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Landscape Metrics and Land-Use Patterns of Energy Crops in the Agricultural Landscape

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Abstract
Energy crops are a new player in the traditional agricultural landscape. The present paper analyses the land uses surrounding and the spatial characteristics of the main energy crops in Sweden (willow, poplar, hybrid aspen and reed canary grass) compared to traditional agricultural crops during the period 2006–2018. Spatial metrics (number of shape characterising points, shape index and rectangularity ratio) are calculated for each field, as well as the nearby land uses at varying distances, at radius: 500 m, 1000 m, 2000 m and 5000 m. A total of 1560 energy crop fields are studied in the 2006 dataset and 3416 fields in the 2018 dataset, which are compared to 58,246 fields with cereal crops in 2006 and 131,354 fields in the 2018 dataset. Results show that, despite being established on previous agricultural land, energy crops present a different spatial profile compared to traditional agricultural crops. Field shapes present less complexity than before, and the overall spatial features become more regular with time in both cases of energy crops and cereals, suggesting an increasing trend in cost-efficient agricultural practices and planning. Important differences concerning land use diversity at different scales are found between plantations versus grasses. In general, willow plantations are located in agriculture-dominated areas (> 70% at 500 m, > 50% at 2000 m), whereas reed canary grass is in forest-dominated landscapes (> 30% at 500 m, > 60% at 2000 m); both contribute to diversifying existing land uses although with varying effects. The results of this study are a basis to assess the impacts of energy crops at landscape level and can translate into applications in energy policy and planning.

Keywords Bioenergy · Energy crops · Landscape diversity · Landscape metrics

Introduction

The European agricultural landscape has changed significantly as a result of changes in the agricultural sector and the European Common Agricultural Policy [1, 2]. In recent decades, the establishment of energy crops has become an additional factor to consider when studying agricultural landscape patterns. Over 3 M ha of cropland have so far been used for energy production [3] and 25 M ha of arable land are estimated to be available for energy crops by 2030 [4, 5], bringing changes in the structural diversity of the agricultural landscape [6, 7].

Since the 1970s, Sweden has been a pioneer in the cultivation of energy crops, particularly fast-growing plantations [8]. Several decades of energy crop expansion [9], as a result of policies (e.g., subsidies on willow plantations, energy tax on fossil fuels and carbon tax on CO_2) and growing demand by the district heating systems [10-13], has caused an energy-driven land-use change. These energy crops are mostly established on former agricultural land, particularly on former cereal lands used for spring barley, winter wheat and, to a lesser extent, grasslands [14]. Energy crops can have lower management intensity and costs of production than traditional agricultural crops, thus offering an interesting business case for the farmers [14-16]. The main fast-growing plantations established in Sweden have been willow

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(*Salix* sp.) and poplar (*Populus* sp.) [17]. In addition, perennial energy grasses are also considered for bioenergy production in more recent years, presenting some benefits concerning yields and management [18].

Cultivating perennial energy crops might lead to a restructuring of the surrounding landscape. Various studies have investigated the positive effects of energy crops at the landscape level concerning, for instance, biodiversity, as bird species richness is higher in willow plantations on agricultural land compared with planting willow in a forest-dominant landscape [19], and studies on poplar plantations established on former agricultural land also presented higher phytodiversity [20-22]. At the same time, there can be negative effects on biodiversity if there is a large and simultaneous adoption of energy crops, which results in large-scale changes in landscape patterns depending on the exact situation [23].

Suitable methods to analyse the characteristics of energy crops from a spatially explicit landscape perspective are based on landscape metrics, which facilitate analyses of spatial configuration, composition and fragmentation of a given landscape based on spatial metrics associated with the different fields and land uses [24]. Landscape metrics are related to spatial units (patches and classes) and mosaic level metrics [24] and have been used as proxy indicators for biodiversity [25] and crop efficiency [26], among others.

Concerning Swedish energy crops, such approaches have, e.g. been used to estimate the economic efficiency of willow plantations [27] and energy grass [28]. In general, regular shapes of agricultural fields (i.e. rectangles) have been shown to be more cost-efficient [28], whereas irregular shapes are likely to have greater ecological and aesthetic benefits [29]. Furthermore, most studies that have been conducted on energy crops and associated land-use change have been focused on a single year or restricted to a specific region, thus overlooking long-term dynamic changes and the overall situation in different locations.

The present study analyses the spatial characteristics of the main energy crops in Sweden: willow, poplar, hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.), and reed canary grass (*Phalaris arundinacea* L.) (RCG) and the associated land-use changes in 2006 and 2018. The underlying hypothesis is that the different management and economic characteristics of energy crops, compared to the main agricultural crops and to each other, are reflected in their spatial metrics. These spatial characteristics should be reflected at different spatial scales, thus contributing to more diverse mosaic patterns in existing land uses. The study can be a basis for discussions on the role and impacts of energy crops in a broader landscape context, where multiple goals and objectives need to be considered, e.g. in the interface between energy, food security and environmental policy and planning.

Material and Methods

Spatial data concerning agricultural fields from 2006 to 2018 were retrieved from the Integrated Administration and Control System (IACS), managed by the Swedish National Board of Agriculture [30]. The dataset included locations and field shapes where crops are cultivated [31]. The energy crops considered were willow, poplar, hybrid aspen and reed canary grass, and the agricultural crops used for reference were winter barley, spring barley, winter wheat and spring wheat (Fig. 1). Other land uses were retrieved from the Copernicus land monitoring service (Copernicus land dataset), CORINE Land Cover for the years 2006 and 2018 [32].

The analysis was structured at two main scales: field level and landscape level. The first addressed the spatial patterns of the individual field, whereas the latter addressed the surrounding land uses at different distances. At the field level, fields dedicated to energy crops were compared to the reference agricultural fields using spatial metrics, in order to identify potential structural differences. For this purpose, three spatial metrics were selected: the number of shape characterising points (NSCP), shape index (SI) and rectangularity ratio (RR) (Table 1). NSCP, SI and RR explain the complexity of the edge diversity for land size adjustment and land aggregation [33]. NSCP was applied to measure land boundaries and counted polygon vertices [25] reflecting borders with other land uses. The larger the NSCP value (the more edges of the land), the more complex landscape patterns. SI was based on the perimeter-area ratio, to address land shape regularity. RR was based on minimum bounding area, to explain land-use efficiency. A field close to a square (refers to SI) gets a value close to 1, and a field close to a rectangle (refers to RR) gets a value close to 100%, which is associated with higher machine performance and (generally) profitability [27]. In some cases, the field shape data could not be related to a single crop, as many crops were grown in the same field area and were excluded from the landscape metrics. For each crop, the fields' spatial metrics were characterised by using their mean, median and their histograms.

