unsuitable for Ricote and other small traditional Mediterranean irrigated agro-ecosystems because either they did not take into account the *degree of dispersion* (Simmon's index, Januszewski's consolidation index, Simpson's index, combined size and shape index) or they did not consider the *degree of separation* (Igbozurike's index, Schmook's index, average distance of a hectare index, grouping index, structural index). To compensate for this, several studies applied in parallel more than one index to describe land fragmentation (Janus and Markuszewska, 2017; Latruffe and Piet, 2014).

The use of various units to represent distance, further reduces the possibility to use existing fragmentation indices systematically. For example, some authors represented distance as the walking time (in minutes) from homestead to plots (Tan et al., 2008), while others defined it as the linear "distance (in km) covered by farmers to visit their plots" (Vijulie et al., 2012, p. 413).

3.3. The Fragmentation Index for Drip Irrigation and Distance Assessment (FIDIDA)

Within the assessment of land fragmentation in Ricote, we create three rankings of the farms based on their *size*, *degree of separation* and *degree of dispersion*. The rankings are implemented by selecting the cases with the highest transaction costs concerning each indicator, i.e. the smallest farm *size*, the highest *degree of separation* (most counters) and the highest *degree of dispersion* (highest standard distance between plots of one farm). Subsequently, we present the results of our own index: the Fragmentation Index for Drip Irrigation and Distance Assessment (FIDIDA) for each one of the selected farms. FIDIDA combines the *degree of separation*, the *degree of dispersion* and a measure of *size*, i.e. mean plot size (see Fig. 4).

Finally, we conduct a rank correlation to assess the relationship between the results of FIDIDA and the *degree of separation*, *degree of dispersion*, mean plot size as well as farm size. We use the Spearman rank correlation because of its non-parametric character, which enables the usage of not normally distributed variables. The results of the correlation show the factors that are most decisive for the outcome of the index.

FIDIDA is calculated according to the following formula:

$$FIDIDA = \frac{C*SD}{A}$$

where *C* is the number of counters per farm, *SD* is the standard distance between the individual plots of a given farm and *A* is the mean cultivated area of plots belonging to one farm. While high values of C (*degree of separation*) and SD (*degree of dispersion*) result in a higher fragmentation and lead to a higher fragmentation index, high values of A (mean plot size) reduce the fragmentation index, implying a better mark for the estimation of the index value because of the higher productiveness of the farm.

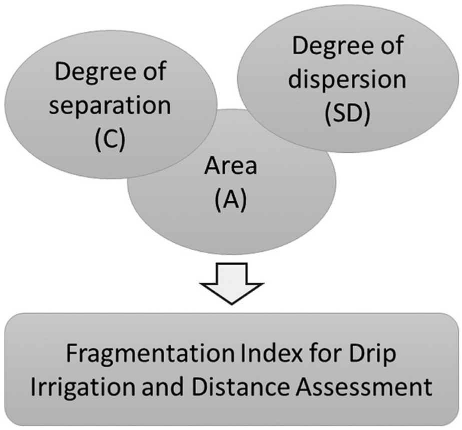

Fig. 4. For the calculation of FIDIDA, the parameters *degree of separation* (C - number of counters), *degree of dispersion* (SD – standard distance) and area (A – mean cultivated plot size) are used.

The number of counters per farm is used as a proxy of plot scattering, which best represents fragmentation in the context of drip irrigation in Spain (Gómez-Limón and Picazo-Tadeo, 2012), where farmers can have several parcels irrigated by the same counter. Using counters per farm instead of parcels per farm in the fragmentation index is an adaptation to the increasing installation of drip irrigation in Spain (Gómez-Limón and Picazo-Tadeo, 2012). Considering this recalculation and the exclusion of parcels without drip irrigation, the overall figures of 1588 parcels for 437 farmers are merged into 981 plots for 397 farmers, which constitute the basis for all further analyses. The observed reduction in the number of farmers is explained by the exclusion of parcels without drip irrigation.

