Land Use Policy 147 (2024) 107380

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Harmonization potential of the fragmented farmlands in Finland: The pros and cons for critical parcel characteristics

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ARTICLE INFO

Keywords:
Distance to farm center
Diversification
Field size
Irrigation
Land exchange
Productivity

ABSTRACT

Agricultural landscapes have been shaped by gradual, partially optimized changes in farms and surrounding areas which have resulted in fragmented agricultural landownership and increased distances on farms. Since Finland joined the EU in 1995, the average farm size has more than doubled which has increased the distances on farms. This may have caused trade-offs with resource use efficiency, productivity, and sustainability. The aim of this study was to evaluate the potential and impacts of land reallocation by integrating regional variability, logistical factors, and emerging satellite imagery, with an emphasis on enhancing resilience in future climates. This study estimated the theoretical potential for land reallocation between farms to reduce farmland fragmentation but also applied fixed land exchange rates (5 % to 40 %) with the primary aim to reduce distances within each farm depending on the farm size and region. The aim was also to identify co-benefits and trade-offs on the number of parcels in a farm, the production capacity of exchanged parcels, diversification potential, and the proximity of parcels to waterways. While keeping the farm size constant, large potential was found to optimize fragmented landscapes and reduce distances within farms especially on large farms. However, only a moderate exchange rate of 5 % almost halved the distances in the best cases of the farms, while exchange rates >20 % provided less additional logistic benefits. Thereby, modest, well targeted measures are not only more acceptable to landowners but may provide the most benefits with fewer trade-offs. In unsatisfactory cases, large parcels were replaced by higher numbers of smaller ones, productivity differences occurred, and closer parcels became more uniform, which may reduce diversification options, which are important for resilience and sustainability. Hence, merging and reshaping nearby parcels after reallocation might be needed to complete rationalization. Estimated changes in the proximity of the parcels to waterways tended to improve the farmers' readiness to implement irrigation as an adaptation measure to climate change. The variable outcome of parcel reallocation emphasizes the central role of the current customer-driven consolidation system chaired by independent land surveyors to boost the land reallocation also in the future to improve logistics, resource efficiency, and sustainability on farms that today struggle with cost-crises.

1. Introduction

In Finland only some seven percent of the land area is agricultural land, while 74 % is forest. Thereby Finland and Sweden are countries with the lowest share of agricultural land in the European Union (EU), while both Ireland and Denmark have the highest share exceeding 60 % of their land area (Balawejder et al., 2023). In general, excessive land fragmentation is a challenge for many EU countries (Balawejder et al., 2023). The total agricultural land area of Finland is 2.24 million hectares, of which 91 % is cultivated and the rest set-aside land (Anon. 2024). Thereby, the Finnish agricultural landscape is often fragmented though this varies largely depending on the region. Land fragmentation has an impact on farm productivity and whether production is intensive or extensive (Hiironen and Riekkinen, 2016; Lu et al., 2018; Orea et al., 2015; Valtiala et al., 2023). The benefits gained by reducing fragmentation differ depending on the degree of heterogeneity and goals set for consolidation actions (Latruffe and Piet, 2014).

Many studies have highlighted that to fully achieve goals, the successful implementation of land exchange calls for tailored planning, involving reasonable numbers of farms (Teijeiro et al., 2020). Prioritized

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https://doi.org/10.1016/j.landusepol.2024.107380
Received 7 April 2024; Received in revised form 30 August 2024; Accepted 30 September 2024
Available online 2 October 2024

goals vary depending on the country and region, but in addition to the general increase in the rationality of agricultural land use, these include: enhanced food security, promotion of rural development and livelihoods, poverty alleviation, better integration of the urban and rural interface, the deployment of abandoned parcels for food production, and the provision of various benefits considering farm management, the economy, resource use efficiency, productivity, and environmental footprint (Crecente et al., 2002; Du et al., 2018; Janus, 2018; Janus and Ertunç, 2023; Li and Song, 2023; Long, 2014; Looga et al., 2018; Lu et al., 2018; Ramírez del Palacio et al., 2022; Zhou et al., 2022). Recent studies have demonstrated how agricultural land rationalization – aiming for shorter distances to the farm center – has markedly reduced the fuel consumption of farm machinery, production costs and the carbon footprint, while often increasing energy and other resource use efficiencies (Balawejder et al., 2023; Ertunç, 2023; Janus and Ertunç, 2023; Ramírez del Palacio et al., 2022). However, this is not necessarily the case when considering irrigation (Kuburić et al., 2022).

Landowners have often opposed consolidation procedures. At the worst, in many focal food production regions such actions have destroyed nature and the environment and suffocated rural livelihoods with the emergence of large land holdings, industrial mega-farms, and international owner-coalitions (Magnan et al., 2023). Past consolidation procedures have today often been replaced by customer-driven, volunteer process that in Finland are chaired by land surveyors and supported by subsidies, without legislative obligations (Balawejder et al., 2023). Like elsewhere in EU, the landowners' primary interest is in supporting rural development, readjusting unfavorable land division, and promoting the rational use of the real property – in Finland, with the main specific objectives of increasing farm size, and improving the road and drainage network (Balawejder et al., 2023; Vitikainen, 2004). Some *post ante* analyses, however, have revealed that in the case of Estonia and the Czech Republic, for example, the land reforms have increased the number of parcels on a farm at the expense of parcel size (Jürgenson, 2016; Sklenicka et al., 2017), which highlights the need for supportive further actions to rationalize parcel use.

Traditionally Finnish farms have been small (Hietala-Koivu, 2002), but the farm size has increased as their number has declined. When Finland joined the EU in 1995, there were some 100,000 farms, but since then the number has systematically decreased: it fell below 70,000 in 2005, was further halved by 2021, and was 42,427 in 2023 (Anon. 2024). The average farm size was 23 ha when Finland joined the EU, while in 2023 it was 53 ha, i.e., the size has more than doubled. The share of farms of $\leq$ 75 ha has decreased and that of larger farms has increased, especially farms with $>$ 150 ha of agricultural land. Family farms dominate (85 %) in Finland. The shift towards a higher farm size has in general increased the distance to the farm center and between parcels on a farm (Hiironen and Ettanen, 2012). On the other hand, larger farms have more suitable land for the cultivation of more diversified crops (Peltonen-Sainio and Jauhiainen, 2019). Furthermore, large economic units have opportunities, but often also a necessity to merge close parcels, reshape them, improve the transport infrastructure, and reconstruct drainage systems to gain logistic advantages and to achieve better resource use efficiency (Balawejder et al., 2023).

Agriculture has a central role in maintaining rural landscapes and preserving biodiversity. Many characteristics of field parcels like their size, distance to farm center, shape and ownership, impact how Finnish farmers allocate crops to them (Hiironen and Niukkanen, 2014; Peltonen-Sainio et al., 2018). Thereby, the reorganization of field parcels between farms may bring benefits by diversifying crops on a farm and could enhance productivity due to better crop sequencing and land use in Finland (Peltonen-Sainio et al., 2024; Peltonen-Sainio et al., 2019a; Peltonen-Sainio and Jauhiainen, 2019). On the other hand, land use rationalization may jeopardize the aim to restore biodiversity with mosaic landscapes and open drainage systems (Herzon et al., 2018, 2011; Mäkeläinen et al., 2019; Riho et al., 2013). The risk for lost heterogeneity can, however, be compensated for by e.g., buffer zones, ecological corridors, allocation of environmental fallows and nature managed fields to the parcels characterized as poor quality, having shelter belts, and maintaining patches of forest in arable land (Kocur-Bera et al., 2023; Peltonen-Sainio et al., 2019b; Toivonen et al., 2013).

Previous studies have shown the benefits of reducing fragmentation, and also that the benefits vary based on the degree of heterogeneity and the goals set for consolidation actions. However, the potential for enhancing resilience in future climates through parcel reorganization has been only partially explored. Furthermore, emerging remote sensing datasets, such as open Sentinel-2 imagery, have not been fully leveraged in these analyses. The objective of this study is to comprehensively evaluate the potential and impacts of land reallocation in Finland by integrating regional variability, logistical factors, and emerging satellite imagery, with an emphasis on enhancing resilience in future climates. This *ex ante* study seeks to address the following research questions. 1) How does the theoretical potential for land reallocation between farms vary across different regions in Finland? 2) How do fixed land exchange rates affect the reduction of distance between field parcels and the farm center, as well as the number of parcels per farm, considering farm size and region? 3) How can emerging open satellite image datasets be utilized to assess the production capacity of exchanged parcels? 4) How does land reallocation affect sustainable development goals, particularly regarding the opportunities to diversify land use as to increase resilience in future climates, and the proximity of exchanged parcels to waterways, thereby influencing future irrigation opportunities? The study encompasses five different regions in Finland to capture a wide range of fragmentation levels, farm sizes, and environmental conditions, ensuring that the conclusions are applicable to a broad geographic context.

