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Does land fragmentation affect farm performance? A case study from Brittany, France

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ABSTRACT

Agricultural land fragmentation is widespread around the world and may affect farmers' decisions and therefore have an impact on the performance of farms, in either a negative or a positive way. We investigated this impact for the western region of Brittany, France in 2007. To do so, we regressed a set of performance indicators on a set of fragmentation descriptors. The performance indicators (production costs, yields, revenue, profitability, technical and scale efficiency) were calculated at the farm level, using Farm Accountancy Data Network (FADN) data. By contrast, due to limits in the available data, the fragmentation descriptors were calculated at the municipality level, using data from the cartographic field pattern registry (RPG). The various fragmentation descriptors enabled not only the traditional number and average size of plots, but also their scattering in the geographical space, to be taken into account. The analysis brought several findings. Firstly, it is relevant to consider the various dimensions of LF when studying its impact on farm performance, in particular shape and distance considerations. Secondly, in all cases but one, the effect of the various LF descriptors on performance indicators conform to expectations, that is to say LF increases production costs and decreases yields, revenue, profitability and efficiency. Thirdly, with a simple simulation we have shown that the benefits from reducing fragmentation may differ with respect to the improved LF dimension and the performance indicator considered. Hence, when setting up consolidation programs, it may be crucial for policy-makers to first decide which performance dimension they aim at favouring in order to choose the most efficient way to do so. Finally, from a methodological point of view, our results support the relevance of using descriptors of LF at the municipality level as a proxy when farm level LF descriptors are not available.

1. Introduction

Fragmentation of agricultural land is widespread around the world and results from various institutional, political, historical and sociological factors, such as inheritance laws, collectivisation and consolidation processes, transaction costs in land markets, urban development policies, and personal valuation of land ownership (King and Burton, 1982; Blarel et al., 1992). Farm land fragmentation (LF) is a complex concept that encompasses five dimensions covering: (i) number of plots farmed; (ii) plot size; (iii) the shape of plots; (iv) distance of the plots from the farm buildings; (v) distances between plots (or plot scattering). From the public economics perspective, LF may generate both positive and negative externalities, and therefore societal gains or cost. On the one hand, it may increase biodiversity and society's economic value of landscape. For example, in the French region Brittany, fragmented agricultural land is usually associated with hedges and natural corridors which have been shown to be beneficial to, *e.g.*, biodiversity, water fluxes and the environment in general (Thenail and Baudry, 2004; Thenail et al., 2009). On the other hand, LF may generate social costs as it may induce additional trips by farmers which may result in extra roadwork, road safety issues, greenhouse gas emissions, etc. From the farmer's point of view, LF is often considered as detrimental to farms' performance, prompting government to apply consolidation programs.

Such programs should however carefully balance the private and societal gains and costs of LF reduction. In this respect, programmes which aim at enhancing the structure of field patterns under the constraint of preserving and/or replanting hedges, such as the 'amicable plot exchange' programme put in place in Brittany by the agricultural extension services and local authorities, may represent an efficient compromise (CA Bretagne, 2011). From a policy point of view it is therefore necessary to first estimate the private cost of LF in agriculture.

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In this context, the present paper aims at contributing to the literature analysing the influence of LF on the performance of farms, by carrying out the analysis for one French region, Brittany, in 2007. Brittany is a NUTS2 region, composed of four NUTS3 regions (the 'départements'), namely 'Côtes-d'Armor', 'Finistère', 'Ille-et-Vilaine' and 'Morbihan'.[1] As in many other regions and countries, agricultural land is very fragmented in Brittany. For example in 2007, according to the cartographic field pattern registry ('Registre Parcellaire Graphique' or RPG) introduced in France in 2002 as the Land Parcel Identification System enforced by the European Council Regulation No 1593/2000 (European Commission, 2000), Brittany farms were composed on average of 14 plots, with a mean plot size of 4.35 ha. Twenty-five percent of the farms had 18 plots or more, and 25% of these plots had an average area of 2.42 ha or less.

Our analysis is original in two respects. Firstly, it considers LF in its various dimensions, by using several LF descriptors and not only the traditional measures used in the literature, namely the number of plots operated by the farm and the farm's average plot size. The number of plots is the most commonly used variable to proxy LF. As mentioned by Wan and Cheng (2001), the rationale for using this variable is twofold: (i) it is easier and more understandable to simulate performance gains obtained from the reduction in the number of plots instead of the reduction in other more complex descriptors and; (ii) it is easier for policy-makers willing to implement land consolidation programme to set targets in terms of number of plots, instead of average plot size or other more complex descriptors. By contrast, in our paper we use ten different LF descriptors, capturing all five dimensions of LF described above. In doing so, we aim at assessing whether the non-traditional measures of LF, in particular those dealing with distances often ignored in the literature, can reveal some significant relationship between LF and farm performance.

The second originality of our analysis is that, while we use farm-level data for the calculation of farm performance indicators, we resort to municipality-level averages for the calculation of LF. More precisely, we investigate the relationship between performance of farms and LF of the municipality where the farms are located. The reason is that no unique database is available in France to allow the calculation of both LF and performance at the farm level at the same time. We therefore had to use two separate databases, one for the calculation of LF and one for the calculation of performance. However, we were not able to link both databases together, as identifiers for a specific farm were different from one source to the other. The only information common to both databases was the municipality of the farms, so that we could link farm performance indicators with municipality fragmentation descriptors. The underlying assumption is that a farm's LF is positively correlated with the LF in the municipality where the farm is located. Our empirical investigation will help shed light on the adequacy of such a 'double level' (individual level and municipality level) method to study the impact of LF on farm performance. This is particularly important as most classic databases to study farm performance exclude information regarding farms' LF or include at most the simple descriptor of the number of plots.

The paper is structured as follows. Section 2 reviews the existing literature and conceptual considerations. Section 3 describes the data and explains the methodology used to calculate the various indicators of performance and of LF. Section 4 presents the methodology used to investigate the effect of LF on performance and the results of the empirical analysis. Section 5 concludes.

[1] The Nomenclature of Territorial Units for Statistics (NUTS) provides a single uniform breakdown of territorial units for the production of regional statistics for the European Union (EU) (Source: http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction).

2. Literature review and conceptual considerations

LF may affect farmers' production decisions and management practices, and therefore may have an impact on the performance of farms. Although it is widely believed that LF is detrimental to farm performance, in some cases it may be beneficial. Table 1 summarises the performance costs and benefits associated with each dimension of LF from the farmer's point of view (see Van Hung et al., 2007, for a related table including public and longer term costs and benefits). In terms of LF measured by plot size, the detrimental effects may arise from the impossibility to exploit economies of scale when the average plot size is too low. In terms of LF measured by plot shape, the negative impact on farm performance may arise from the lower field-efficiency of machines in irregular plots and the loss of harvest along boundaries or in the corners of fields (Jabarin and Epplin, 1994; Nguyen et al., 1996; Van Hung et al., 2007; di Falco et al., 2010; Kawasaki, 2010; del Corral et al., 2011). In addition, the literature suggests that farmers are reluctant to adopt innovations, to uptake modern technologies or to apply soil investment such as drainage, when plots are too small or irregularly shaped (Nguyen et al., 1996; Van Hung et al., 2007; Tan et al., 2010; Rahman and Rahman, 2008; di Falco et al., 2010), which may limit productivity and profitability. In terms of LF measured by distances (between the plot and the farm, as well as among the plots), the detrimental effect may arise from the increased travelling cost for the transportation of inputs, workers, outputs, equipment and grazing livestock (Jabarin and Epplin, 1994; Wan and Cheng, 2001; di Falco et al., 2010; Kawasaki, 2010; del Corral et al., 2011; Manjunatha et al., 2013). The latter may be forced to remain on pastures close to the farmstead, possibly limiting feed quantity and quality. Lengthy travelling may also be harmful in terms of time spent on the road rather than on more productive tasks, and in terms of conflicts in labour allocation. Water management may be a problem as irrigation may not be applied due to the cost of water transportation (Van Hung et al., 2007; Kawasaki, 2010; Tan et al., 2010; Manjunatha et al., 2013). It has also been suggested by Wan and Cheng (2001) that some inputs might be wasted more in the presence of high LF measured by distances, due to leakage or evaporation that can take place during transportation. Also, additional equipment, secondary farm buildings and/or external service expenses may be required to farm distant plots. All the various mechanisms explained above summarise in higher costs of organising and controlling the production process (di Falco et al., 2010). Jabarin and Epplin (1994) add that dealing with numerous landowners increases transaction costs.