In the next step, the *degree of dispersion* is included to count for distance, which plays a determinant role on transaction costs. We analyse each farm of the selected cases separately to assess the *degree of dispersion* between plots at the farm-level.

We propose a measure of distance, namely standard distance, representing the dispersion of a farm around the farm centre. The standard distance (SD) is calculated according to the following formula:

$$SD = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{X})2}{n} + \frac{\sum_{i=1}^{n} (y_i - \overline{Y})2}{n}}$$

where x_i and y_i are the coordinates for plots i, $\{\overline{X}, \overline{Y}\}$ represents the mean centre of the plots, and n is equal to the total number of plots. Fig. 5 illustrates the standard distance as the radius of a circle. In this case, the standard distance is 900 m (see Table 2, farmer number 70).

For the calculation of standard distance, the polygon data of every farm is converted to point features, which is necessary to conduct a *spatial point pattern analysis* in SAGA-GIS. One output of the spatial point pattern analysis is standard distance, which we choose as an indicator to assess the *degree of dispersion*. The *degree of dispersion* is a proxy for traveling time and emission potential due to transportation between the plots of one farm. It is measured from the centre of a plot.

Moreover, the mean cultivated plot size is included in FIDIDA as an indicator for productiveness. The analysis is based on the *cultivated* land area because it is the most precise information of agricultural land area and the most reliable information concerning the land area according to the local experts of the irrigators' community in Ricote.

4. Results

First, we assess land fragmentation in terms of *size*. The mean farm size in Ricote is 3178 m^2 (0.3178 ha); the largest being 54,927 m^2 and the smallest 70 m^2. The median farm size is 1698 m^2 (standard deviation 4883.96 m^2). The farm size alone is a poor indicator for value of land in a context of land fragmentation (van Dijk, 2003; Vijulie et al., 2012).

Second, we investigate the *degree of separation*. The range varies between one, which is the minimum number of counters for a farm included in the analysis, and 16 counters, which is the farm with the highest number of counters. The mean number of counters is 2.47 and the median is 2 (standard deviation 2.12).

Third, we use the *degree of dispersion*. It ranges in Ricote between 1 m, which is assigned to farms that consist of only one counter, and 1062.17 m representing the highest measured value of standard distance between plots of the same farm in Ricote. The mean standard distance of farms in Ricote is 240.61 m and the median is 73.57 m (standard deviation 284.12).

Finally, FIDIDA combines the *degree of separation*, *the degree of dispersion* and a *size* measure into one index describing the state of fragmentation of a farm. FIDIDA results in Ricote range between near zero and 13.97. An index result near zero is reached if e.g. the number of counters is one, as well as the SD. While low values represent a low fragmentation of the farm with small numbers of counters and small distances between plots, relative to the mean size of plots; higher values represent a higher fragmentation of the farm with a higher number of counters and longer distances between plots. The mean value of FIDIDA index results in Ricote is 1.42 and the median is 0.22 (standard deviation 2.22).

The histograms of farm size, number of counters, standard distance and FIDIDA are illustrated in Fig. 6. The determination of class numbers is based on the following formula:

$$k = 5 * \log n$$

where k is the number of class intervals and n is the number of plots (Pankowski and Brier, 1958). The majority of the farms in Ricote are small, have one counter and small standard distances with a size of < 80 m. Despite the small farm sizes, most of the farms have a low fragmentation index < 1.

Table 2 shows that high values of FIDIDA often occur together with high values of standard distance and high counter numbers. For the construction of Table 2, we selected the 10 cases with the highest transaction costs according to three selected measures: farm size, *degree of separation* and *degree of dispersion*. In the last column, the Fragmentation Index for Drip Irrigation and Distance Assessment (FIDIDA) is shown. According to farm size, the smallest properties are selected. According to the *degree of separation*, the farms with the most counters are selected. According to the *degree of dispersion*, the farms with the highest standard distance between plots are selected. The results of FIDIDA represent how these parameters (*degree of separation*, *degree of dispersion* and mean plot size) are brought together into one value.