The resulting landscape metrics were contrasted for differences among energy crops, between energy crops and agricultural crops, and between energy crops over time. In the first case, direct comparisons of the histograms of the field metrics, as well as mean and median were compared. In the second case, the analyses were performed including all agricultural fields in the country and using a subset for the core areas where energy crops are grown, as defined in Xu and Mola-Yudego [14]. The core area was the minimum area to encompass 90% of all the fields established with energy crops in the country, using 2006

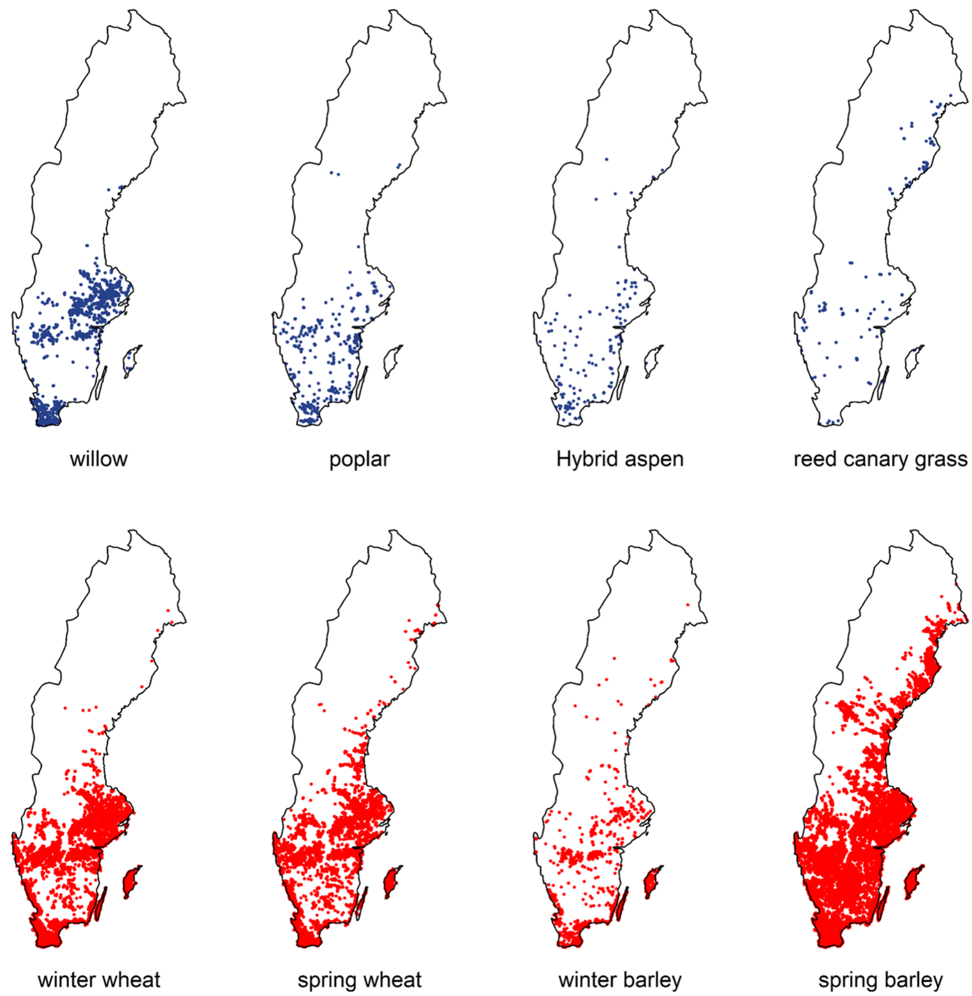

Fig. 1 Location of fields' centroids with energy crops (willow, poplar, hybrid aspen and reed canary grass) and common agricultural crops (winter wheat, spring wheat, winter barley and spring barley) in Sweden in 2018

Table 1 Landscape metrics defining the fields, where *i* is the plantation; *N* is the number of vertices of the plantation (e.g., triangle: NSCP = 3-; rectangle: NSCP = 4-; pentagon: NSCP = 5-); *Perimeter* is the length of the perimeter of the plantation; *Area* is the area of the plantation and *min.Area* is the minimum bounding area in the shape of a rectangle

Functions	Spatial metrics	Definitions
Land connectivity	Number of shape characterising points (NSCP)	$NSCP_i = N_i$
Land shape regularity	Shape index (SI)	$SI_i = \frac{0.25*Perimeter_i}{\sqrt{Area_i}}$
Land-use efficiency	Rectangularity ratio (RR)	$RR_i = \frac{Area_i}{min.Area_i}$

as the reference year (Fig. 2). Due to the lack of normality, the analyses were based on pairwise comparisons using a Mann–Whitney *U* test with a 0.05 significance threshold.

In the third case, all fields available with energy crops in 2006 were individually traced in 2018, using their centroid for reference, in order to assess changes in land use as well as field landscape metrics. This resulted in a repeated measures structure, where the same field presents two values, corresponding to 2006 and 2018, concerning their land use (the crop cultivated in that field) as well as field area, NSCP/ha, SI and RR. Changes in these for the same field were tested using a *t*-test.

At the landscape level, the analysis identified the main land uses within buffers of 500 m, 1000 m, 2000 m and 5000 m radius around the centroid of the energy crop fields, using the CORINE land-use classification levels, for 2 years available within the study period (2006 and 2018). The main categories considered were *Wetlands*, *Artificial lands*, *Water bodies*, *Forest lands and Agricultural lands* following the CORINE land-cover nomenclature [34]. The overall data was processed using R v4.0.4 [35] and ArcGIS v10.5 [36].