2. Materials and methods

2.1. Study area and background

Finnish agricultural landscape is fragmented though this varies largely depending on the region. The share of agricultural land is high in South-, South-West- and West-Finland. In East- and North-Finland as well as in inland regions, forests dominate the landscapes, farms are often detached, and agricultural landscapes are scattered, which may reduce opportunities for parcel rearrangements between farms (Balawejder et al., 2023). Fig. 1 illustrates the different regions, labeled A-E.

Prehistoric settlement has played a significant role in determining the basis for agriculture and land use (Zvelebil and Rowley-Conwy, 1984). In Finland likewise in Europe, lakeside settlements were common because they offered various ecosystem services for developing agrarian societies (Pollmann, 2014). The postglacial land upheaval of coastal areas in Finland provided fertile soil for agriculture (Taavitsainen et al., 1998). Hence, contrary to inland regions traditional slash-and-burn cultivation was not the dominant practice in the coastal regions. Instead, cereals were grown in permanent fields while shore meadows provided feed for livestock (Roeck Hansen, 1998; Wallin and Segerström, 1994). However, from time-to-time settlements were relocated closer to the seashore as land upheaval advanced.

From 1757 *the general parceling out of land*, i.e., *basic land consolidation* took place in Finland, as part of Swedish Kingdom, to increase food production capacity and security (Balawejder et al., 2023; Vitikainen, 2004). In 1848, when Finland was part of Russian Empire, *the further reorganization of farm boundaries,* i.e., a *re-arrangement of basic land consolidation* was implemented with the aim to reallocate pieces of land to provide larger, less scattered field areas (Hiironen and Riekkinen, 2016). Since Finland's independency in 1917, new land consolidation actions have been implemented based on national legislation. The current prime crop production regions in the southern and western Finland (Fig. 1) were among the pioneering regions that implemented the large

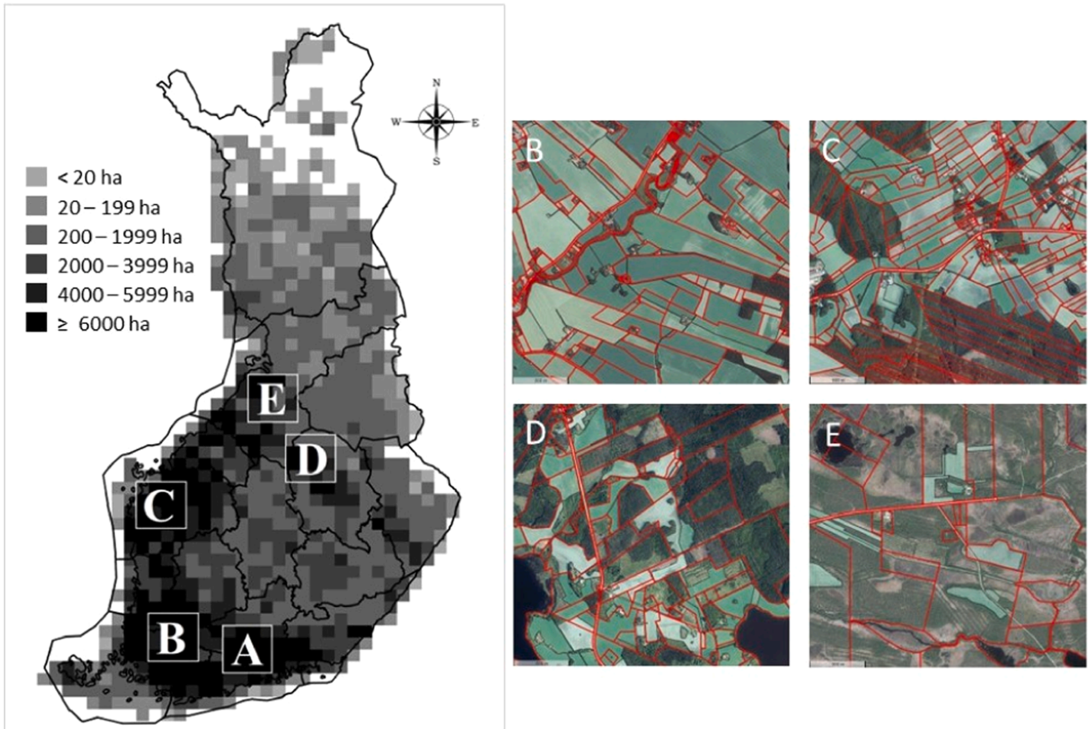

Fig. 1. The total agricultural land (ha) in 20 × 20 km grids in Finland (left map) with five studied subregions: A = South-, B = South-West-, C = West, D = East- and E = North-Finland. Typical Finnish agricultural landscapes from different areas of Finland (red lines indicate cadastral boundaries).

and ambitious reforms (Balawejder et al., 2023).

2.2. Estimating maximum potential for parcel exchange and impacts on distances

To determinate the overall potential of land exchange in different regions of Finland, the theoretical maximum potential was first estimated. The basic requirement was that both the location of the farm center and the farm size remained unchanged. The theoretical maximum exchange potential was estimated by redistributing parcels in each region by minimizing distances without setting any limits for exchanged land area per farm.

The share of agricultural land associated with the number of field parcels in Finland differs largely depending on the region being the highest in the southern and western coastal regions and the lowest in the inland, eastern, and northern parts of the country (Fig. 1). To estimate the theoretical, maximum potential for parcel exchange and to understand how this varied depending on region, an unlimited exchange procedure was first carried out by minimizing the parcel distance to the farm centers. All analyses were done for 20 × 20 km grids. A farm in each grid was included in analyses provided that it had 1) a field area more than 20 ha, 2) at least six field parcels, and 3) at least 75 % of the parcels were inside the 20 × 20 km grid and the rest 25 % inside a 40 × 40 km grid. Furthermore, at least six farms in a 20 × 20 km grid needed to fulfil these conditions to be included in the analyses.

Farm and parcel data were from the Finnish Food Authority. The data (shp file) covered > 99 % of all field parcels in Finland (2.2 M hectares). The coordinates of the boundary of parcels, the parcel area (ha), and the parcels cultivated by each farm were known. The data indicated whether parcels were owned or rented. The data was from 2020. The total agricultural area of each farm (ha) was calculated. First, the shp-file was read and the current average distance from the farm center to the parcels was calculated for each farm using the SAS software. After that, the average distance over all farms in each 20 × 20 km grid cell was calculated. The following groups of the average distance before land exchange analyses (current) were set: 1) ≤ 1200 m in a 20 × 20 km grid, 2) 1201–1400 m, 3) 1401–1600 m, 4) 1601–1800 m, 5) 1801–2000 m, and 6) > 2000 m. Thereafter, a full-scale exchange of field parcels was computed to minimize the distance from farm center to the field parcels by keeping each farm's agricultural land area as constant as possible (i.e., maximum tolerance of ±1.0 ha) but allowing unlimited number of parcels to shift between farms. All distances were calculated as the crow flies. The actual distance along roads was 1.4–2.1 times based on a sample of 4 × 100 field parcels. After this procedure, the average decline in distance from the current situation was calculated and 20 × 20 km grid cells were grouped as follows: 1) ≤ 400 m in a grid cell, 2) 401–500 m, 3) 501–600 m, 4) 601–700 m, 5) 701–800 m, and 6) > 800 m. The decline in the average distance was also presented in percentages: 1) ≤ 40 % in a 20 × 20 km grid, 2) 41–50 %, 3) 51–60 %, 4) 61–70 %, 5) 71–80 %, and 6) > 80 %. Furthermore, the share of parcels left of a farm were calculated as a weighted average by taking into account the parcel sizes: 1) ≤ 35 % in a 20 × 20 km grid cell, 2) 36–45 %, 3) 46–55 %, 4) 56–65 %, 5) 66–75 %, and 6) > 75 %.