Small farm sizes hardly have any effect on the results of FIDIDA because small farms often present low values of standard distance and counter number, representing low transaction costs leading to a good index result. Large farms do not necessarily have a good index result because of high transaction costs due to the high number of counters and high standard distances, which suggest lower efficiency compared to small farms. The high number of counters observed for large farms applies in particular to traditional irrigation systems like Ricote.

The Spearman correlation between the results of FIDIDA and the parameters of the index formula as well as the farm size are shown in Table 3. We find a high positive correlation between counter number (0.89) as well as standard distance (0.90) and the results of FIDIDA. In contrast, mean plot size has a negative correlation (−0.22) with FIDIDA. This stresses the focus on the *degree of dispersion* and the *degree of separation* within FIDIDA. Finally, farm size has a positive correlation (0.42) with the results of FIDIDA.

5. Discussion

The estimation of fragmentation in the framework of FIDIDA

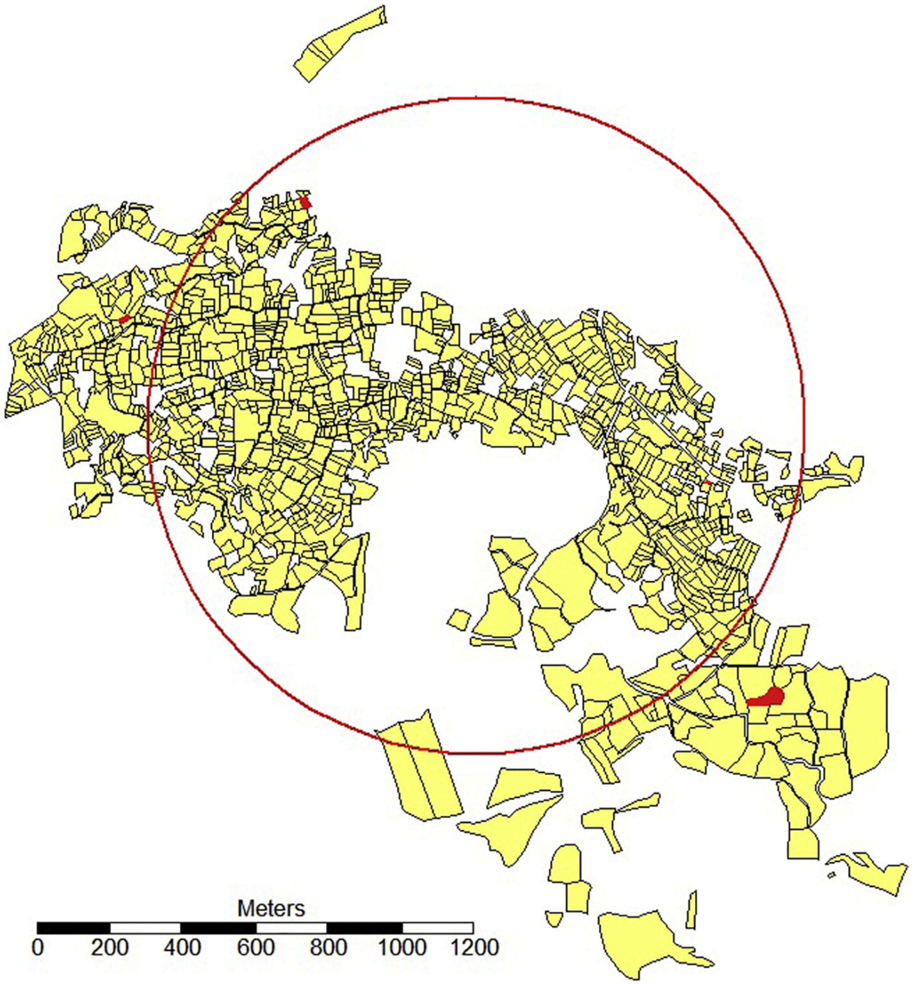

Fig. 5. Illustration of standard distance. Standard distance equals the radius of the red circle. The result is based on the location of the mean centre of each of the four red plots belonging to farmer number 70. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Tables 1 and 2) aims at an assessment of agricultural land properties that takes into account transaction costs, which make land management less efficient and less sustainable. This objective is reached by quantifying farms based on *degree of separation, degree of dispersion* and mean plot size. In contrast to other reviewed fragmentation indices (Gonzalez et al., 2004; Gónzalez et al., 2007; King and Burton, 1982; Latruffe and Piet, 2014; Vijulie et al., 2012), FIDIDA is adapted to the needs of drip-irrigated agriculture in traditional and historical contexts characterised by inherited high land fragmentation. FIDIDA combines the above-mentioned fragmentation descriptors into one index. The index aims at guiding strategies to (a) reduce counters and (b) reduce traveling distance between plots. These strategies have the potential to save time and mitigate emissions on farm-level. Thus, economic and mitigation aspects are considered.