Results

Several fields from the 2006 dataset could not be included in the landscape metrics since several crops were grown in the same polygon. This affected energy crops as well as

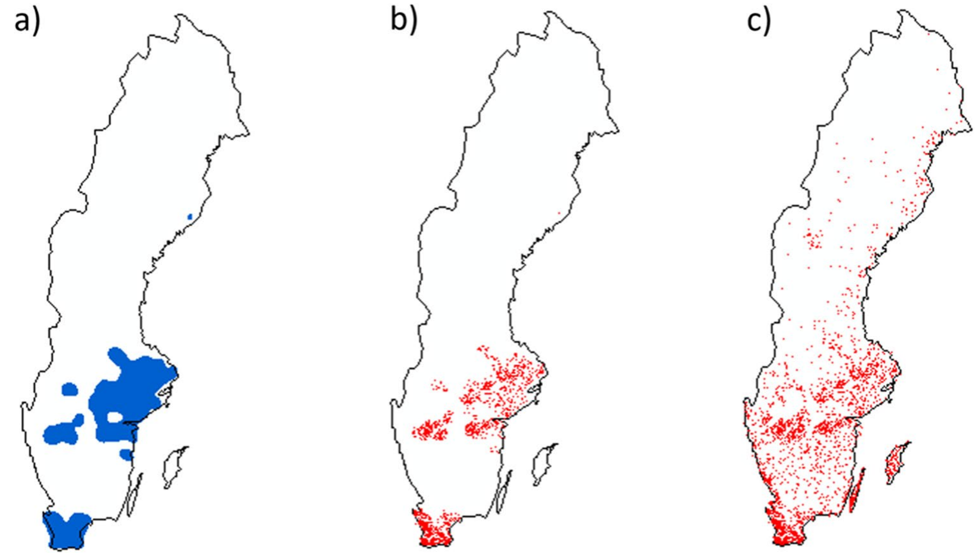

Fig. 2 Areas with energy crops in Sweden. **a** Core areas, encompassing 90% of fields with energy crops, **b** agricultural fields within the core areas of energy crops, **c** all agricultural fields

agricultural crops. However, over 40% of the total cultivated area for all targeted crops was represented in the calculations and in the case of the 2018 dataset, nearly 100% of the area was included. In total, 1560 fields with energy crops and 58,246 fields with cereal crops were analysed in the 2006 dataset and 3416 fields with energy crops and 131,354 fields with cereal in the 2018 dataset (Table 2).

The spatial metrics used to characterise the field's shape showed important differences between energy and agricultural crops. In all cases (field area, NSCP, NSCP/ha, SI and RR), the values' distributions were asymmetrical, being skewed due to large variance. In general, 2006 data for hybrid aspen and RCG precluded meaningful comparisons due to the few fields with these crops in that year.

The field areas show a large variance, especially in the case of willow (largest field, 41.32 ha), poplar (31.23 ha) and hybrid aspen (50.82 ha) plantations in 2018 (Fig. 3). In general, willow presented larger fields than the rest of energy crops, and energy crops presented smaller fields than agricultural crops in the same areas for the same year (p-value < 0.001 for nearly all comparisons, see full statistical values in Table A1 and Table A2).

In the case of NSCP, there were not large differences among energy crops (although RCG and willow presented lower values than poplar and hybrid aspen plantations, particularly in 2018). NSCP values per hectare were significantly higher than in cereal lands in the same areas for the same year (Fig. 4). In all cases, whether agricultural or energy crops, NSCP values decreased between 2006 and 2018 (p-value < 0.001 for nearly all comparisons, Table A1).

Concerning the field shapes measured in the SI (Fig. 5), nearly 30% of willow plantations had values close to 1. SI values increased in all the crops studied, except in hybrid aspen and RCG (although caution must be placed due to the limited amount of fields for these crops in 2006). The RR values of energy crops were distributed between 63 and 75%, which presented a high ratio of their minimum bounding rectangle area (Fig. 6). The values of RCG (mean = 70.46% in 2006) were significantly higher than for willow and poplar plantations (p-value < 0.001 in all cases for 2018) and even compared to agricultural crops, indicating a higher land-use

Table 2 Individual fields and areas included in the landscape metrics for 2006 and 2018

	Year	Willow	Poplar	Hybrid aspen	Reed canary grass	Winter wheat	Spring wheat	Winter barley	Spring barley
Number	2006	1507	33	8	12	20,207	2982	452	34,605
	2018	2133	799	243	244	37,390	14,275	2381	77,308
Area (ha)	2006	6297	62	16	33	130,991	17,164	1936	124,582
	2018	7050	1719	696	607	295,622	85,406	14,941	381,898
Total area (ha)	2006	13,341	220	44	48	319,137	43,785	5912	310,357
	2018	7050	1719	696	607	295,622	85,406	14,941	381,898