However, the impact of LF on farm performance may be positive on three grounds. The first reason is the cropping pattern optimisation effect. LF may result in an increased diversity in land quality and in growing conditions, so that the allocation of crops across plots may be optimised in terms of crop match for soil types or local climatic conditions, and of labour synchronisation, resulting in potentially higher overall yields (Jabarin and Epplin, 1994; Nguyen et al., 1996; Wan and Cheng, 2001; Van Hung et al., 2007; di Falco et al., 2010; Tan et al., 2010; del Corral et al., 2011). The second reason is that LF may give greater opportunities for risk diversification, thereby reducing production risks at the farm level (Jabarin and Epplin, 1994; Nguyen et al., 1996; Van Hung et al., 2007; di Falco et al., 2010; Kawasaki, 2010; del Corral et al., 2011). For example, a fragmented farm would be less affected by a pest outbreak that spreads on contiguous plots only, or by local hail storms or floods. A third reason is that, according to Chukwukere Austin et al. (2012), farmers may pay greater attention to the management of remote land, thus compensating the negative effect of a tedious transportation.

Table 1
Private performance costs and benefits associated with each dimension of LF. Source: authors' interpretation based on literature review (see Section 2).

LF dimension	Mechanism behind the effect on farm performance	Effect on farm performance
High number of plots	Higher organising and controlling costs	–
	Transaction costs due to working with numerous landowners	–
	Cropping pattern optimisation permitted by better matches between crops and soils, and labour synchronising	+
	Reduced production risks through crop diversification	+
Low plot size	Impossibility to exploit economies of scale	–
	Limited uptake of innovations or investments	–
Irregular plot shape	Reduced field-efficiency of machinery	–
	Harvest loss along field boundaries and in corners	–
Long distances (from plots to the farm and/or between plots themselves)	Increased cost for transportation of inputs, workers, outputs, equipment and grazing livestock	–
	Less labour dedicated to productive tasks and conflicts in labour allocation	–
	Difficult water management	–
	Inputs wasted due to leakage and evaporation during travel	–
	Additional equipment, secondary farm buildings and/or external service expenses required	–
	Cropping pattern optimisation permitted by better matches between crops and soils, and labour synchronising	+
	Reduced production risks through crop diversification	+
	Better attention of farmer to remote plots	+

Several authors have tested empirically the effects of LF on the performance of farms, whether purposely or in passing while investigating the various determinants of farm performance. For example, Jabarin and Epplin (1994) investigated the impact of LF on the production cost of wheat in Jordan in 1992. In China, Nguyen et al. (1996), Wan and Cheng (2001) and Tan et al. (2010) investigated the effect of LF on, respectively, the productivity of major crops in 1993–1994, crop output of rural households in 1993–1994, and technical efficiency of rice producers in 2000–2001. Also in Asia, Van Hung et al. (2007) analysed the impact of the number of plots on crop yields in Viet Nam in 2000–2001. Kawasaki (2010) evaluated both the costs and benefits of LF in the case of rice production in Japan in 1995–2006, similarly to Rahman and Rahman (2008) in Bangladesh in 2000. Parikh and Shah (1994) investigated the influence of several determinants, including LF, on the technical efficiency of farms in the North-West Frontier Province of Pakistan in 1988–1989, while Manjunatha et al. (2013) analysed the effect of LF on cost efficiency and on profit in India in 2007–2008. Chukwukere Austin et al. (2012) assessed the influence of LF on production of farmers in Nigeria. In Europe, di Falco et al. (2010) analysed how LF affects farm profitability in Bulgaria in 2005 and del Corral et al. (2011) analysed how LF affects the technical efficiency and profits of Spanish dairy farms in 1999–2007. All authors found that LF was detrimental to the specific performance indicator considered. However, in their literature review some of these authors alluded to papers where the opposite effect or no significant effect is given evidence, and therefore recommended that, in the absence of theory and consensus, empirical studies be carried out (Rahman and Rahman, 2008; del Corral et al., 2011). As several opposite effects may be at play, it is indeed difficult to draw unambiguous hypotheses on the effect of a particular LF dimension on farm performance.

In most of the above-mentioned research, LF is represented by the number of plots (Parikh and Shah, 1994; Wan and Cheng, 2001; Van Hung et al., 2007; Rahman and Rahman, 2008; Kawasaki, 2010; Tan et al., 2010; del Corral et al., 2011; Manjunatha et al., 2013[2]) and/or their average size (Jabarin and Epplin, 1994; Nguyen et al., 1996; di Falco et al., 2010; Tan et al., 2010). These two variables are employed either directly or, more rarely, indirectly by the use of more elaborate measures, such as the Simpson index (*e.g.*, Kawasaki, 2010) or the Januszewski index (*e.g.*, Chukwukere Austin et al., 2012). However, these variables do not account for all dimensions of LF and may not capture all the constraints that LF imposes on production systems, in particular in terms of distance. There are a few exceptions to the use of these sole variables. For example, Tan et al. (2010) also considered the average distance from the plots to the homestead, while Gonzalez et al. (2007) used elaborate measures which accounted for the size, shape and dispersion of plots. However, in this latter case, these measures were not tested on a real sample of farms, but instead were applied to a hypothetical dataset.

[2] In fact these authors do not use the number of plots as such, but a dummy equal to one if a farm operates more than one plot, and zero if the farm operates only one plot.

3. Data and methodology

3.1. Measuring farm performance

Farm-level performance was calculated with the French Farm Accountancy Data Network (FADN) 2007 database. The FADN database, which is managed by the French Ministry of Agriculture, contains structural and bookkeeping information for a five-year rotating panel of commercial farms. This latter characteristic means that farms in the FADN database are larger on average than farms in the agricultural censuses. Excluding smaller farms from our analysis is made inevitable by the fact that databases which include them (*e.g.*, national agricultural censuses or farm structural surveys) do not provide sufficient information to calculate economic performance. The FADN database is the only database that permits such calculations on a large sample that is representative of commercial farms. Focusing on those farms is nonetheless relevant as these farms produce most of the country's output and as their main objective is to maximise performance, whereas smaller farms often have other objectives such as lifestyle, recreation or asset ownership.

In 2007, 480 farms of the FADN sample were located in Brittany. Among those 480 farms we excluded ten farms which used no land and two farms with inconsistent data. The final sample thus consisted of 468 farms. Fig. 1 shows the location of the municipalities of the 468 FADN farms for Brittany.

Table 2 reports the distribution of these 468 farms according to their main type of farming as defined by the European Commission

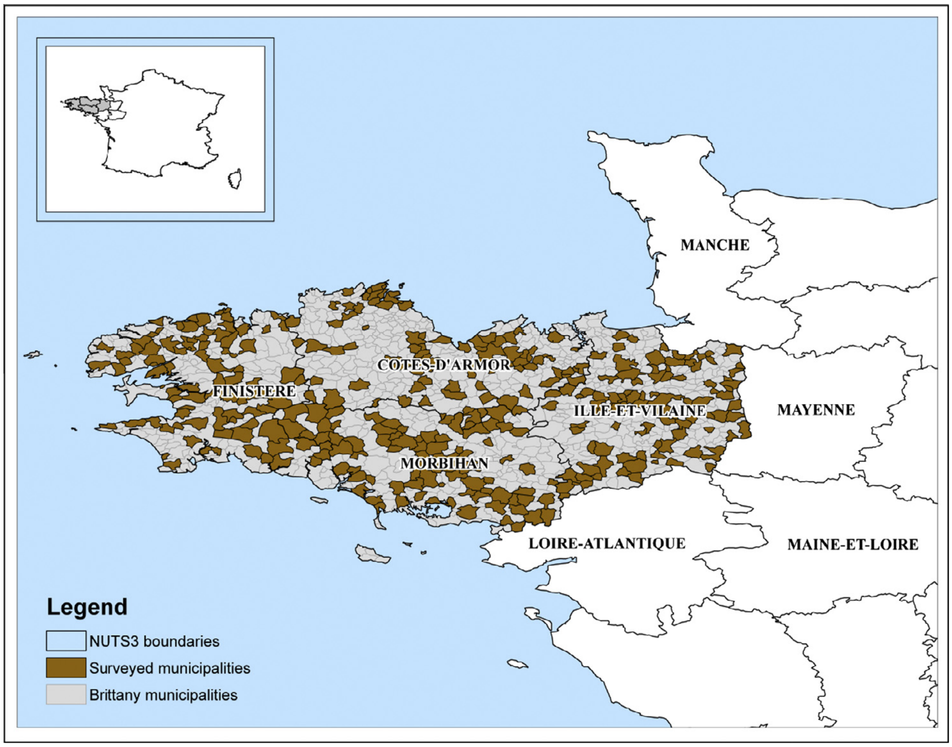

Fig. 1. Brittany NUTS3 regions and studied municipalities.