An interesting result is the positive relationship between farm size and a high FIDIDA index. One explanation is that many farmers have only one counter, which serves a single plot, i.e. a single parcel or a cluster of contiguous parcels. This represents low transaction costs (low *degree of separation* and *dispersion*). In fact, > 40% of farmers in Ricote own only one counter. The high number of small farms in Ricote relates to the high presence of farmers who do farming as a hobby or as a secondary supplement to household income. At the other end of the spectrum, most large farms in Ricote suffer from high transaction costs due to the high number of counters and high standard distances between plots, leading to a high FIDIDA index. Overall, the *degree of separation* in Ricote is high based on the number of counters used and the underlying “parcellisation” (King and Burton, 1982).

As a measure for *degree of dispersion*, we propose standard distance. It has to be considered that standard distance is only used as a proxy for traveling distance and travel distances between plots are longer in reality. Thus, the potential to save emissions is higher than represented by standard distances.

Within this framework, the FIDIDA index fosters (a) a more accurate and holistic quantification of land properties, (b) increased transparency in the assessment of land fragmentation costs, (c) and the emergence of a clearer and more sustainable land market. Stakeholders have the possibility to address extreme cases of land fragmentation, enriching market evaluation of land with an integrated assessment of land use that includes efficiency and transaction costs.

While some northern European countries have already initiated land consolidation programs to address high land fragmentation (Tan et al., 2006; van Dijk, 2003; van Dijk, 2007), Southern Europe seems to be lagging in this sense. This delay may be partially due to a stronger attachment to the land and continuity of traditional inheritance systems. With FIDIDA, we advocate for plot fusion with minimal changes to the physical and social structure of the traditional field system, to conserve the cultural values of these agricultural landscapes.

GIS mapping in Ricote highlights potential for further merging of contiguous plots under single counters, as a possible pathway towards reduction of land fragmentation. For instance, single-counter farms could be included in a fragmentation-reduction process based on voluntary land swapping, i.e. the targeted selling or purchasing of land. Farmers with a high fragmentation index could offer land-swapping to single-counter farmers located in the proximity of their larger plots.