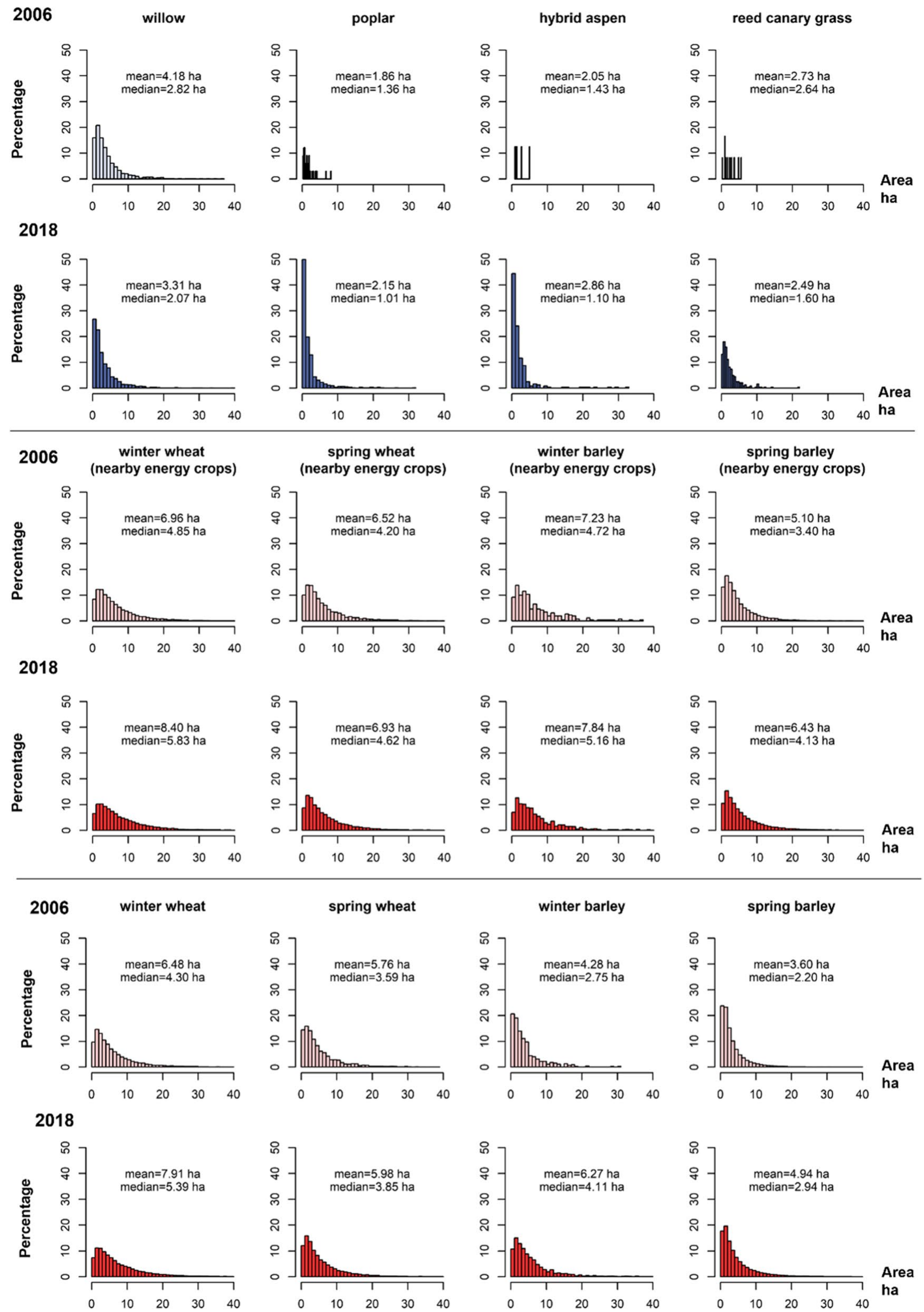

Fig. 3 Distribution of field area for willow, poplar, hybrid aspen and reed canary grass (RCG), compared to winter wheat, spring wheat, winter barley and spring barley in 2006 and 2018 in Sweden. The x-axis represents the field area (ha) and the y-axis is the percentage of fields. Top: fields with energy crops; centre: fields with agricultural crops nearby energy crops; bottom: all agricultural fields in Sweden

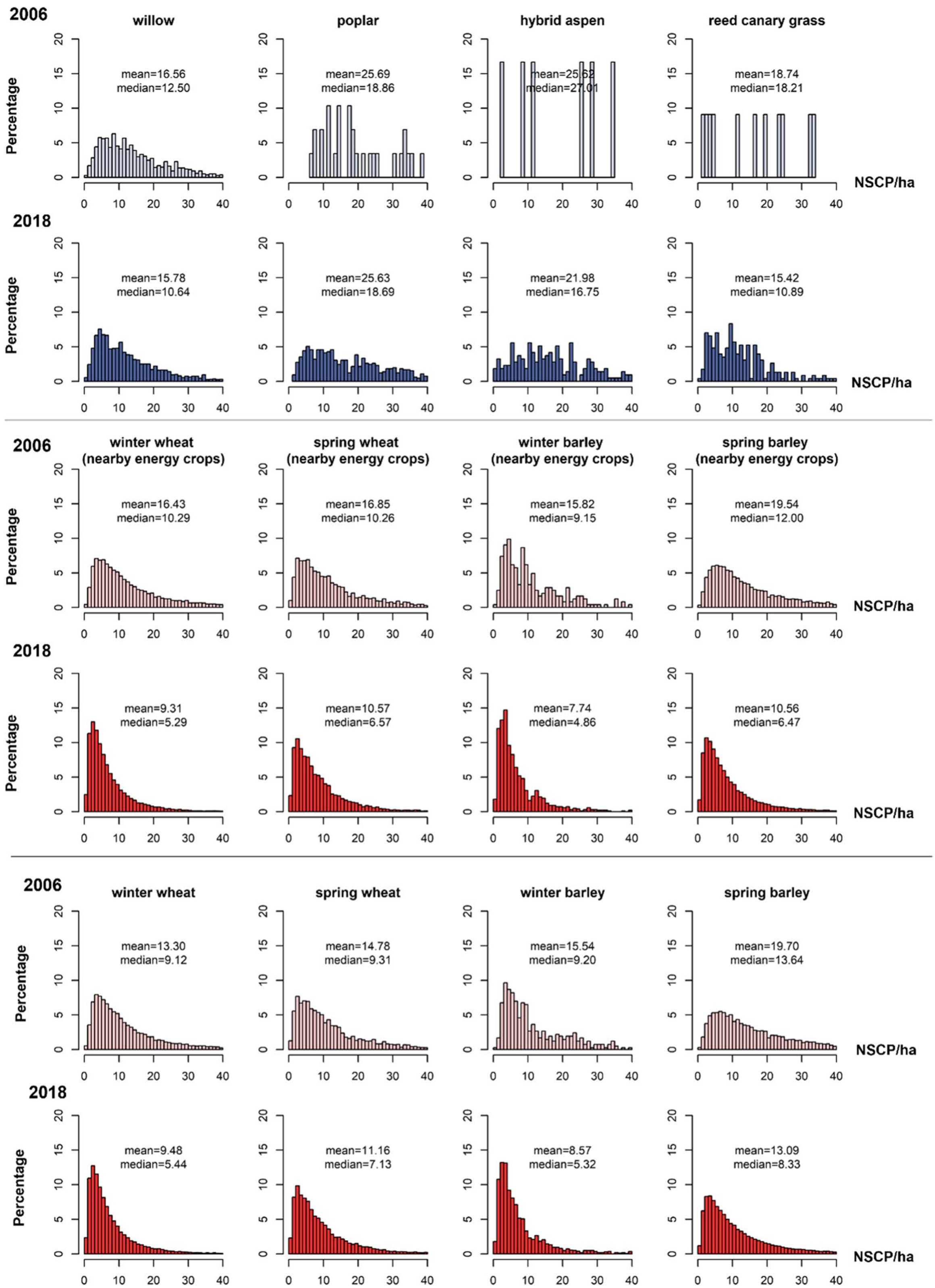

Fig. 4 Number of shape Characterising points (NSCP) per ha for willow, poplar, hybrid aspen and reed canary grass (RCG), and for winter wheat, spring wheat, winter barley and spring barley, in 2006 and 2018. The x-axis is the value of NSCP per ha and the y-axis is the percentage of the value. Top: fields with energy crops; centre: fields with agricultural crops nearby energy crops; bottom: all agricultural fields in Sweden