Table 2
Main characteristics of the farms in the FADN sample used (468 farms). Source: authors' calculations based on the French FADN 2007 database.

	Farms in the sample (% of total)
According to their main production	
Field crops	62 (13%)
Dairy	134 (29%)
Other grazing livestock	66 (14%)
Granivores	126 (27%)
Mixed (crops and livestock)	53 (11%)
Other crops	27 (6%)
In areas with nitrate pollution zoning restrictions	21 (4%)

	Mean	Std. deviation	Minimum	Maximum
Utilised agricultural area (hectares)	62.00	44.30	0.12	398.96
Number of full time labour equivalents	2.40	2.43	1.00	23.96
Number of livestock units	245.38	359.83	0.00	2522.11
Share of land rented in (%)	77	33	0	100
Share of hired labour (%)	15	25	0	100

(2010) with respect to the farm's standard gross margin. The distribution reflects Brittany's agriculture where dairy, poultry and pig breeding prevail: 29% of the sample specialised in dairy, and 27% in granivores. Mixed crop and livestock farming (generally the production of cows' milk and field crops) accounted for 11% of the sample, and the breeding of other grazing livestock (goats and sheep) for 14%. Finally, 13% specialised in field crops, and another 6% in crops other than field crops (mainly vegetables). Fig. 2 shows the distribution of Brittany municipalities according to the main production of each municipality based on the 2010 Agricultural Census (municipalities where the 468 studied farms are located are cross-hatched). Granivore farms were located principally in central and eastern Brittany, while crops were mainly produced on the coast and grazing livestock breeding in the western part of the region. Four percent of the farms in the sample used were located in areas subject to nitrate pollution zoning regulations (Table 2). In 2007, the studied farms utilised on average 62.0 ha, a figure greater than the average for the whole farm population in Brittany (47.3 ha) as expected, but close to the average of Brittany's commercial farm sub-population (60.0 ha) (2010 Agricultural Census). The farms in our sample used, on average, 2.4 full time equivalents calculated as Annual Working Units (AWU; where 1 AWU corresponds to 1200 h of labour per year). This is higher than the region's average (1.7 AWU) and similar to the region's commercial farms' average (2.1 AWU) (2010 Agricultural Census). The average number of livestock units (calculated using the European standard coefficients applied to each livestock type) was 245.4. This relatively high figure is due to the numerous farms in Brittany specialised in livestock and, in particular, in poultry and pig. On average, farms rented in 77% of their utilised area and hired 15% of their labour force.

Several indicators of farm performance were computed for each farm in the sample. Firstly, various categories of production costs were calculated per farm and per unit of utilised area. These consisted of costs of fertilisers, seeds, pesticides, fuel, intermediate consumption (which includes, among others, fertilisers, seeds,

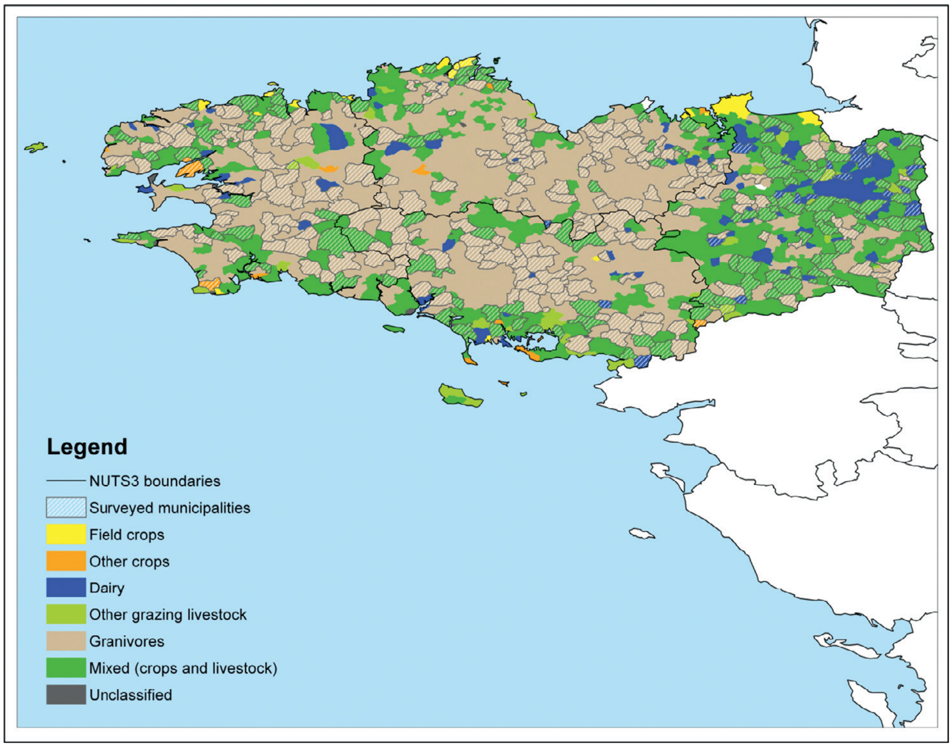

Fig. 2. Main productions in Brittany's municipalities. Source: authors' calculations based on Agricultural Census 2010.

pesticides and fuel) and hired labour. Secondly, two production yields were calculated: wheat yield in tons of wheat produced per hectare of wheat cultivated; and milk yield in litres of milk produced per dairy cow. Thirdly, four revenue or profitability results were calculated per farm and per unit of utilised area: the farm gross product, composed of farm sales and insurance compensations; the farm gross margin, obtained from the farm gross product minus variable costs specific to crop and livestock production; the farm operating surplus, obtained from the farm gross margin minus land, labour and insurance costs; and the farm pre-tax profit, given by the farm operating surplus minus depreciation and interest, and before taxes are deducted. Subsidies were not included in the farm gross product, and therefore not included either in the three profitability indicators. Finally, technical efficiency and scale efficiency were calculated for each farm. Technical efficiency assesses how far farms are located from the maximum production frontier for a given combination of inputs. It is a more complex measure than partial productivity indicators such as yields, since it relates all outputs produced to all inputs used on the farm. Technical efficiency, also called total technical efficiency, is composed of pure technical efficiency (that is to say, whether farmers operate their farm efficiently) and of scale efficiency (that is to say, whether the farm's production scale is optimal). Technical and scale efficiencies were computed using the non-parametric method Data Envelopment Analysis (DEA), which employs linear programming to construct a frontier that envelops the data used (Charnes et al., 1978). Efficiency scores obtained by DEA are between one for a fully efficient farm (*i.e.*, a farm located on the efficient frontier), and zero for a fully inefficient farm (with smaller scores indicating lower efficiency). Since the efficient frontier depends on the sample used, efficiency scores may be overestimated if the most highly performing farms in the population are not included. For this reason, we performed the analysis on the whole sample (468 farms) but, in order to account for the fact that technologies differ across production specialisations as is visible from the large sample's standard deviations shown in Table 2 (*e.g.*, for livestock units), we constructed a separate DEA frontier for each of the six types of farming sub-samples. Then, for the subsequent analyses, we pooled the calculated technical efficiency scores for all types of farming into one dataset. The DEA model was output-oriented, meaning that farms were assumed to maximise their output level, given input levels. The model had one single output, namely the farm output produced in Euros, and four inputs: the utilised area in hectares; the labour used in AWU; the intermediate consumption in Euros; and the capital value in Euros. Under the assumption that farms operated under constant returns to scale, the total technical efficiency score for each farm was obtained. Total technical efficiency was then decomposed into pure technical efficiency and scale efficiency. Pure technical efficiency was obtained assuming that farms operated under variable returns to scale, and indicated the efficiency of farmers' practices irrespective of farm size. By contrast, scale efficiency, which was calculated for each farm as the ratio between its total technical efficiency and its pure technical efficiency, revealed whether the farm operated at the optimal scale of production.