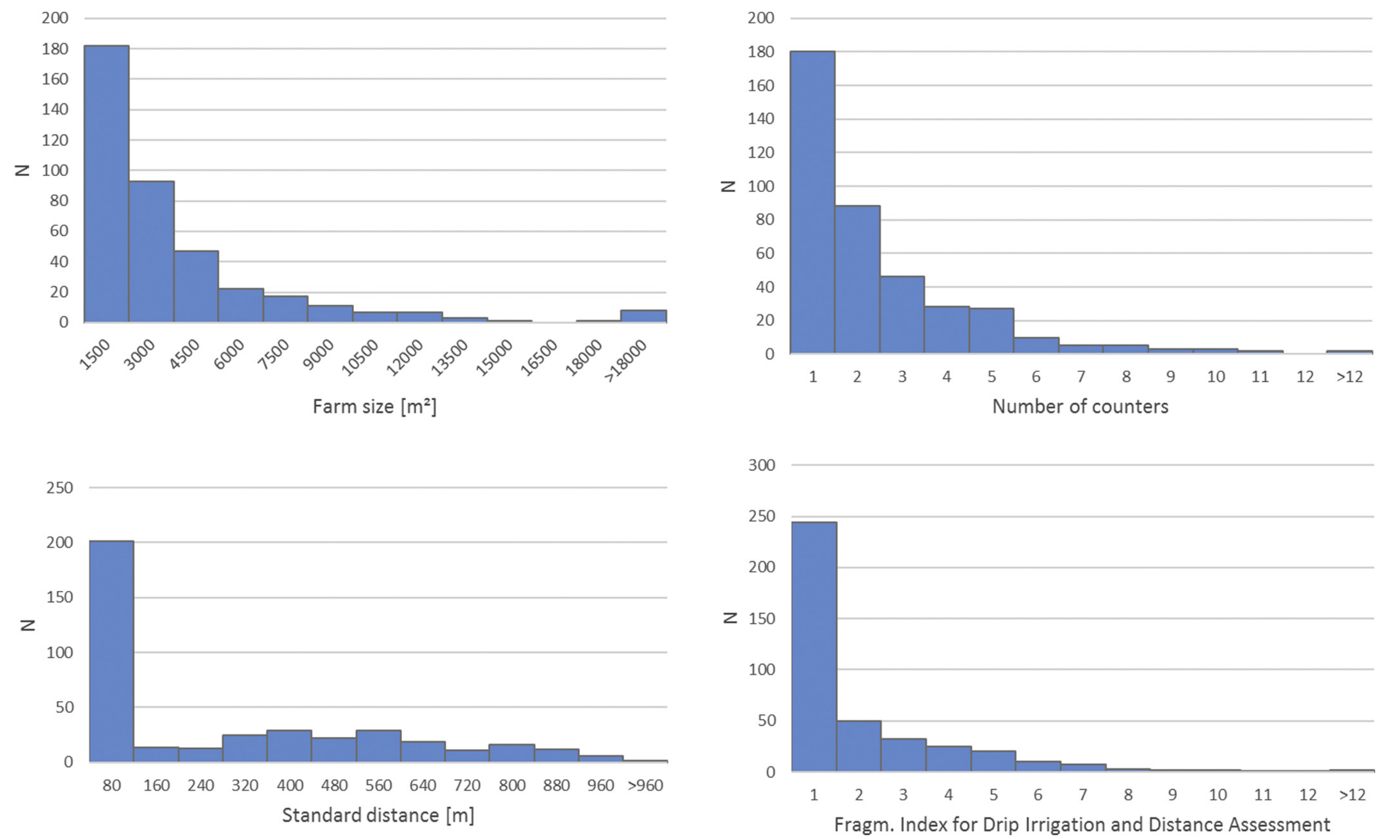

Fig. 6. Histograms of farm size, number of counters (*degree of separation*), standard distance (*degree of dispersion*) and the results of FIDIDA in Ricote. N = number of farms.

Table 1
Basic statistics of total drip irrigation farm data in Ricote: farm size, number of counters per farm (*degree of separation*), standard distance between plots of one farm (*degree of dispersion*) and the Fragmentation Index for Drip Irrigation and Distance Assessment (FIDIDA).

	Farm size [m^2]	No. of counters	Standard distance [m]	FIDIDA
Min	70	1	1	0
Max	54,927	16	1062.17	13.97
Mean	3178.01	2.47	240.61	1.42
Median	1698	2	73.57	0.22
Std. dev.	4883.96	2.12	284.12	2.22

Nevertheless, this process should consider farmers' attitudes (other than economic) towards inherited land, a paramount parameter for the feasibility of such land consolidation programs. Thus, a model that illustrates swapping possibilities should include a parameter mirroring the willingness of people to sell or swap plots, based on an evaluation of the emotional bonds of farmers to the land (van Dijk, 2007).