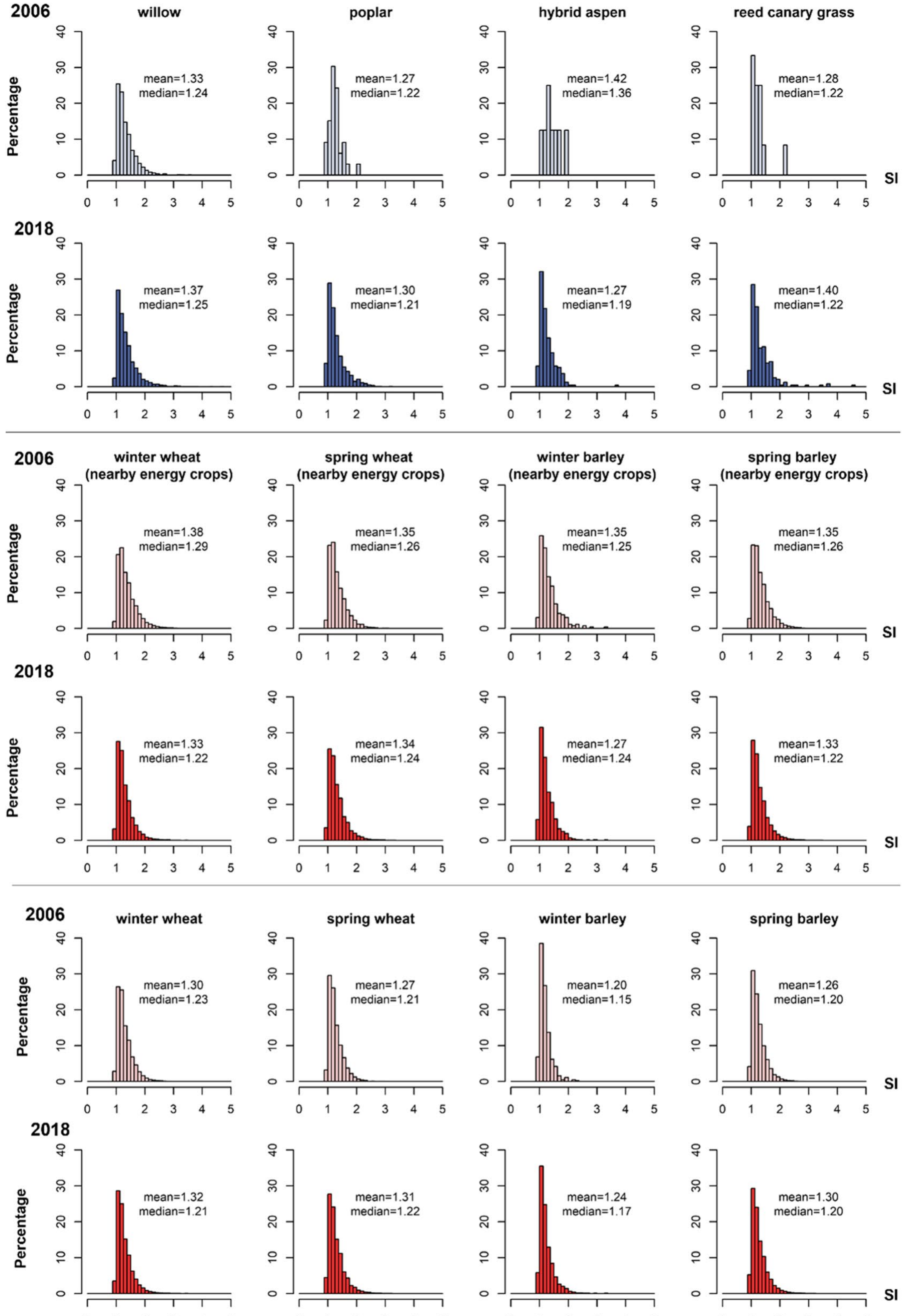

Fig. 5 Shape index (SI) of willow, poplar, hybrid aspen and reed canary grass (RCG), and for winter wheat, spring wheat, winter barley and spring barley in 2006 and 2018. The x-axis is the SI value and the y-axis is the percentage of the value. Top: fields with energy crops; centre: fields with agricultural crops nearby energy crops; bottom: all agricultural fields in Sweden