2.3. Using limited acceptance rates for land exchange between farms

After identifying the theoretical maximum potential for land exchange, limits were set to understand how big part of this potential is achieved when rationalizing the magnitude of the change by limiting the exchange rate between farms so that the farm would keep at least 60–95 % of its current field area that was closest to the farm center. Thereby, only distant fields were included in the estimations of land exchange. Based on these analyses it was possible to study differences between the exchanged parcels that contribute to logistics, resource efficiency, resilience, and sustainability.

After estimating the theoretical potential for parcel exchange in Finland, five sub-regions, 80 × 80 km in size (the square-shaped areas labeled with letters A-E in Fig. 1), were selected for more detailed analyses to identify regional differences in capacity and outcomes of land exchange. Furthermore, sub-regions were expected to have overall potential for parcel exchange. The capacity to reduce the distance between parcels and the farm center were estimated for each farm in each of the sub-regions by using eight acceptance rates to control the scale of changes: from a 5 % acceptance rate up to 40 % at 5 %-unit intervals, while 0 % represented the current situation. Thereby, in these eight calculations, a maximum of 5 % (to 40 %) of the farm's arable area was allowed to come from other farms (maximum tolerance ±1.0 ha shift). Correspondingly, the furthermost parcels of the farm (5 % of the arable land; maximum tolerance ±1.0 ha) were allocated to some other farm (s). The percentage was allowed to be lower if the farm's own parcels were closer to the farm center than the parcels of the other nearby farms.

The average distance increased the larger the farm. In this case, the benefit of the theoretical potential for parcel exchange, measured in meters, increased with increase in the farm size. Therefore, all the statistical indicators described above were calculated for farms differing in size. It was also tested whether the sub-region-by-indicator interaction was significant by using a standard two-way ANOVA using the SAS/GLM software.

The distribution was presented for the following statistical indicators: the 10th and 90th percentiles, lower and upper quartiles and median. These were used to indicate the impacts of an increase in the land exchange rate in different sub-regions on the decline in the average distance to the parcels on a farm (% and meters) and the share of original parcels that remained on a farm (%). Similarly, the impacts of the applied land exchange rate on the distances and share of original parcels left on a farm were calculated for all farms in a region and for different farm sizes: ≤ 50 ha (small), 51–100 ha (medium), 101–200 ha (large) and >200 ha (very large).

2.4. Estimating impacts of fixed parcel exchange rates on field parcel characteristics

The potential impacts of parcel exchange between farms on opportunities to diversify land use with alternative crops was estimated with a case study. West-Finland (Area C in Fig. 1) was selected as the case area because diversifying crop species can be cultivated there but spring cereals, barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.) and wheat (*Triticum aestivum* L.) are very common in land use. Only farms exceeding 50 ha field area were included as potential for diverse land use, i.e., to have more suitable parcels and thereby, sufficient lot sizes of special crops (Peltonen-Sainio et al., 2020). A total of 394 field parcels were used as data, and the changes in the potential to use more diverse crops was estimated after land exchange in a comparison to the current situation. Farms were first grouped according to the share of hectares suitable for spring cereals in current situation: > 90 %, ∼70 %, ∼50 %, ∼30 %, and ∼20 %. After using the 30 % land exchange rate, the changes in suitability of the parcels on each farm were estimated again farm by farm by acknowledging farmer preferences in the allocation of parcels for different crops depending on the parcel characteristics (Peltonen-Sainio et al., 2020, 2018).

A productivity gap is a Normalized Difference Vegetation Index (NDVI value from Sentinel 2) -based an estimate of the biomass production capacity of a field parcel in a region when compared to the regional mean of NDVI-values in the same year and for the same crop species (Peltonen-Sainio et al., 2019b). NDVI time series were extracted using the EODIE tool (Wittke et al., 2023). The productivity gap cannot be assumed to vary randomly from parcel to parcel, and the productivity gap of adjacent parcels can be assumed to be more similar than parcels further apart. Therefore, in the case of a parcel exchange, one farm may get several high-quality parcels, while another farm may receive several poor parcels. The spatial dependence of the productivity gap was measured using a variogram. The variogram measures dissimilarity as a function of the distance of observations (Oliver and Webster, 2015). Variograms were calculated for the data of a case region, West-Finland, in two years, 2018 and 2019. The variograms were modeled with a double-exponential model (including short- and long-range component). The spatial dependency of the short-range component ranged up to 300 m, while the long-range component ranged up to 6–10 km, depending on the year. The productivity gap of two field parcels is spatially independent if the distance between parcels is greater than the range of the long-range component. The fitted model was:

$$\gamma(h) = \begin{cases} c_n & , if h = 0 \\ c_n + \delta^2_{short}\left[1 - \exp(-\dfrac{h}{a_{short}})\right] + \delta^2_{long}\left[1 - \exp(-\dfrac{h}{a_{long}})\right] & .if h > 0 \end{cases}$$

in which h is the distance between any two field parcels, c_n is the nugget variance, δ^2_{short} and δ^2_{long} are sill parameters for short- and long-range components, and a_{short} and a_{long} are range parameters of short- and long-range components. The model for the variogram was fitted using the SAS/VARIOGRAM and SAS/NLIN procedures.

Considering the irrigation potential, such field parcels were defined that were next to or < 100 m apart from any waterway (WW: river, lake, pond, stream). The distribution of the proportion of parcels thereby having some form of irrigation potential was studied as in the case for all the other statistical indicators. In addition, the average distance between parcels with opportunities for irrigation was calculated. Organizing irrigation was considered more feasible the closer the parcels were to each other. The change in irrigation potential following land exchange was examined by dividing the farms into four groups according to the current situation: 1) 0–25 %, 2) 26–50 %, 3) 51–75 % and 4) >75 % of the parcels on a farm with irrigation opportunities. Such a comparison was made for the West-Finland sub-region, which is characterized as the most drought-prone region in Finland (Peltonen-Sainio et al., 2021). The calculations of the 30 % land exchange rate were compared to baseline calculations (1.00 = no change) using three variables: a) the average change in proportion of WW parcels, b) the average mutual distances between WW parcels, and c) the variation of the average distance between WW parcels from one farm to another.

3. Results

3.1. Theoretical potential for land exchange to reduce distance between farm center and parcels

The share of agricultural land and the number of field parcels differs depending on region – being highest in southern and western coastal regions and lowest in the inland, eastern, and northern Finland (Fig. 1). Hence, especially in the western coastal primary production regions the current distance to a farm's field parcels was high averaging in some 20 × 20 km grids as > 2000 m and being most often at least 1600 m (Fig. 2). However, distances were also high in northern coastal regions and to some extent in the inland and eastern part of the country, where the averages varied largely even in the nearby grids depending on forest cover. In the southern regions the agricultural landscapes are in general less fragmented and the average distance to the parcels exceeds 1400 m only in a few cases. When estimating the theoretical, maximum potential for parcel exchange to minimize the distances to the farm centers, it was found that the distances would reduce quite dramatically everywhere (Figs. 2 and 3). The potential was, however, highest in all coastal regions from south to north (that have a high share of agricultural land), where the distances could be reduced even to ≤ 400 m in many grids, and only occasionally to exceed 500 m (Fig. 2). Distances declined also in the other regions though were scattered on the map and remained systematically higher than in the coastal regions (Figs. 2 and 3). Hence, in coastal regions the average distance between a farm center and field parcels could often be reduced by > 70 %, in some grids even >80 %. The only exceptions were found in some southernmost areas and in the archipelago where the decline was sometimes < 60 %, and in some grids even ≤ 40 % (Fig. 3). High potential reductions in the distance to the farm center were associated with a low share of remaining original