Interventions on farms with a high *degree of separation* should be prioritised to the advantage of all farmers, given that the use of an excessive number of counters increases the cost of the irrigation system for the whole community. Stressing this aspect, one of the key insights emerging here is not on increasing mean plot size, often considered one of the most important aspects of land consolidation for higher lucrativeness by Janus and Markuszewska (2017), but rather on reducing the number of counters and related (and mutualised) transaction costs, individuated as a key impediment to land profitability by stakeholders in Ricote. In addition, the reduction of fragmentation implies an overall reduction of emissions and traveling time between plots within single farms, another key element of sustainable rural development.

Although not discussed in the present work, we acknowledge the proven potential positive effects of land fragmentation on biodiversity and risk diversification, e.g. relative to soil erosion (Bentley, 1987; Crecente et al., 2002; Tan et al., 2006; Tan et al., 2008). Furthermore, research in the Mediterranean has shown that fragmented agro-ecosystems aim for stability rather than productivity (King and Burton, 1982). The future challenge for land consolidation will be to adopt a pathway that considers economic, environmental and social aspects in a balanced way.

Here, Ricote has been selected as an open laboratory, a model community for the development and implementation of a new fragmentation index adapted to drip irrigation contexts. Nevertheless, the suggested fragmentation index could be implemented in other study areas with drip irrigation systems and similar issues of fragmentation, over-deployment of counters and high transaction costs.

The introduction of free and open source digital mapping technologies is suggested to alter efficiency in agriculture (Janssen et al., 2017; Wolfert et al., 2017). Data and software used in this paper have recently been introduced in the irrigators' community of Ricote, enabling in-house experimentation and implementation. Further applications of the GIS platform are planned in cooperation with local stakeholders. Digital technologies have the potential to produce jobs in the countryside and counter the loss of knowledge by the digitalisation of information. Besides addressing land fragmentation, GIS opens new planning possibilities for emergency water management, collective actions for the control of parasites, planning of ecological agriculture and tourist activities as well as the conservation of local and traditional knowledge.

Following a pathway of information-driven innovation on a local level constitutes the basis for smart sustainable development in the future (Janssen et al., 2017; Naldi et al., 2015; Wolfert et al., 2017). Smart and sustainable development can help small agro-ecosystems to compete with intensive fruit and vegetable irrigation systems in littoral regions, which is important in the light of globalization and the

Table 2
Extract of the farm data in Ricote. The 10 cases with highest transaction costs according to farm size, number of counters (*degree of separation*), and standard distance (*degree of dispersion*) are selected and FIDIDA is calculated encompassing mean plot size, number of counters and standard distance. The farm (farmer number 248) with the highest fragmentation index (13.97) is not listed in Table 2 because it is considered an outlier based on our selection method.

Farmer number	Farm size	No. of counters	Standard distance	FIDIDA
147	11,292	16	534.21	13.44
192	526	2	914.00	9.61
31	8186	9	435.62	8.92
3	11,425	10	703.21	7.49
99	490	2	871.79	7.12
219	7550	9	597.89	6.97
511	16,847	10	539.02	6.89
353	5498	9	438.99	6.47
205	13,273	10	555.71	4.77
151	20,100	11	551.34	4.45
70	3265	4	899.63	4.41
46	1615	2	871.20	4.32
209	21,768	11	598.23	4.31
370	54,927	14	514.59	2.99
478	2241	2	923.75	2.13
477	5898	3	896.92	1.81
203	2435	2	913.86	1.50
400	13,931	3	1014.45	1.27
58	5127	2	950.38	0.79
48	25,722	2	1062.17	0.49
15	70	1	1.00	0.01
461	150	1	1.00	0.01
623	150	1	1.00	0.01
372	180	1	1.00	0.01
593	180	1	1.00	0.01
622	186	1	1.00	0.01
167	190	1	1.00	0.01
652	209	1	1.00	0.00
691	210	1	1.00	0.00
287	220	1	1.00	0.00

Table 3
Spearman rank correlation between farm size, counter number (*degree of separation*), standard distance (SD, *degree of dispersion),* mean plot size and the results of FIDIDA based on the total drip irrigation farm data set.