Table 3 presents the descriptive statistics of the performance indicators for the 468 sample farms. Among these, 341 farms (73% of the sample) produced wheat with an average yield of 5.3 tons per hectare, and 269 farms (57% of the sample) produced milk with an average yield of 7043 l per cow. The 468 farms generated on average almost 1800 Euros per hectare of pre-tax profit without subsidies. Their total technical efficiency score was 0.771 on average, indicating that they could increase their output by 22.9% without increasing their input use.

3.2. Measuring land fragmentation

LF was measured using the 'Registre Parcellaire Graphique' (RPG) put in place in France in 2002 as the Land Parcel Identification System enforced by the European Council Regulation No 1593/2000 (European Commission, 2000). This is a Geographic Information System (GIS) database which gathers the field patterns

Table 3
Performance of the farms in the FADN sample used. Source: authors' calculations based on the French FADN 2007 database.

Farm performance indicator	Average value (*st. dev.*)		Number of observations
	Per farm	Per hectare	
Production costs (Euros)			
Fertiliser cost	7052.46 (*7799.38*)	342.40 (*1321.40*)	468
Seed cost	7638.75 (*13491.97*)	1145.79 (*7151.02*)	468
Pesticide cost	5839.18 (*5403.11*)	225.63 (*848.11*)	468
Fuel cost	4765.48 (*4392.81*)	156.71 (*608.01*)	468
Intermediate consumption cost	193580.80 (*250404.00*)	13566.19 (*61713.45*)	468
Hired labour cost	13227.82 (*39380.71*)	3365.43 (*18693.75*)	468
Yields			
Wheat yield (tons/hectare)	5.3 (*2.0*)		341
Milk yield (litres/cow)	7043 (*1337*)		269
Revenue and profitability without farm subsidies (Euros)			
Gross product	294199.00 (*314714.30*)	23936.21 (*110367.30*)	468
Gross margin	100618.30 (*100130.60*)	10370.03 (*51159.35*)	468
Operating surplus	62754.91 (*61332.70*)	5267.21 (*28134.14*)	468
Pre-tax profit	13269.57 (*55615.65*)	1758.27 (*22838.83*)	468
Efficiency scores			
Total technical efficiency	0.771 (*0.162*)		468
Pure technical efficiency	0.835 (*0.149*)		468
Scale efficiency	0.925 (*0.109*)		468

declared by farmers who apply for support under the framework of the Common Agricultural Policy (CAP).[3] In fact, farmers are not requested to delineate each of their individual fields but rather each of their 'plots', which we define for this paper as a set of contiguous fields (which may or may not all bear the same crop) delimited by easily identifiable landmarks (such as agricultural byways, roads, rivers, or another plot) and stable from year to year.

We used the 2007 RPG database which identifies 450,787 plots used by 31,921 farms for Brittany. Each of these farms could be categorised as one of the following: (i) a farm that was registered in one of the four NUTS3 regions of Brittany and whose plots were all located inside this single region; (ii) a farm that was registered in one of the four NUTS3 Brittany regions, but whose plots were partly located outside that region; and (iii) a farm that was registered outside Brittany but whose plots were located totally or partly inside one of the four NUTS3 Brittany regions. We retained all farms and plots corresponding to case (i). As regards case (ii), we only retained those farms whose plots were located in one of the NUTS3 regions directly neighbouring Brittany (namely 'Loire-Atlantique', 'Maine-et-Loire', 'Manche' and 'Mayenne', see Fig. 1) and considered all of their plots, be they located in Brittany or in these four directly neighbouring regions. Similarly, as regards case (iii), we retained those farms registered in one of the four above-mentioned NUTS3 regions directly neighbouring Brittany and we considered both their plots located in Brittany and in one of these four directly neighbouring regions. Finally, in order to ensure that we included 'entire' farms only, we excluded those farms whose total area declared by the farmer in the RPG was 0.02 ha or more different from the area obtained by summing the areas of each individual plot of the farm. In the end, the database used consisted of 29,433 farms and 398,865 plots.

For each farm i among these 29,433 farms, ten fragmentation descriptors were computed, which relate to one of the five dimensions of LF as described in the introduction (the formal definitions of the descriptors are given in the Appendix A).

(1) One LF descriptor relating to the number of plots, namely the number of plots on the farm ($nplot_i$).
(2) Two LF descriptors relating to the shape of plots: the weighted average of the shape index of the plots ($wshsq_i$) (Akkaya Aslan et al., 2007); and the average of the areal form factor of the plots ($aform_i$) (Gonzalez et al., 2004). Both descriptors involve the ratio of the perimeter and the area of the plots, and represent the simple (for the former descriptor) and the weighted (for the latter descriptor) farm level average of individual plot descriptors.
(3) Three LF descriptors relating to the size of plots: the average plot size ($avpls_i$); the Simpson index ($simps_i$) (Blarel et al., 1992; Van Hung et al., 2007; Kawasaki, 2010) and; the Januszewski index ($janus_i$) (King and Burton, 1982). With respect to the simple average plot size, both the more elaborate Simpson index and Januszewski index incorporate information regarding the distribution of individual plot sizes.
(4) Three LF descriptors relating to the distance of plots from the centre of the farm: the average distance of a hectare from the centre of the farm ($avdha_i$); the grouping index ($grpgi_i$) (Marie, 2009) and; the structural index ($strui_i$) (Marie, 2009). Both the more elaborate grouping index and structural index relate to the maximum distance of a plot from the centre of the farm, using different distance normalisations.
(5) One LF descriptor relating to the scattering of plots (*i.e.*, to the distance between plots), namely the normalised average nearest neighbour distance ($nannd_i$), which is a normalised average of the minimum distance between two plots belonging to the same farm.

Since there was no information in the RPG concerning the location of farmsteads, the barycentre of the farm was used as a proxy for its 'centre'. The barycentre was computed as the 'centre of mass' of the geometric centroids of plots, with the 'mass' associated to each plot being its area. Distances were then computed with respect to the barycentre of the farm in those LF indicators requiring such information for their computation (namely $avdha_i$, $grpgi_i$ and $strui_i$).

It should be stressed that the relationship between a descriptor and LF may be positive (*i.e.*, a higher value of the descriptor indicates higher fragmentation) or negative (*i.e.*, a higher value of the descriptor indicates lower fragmentation). Descriptors positively related to LF are the number of plots, the weighted average shape index, the Simpson index, descriptors relating to the distance from the barycentre of the farm and the normalised average nearest neighbour distance, while descriptors negatively related to LF are the average areal form factor, the Januszewski index and the average plot size (see column 'Frag.' in Table 4).

As explained in Section 1, we analysed the influence of LF in the municipality where a farm was located on the farm's performance. To do this, we calculated the aggregated fragmentation descriptors at the level of each municipality r for the 29433 farms in the RPG database. We computed the weighted average of each descriptor considering all farms with at least one plot in r, with weights being

[3] For more information on the RPG, see the dedicated pages on the website of the 'Agence de Service et de Paiement', the public body which maintains the RPG and delivers CAP subsidies to farmers based on these declarations (http://www.asp-public.fr/?q=node/856).

Table 4
Descriptive statistics of the fragmentation descriptors at the municipality level. Source: authors' calculations based on the field pattern registry 'RPG anonyme ASP 2007' database.