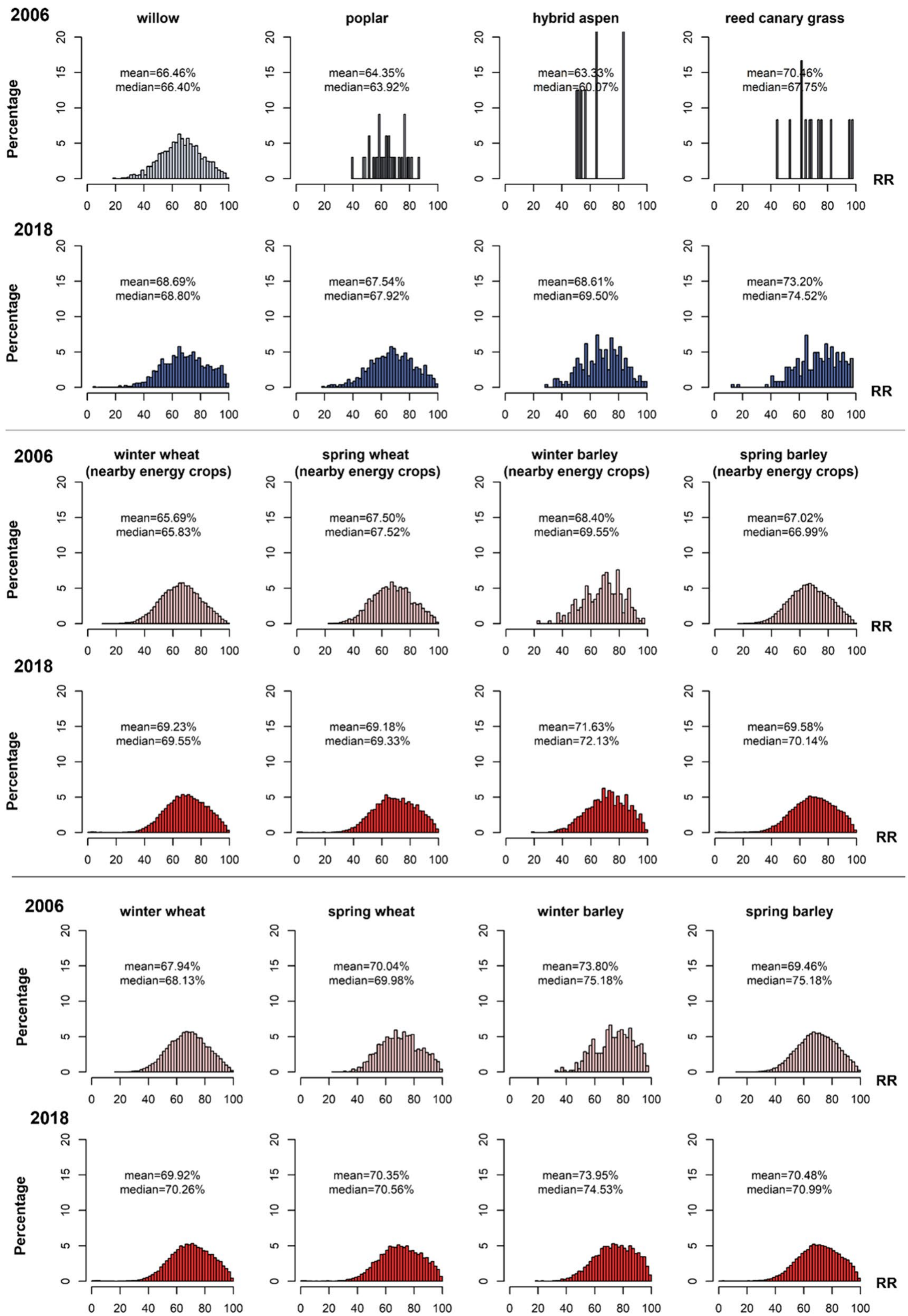

Fig. 6 Rectangularity ratio (RR) of willow, poplar, hybrid aspen and reed canary grass (RCG), and for winter wheat, spring wheat, winter barley and spring barley in 2006 and 2018. The x-axis is the RR value and the y-axis is the percentage of the value. Top: fields with energy crops; centre: fields with agricultural crops nearby energy crops; bottom: all agricultural fields in Sweden

efficiency for this crop. RR values also increased in the studied period (2% in the case of willow and winter wheat, 1% in spring barley and 0.15% in winter barley).

Finally, fields with energy crops in 2006 were individually traced over time for the same spatial metrics. The results showed that 67.69% of the fields with energy crops in 2006 remained in the same location in 2018 ($N=1023$ for willow, $N=22$ for poplar, $N=9$ for RCG and $N=2$ for hybrid aspen). The field area decreased, however, in all energy crops, with a mean reduction of 0.11 ha (2.2%), statistically significant (p-value < 0.001). For willow and poplar, the NSCP/ha were reduced in 3.5 and 2.3, respectively, SI was practically unchanged in both crops and the RR increased in 0.80 and 1.41 units, respectively. These changes (for NSCP/ha and RR) were only statistically significant in the case of willow (p-value < 0.001), due to the few records available concerning the other crops.

Considering the agricultural land use surrounding the plantation, most of the crops were placed in lands mainly dedicated to agriculture (Fig. 7), although some changes occurred during the study period, and this pattern was less obvious at larger scales (i.e. within a 5000-m radius). Willow and poplar plantations were typically located in areas dominated by agriculture (> 65% of land use in close vicinity, at 500 m in 2006) and no changes were observed across time. Willow plantations in particular showed a stable and consistent pattern at all scales. For other crops, agriculture accounts for less than 50% of adjacent land use. The greater the scale, the less agriculture in relative terms (~ 50% in willow and ~ 25% in the other crops, at 5000 m). A small percentage of the plantations were close to water bodies or wetlands. In RCG, this percentage was higher, particularly in 2018. Willow showed the highest proximity to urban centres (artificial areas), markedly in 1000-m areas.

The distribution of these values revealed some notable clusters, especially for willow plantations. The share of agricultural land in the willow buffers was mainly distributed between 40 and 50% in 2006, which then slightly decreased to 35 to 45% in 2018 (Fig. 7). Poplar had a higher share of agricultural land in the buffers in 2006 with 85%, which then dropped to 20% in 2018. Hybrid aspen and RCG had a similar share of agricultural land as poplar in 2018, but the share in 2006 is inconsistent between buffer sizes. In both years, the share of agricultural land was more uniform at a smaller scale (cf. 500 m and 5000 m buffers in Fig. 8).

The share of forest in poplar and hybrid aspen buffers was mainly distributed around 20% in 2006, which then increased to 80% in 2018. RCG buffers had a similar share of forest in 2018, despite having a lower and more broadly distributed forest share in 2006. In willow buffers, the share of the forest has been relatively stable, mainly distributed around 40% in both 2006 and 2018. In general, the share of the forest was more evenly distributed in the larger buffers in 2006; in 2018, the forest density division was more evident at a larger buffer scale for the energy crops.