Farm size; FIDIDA	Counter; FIDIDA	SD; FIDIDA	Mean plot size; FIDIDA
0.42	0.89	0.90	−0.22

integration within the broader economy (Cárdenas et al., 2017; Naldi et al., 2015). These intensive irrigation systems have a higher potential of pollution and water related problems caused by excessive water consumption, the use of fertilizers and pesticides (Gómez-Limón and Picazo-Tadeo, 2012; Reynolds et al., 2014). Small fruit and vegetable irrigation systems in inland valleys like Ricote have less ecological and environmental impacts and can be regulated more easily (Campillo et al., 2013; Campillo et al., 2015; Gómez-Limón and Picazo-Tadeo, 2012; Velasco et al., 2006). Moreover, smallholder agriculture needs to be supported in order to preserve cultural landscapes worldwide considering their ecological, cultural and historical values (Spanò et al., 2018). Thus, smallholder agriculture plays an important role for a sustainable and climate-compatible agriculture in the future (Leggewie and Messner, 2012).

6. Conclusion

In this study, we assessed agricultural land properties considering the influence of land fragmentation in small Mediterranean agro-ecosystems. For this purpose, we developed a single combined fragmentation index, specific to drip-irrigated traditional field systems: the Index for Drip Irrigation and Distance Assessment (FIDIDA). FIDIDA is adapted to the needs of the study area. It quantifies farms considering their *degree of separation*, *degree of dispersion* and mean plot size.

The farms in Ricote show a high heterogeneity of FIDIDA values. Approx. 60% of farms in Ricote have a FIDIDA value below 1 constituting a low degree of fragmentation. The highest FIDIDA value is 13.97 and the mean is 1.42 with a standard deviation of 2.22. FIDIDA values have a strong positive correlation with the number of counters (*degree of separation*) and the standard distance (*degree of dispersion*) of farms. Another positive correlation was found between farm size and FIDIDA values. This can be explained by the long history of land heritages and transmissions in Ricote, which led to land divisions and a high number of counters on large farms.

Researchers or authorities can use FIDIDA to compare the land fragmentation of individual farms or the land fragmentation between different study areas on a broader level. Moreover, FIDIDA aims at supporting the reasonable management of fragmentation thresholds in order to lower the main transaction costs of drip irrigation systems and to mitigate emissions by reducing the number of counters, maintenance costs and traveling distance between plots. To lower land fragmentation, we advocate for the exchange or sale of agricultural plots without changing the physical structure of the traditional field system with its terraces shaped by stone walls and ditches forming a landscape of high cultural, historical and ecological value.

Further research is needed for the implementation of the results. For example, the willingness of people to switch land needs to be assessed in the future. Furthermore, this assessment can be adapted to other areas in the Mediterranean region, with different socio-economic issues (e.g. water management, or soil degradation).

Smallholder agriculture plays a crucial role considering its importance for food security, especially in developing countries, and for the conservation of cultural landscapes worldwide. Hence, farmers need to participate in the research and implementation of sustainable agriculture from the beginning (Cárdenas et al., 2017). Further development of GIS applications and their implementation in the study area is a mutual process of co-creation pursued by researchers and stakeholders in Ricote at eye level. This process profits from the local and traditional knowledge of the community and the scientific expertise. To find sustainable solutions for land fragmentation, it is important to work on the local level and integrate local stakeholders (Zamora Acosta and Acosta Naranjo, 2011) to prevent a *tragedy of property*.

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