	Frag.[a]	Studied municipalities (348 observations)				All municipalities in Brittany (1255 observations)				
		Mean	Std. deviation	Min	Max	Mean	Std. deviation	Min	Max	Corr.[b]
Number of farms		60.63	29.74	3	200	45.67	28.72	1	200	
Farmed area (hectares)		3593.02	1844.73	53.32	11811.04	2781.25	1704.15	9.01	11811.04	
Land fragmentation descriptor										
Number of plots ($nplot_r$)	+	19.25	7.01	8.84	62.09	20.97	8.34	3.00	85.18	0.396
Weighted average plot shape index ($wshsq_r$)	+	1.345	0.065	1.172	1.542	1.347	0.075	1.084	1.848	0.292
Average plot areal form factor ($aform_r$)	–	0.043	0.002	0.038	0.049	0.043	0.002	0.026	0.056	0.258
Average plot size ($avpls_r$)	–	4.77	2.10	0.31	30.24	4.87	15.23	0.31	540.57	0.135
Simpson index ($simps_r$)	+	0.841	0.043	0.727	0.954	0.850	0.049	0.404	0.973	0.224
Januszewski index ($janus_r$)	–	0.302	0.047	0.158	0.422	0.290	0.052	0.124	0.668	0.276
Average distance of a hectare ($avdha_r$)	+	1675	443	897	4339	1670	562	217	6854	0.130
Grouping index ($grpgi_r$)	+	9.560	2.845	4.332	26.063	9.358	3.207	1.976	43.073	0.147
Structural index ($strui_r$)	+	3.181	3.756	0.780	47.152	3.075	2.620	0.582	47.152	0.188
Normalised average nearest neighbour distance ($nannd_r$)	+	0.986	0.281	0.415	2.444	0.937	0.350	0.289	5.344	0.087

[a] 'Frag.': expected relationship between the descriptor and land fragmentation (see text).
[b] 'Corr.': correlation between the municipality-level descriptors and the farm-level descriptors; all correlations are significant at the 1% level.

the ratio of the farm operated area located in r to the total operated area in r, or, formally:

$$x_r = \frac{1}{A_r}\sum_{i \in r} A_{ir} x_i \quad (1)$$

where x represents one of the ten fragmentation descriptors, A_{ir} represents farm i 's operated area located within municipality r and $A_r = \sum_{i \in r} A_{ir}$ is the total operated area in municipality r. It should be noted that, even though the RPG only includes farms which apply for CAP payments, the municipality-level descriptors calculated here may be viewed as quite accurate proxies for the true farmland fragmentation of municipalities since, according to the FADN, 98% of the farms in Brittany, representing 99.9% of the hectares utilised in the region, received some CAP payments in 2007.[4]

In total, 348 municipalities were related to the 468 farms of the FADN, out of the 1255 municipalities of Brittany for which we had data in the RPG. Table 4 reports descriptive statistics of the fragmentation descriptors for the 348 municipalities, as well as for all the 1255 Brittany municipalities. It appears from this table and from a further examination of the distributions for all LF descriptors, that our sample of 348 municipalities is skewed towards higher values of LF compared to the full sample of 1255 municipalities, but that the discrepancy is very slight. We are confident, therefore, that our sample can be regarded as representative of Brittany.

Finally, the assumption, explained in Section 1, that a farm's LF is positively correlated with the municipality-level LF was checked for the 29433 farms and the 1255 municipalities by computing the correlation between the LF descriptors at the farm level and the LF descriptors of the municipalities where each farm had at least one plot. The column 'Corr.' of Table 4 confirms that this correlation is positive and significant at the 1% level in every case, though its magnitude differs from one descriptor to the other: it is below 0.10 for one LF descriptor, namely the normalised average nearest neighbour distance (*nannd*), lies above 0.20 for five out of the ten LF descriptors and reaches 0.396 for the number of plots (*nplot*).

3.3. The relationship between LF and farm performance

The influence of LF on farm performance was investigated using Ordinary Least Squares (OLS) regressions, where the dependent variables were, in turn, each of the 15 per-farm performance indicators described above. All LF indicators were introduced in turn in the regressions as explanatory variables. Therefore, there were $15 \times 10 = 150$ regressions, which differed according to the performance indicator used as the dependent variable and the LF indicator used as the explanatory variable.

Before being used in the regressions, the LF descriptors were modified in two ways. Firstly, LF in the neighbouring municipalities was accounted for. Indeed, it appeared from the RPG database that 68% of the 16263 farms operating at least one plot in the 348 studied municipalities also operated plots in other, neighbouring, municipalities. In the regressions, using the LF descriptors calculated for the sole municipality where a specific FADN farm was registered could therefore inadequately capture the fragmentation level that this farm was actually facing. For this reason, LF descriptors accounting for the fragmentation level of the farm's municipality as well as the fragmentation of surrounding municipalities were considered as more accurate proxies. We therefore used, as LF explanatory variables in the regressions, the weighted average of LF indicators of all municipalities located in a radius of 20 km to the municipality where each FADN farm was located.[5]

Secondly, in order to ease the reading and interpretation of tables and results, LF descriptors at the municipality level were transformed as follows: (i) they were normalised with respect to their minimum and maximum sample values so that they all ranged between zero and one and; (ii) they were reversed where necessary so that, for each descriptor, the higher the descriptor, the greater the LF.

Various control variables, available in the FADN data, were used in all 150 regressions in addition to LF descriptors: farmer's age; farm size in terms of utilised area in hectares; a farm size dummy based on classes of economic size (the dummy is equal to one if the farm is greater than 100 Economic Size Units (ESU), with 1 ESU equivalent to 2200 Euros of standard gross margin, and zero if it is less than 100 ESU); a farm legal status dummy (equal to one for an individual farm, and zero for a partnership or company); the share of rented land in the farm utilised area; the share of hired labour in total labour used on the farm; the farm capital to labour ratio; the operational subsidies received by the farm, related to hectares of utilised area; a farm location dummy (equal to one if the farm is located in an area subject to nitrate pollution zoning

[4] Similarly, in our sample, 461 out of the 468 studied farms (that is to say 98.5 percent of them), representing also 99.9 percent of the hectares utilised, received some CAP payments in 2007.

[5] The radius of 20 km was chosen because it is, according to the RPG, the maximum distance of a plot from the barycentre of the farm for 99% of the farms in Brittany in 2007.

restrictions, and zero if not); and farm production specialisation dummies (based on the categories in Table 2 with 'other crops' being the reference).

The choice of the control variables was based on theoretical grounds and findings from previous literature (*e.g.*, Schmitt, 1991; Johnson and Ruttan, 1994; Kimhi, 2006; Gorton and Davidova, 2004; Larue and Latruffe, 2009; di Falco et al., 2010; Latruffe, 2010; del Corral et al., 2011). Based on production theory, it can be expected that the larger the farm, the higher the cost and gross output (measured per farm). The link between farm size and profit, and between farm size and efficiency, may be expected to be positive due to economies of scale. However, previous literature is not consistent on the existence of such economies of scale in agriculture (see the review by Gorton and Davidova, 2004), and therefore the link may not always be positive.

The performance of individual farms as opposed to partnerships or companies is not clear-cut either. Companies may suffer from increased labour supervision but may benefit from privileged access to input and output markets. The share of rented land is often considered as an explanatory variable in the literature due to the incentives that it may provide, although here also incentives may play in both directions and the net effect is ambiguous. On the one hand, renting in land may force farmers to produce in a profitable and efficient way in order to be able to repay the rentals; on the other hand, investments in soil quality improvement may not be carried on on land that is not owned, which may limit performance. As for hired labour, it may be a financial burden but it may also help a better allocation of labour: for example, skilled workers perform technical tasks while the farmer focuses on managerial tasks. However, this variable, as well as the capital to labour ratio, may also represent the type of technology used on the farm more precisely than production specialisation dummies would do. For this reason it is difficult to derive *a priori* hypotheses on the effect of hired labour and capital to labour ratio on farm performance. As regards subsidies, in the period studied here (2007) they were mostly in the form of decoupled payments provided per hectare of utilised land (the Single Farm Payments, SFP) but also encompassed a non-negligible part of direct payments coupled to hectares cultivated with specific crops or coupled to the number of heads of specific livestock. SFP and crop/livestock direct payments can be production facilitating by covering expenses for inputs, and therefore can be expected to increase input costs, yields, gross product and profitability. As for the effect of subsidies on efficiency, in general in the literature a negative impact is found on technical efficiency (due to their impact on farmers' effort and risk attitudes), but either negative or positive impacts are found on scale efficiency. The location in an area subject to nitrate pollution zoning restrictions may have various impacts on farm performance. On the one hand, as farmers in these areas are constrained in their practices, they may incur larger expenses and produce in a less profitable and efficient way than farmers who are located outside. On the other hand, the constraints imposed on farmers may give them incentives to change their technology and practices, which could result in higher performance (the so-called 'Porter hypothesis', based on Porter and van der Linde, 1995). Finally, no expectation can be drawn regarding farmer's age, as on the one hand elder farmers may be more experienced but on the other hand they may be less capable or skilled than younger farmers.