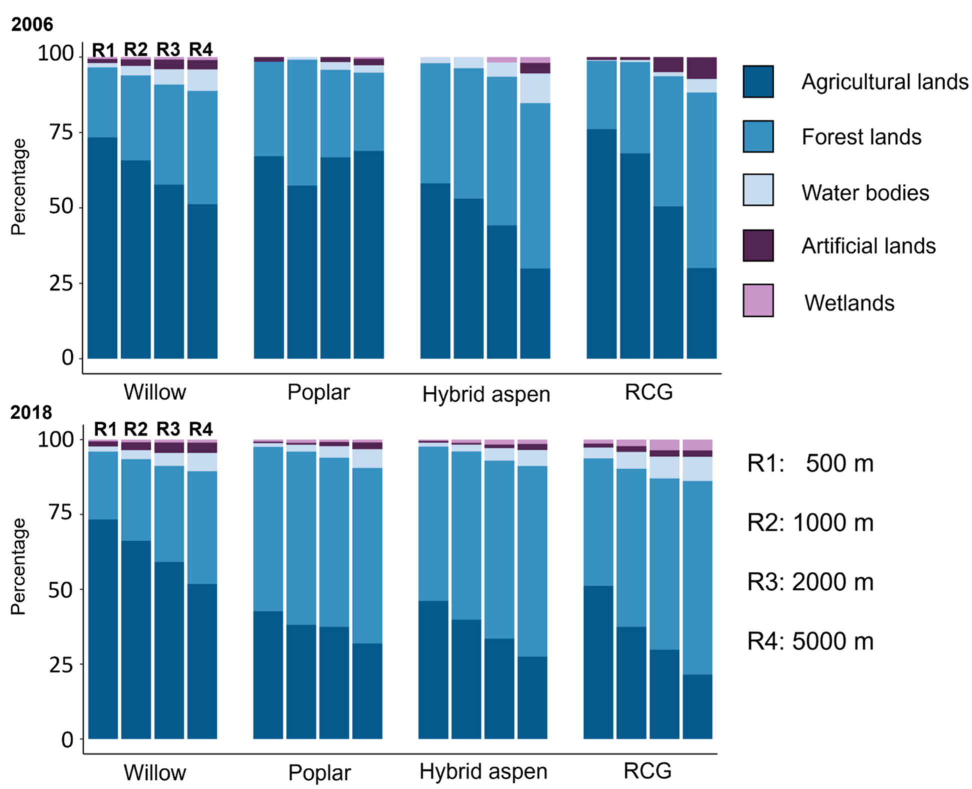

Fig. 7 Land uses around the biomass production systems considered (in percentage for agricultural land, forest land, water bodies, artificial lands and wetlands) for 2006 and 2018. R1–R4 refers to buffer areas with a radius of 500 m (R1), 1000 m (R2), 2000 m (R3) and 5000 m (R4), respectively

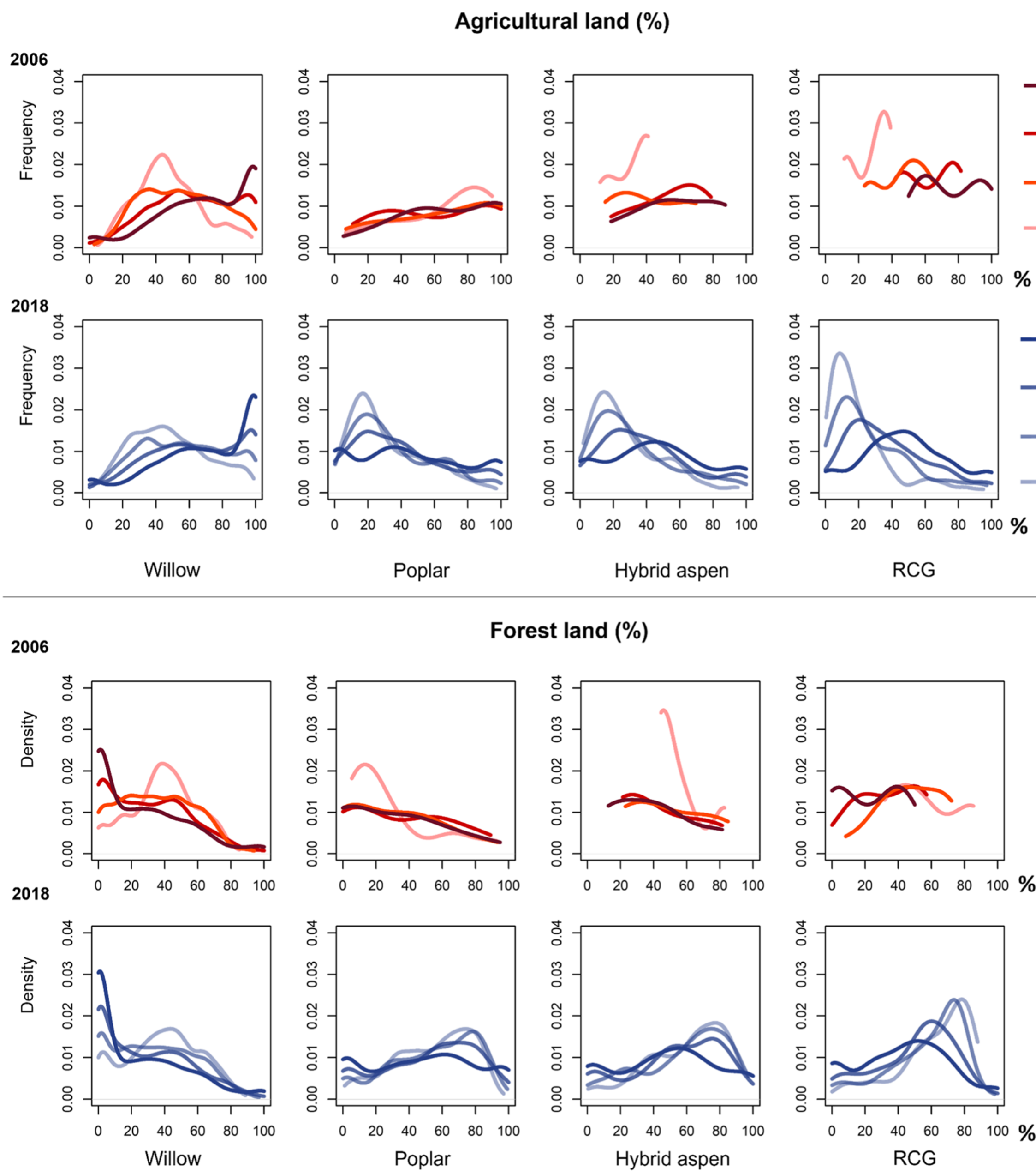

Fig. 8 Percentages of agricultural and forest land around the biomass production systems considered, in areas within an increasing radius (500 m, 1000 m, 2000 m and 5000 m) and changes over time

Discussion

The cultivation of energy crops is a rather new practice in the agricultural landscape. Due to long experience in the cultivation of fast-growing woody and herbaceous plants, Sweden is an interesting case for studying spatial patterns associated with energy crops over time, and the possible implications. Spatial analyses, such as the ones applied here, are necessary to identify overall agricultural land-use structure and changes as well as land-diversity and their associated effects of energy crop cultivation [37].

The results are based on spatially explicit and comprehensive land-use data from the land registry as well as from the European CORINE land-cover maps—both reliable and extensive datasets used in previous studies with similar methods [27]. There are, however, limitations in the use of these data sources: the land registry, for example, does not have information on other land uses other than agriculture.

Although Swedish national land-cover data of high quality exist, it was only available for 2018, which made the dataset unsuitable for temporal comparisons, justifying the use of the CORINE land-cover data. In addition, the land register for 2006 available for this study prevented the use of all the fields, due to differences in the records of cultivated crops for the same field. All in all, however, the amount of fields included in the study was quantitatively large, providing a solid basis for spatial analysis.

Regarding the energy crops analysed, they represented the four main biomass production systems grown in the country. However, in the case of poplar and hybrid aspen, there were fewer planted areas in the early 2000s, as observed in [14] and [18], which precluded a solid statistical analysis of these two plantation systems. The few records available were, however, exhaustive and reflected the reality of their cultivation. Regarding the agricultural crops selected for reference, these represented the main land use prior to the establishment of energy crops in Sweden for woody plantations [14] and RCG [18].