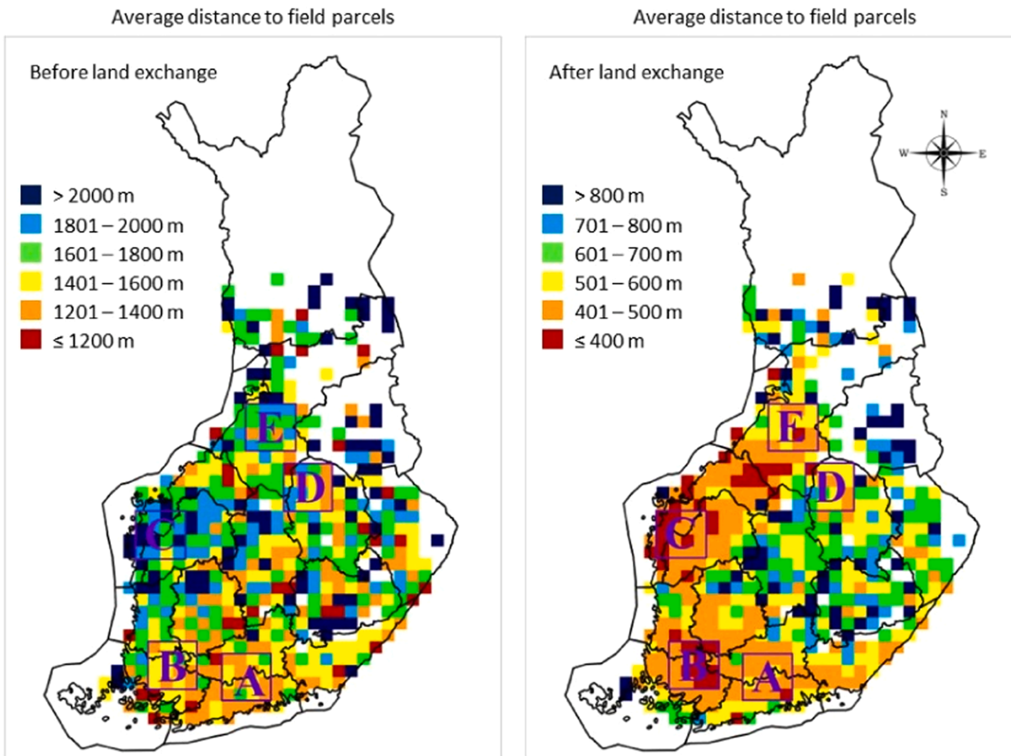

Fig. 2. Average distance to field parcels in meters before (left) and after an unlimited parcel exchange (right) in 20 × 20 km grids in Finland. This extreme case indicates the theoretical potential to reach harmonized farmlands, when the number of exchanged parcels between farms were not limited, but only the field area on a farm was maintained unchanged.

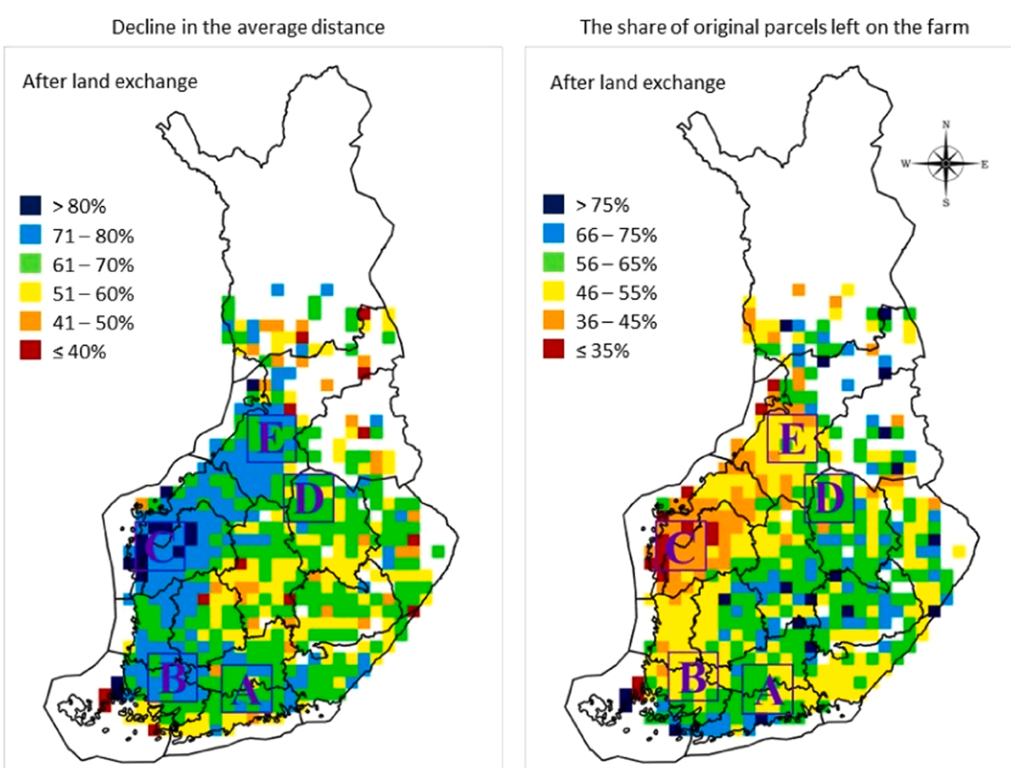

Fig. 3. Decline (%) in the average distance of field parcels to the farm center (left) and share of the original parcels (%) remaining on a farm (right) in 20 × 20 km grids in Finland. These maps indicate the theoretical potential, when the number of exchanged parcels between farms were not limited, but only the field area on a farm was maintained unchanged.

parcels on a farm. In western coastal regions the share was at most 55 % of original parcels, in some grids ≤ 35 %, while in the southern, inland, eastern, and northern regions it was usually > 55 %, and hardly ever lower than 45 % (Fig. 3).

3.2. Fixed land exchange rates and shifts in distances depending on sub-region and farm size

Only the farm size and region explained the variation in the average distance from the field parcels to the farm center: farm size by 37 % (p<0.001) and region by 3 % (p<0.001). The farm type explained <0.1 % (p<0.31), the rest none. The average distances were: 1735 m (s.e.=55 m) for the south sub-region, 1805 m (s.e.=51 m) for the south-west, 2340 m (s.e.=53 m) for the west, 1967 m (s.e.=62 m) for the east, and 1995 m (s.e.=63 m) for the north. The average distances were: 1029 m (s.e.=48 m) for ≤ 50 ha farms, 1626 m (s.e.=50 m) for 50–100 ha farms, 2258 m (s.e.=55 m) for 100–200 ha farms, and 2959 m (s.e.=81 m) for > 200 ha farms.

The significance of the interaction effects was tested using the variance component model. Based on the model, of course, the land exchange rates (from 5 % to 40 %) was the one that had a big effect on the average distance to parcels (explained 87.7 % of the variation), the region explained 4.1 % and the size of the farm 0.5 % only. The largest of the interaction effects was region-by-farm size, which explained 4.1 % of the variation, i.e. as much as the main effect of the region and more than farm size. The land exchange rates-by-farm size interaction (1.9 %) also had a greater effect than farm size alone. This means that a large part of the effect of the region and farm size comes out with the interaction effects rather than the main effects.

The current distance between the farm center and parcels varied a lot between and within regions (Fig. 4). The ascending order of the median distance (from 1030 to 1342 m) was: south → south-west → west → east → north. When 5 %, 20 % and 40 % land exchange rates were used, the median distances were 768–1167 m, 551–761 m and 436–538 m depending on the sub-region. In the best case (the 10th percentile) the distance ranged from only ≤ 363 m in the south to ≤ 609 m in the west, while in the worst case (the 90th percentile of farms) from ≥ 2902 m in the east to ≥ 3578 m in the west.

When applying the 5 % land exchange rate, the distance was in the best case only 55–61 % and in the worst case 89–93 % of the original distance. For the 20 % exchange rate the comparable ranges were 30–37 % and 72–87 %, respectively, and for the 40 % exchange rate 18–25 % and 59–84 %, respectively (Fig. 4). The share of original parcels that remained on a farm declined with a higher land exchange rate quite consistently in all sub-regions. When 5 %, 20 % and 40 % land exchange rules were used, 95 %, 78 % and 55–57 % of the original parcels, respectively, were left in the 10th percentile farms, while this was 100 %, 86–89 % and 65–81 %, respectively in the 90th percentile farms.

The sub-region × farm size interaction was significant (p<0.001). Differences between farm size groups and regions were negligible when 5–10 % land exchange rates were used, but when the rate was ≥ 30 %, the average distance to parcels was often ≤ 50 % from the original, and this was true especially in the case of the large and very large farms (Fig. 5). Contrary to elsewhere, farms in the west hardly differed depending on farm size. As expected, the average distance from the parcels to the farm center was systematically higher on larger farms, though this varied depending on the regions. Nonetheless, they were substantially shortened in meters much more in the larger farms, and halved when a 25 % land exchange rate was used. The share of original parcels that were left on a farm did not often differ greatly depending on the farm size and region.