For each regression, we computed the confidence interval of the estimated parameters from the White or 'sandwich' estimator of the variance–covariance matrix, which is robust to misspecification problems such as heteroskedasticity and small sample size.

4. Results

Table 5 summarises the accuracy with which the 150 models fit the data, as measured by the R-squared statistics. This accuracy ranges from an average of 0.145 for the regressions with pure technical efficiency as the dependent variable, to an average of 0.664 for the regressions with hired labour cost as the dependent variable; 80 out of the 150 regressions exhibited an R-squared statistic above 0.35, which is fairly satisfactory for such cross-sectional microdata models based on a limited sample. It is also worth noting that the standard deviations of the R-squared statistics are low, indicating that, for a given farm performance indicator, the fit of the model is quite similar whatever the LF descriptor used as a regressor.

Results for the control variables are consistent with findings in the existing literature or theoretical expectations (not reported). For example, larger farms (in terms of utilised area or economic size) incurred higher production cost per farm and generated higher gross product and profit per farm. Individual farms had less intermediate and hired labour cost but lower performance in terms of milk yield, gross product, profits and total and pure technical efficiency. Age and the reliance on rented land had no significant impact on any performance indicator, confirming the ambiguous expectations for these two variables. Despite raising the production cost, a higher reliance on hired labour compared to

Table 5
R-squared statistics for the 150 OLS regressions. Source: authors' calculations.

Farm performance indicator (dependent variable)	Obs.	Mean	Std. deviation	Min	Max
Production costs					
Fertiliser cost per farm	468	0.355	0.001	0.354	0.357
Seed cost per farm	468	0.432	0.001	0.431	0.433
Pesticide cost per farm	468	0.638	0.001	0.637	0.640
Fuel cost per farm	468	0.474	0.003	0.472	0.481
Intermediate consumption cost per farm	468	0.542	0.002	0.541	0.547
Hired labour cost per farm	468	0.664	0.002	0.660	0.667
Yields					
Wheat yield	341	0.266	0.017	0.245	0.298
Milk yield	269	0.172	0.011	0.161	0.193
Revenue and profitability without farm subsidies					
Gross product per farm	468	0.578	0.002	0.576	0.581
Gross margin per farm	468	0.480	0.002	0.477	0.483
Operating surplus per farm	468	0.240	0.003	0.238	0.245
Pre-tax profit per farm	468	0.184	0.002	0.182	0.190
Efficiency scores					
Total technical efficiency	468	0.214	0.007	0.206	0.222
Pure technical efficiency	468	0.145	0.003	0.141	0.151
Scale efficiency	468	0.151	0.005	0.147	0.163

own labour enabled farms to generate higher gross product and gross margin, but lower pre-tax profit (the latter result presumably being caused by the higher cost of hired labour), and higher total technical and scale efficiency. Similar findings are obtained for the capital to labour ratio, confirming the expectation that both these variables capture specific aspects of farms' technology. Operational subsidies received per hectare of land increased the cost of pesticides confirming the expectations that they are input use facilitators, and contributed to higher farm performance in terms of milk yield and scale efficiency. The location in an area subject to nitrate pollution zoning restrictions had a positive impact on milk yield and pure technical efficiency, giving grounds for the Porter hypothesis.

Due to space constraints, we do not present the detailed results for each of the 150 regressions. Instead, we report in Table 6 the signs and significance levels of the regression coefficients obtained for each LF descriptor.

The first observation is that most of the performance indicators are explained by more than one LF descriptor. In addition, several performance indicators (intermediate consumption cost, gross product, gross margin, operating surplus) which are not significantly explained by the –traditionally used– LF descriptors (number of plots and average size of plots) are explained by more elaborate indexes. This gives support to our strategy of considering the various dimensions of LF when studying its impact on farm performance.

Table 6

Fragmentation and FADN farms' performance: sign and significance of regression coefficients for the transformed LF descriptors.[a] Source: authors' calculations.

Farm performance indicator (dependent variable)	Fragmentation in terms of number of plots	Fragmentation in terms of plot shape		Fragmentation in terms of plot size		
	Number of plots ($nplot_r$)	Weighted average plot shape index ($wshsq_r$)	Average plot areal form factor ($aform_r$)	Average plot size ($avpls_r$)	Simpson index ($simps_r$)	Januszewski index ($janus_r$)
Production costs						
Fertiliser cost per farm	ns	ns	ns	ns	ns	ns
Seed cost per farm	ns	ns	ns	ns	ns	ns
Pesticide cost per farm	ns	ns	ns	ns	ns	ns
Fuel cost per farm	ns	ns	ns	+**	ns	ns
Intermediate consumption cost per farm	ns	ns	ns	ns	ns	ns
Hired labour cost per farm	+°	−*	ns	+°	+*	+*
Yields						
Wheat yield	−**	ns	ns	−*	−*	−**
Milk yield	−°	ns	ns	ns	−°	−*
Revenue and profitability without farm subsidies						
Gross product per farm	ns	−°	ns	ns	ns	ns
Gross margin per farm	ns	−*	−*	ns	ns	ns
Operating surplus per farm	ns	−°	−*	ns	ns	ns
Pre-tax profit per farm	−°	ns	ns	ns	ns	ns
Efficiency scores						
Total technical efficiency	−**	ns	ns	−*	−*	−**
Pure technical efficiency	−*	ns	ns	ns	ns	−°
Scale efficiency	ns	ns	ns	ns	ns	ns

Farm performance indicator (dependent variable)	Fragmentation in terms of distance from the farm			Fragmentation in terms of plot scattering
	Average distance of a hectare ($avdha_r$)	Grouping index ($grpgi_r$)	Structural index ($strui_r$)	Normalised av. nearest neighbour distance ($nannd_r$)
Production costs				
Fertiliser cost per farm	ns	ns	ns	ns
Seed cost per farm	ns	ns	ns	ns
Pesticide cost per farm	ns	ns	ns	ns
Fuel cost per farm	ns	+*	ns	ns
Intermediate consumption cost per farm	+*	ns	ns	ns
Hired labour cost per farm	+*	+*	ns	ns
Yields				
Wheat yield	−*	−*	−**	ns
Milk yield	−**	−***	−*	ns
Revenue and profitability without farm subsidies				
Gross product per farm	+°	+°	ns	+°
Gross margin per farm	ns	+°	ns	+**
Operating surplus per farm	ns	ns	+*	+**
Pre-tax profit per farm	ns	ns	ns	ns
Efficiency scores				
Total technical efficiency	−*	−*	ns	ns
Pure technical efficiency	ns	ns	ns	+*
Scale efficiency	ns	ns	ns	ns

[a] The fragmentation descriptors (columns) are calculated at the municipality level and transformed so that for each descriptor, a rise in its value implies greater fragmentation. Hence, positive (resp. negative) sign indicates a positive (resp. negative) impact of fragmentation on the performance indicator considered.
ns: not significant at the 10% level.
*** Significance at the 0.1% level.
** Significance at the 1% level.
* Significance at the 5% level.
° Significance at the 10% level.