The spatial analysis was based on indicators describing landscape metrics as well as land-use changes around the studied fields. There are a large number of indicators and metrics available for spatial analysis, and the selected ones were considered representative for the scope of the study with limited overlap [24, 38]. NSCP measures the complexity of a field's shape and has been used as a proxy of species richness in the landscape [25], SI has been widely applied in landscape ecological studies [24, 39] and RR is considered an important parameter to describe agricultural fields, particularly considering the management of the crops and its profitability [26].

The overall distribution of the parameters was bell-shaped although skewed, particularly in the case of NSCP and SI. In the case of RR, the results showed a more centred Gaussian distribution, similar in shape and mean to previous studies in Southern Finland [26]. In the case of NSCP, the results showed higher values for energy crops than for cereal crops, which implies a less regular shape and higher complexity in the field borders. In addition, the distribution of NSCP values presented a much larger variance, possibly linked to the distribution of field sizes [25]. Meanwhile, cereals presented a more homogeneous and regular shape, suggesting the use of better land quality, as pointed out in [27].

Both SI and RR have been used to describe regularity in energy crops in Sweden, linked to land-use efficiency and field operating efficiency [27]. In a field with an irregular shape (SI = 1.75) the estimated time for harvesting, *ceteris paribus*, was 15% higher than in a regular field [27]. The results indicated less regular shape fields dedicated to energy crops than in the agricultural fields used as a reference, suggesting a lower field operating efficiency. This goes in line with previous studies reflecting the use of lower quality agricultural land for the establishment of energy crops, which is confirmed in the case of plantations [8, 40]. In this line, Nilsson and Rosenqvist [41] stressed that financial attention to perimeter-based subsidies should be placed, particularly for small plantations, in order to compensate for the difficulties derived in the management of irregular shape of lands. In the case of RCG, however, values were even higher than in agricultural crops, suggesting the use of different fields and, arguably, more economic optimization, which could be explained by the different locations where grasses are established in Sweden, as well as the management and profitability of the crops [18].

The overall results of landscape metrics indicate that all crop fields have generally become less complex in their land edges and shapes over time, particularly cereal fields, reflecting a general trend in the Swedish agricultural land use [42] possibly linked to agricultural policies [31]. The Swedish agricultural policies highlight farm restructuring which leads to more highly efficient farms [43]. The high efficiency for energy crop cultivation can be presented in the form of the field efficiency for crop harvesting, which is strongly correlated to spatial boundary descriptors [44]. The field geometry characteristics of our research are in line with this, with more rectangular fields both in energy crops and agricultural crops. Other policy drivers, such as financial support for willow, poplar and hybrid aspen planting from the 2014–2020 Rural Development Programme of the EU's Common Agricultural Policy, provide to a certain extent financial incentives to enhance more regular geometry features of the crop fields [45].

At a higher scale, the results confirm the positive contribution of energy crops to a more diverse agricultural landscape, particularly in the case of willow, i.e. a forest plantation system located in a cereal-dominated landscape, and RCG, i.e. a grass crop located in a forest-dominated landscape. In the case of poplar and hybrid aspen, this role is less evident, although the analysis was more difficult due to the scarcity of plantations [14]. This agrees with Berndes et al. [46], in terms that landscape diversity increases around biomass plantations, and maintaining or recreating the landscape heterogeneity could contribute to enhanced sustainability of agricultural systems [47]. For instance, agricultural areas containing willow or poplar plantations in Germany are more heterogeneous and present higher phytodiversity values than arable lands, due to longer rotation periods than systems based on annual crops [48]. However, in the case of RCG, there are important differences: a field study in Finland showed that large-scale RCG cultivation alters the agricultural landscape to a large extent and causes negative effects on bird populations [23]. Similarly, Nilsson and Rosenqvist [41] indicated different cultivating intensities required for planting willows and RCG in Sweden, which might enlarge the differences in their respective surrounding landscapes.

Finally, it is noticeable the establishment of energy crops closer to urban areas over time, highlighting the role of reducing the transportation time required for energy crops and the overall availability to match biomass demand [49, 50]. Similarly, the increasing presence of plantations next to water bodies is interesting, as there are demonstrated benefits concerning water quality [17, 51] that could be further stimulated through strategic landscape planning [52, 53]. Multifunctional land management in the agricultural landscape could be a solution to tackle environmental issues and provide production resources [54-56]. Concerning the energy purpose, integrating the plantations of energy crops into the agricultural landscape could not only supply biomass but can be used for, e.g. wastewater treatment, increasing soil carbon and increasing biodiversity [52, 57, 58]. A deeper understanding of these spatial designs requires combining farmers' preferences, policy goals and economic indicators, which could be a step for further research.

Conclusions

The present study focused on the landscape metrics of energy crops in the Swedish agricultural landscape. Energy crops present a distinct spatial profile compared to traditional agricultural crops. There are, at the same time, important differences between energy crops, particularly woody plantations versus grasses, with implications in the management and operational efficiency of energy crops, and for land-use diversity at different scales.

There are important changes over time, as the fields studied tended to become more regular and stable in their spatial metrics. Willow plantations are typically located in agriculture-dominated landscapes, whereas RCG fields are located in forest-dominated landscapes. In both cases, they contribute to diversifying the land use at the landscape scale, with important effects on biodiversity and different ecosystem services. These results support the overall hypothesis that energy crops can have a positive effect diversifying agricultural landscapes.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12155-023-10584-9.

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Author Contribution Conceptualization: Xiaoqian Xu, Blas Mola-Yudego; methodology: Xiaoqian Xu, Blas Mola-Yudego; software: Xiaoqian Xu; validation: Xiaoqian Xu, Blas Mola-Yudego; formal analysis: Xiaoqian Xu; data curation: Xiaoqian Xu, Blas Mola-Yudego; writing—original draft preparation: Xiaoqian Xu, Blas Mola-Yudego, Oskar Englund, Ioannis Dimitriou, Håkan Rosenqvist, Guangzhe Liu; writing—reviewing and editing: Xiaoqian Xu, Blas Mola-Yudego, Oskar Englund, Ioannis Dimitriou, Håkan Rosenqvist, Guangzhe Liu; visualisation: Xiaoqian Xu, Blas Mola-Yudego, Oskar Englund; supervision: Blas Mola-Yudego; funding acquisition: Xiaoqian Xu, Blas Mola-Yudego. All authors read and approved the final manuscript.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

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