Average distance compared to the original (%)

Exchanged area	Region A (South) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region B (South-West) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region C (West) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region D (East) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region E (North) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile
0 %	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5 %	0.59	0.72	0.81	0.88	0.93	0.55	0.69	0.80	0.87	0.91	0.55	0.68	0.78	0.85	0.89	0.60	0.73	0.81	0.88	0.93	0.61	0.71	0.80	0.87	0.91
10 %	0.50	0.62	0.74	0.83	0.91	0.45	0.59	0.71	0.81	0.88	0.43	0.56	0.68	0.77	0.83	0.49	0.62	0.73	0.82	0.89	0.48	0.59	0.72	0.80	0.86
15 %	0.40	0.55	0.67	0.79	0.90	0.37	0.51	0.65	0.76	0.85	0.35	0.48	0.60	0.70	0.77	0.40	0.54	0.66	0.77	0.87	0.40	0.51	0.64	0.74	0.83
20 %	0.37	0.49	0.63	0.75	0.87	0.32	0.46	0.59	0.71	0.82	0.30	0.41	0.53	0.63	0.72	0.35	0.48	0.61	0.73	0.85	0.34	0.44	0.58	0.68	0.80
25 %	0.32	0.44	0.59	0.71	0.87	0.29	0.41	0.55	0.68	0.80	0.26	0.36	0.48	0.58	0.67	0.31	0.44	0.58	0.71	0.84	0.30	0.41	0.53	0.65	0.76
30 %	0.29	0.41	0.55	0.69	0.86	0.26	0.37	0.51	0.65	0.79	0.23	0.32	0.43	0.54	0.64	0.28	0.40	0.55	0.68	0.84	0.27	0.37	0.49	0.62	0.73
35 %	0.27	0.38	0.52	0.68	0.84	0.24	0.34	0.47	0.62	0.78	0.20	0.28	0.39	0.50	0.60	0.26	0.38	0.51	0.67	0.83	0.25	0.34	0.46	0.58	0.72
40 %	0.25	0.36	0.49	0.66	0.84	0.22	0.32	0.45	0.61	0.78	0.18	0.26	0.36	0.47	0.59	0.23	0.35	0.49	0.66	0.82	0.23	0.32	0.44	0.56	0.71

Average distance to parcels in a farm (meters)

Exchanged area	Region A (South) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region B (South-West) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region C (West) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region D (East) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region E (North) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile
0 %	363	560	1030	1818	2954	380	617	1065	1899	3057	609	1012	1616	2500	3578	420	634	1187	1866	2902	529	814	1342	2298	3336
5 %	298	435	779	1341	2264	294	445	768	1389	2317	413	693	1167	1892	2724	344	483	879	1435	2353	387	600	1046	1759	2679
10 %	284	407	689	1165	1943	273	408	680	1199	1904	361	605	998	1580	2341	315	444	746	1251	1911	354	549	886	1499	2297
15 %	275	382	629	1044	1664	264	378	601	1032	1688	334	531	865	1394	2014	305	408	668	1080	1631	327	511	786	1286	1995
20 %	275	374	567	920	1459	259	356	551	912	1457	311	464	761	1234	1767	296	390	624	976	1516	326	464	705	1152	1747
25 %	262	349	525	844	1327	254	344	509	811	1271	295	419	677	1088	1569	281	388	566	898	1347	309	425	637	1028	1583
30 %	258	342	506	780	1192	248	329	478	740	1149	272	388	615	963	1386	288	378	536	825	1220	298	401	600	942	1412
35 %	253	334	484	736	1089	240	319	455	678	1039	254	358	557	859	1246	285	375	508	757	1129	288	380	562	852	1304
40 %	251	323	470	699	1003	236	309	436	628	951	251	335	502	792	1125	277	364	494	724	1087	278	368	538	805	1164

Original parcels remained in a farm (%)

Exchanged area	Region A (South) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region B (South-West) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region C (West) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region D (East) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile	Region E (North) 10th Percentile	Lower Quartile	Median	Upper Quartile	90th Percentile
0 %	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5 %	0.95	0.95	0.96	0.98	1.00	0.95	0.95	0.96	0.98	1.00	0.95	0.95	0.96	0.98	1.00	0.95	0.95	0.96	0.99	1.00	0.95	0.95	0.96	0.98	1.00
10 %	0.89	0.90	0.91	0.93	0.99	0.89	0.90	0.91	0.93	0.98	0.90	0.90	0.91	0.93	0.98	0.89	0.90	0.91	0.93	0.99	0.90	0.90	0.91	0.93	0.98
15 %	0.83	0.85	0.86	0.88	0.94	0.83	0.85	0.86	0.88	0.93	0.84	0.85	0.86	0.88	0.92	0.84	0.85	0.86	0.88	0.93	0.84	0.85	0.85	0.87	0.91
20 %	0.78	0.79	0.80	0.83	0.89	0.78	0.79	0.80	0.83	0.88	0.78	0.80	0.80	0.82	0.86	0.78	0.80	0.80	0.83	0.88	0.78	0.80	0.80	0.82	0.87
25 %	0.72	0.74	0.75	0.79	0.87	0.72	0.74	0.75	0.77	0.83	0.72	0.74	0.75	0.77	0.80	0.73	0.75	0.76	0.78	0.85	0.72	0.74	0.75	0.77	0.80
30 %	0.67	0.69	0.70	0.74	0.85	0.66	0.69	0.70	0.73	0.79	0.67	0.69	0.70	0.72	0.75	0.68	0.69	0.70	0.74	0.84	0.67	0.69	0.70	0.72	0.77
35 %	0.61	0.64	0.65	0.70	0.82	0.61	0.64	0.65	0.68	0.76	0.61	0.64	0.65	0.66	0.70	0.62	0.64	0.66	0.70	0.83	0.62	0.64	0.65	0.67	0.75
40 %	0.56	0.59	0.61	0.68	0.81	0.56	0.58	0.60	0.63	0.74	0.55	0.58	0.60	0.61	0.65	0.57	0.59	0.61	0.69	0.81	0.56	0.59	0.60	0.62	0.73

Fig. 4. The average distance to parcels on a farm when compared to the original (%) and shown in meters as well as the share of original parcels which remained on the farm depending on how high a share of the agricultural land on the farm was accepted for exchange (i.e., from 5 % to 40 % at 5 % intervals; 0 % indicates the current situation). Regional outcomes are shown for 10th and 90th percentiles, lower and upper quartile and median.