Most results regarding the detailed links between LF descriptors and performance indicators conform to expectations, that is to say LF increases production costs and decreases yields, revenue, profitability and efficiency. For example, fragmentation measured by the number of plots has a positive significant impact on hired labour cost, and a negative significant impact on both yields, on pre-tax profit and on technical efficiency (total and pure). This supports the expectation of higher costs of organising and controlling the production process. Greater fragmentation in terms of plot size (when measured by either of the three corresponding descriptors) significantly raises hired labour cost, and significantly reduces milk yield and total technical efficiency, confirming the impossibility to exploit of economies of scale. Greater fragmentation in terms of plot shape significantly reduces gross product and profitability, confirming the expectation of lower machinery's field-efficiency and higher harvest loss when plots are irregularly shaped. Results for all three descriptors capturing fragmentation in terms of distance from the farm reveal that the greater the fragmentation, the lower the wheat and milk yields. In addition, two of these descriptors (namely $avdha_r$ and $grpgi_r$) show that fragmentation has a positive impact on hired labour cost and a negative impact on total technical efficiency. These findings may be explained by conflicts in labour allocation or problematic water management as suggested in Section 2. However, the opposite mechanisms also seem to play a role: fragmentation as measured in terms of distance from the farm increases farm gross product and profitability and the greater the fragmentation in terms of plots' scattering, the greater the gross product, profitability and pure technical efficiency. As also explained in Section 2, such positive effects may reveal better matches between crops and soils, more efficient labour use and lower production risk, implied by crop diversification.

Only one result shown in Table 6 does not conform to *a priori* expectations: the estimated coefficient for the weighted average plot shape index ($wshsq_r$) reveals that fragmentation in this dimension reduces hired labour cost. A possible explanation pertains to the specific use of irregularly shaped plots: due to low field-efficiency of machines and harvest loss on such plots, farmers may prefer not to cultivate field crops (such as cereals) there but rather to use them as permanent pastures or even leaving them unutilised, thus reducing the need for labour.

In order to present the regression results in a more vivid way, we simulated the impact of a reduction in LF at the municipality level on three key performance indicators: wheat yield, pre-tax profit and total technical efficiency. This reduction in LF could hypothetically be reached by, for example, a consolidation programme. To this end, we computed for each LF descriptor what improvements in wheat yield, pre-tax profit and total technical efficiency could be obtained by the average farm when moving, at the municipality level, from one LF quartile to the next in the direction of reducing fragmentation. With this, fragmentation improvements are immediately readable in terms of tons per hectare for wheat yield, Euros for pre-tax profit and efficiency score for total technical efficiency. Therefore, this can illustrate the relative importance of LF descriptors whose estimated regression coefficients are not directly comparable with each other.

Table 7 illustrates that, in terms of wheat yield, the highest benefits (around 0.6 ton per hectare, or a 11% increase) would be obtained from a reduction either in the structural index ($strui_r$) or the grouping index ($grpgi_r$), *i.e.*, by reducing the maximum distance of plots from their barycentre, rather than their average distance ($avdha_r$) which would only result in a 0.3 ton per hectare yield increase. The second best option would consist in improving the distribution of plot sizes at the municipality level as measured by the Januszewski ($janus_r$) and the Simpson ($simps_r$) indexes, rather than reducing the number of plots per farm, with expected gains estimated above 0.41 ton per hectare (or an 8% increase). In terms of total technical efficiency, reducing fragmentation in terms of plot size as measured by the Januszewski index ($janus_r$) would bring the highest improvement, on average, in efficiency score,

Table 7
Wheat yield and total technical efficiency regression results and potential improvements for each land fragmentation descriptor.[a] Source: authors' calculations.

Land fragmentation descriptor	Descriptor quartiles		Transformed quartiles		Regression estimate (*std. dev.*)		Improvement (*std. dev.*)	
	Q1	Q3	Q1	Q3	Wheat yield	Total technical efficiency	Wheat yield (tons per hectare)	Total technical efficiency
Number of plots ($nplot_r$)	15.58	21.53	0.184	0.380	−1.999** (*0.669*)	−0.128** (*0.045*)	0.393** (*0.131*)	0.0252** (*0.0088*)
Weighted average plot shape index ($wshsq_r$)	1.312	1.374	0.338	0.575	ns	ns	ns	ns
Average plot areal form factor ($aform_r$)	0.042	0.044	0.395	0.641	ns	ns	ns	ns
Average plot size ($avpls_r$)	3.85	5.79	0.371	0.574	−2.011* (*0.800*)	−0.122* (*0.059*)	0.408* (*0.162*)	0.0248* (*0.0121*)
Simpson index ($simps_r$)	0.820	0.863	0.400	0.649	−1.654* (*0.652*)	−0.101* (*0.041*)	0.412* (*0.162*)	0.0252* (*0.0103*)
Januszewski index ($janus_r$)	0.276	0.327	0.371	0.632	−1.733** (*0.608*)	−0.112** (*0.040*)	0.451** (*0.158*)	0.0292** (*0.0103*)
Average distance of a hectare ($avdha_r$)	1.515	1.778	0.214	0.391	−1.749* (*0.851*)	−0.093* (*0.044*)	0.311* (*0.151*)	0.0165* (*0.0078*)
Grouping index ($grpgi_r$)	8.097	10.357	0.193	0.391	−3.004* (*1.180*)	−0.132* (*0.052*)	0.596* (*0.234*)	0.0263* (*0.0103*)
Structural index ($strui_r$)	1.847	3.363	0.015	0.048	−18.309** (*7.017*)	ns	0.603** (*0.231*)	ns
Normalised average nearest neighbour distance ($nannd_r$)	0.843	1.075	0.240	0.442	ns	ns	ns	ns

[a] For each LF descriptor, the 'improvement' (two last columns) represents what would be, for the average farm, the impact on the wheat yield and on the total technical efficiency of a reduction in the fragmentation of the surrounding municipalities obtained by moving from the transformed quartile Q3 to the transformed quartile Q1 (columns four and five) given the estimated regression coefficients (columns six and seven).
ns: not significant at the 10% level.
*** Significance at the 0.1% level.
** Significance at the 1% level.
* Significance at the 5% level.
° Significance at the 10% level.

namely an increase of the score by 0.0292. This implies that the possible increase in output without increasing inputs would be reduced from 22.9% on average (for an average score of 0.771) to 20.0% (for an average score of 0.771 + 0.0292), that is to say a reduction in output waste of 12.7%. Improving fragmentation in terms of the two other plot size indicators (average plot size and Simpson index), the grouping index or the number of plots would bring a reduction in output waste of about 11%, while the improvement would only be of 5.8% for a decrease in the average distance of a hectare ($avdha_r$). As for pre-tax profit, the only significant regression estimate regarded the number of plots (Table 6); it reveals that moving from one quartile to the next better (*i.e.*, with fewer plots) would increase the pre-tax profit by 3824.94 Euros per farm on average that is to say an improvement by 29% (result not shown in Table 7). As a comparison, del Corral et al. (2011) found an improvement in farm profit of 11.7% for a reduction in the number of plots, at the farm level, from 14 to 4 for their sample of Spanish dairy farms.

Such improvement figures may look quite substantial. However, they are mainly intended to illustrate our results and especially to compare the marginal benefit (or, reciprocally, the relative burden) of each LF dimension on the various aspects of performance. They should not be viewed as accurate predictions, for at least three reasons. Firstly, the simulated LF improvements may actually be very substantial themselves, hence very costly to implement in real life. Thus these implementation costs should be compared, in addition to comparing the benefits from improving one LF descriptor with respect to the others. Secondly, it is hardly plausible that a particular consolidation programme would enhance one LF descriptor only, leaving the others unchanged. In general, a consolidation programme would seek to improve several LF dimensions at the same time, *e.g.*, by reducing the number and distance of plots, improving their shapes and increasing their average size. However, these dimensions may be competing among themselves to some extent, so that a compromise would have to be reached, leading to a limited improvement in each dimension – if not to a deterioration for some descriptors in some cases. It is our view that the way in which these multi-dimensional benefits and costs aggregate together remains an empirical question, which may be addressed only thanks to hypothetical simulations such as that of Gonzalez et al. (2007) or for specific case studies. Thirdly, the improvements revealed by our simulations may also reveal that such heavy consolidation programmes are likely to induce additional changes in farming practices and in farm production, so that they should not be simply compared to the average pre-consolidation figures as if they were *ceteris paribus*.