		Region A (South)					Region B (South-West)					Region C (West)					Region D (East)					Region E (North)				
	Exchanged area	All farms	≤ 50 ha	51 – 100 ha	101 – 200 ha	> 200 ha	All farms	≤ 50 ha	51 – 100 ha	101 – 200 ha	> 200 ha	All farms	≤ 50 ha	51 – 100 ha	101 – 200 ha	> 200 ha	All farms	≤ 50 ha	51 – 100 ha	101 – 200 ha	> 200 ha	All farms	≤ 50 ha	51 – 100 ha	101 – 200 ha	> 200 ha
Average distance compared to the original (%)	0 %	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5 %	0.79	0.79	0.78	0.79	0.82	0.76	0.75	0.77	0.79	0.80	0.75	0.72	0.76	0.79	0.82	0.79	0.79	0.78	0.80	0.81	0.78	0.77	0.78	0.79	0.81
	10 %	0.72	0.73	0.71	0.70	0.71	0.69	0.69	0.69	0.69	0.68	0.65	0.64	0.66	0.69	0.72	0.71	0.72	0.69	0.72	0.70	0.69	0.69	0.69	0.69	0.69
	15 %	0.66	0.69	0.66	0.63	0.64	0.63	0.64	0.62	0.62	0.62	0.58	0.57	0.59	0.61	0.64	0.65	0.67	0.62	0.64	0.63	0.62	0.64	0.61	0.62	0.61
	20 %	0.62	0.66	0.61	0.58	0.59	0.58	0.61	0.57	0.56	0.56	0.52	0.51	0.53	0.54	0.58	0.61	0.64	0.57	0.59	0.59	0.57	0.60	0.55	0.57	0.55
	25 %	0.58	0.63	0.57	0.53	0.55	0.55	0.58	0.54	0.52	0.51	0.47	0.47	0.47	0.49	0.53	0.58	0.61	0.53	0.55	0.56	0.53	0.56	0.51	0.52	0.50
	30 %	0.56	0.60	0.55	0.50	0.51	0.51	0.55	0.51	0.48	0.47	0.44	0.43	0.44	0.45	0.49	0.55	0.59	0.51	0.51	0.54	0.50	0.54	0.47	0.49	0.46
	35 %	0.53	0.59	0.52	0.47	0.48	0.49	0.53	0.48	0.45	0.43	0.40	0.39	0.40	0.42	0.45	0.53	0.58	0.48	0.48	0.51	0.47	0.51	0.45	0.46	0.43
	40 %	0.52	0.57	0.50	0.45	0.46	0.47	0.51	0.46	0.43	0.41	0.37	0.37	0.37	0.39	0.42	0.52	0.56	0.47	0.46	0.50	0.45	0.49	0.43	0.44	0.40
Average distance to parcels in a farm (meters)	0 %	1419	890	1421	2168	2785	1474	1003	1489	2146	2882	1911	1506	2071	2568	3281	1458	1040	1715	2341	2841	1729	1106	1800	2292	3021
	5 %	1085	651	1076	1710	2254	1101	697	1114	1682	2304	1438	1079	1569	2032	2688	1125	784	1315	1895	2252	1332	838	1376	1777	2425
	10 %	951	582	951	1477	1930	961	627	961	1460	1955	1232	931	1333	1745	2344	982	686	1133	1689	1905	1150	740	1171	1544	2041
	15 %	848	523	848	1311	1705	852	560	851	1285	1744	1082	810	1179	1537	2081	869	618	991	1479	1706	1011	671	1001	1365	1801
	20 %	768	483	763	1178	1548	769	512	767	1150	1561	956	718	1037	1351	1873	791	572	889	1333	1582	902	612	879	1220	1591
	25 %	707	448	704	1070	1428	697	466	697	1036	1396	848	637	916	1209	1683	730	531	820	1210	1490	821	563	802	1100	1435
	30 %	654	419	652	986	1318	638	430	643	940	1266	763	566	832	1091	1534	678	497	756	1120	1414	754	524	726	1015	1319
	35 %	611	397	607	913	1227	591	403	595	867	1157	689	510	749	987	1400	638	472	710	1034	1346	700	493	668	941	1222
	40 %	577	380	572	853	1146	554	379	558	810	1073	631	467	684	909	1286	604	449	671	971	1308	656	465	633	876	1120
Original parcels remained in a farm (%)	0 %	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	5 %	0.97	0.97	0.96	0.96	0.95	0.97	0.97	0.97	0.96	0.95	0.97	0.97	0.96	0.96	0.95	0.97	0.97	0.96	0.96	0.95	0.97	0.97	0.97	0.96	0.96
	10 %	0.92	0.93	0.91	0.91	0.90	0.92	0.93	0.91	0.91	0.90	0.92	0.93	0.91	0.91	0.90	0.92	0.93	0.91	0.91	0.90	0.92	0.93	0.91	0.91	0.91
	15 %	0.87	0.88	0.87	0.86	0.85	0.87	0.88	0.86	0.86	0.85	0.87	0.88	0.86	0.85	0.85	0.87	0.88	0.86	0.86	0.85	0.87	0.88	0.86	0.86	0.85
	20 %	0.82	0.83	0.81	0.80	0.80	0.82	0.83	0.81	0.80	0.80	0.81	0.82	0.81	0.80	0.80	0.82	0.83	0.81	0.80	0.80	0.82	0.83	0.81	0.80	0.80
	25 %	0.77	0.79	0.77	0.75	0.75	0.76	0.78	0.75	0.75	0.75	0.76	0.77	0.75	0.75	0.75	0.77	0.79	0.76	0.75	0.75	0.76	0.77	0.76	0.75	0.75
	30 %	0.73	0.75	0.72	0.70	0.71	0.72	0.73	0.71	0.70	0.70	0.71	0.72	0.70	0.70	0.70	0.73	0.74	0.71	0.71	0.71	0.71	0.73	0.70	0.70	0.70
	35 %	0.68	0.71	0.67	0.66	0.66	0.67	0.69	0.66	0.65	0.65	0.65	0.66	0.65	0.65	0.65	0.69	0.70	0.67	0.66	0.67	0.67	0.69	0.66	0.65	0.65
	40 %	0.64	0.67	0.63	0.61	0.61	0.62	0.64	0.61	0.60	0.61	0.60	0.61	0.60	0.60	0.61	0.65	0.67	0.63	0.62	0.64	0.62	0.65	0.61	0.61	0.60

Fig. 5. The average distance to the parcels on a farm when compared to the original (%) and shown in meters, as well as share of original parcels remaining on a farm depending on the region, farm size and how high a share of the agricultural land on the farm was accepted for exchange (i.e., from 5–40 % at 5 % intervals; 0 % indicates the current situation).

3.3. Shifts in parcel characteristics when fixed land exchange rates were applied

The change in the number of parcels on a farm did not differ depending on the sub-region (Fig. 6). When the 5 % land exchange rule was used, the number of parcels in the lower quartile of farms decreased by ca. 5 %, meaning that the average parcel size increased correspondingly (because the land area was kept constant on each farm). Shifts in the land exchange rate did not change this outcome largely. However, in the case of the upper quartile farms, the number of parcels increased steadily from 5 % to 25 % with the land exchange rates of 5–40 %, respectively.

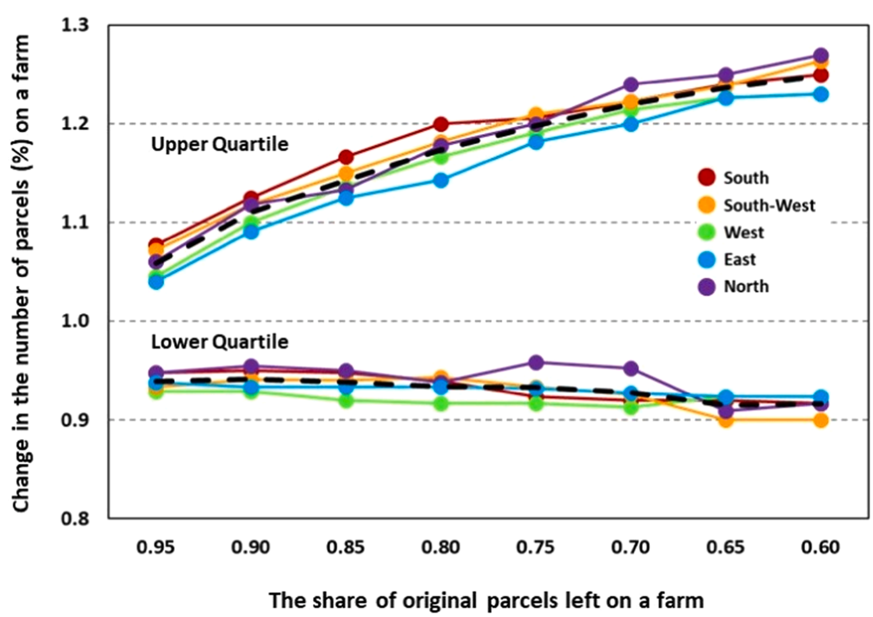

Fig. 6. Lower and upper quartiles for a change in the number of parcels on a farm in different regions depending on how high a share of the original field parcels was left on the farm, i.e., corresponding to land exchange rules of 5–40 % at 5 % intervals.

The potential impacts of land exchange on parcel suitability to diverse crop rotations were estimated only as a case study in the west sub-region with 394 farms that had > 50 ha field area, i.e., with a generally sufficient land area to enable diversified rotations and land use. When spring cereals (barley, oats, and wheat) dominated the current land use by > 90 %, the 30 % land exchange rule increased the potential to diversify crop choices for 10 % of the parcels (Table 1). If the current spring cereal area was ≤ 70 %, the opportunities to diversify land use decreased rather than increased.

The parcels' distance to waterways is critical for the irrigation capacity. When a 30 % land exchange rate was applied in the west case region, it was apparent that the share of parcels that were close to a waterway increased for farms with a low original share of parcels ≤ 100 m from a waterway, which was in contrast to farms with a high original share (Table 2). Only rarely – and in such case most frequently on farms with a high share of parcels next to a waterway – did the share of such parcels remain unchanged. On average the share of parcels next to a waterway on a farm declined by 5 %, 3 % and increased by 6 % and 20 % in the case that the share of field parcels on a farm located nearby a waterway was > 75 %, 50–70 %, 25–50 % and < 25 %, respectively. Thereby, the change was modest: e.g., a 3 % decline on a farm with 80 % of parcels close to a waterway had a 0.24 percentage unit decline, while a 40 % increase on a farm with only 10 % of the parcels close to a waterway had a 4.0 percentage unit increase. However, on average the distance between parcels close to a waterway decreased on a farm: by some 27 %, 15 %, 4 % and 18 % in the case of belonging to the original farm group of < 25 %, 25–50 %, 50–75 % and > 75 % of field parcels close to waterways (Table 2). Farms differed in how scattered the parcels next to waterways were within the farm groups, but such a fragmentation diminished for all farm groups, though most in the case of < 25 % of fields close to a waterway.

In the west case region, the spatial dependency for a parcel productivity gap was found up to 15 km, but a steep angle already occurred for around 800 m, meaning that the closer parcels had high probability that their productivity gaps were alike (Fig. 7). The steep angle at 800 m distance implies that in the case of theoretical potential land exchange parcels on each farm tend to be very alike considering their productivity opposite to the current situation (Fig. 2). However, when comparing this to the outcomes when different land exchange rates were applied for farms differing in size, the average distance to parcels on the medium sized farms (51–100 ha) turned out to be below 800 m in the case of a ≥ 20 % exchange rate in the south and south-west, while elsewhere this distance was reached with a 25–35 % exchange rate (Fig. 5). On the other hand, the average distance was > 1000 m even in the case of a 40 % land exchange rate on the very large farms (> 200 ha).

Table 1
An example of changes in the opportunities for crop choices for parcels in South-West Finland in the case that 30 % of parcels were exchanged between farms. The suitability of the crops is based on large data on how farmers allocate parcels for different crops in Finland (Peltonen-Sainio et al., 2018). Spring cereals are the most common field crops and hence, are shown as a reference, while the alternative crops are shown if their share was >4 % (SP, special crops: rapeseed, field peas and faba beans; WC, winter cereals: rye and wheat; PO, potatoes; these crops most commonly). The test region in South-West Finland has most alternatives for diverse land use (Peltonen-Sainio and Jauhiainen, 2020, 2019).

Land use before parcel exchange		N	Potential to change crops after parcel exchange		
Share of spring cereals	Other most common crops		Increased %	Unchanged %	Decreased %
> 90 %	SP	256	10	90	0
~ 70 %	SP, WC	86	6	67	27
~ 50 %	SP, WC, PO	28	7	39	54
~ 30 %	SP, WC, PO	16	12	44	44
~ 20 %	SP, WC, PO	8	0	38	62
All farms		394	9	78	13

4. Discussion

4.1. Impact of regional variations in the potential for land reallocation

Land exchange may have strong potential to correct fragmented landscapes caused by long-term evolutionary changes in land use – although the outcomes differ largely depending on the region and local conditions (Balawejder et al., 2023; Hiironen and Riekkinen, 2016; Jin et al., 2018). In Finland only the farm size (37 %) and region (7 %) explained variations in the current distance from the field parcels to the farm center. The distance and potential to reduce it were particularly high where agriculture dominated landscapes and farms tended to be larger (Fig. 4). Thereby, farms in the southern and western coastal regions of Finland had much higher potential to benefit from parcel exchange than those in the inland, East, and North (Fig. 2), where farms are usually more fragmented and distant (Fig. 1) due to forestry – but also because of the large lake district especially in the East (Peltonen-Sainio et al., 2015). This result is in agreement with earlier studies where land exchange potential in Finland has been assessed (Hentunen, 2022; Hiironen and Ettanen, 2012). In the coastal regions the average distance between the farm center and parcels could be reduced even by > 70 %, while markedly less elsewhere (Fig. 3). This indicates high potential for logistic advantages especially for large farms where the distances in kilometers were originally very high. Better logistics are often associated with reductions in working hours, fuel consumption, production costs, and environmental footprint (Balawejder et al., 2023; Ertunç, 2023; Janus and Ertunç, 2023; Ramírez del Palacio et al., 2022). The overall high potential to reduce the average distance means a lower share of original parcels left on a farm: even < 55 % in the western regions of Finland, while this was more elsewhere. These figures highlight the current fragmentation of the agricultural land between farms in Finland and thereby indicates the theoretical potential for land exchange. Today the exchanged land areas between farms are, however, modest (Balawejder et al., 2023) but from the negotiated lands even some 25–60 % is changed between farms. This indicates cautiousness, i.e., the participating farmers intend to find feasible solutions for the logistically most critical shortcomings in their farms.

In general, the benefits gained from land exchange differ depending on existing land fragmentation, although these are also affected by the type and exactness of desired changes (Latruffe and Piet, 2014). In this study, in the best case of the farms (the 10th percentile), a 5 % land exchange rate already almost halved the distance to parcels on a farm, while for the other extreme end of the farms (the 90th percentile) reductions were marginal (Fig. 4). Furthermore, at 5–10 % land exchange rates differences between farm size groups and regions were negligible (Fig. 5). Land exchange rates exceeding 20 % provided fewer additional logistic benefits, which underlines that relatively speaking modest, well targeted measures are likely to provide the most benefits.

4.2. Impacts of reallocation on logistical aspects

Even though logistic advantages are primarily sought with land exchange between farms (Balawejder et al., 2023; Janus, 2018), many compromises may occur. Critical trade-offs for Finnish farmers (Peltonen-Sainio et al., 2018, 2015; Peltonen-Sainio et al., 2019b) to be considered include unfavorable changes in parcel number and size, productivity differences between exchanged parcels, the suitability of parcels for diverse crop choices, as well as their proximity to waterways. The parcel size varies a lot in Finland and is critical to crop choices, management, and logistics (Peltonen-Sainio et al., 2018). For example, in Estonia and the Czech Republic land reform has increased the number of parcels on farms at the expense of parcel size (Jürgenson, 2016; Sklenicka et al., 2017). When the land area was kept constant per farm, in the best case for farms (the lower quartile), the number of parcels

Table 2
Four groups of farms differing in the share of the parcels ≤ 100 m apart from a waterway (WW) in South-West Finland and estimated shifts in the proximity to a WW of the four groups in the case that a 30 % land exchange rate was applied, average change as well as change in distance between parcels and fragmentation of parcels between farms close to WW.

Groups of farms with different shares of parcels close to WW	Changes after 30 % land exchange between farms					
	Increased %	Unchanged %	Decreased %	Average change (1.00 = no change)	Average distance between parcels close to WW (1.00 = original distance)	Fragmentation of parcels close to WW between farms (1.00 = original standard deviation between farms)
0– 25 %	70.0	0.4	29.6	1.40	0.74	0.72
26 50 %	61.9	0.9	37.2	1.06	0.85	0.89
51– 75 %	41.3	1.1	57.6	0.97	0.96	0.94
>75 %	18.5	8.6	72.8	0.95	0.82	0.88

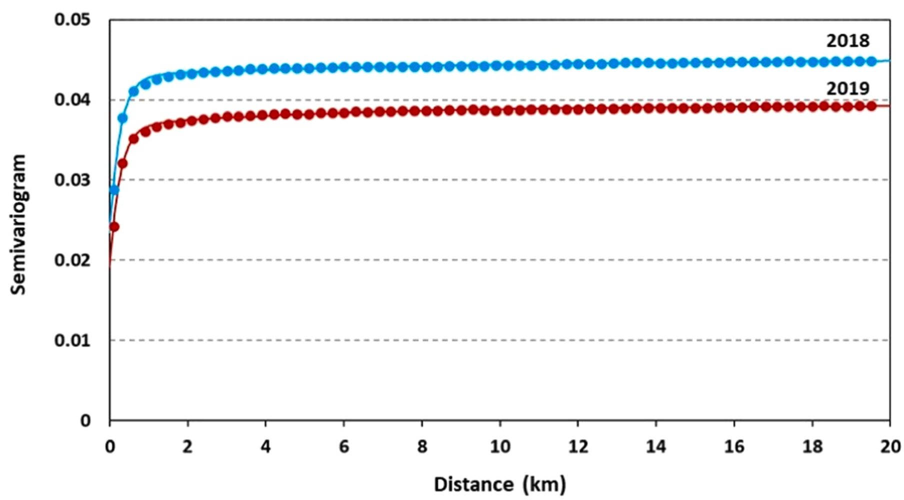

Fig. 7. A semi-variogram indicating the spatial dependence on median of the productivity gap of field parcels in South-West Finland in two years.

declined and thereby, the average parcel size increased by some 5 % independently of the parcel exchange rate (Fig. 6). However, in the case of the upper quartile farms, the number of parcels increased steadily with increasing land exchange rate: a 5 % exchange rate increased the parcel number by 5 % and in the extreme case of a 40 % exchange rate even by 25 %. Thereby, on some farms, reductions in distance might be unsatisfyingly compromised by the higher number of small parcels, which goes against the intended financial benefits of land exchange – if not compensated for by merging nearby parcels into larger units. In Finland, farming costs decrease by 15 % on average according to typical Finnish land consolidation activity (Hiironen and Riekkinen, 2016). According to (Lu et al., 2018), one unit increase in parcel size reduced the average management costs by 8 % when the total farm agricultural area remained constant.