5. Conclusion

We have investigated the relationship between agricultural land fragmentation (LF) and farm performance in 2007 in the French region of Brittany. Various farm performance indicators (in terms of costs, yields, revenue, profitability, technical and scale efficiency) calculated for a sample of FADN farms were regressed on several explanatory variables, including LF descriptors computed for the municipalities where those farms were located as well as their neighbouring municipalities to account for the fact that farms usually operate several of their plots outside the farmstead's municipality. The choice of calculating LF at the municipality level to proxy farm fragmentation was primarily caused by data limitations. Firstly, in France there exists no single database which permits the simultaneous calculation of LF descriptors and of performance at farm level for a large sample of farms. Secondly, the two databases used (RPG for calculating LF and FADN for calculating performance) include farm-level data but farm identifiers differ, and only the farm municipality is common to both databases. Our analysis therefore aimed at assessing whether using farm-level performance and municipality-level LF, could be relevant for studying the link between performance and fragmentation in agriculture. Among the LF descriptors used, we considered not only the number of plots and the mean size of plots which are traditionally used in the economic literature investigating the impact of LF on farm performance, but also more complex indexes, in order to account for: the shape of plots; (a proxy of) the distance between plots and farmsteads; and (a proxy of) the distance between plots themselves (or scattering of plots).

In our view, our analysis highlights that, from a methodological perspective, the measures of LF traditionally used in the literature, namely the number of plots and the average plot size, may not reveal the full set of significant relationships with farm performance because they do not capture all the dimensions of LF. In particular, they exclude shape and distance considerations, while we have shown that these dimensions significantly impact the performance of our sample farms. However, circumventing the absence of information regarding the location of the farmsteads by computing distances relative to the farm barycentre, as we have done in this paper, may introduce some bias that would be worth investigating.

Considering only the significant relationships, we reached three main findings. Firstly, consistent with results found in the previous literature and with theoretical considerations, LF is overall harmful to farm performance. Several explanations may be brought forward, depending on the LF descriptor: *e.g.*, costs of organising production (in case of numerous plots), limited innovations uptake (when plots are too small), harvest losses (caused by irregular plot shape), increased labour costs (due to plots' dispersion). However, we also found that LF may favour farm performance, which is also consistent with theoretical considerations. This finding was evidenced for the effect of fragmentation measured in terms of plots' distance from the farm on gross product, profitability and pure technical efficiency. It may be explained by the cropping pattern optimisation effect, where the spatial dispersion of plots allows better matches between crops and soils and micro-local climatic conditions, a more efficient use of labour and the mitigation of risks. Secondly, these general conclusions should not hide the fact that in one case the impact of LF on farm performance was the opposite of that expected, namely higher fragmentation in terms of plot shape reduces hired labour cost. This finding may reveal farmers' strategy regarding land use in the presence of fragmentation, as irregularly shaped plots may not be used for producing crops that would require intensive machinery and labour use. Thirdly, a simple simulation has shown that the benefits from reducing fragmentation may differ with respect to the improved LF dimension and the performance indicator considered. The overall impact of a real-life consolidation programme, which may modify several LF dimensions at the same time, remains an empirical open question which should be investigated carefully in each specific case.

From a policy point of view, using various performance indicators and various LF descriptors has allowed to show that the effect of LF may be negative or positive, depending on how both aspects are measured. For our sample this is in particular the case of LF descriptors measuring the distance of plots from the farmsteads: a greater fragmentation in this dimension reduces productivity as well as total technical efficiency but increases gross product and profitability. Hence, policy-makers may have to decide which performance dimension they aim at favouring before setting up consolidation programs.

From a methodological point of view, using LF at the municipality level to proxy farm LF, as we did, appears a relevant approach, for two reasons. Firstly, many significant relationships between performance and LF were found. Secondly, signs of these relationships but one were consistent with theoretical expectations. This is a useful conclusion for countries like France where the available databases to study farm performance on a large sample (*e.g.*, FADN) do not include information about fragmentation. However, this approach relies on the assumption of a direct positive correlation between the LF of the municipality where the considered farm is located, and the LF within the farm itself. In fact, it may happen that a lowly (respectively, highly) fragmented farm may be located in a highly (lowly) fragmented municipality. Finding a way to gain access to a measure of fragmentation at the individual farm level constitutes a major challenge. While in France the easiest would be to modify farm identifiers so that they are the same in the FADN database and in the RPG, it is not something that will happen in the near future. From a general point of view, ideally a single database needs to be constructed at the farm level which would include information on both aspects. This could be done by enlarging the collected bookkeeping data, so as to include information on the farms' LF (*e.g.*, the number of plots, the share of farming area within a certain distance from the farmstead, etc.). Another possibility is to conduct specific surveys on a large number of farms, and to collect all data needed at the same time. This strategy has been carried out in several papers, such as Nguyen et al. (1996), Van Hung et al. (2007) and di Falco et al. (2010). The main limitation is the incurred cost, which means that often very few farms are surveyed.

Finally, some methodological limitations should be considered with great care before our approach could be used to set up an effective consolidation programme. Firstly, endogeneity issues would have to be investigated carefully: although we can be relatively confident that the relationship between variables is mainly in one direction from a static point of view, namely that municipalities' LF influences farms' performance, it might be that, in a dynamic perspective, efficient farms are more likely to decrease their fragmentation at the expense of neighbouring farms. Secondly, as explained above, some relationships between LF and performance which appear contrary to expectations in our work may be explained by land use decisions rather than farming practices. That is to say, farmers act rationally so as to make the best use of their land given the LF. Detailed information about land use and crop pattern on the farm may therefore be required. Although our analysis has shed some light on the link between the performance of a farm and the LF in the municipality where it is located, further investigation is therefore needed, especially before any policy recommendations can be made.

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Appendix A.

Formal definitions of the LF descriptors used before their transformation

Considering:

- i a subscript denoting the farms
- $k, l = 1, \ldots, K_i$ subscripts denoting the plots of farm i
- (x_k, y_k) the plane coordinates of the centroid of plot k
- a_k the area of plot k and $A_i = \sum_{k=1}^{K_i} a_k$ the total area of farm i
- p_k the perimeter of plot k
- $(\bar{x}_i, \bar{y}_i) = \left(\frac{1}{A_i}\sum_{k=1}^{K_i} a_k x_k, \frac{1}{A_i}\sum_{k=1}^{K_i} a_k y_k\right)$ the plane coordinates of the barycentre of farm i.

The LF descriptors are defined as follows:

1. LF descriptors relating to the number of plots
- Number of plots: $nplot_i = K_i$

2. LF descriptors relating to the shape of plots
- Weighted average plot shape index: $wshsq_i = \frac{1}{A_i}\sum_{k=1}^{K_i} a_k \frac{p_k}{4\sqrt{a_k}}$
- Average plot areal form factor: $aform_i = \frac{1}{K_i}\sum_{k=1}^{K_i} \frac{a_k}{p_k^2}$

3. LF descriptors relating to the size of plots
- Average plots' size: $avpls_i = \frac{A_i}{K_i}$
- Simpson index: $simps_i = 1 - \frac{\sum_{k=1}^{K_i} a_k^2}{A_i^2}$
- Januszewski index: $janus_i = \frac{\sqrt{A_i}}{\sum_{k=1}^{K_i}\sqrt{a_k}}$

4. LF descriptors relating to the distance of plots from the barycentre of the farm
- Average distance of a hectare:

$$avdha_i = \frac{1}{A_i}\sum_{k=1}^{K_i} a_k \sqrt{(x_k - \bar{x}_i)^2 + (y_k - \bar{y}_i)^2}$$

- Grouping index:

$$grpgi_i = \frac{\arg\max_{k=1}^{K_i}\left(\sqrt{(x_k-\bar{x}_i)^2+(y_k-\bar{y}_i)^2}\right)}{\sqrt{A_i/\pi}}$$

- Structural index:

$$strui_i \equiv \frac{grpgi_i}{avpls_i} = \frac{K_i \cdot \arg\max_{k=1}^{K_i}\left(\sqrt{(x_k-\bar{x}_i)^2+(y_k-\bar{y}_i)^2}\right)}{A_i\sqrt{A_i/\pi}}$$

5. LF descriptors relating to the scattering of plots
- Normalised average nearest neighbour distance:

$$nannd_i = \frac{\sum_{k=1}^{K_i} \arg\min_{l=1}^{K_i}\left(\sqrt{(x_k-x_l)^2+(y_k-y_l)^2}\right)}{K_i\sqrt{A_i/\pi}}$$

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