4.3. Using remote sensing for optimization and analysis

To safeguard parcel exchange from compromising yields is critical for farmers. According to a French study based on data from the Farm Accountancy Data Network (FADN), current agricultural land fragmentation was found to increase production costs while decrease yields, revenues, profitability, and resource efficiency (Latruffe and Piet, 2014). When modelling *ex ante* the attainable improvements in productivity following consolidation activities in Shenyang, China, the results indicated the potential of a 20 % increase in the total yield of the region (Guanghui et al., 2017). Today remote sensing opens opportunities for farmers to be better proactively aware of possible differences in the yielding capacity of exchanged parcels (Hong et al., 2020; Näsi et al., 2023). *Ex post* analyses where productivity changes were estimated based on NDVI-values, indicated that ~60 % of the consolidation projects improved and ~55 % stabilized yields (Du et al., 2018). In this study, NDVI-values were used as a time series over the growing season to estimate productivity gaps at the field parcel scale (i.e., by comparing each parcel to the best 10 % of parcels in the region). It was found that the spatial dependence of the productivity gap lasted until some 15 km, but already around 800 m the productivity of the nearby parcels was more likely to be similar (Fig. 7). This is likely to be attributable to similarities in soil types and conditions as well as the microclimate. Hence, when aiming to reduce the distance between parcels and the farm center, the productivity of the exchanged parcels does not necessarily differ on small farms (≤ 50 ha). However, parcels may become more uniform, especially on large farms located in the agriculture dominated regions, because such farms have the highest capacity to (sometimes dramatically) reduce the distance to the parcels via land exchange (Fig. 5). Thereby, it depends on the region and general farming prerequisites of each farm whether it loses or wins considering shifts in parcel productivity. To overcome the loss of productivity for a farm, in the practical implementation of land exchange in Finland, the shifts are done based on the market value of the field parcel, not only based on coverage. When defining the market value different parcel characteristics that affect productivity such as the soil type and quality of drainage system are considered (Luotamo et al., 2022; Yli-Heikkilä et al., 2022).

Satellite image-based productivity gap data could support parcel exchange negotiations. Firstly, it provides information for farmers on the performance potential of exchanged parcels in relation to their own parcels, which could provide additional certainty regarding the profitability of the changes. Secondly, this information provides farmers with essential basic information about the performance of their new parcels with different crops in various weather conditions, supporting their decision-making, including improving soil and drainage systems, cultivation methods, and crop varieties. Since open satellites provide annual datasets over a long time scale, information on field performance is becoming comprehensive and increasing over time. However, the resolution of the most used open satellite image datasets is 10 m (Sentinel-2), which does not allow for very detailed analysis. Therefore, higher resolution drone image datasets could provide detailed information about field parcel characteristics, supporting land exchange as well as the planning of efficient cultivation of the new parcels (Näsi et al., 2023).

4.4. Impacts of reallocation in climate resilience

The suitability of parcels for cultivation of different crop species is in general higher on larger farms but varies depending on parcel characteristics, especially size (Peltonen-Sainio et al., 2018). In Finland, large zonal shifts in the use of diversifying crops have taken place with the highest potential on large farms (Peltonen-Sainio and Jauhiainen, 2020). The support of further diversification actions is an important measure to improve climate resilience (Chittapur et al., 2017; Elmqvist et al., 2022; Gaudin et al., 2015), because extreme weather events (Ruosteenoja and Jylhä, 2023) may further increase crop production risks in the future. In our case study, only farms with a sufficient land area (> 50 ha) to enable the diverse use of crops were considered in a sub-region where growing conditions in general enable the cultivation of a high number of alternative species (Peltonen-Sainio and Jauhiainen, 2020, 2019). Spring cereals, however, often dominate current land use. In the case that cereals were grown on > 90 % of the farm area, land exchange increased the potential to diversify crop choices for 10 % of the parcels (Table 1). On the other hand, in the case of more diverse land use (≤ 70 % spring cereal area on a farm), land exchange reduced rather than increased the opportunities to diversify land use if it affected at all. The reduction in diversification potential following land exchange was probably attributable to more uniform parcel characteristics on farms, while farms with enough parcels that differed in their characteristics enabled the use of various crops in a logistically feasible way (Peltonen-Sainio and Jauhiainen, 2019). On the other hand, merging and reshaping nearby parcels might be a measure that to some extent could improve the opportunities for use of special crops instead of monotonous cereal sequencing. Not least, because special crops such as grain legumes and oil crops closer to the farm center may support early identification of emerging invasion of pests and diseases.

The parcels' distance to a waterway is a critical measure to indicate the capacity of a farm to irrigate, which might be compromised when aiming to reduce driving distances on a farm using land exchange measures (Kuburić et al., 2022). Finland is an exceptionally water rich country. One third of the field parcels (in total ca. 1.1 million) are next to a waterway and half are less than 100 m away, but currently field crop production is rainfed (Peltonen-Sainio et al., 2015). Early summer drought causes an average of a 20 % yield reduction in the most drought prone western crop production regions of Finland, and thereby the irrigation potential should be reserved as a future opportunity to adapt to climate change and increase resilience against weather variability, extreme events, and especially more severe drought episodes (Peltonen-Sainio et al., 2021). A 30 % land exchange rate was used in impact assessments to determine a sufficiently high number of exchanged parcels between farms (Table 2). Only rarely the share of parcels that were ≤ 100 m away from a waterway remained unchanged, but the changes were modest – especially when compared to the benefits: the distance between parcels close to waterways decreased on farms as did the fragmentation of parcels close to waterways between farms. This indicates likely improvements in logistics and resource efficiency of irrigation without significant disservice for adaptation to climate change.

5. Conclusions

Large potential to harmonize fragmented landscapes was found especially on large farms in the primary crop production regions with high share of agricultural land. In general, modest, well targeted measures provided most benefits with fewer trade-offs. Identified drawbacks for logistics and farm economy were that large parcels might be replaced by higher numbers of smaller ones when keeping the farm size constant and exchanged parcels might differ in productivity. Furthermore, when parcels are closer to each other they are often more uniform, which again may reduce capacity to diversify land use. This can hinder the shift towards more resilient and sustainable farming. Distortions caused by land reallocation might be partly fixed by merging and reshaping nearby parcels. On the other hand, land exchange did not unequal farmers' opportunities to implement irrigation as an adaptation measure to climate change. High potential for land exchange, risk of some critical trade-offs, and their impacts on farms' logistics, resource efficiency, resilience, and sustainability highlight the importance to further strengthen the current customer-driven, volunteer farmland consolidation system and to provide sufficient incentives to empower change towards farmland rationalization. Not least, to fix the logistic distortions driven e.g., by fast-paced structural changes on Finnish farms since EU-membership. Our study also demonstrated that the present open satellite image databases improve productivity gap data assessments. Systematic satellite image use supports parcel exchange negotiations and management decisions by providing farmers improved insight into the performance potential of exchanged parcels, aiding in decisions related to profitability, crop performance, and improvements in soil, drainage, and cultivation practices. This study proposed new elements for the land consolidation evaluation process, specifically climate resilience and productivity analysis using free satellite image time series. These enhancements have the potential to improve the sustainability, resilience, and acceptability of activities, are cost-effective to implement, and are therefore recommended for inclusion in farmland consolidation processes.

CRediT authorship contribution statement

Eetu Puttonen: Writing – review & editing, Investigation, Data curation, Conceptualization. **Roope Näsi:** Writing – review & editing, Visualization, Investigation, Data curation, Conceptualization. **Eija Honkavaara:** Writing – review & editing, Project administration, Investigation, Data curation, Conceptualization. **Lauri Jauhiainen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pirjo Peltonen-Sainio:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

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