

Highlights:

- We analysed soil organic carbon stock in Majorcan agricultural soils
- We evaluated soil carbon sequestration in Mediterranean agricultural soils
- We modelled the spatial variability of temporal changes in carbon storage
- We estimated that the increase in the last 11 years was 11.26 tC/ha

1 **Soil organic carbon stock on the Majorca Island: temporal change in agricultural soil**
2 **over the last 10 years**

3

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26

27 **Abstract**

28 For quite a long time, soil organic carbon stock (SOCS) has reduced from reconvertig forest
29 areas into agricultural land or by inadequate agronomic practices. However in recent decades
30 in Mediterranean areas, abandonment of agricultural areas due to lack of economic profits and
31 to promoting tourism has fostered a change in land use that has impacted edaphic carbon. In
32 line with this, the Majorca Island (Spain) could be a good scenario to evaluate temporary
33 changes in carbon stocks in soils in areas with a Mediterranean climate. For 11 years, the
34 present study analysed the spatial distribution of SOCS and assessed temporal changes in

1 agricultural soils in relation to the influence of human activities and land use. The global
2 carbon budget on the Majorca Island was estimated at 31.23 Tg C, and showed wide spatial
3 variability. As expected, SOCS was higher in the forest areas of the Tramuntana Mountain
4 Range (more than 100 tC ha⁻¹), while the lowest contents were found in agricultural use (79.3
5 tC ha⁻¹), located mainly in the centre and south of this island.

6
7 The total C stored from 2006 to 2017 increased by 2.62 Tg C (15%) in agricultural areas on the
8 island. We noted a major increase in SOCS in the agricultural zones on mountain slopes (> 2-
9 fold higher), associated with abandoned crops in terrace cultivation, but grassland systems
10 also increased. Nonetheless, the present study shows a sharp drop in SOCS in the centre and
11 south of this island. This decrease was more pronounced in annual crops (-14.5%), which could
12 be attributed to intensive soil management and increased irrigated land. Land abandonment
13 has been indicated as the main potential to carbon sequestration in soil, but this SOC
14 sequestration is no infinite process. Certain changes in agricultural practices on Majorca, and
15 in rural Mediterranean areas in general, are necessary to avoid carbon loss in crop soils.
16 Adoption of conservation agriculture practices, e.g. cover crops, crop rotation, organic
17 additions and reduced tillage techniques, can help increase SOC levels in rural Mediterranean
18 areas.

19
20 **Keywords:**

21 Majorca carbon storage; Mediterranean soil carbon temporal change; soil carbon
22 sequestration; spatial variation; crop management

23
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1 1. INTRODUCTION

2 Soil organic carbon (SOC) has been frequently used as one of the most important indicators
3 when soil quality/health has to be evaluated (Takoutsing et al., 2018). It is difficult to define a
4 critical value below which soil can be considered degraded given the variability of soil types
5 and climatic conditions worldwide. A review on critical organic carbon levels in soils under
6 temperate conditions (Loveland and Webb, 2003) has suggested 1% as the threshold, below
7 which soil becomes unstable and is prone to degrade. In past decades many world regions
8 have suffered permanent SOC loss and have exceeded this 1% threshold, mostly because of
9 inadequate agronomic practices. Historically, soil organic carbon stock (SOC) has decreased in
10 line with deforestation and by reconverting forest areas into agricultural land. Global changes
11 in land use between 1850 and 1980 have been estimated to increase agricultural land by
12 2230×10^6 ha, with the disappearance of 600×10^6 ha of forest areas (Houghton, 1995). These
13 changes in land use have been responsible for about 140 Pg C being released between 1850
14 and 1990 (Houghton, 1995). SOC is lost mainly as CO_2 which increases greenhouse gas
15 emissions (GGE). Human activities have increased CO_2 emission rates up to $3.5 \text{ Pg C year}^{-1}$. The
16 first metre of soil retains around 1,500 Pg C, which is 3-fold higher than the 550 Pg C stored in
17 plants with a longer residence time (Jobbágy and Jackson, 2000). Moreover, the atmospheric C
18 pool is half the SOC pool, whereas it is estimated that 270 Pg CO_2 have been emitted through
19 fossil fuel use with losses from soil since 1850 estimated at 78 Pg CO_2 (Lal, 2004). In recent
20 decades, carbon capture in soil has been promoted to mitigate CO_2 emissions. One of
21 policymakers' objectives is to implement soil management techniques to increase organic C
22 inputs and to reduce SOC losses, such as application of organic waste, reducing tillage
23 intensity, leaving crop residue, including crop rotation and cover crops, and proper irrigation
24 management. Application of organic matter (manure, sludge, crop residue, compost) to
25 increase soil fertility has been used ever since agriculture began, and soils fertilised with
26 organic matter tend to have higher SOC than those fertilised with synthetic fertilisers.
27 Likewise, reducing tillage intensity and crop rotation can help increase SOC (García-González et
28 al., 2018).

29

30 Climate conditions play an important role in the amount of SOC that soil can accumulate.
31 Under Mediterranean conditions, characterised by seasonal dryness due to hot-dry summers
32 and mild-wet winters, several authors have observed lower SOC levels than in temperate areas
33 (Aguilera et al., 2013; Chiti et al., 2012), and have remarked on the difficulty of increasing SOC
34 due to the rapid mineralisation and low humification rates under hyper-thermic conditions
35 (Gervois et al., 2008). Several studies have reported national or regional SOC stocks under

1 these Mediterranean conditions (Álvaro-Fuentes et al., 2008; Doblas-Miranda et al., 2013;
2 Muñoz-Rojas et al., 2012; Rodríguez Martín et al., 2016), with some simulations made about
3 the possible climate change effect on lowering SOC levels (Jebari et al., 2018; Pardo et al.,
4 2016). However, information on the tendencies of these SOC stocks based on real situations
5 through different temporal soil samplings is lacking. In line with this, as the Majorca Island
6 (Spain) is located in the centre of the Mediterranean region, it could be a good scenario to
7 evaluate temporary changes in soil carbon stocks. This Mediterranean island has forest and
8 natural landscapes in the Tramuntana Mountain Range in the north, and fertile agricultural
9 plains in the centre and south. However in recent years, tourism pressure has led to important
10 land use changes and to agricultural areas being abandoned. This circumstance makes this
11 region a good model for other Mediterranean or semi-arid regions. The present study intended
12 to evaluate alterations to, and temporal changes in, SOC with a Mediterranean climate that
13 can be affected by soil degradation. In this setting, agriculture has the potential to partially
14 compensate this large C loss. Some studies (Smith et al., 2008) support the notion that soil C
15 sequestration represents 89% of the potential of agricultural GGE mitigation. This effect can be
16 even stronger under Mediterranean conditions, where SOC levels are low (Gil et al., 2018;
17 Jiménez-Ballesta et al., 2012; Rodríguez Martín et al., 2016), although such losses could be
18 limited by soil management and climate changes (Jebari et al., 2018). The main goals of this
19 study were to: i) determine the SOCS on the Majorca island; ii) analyse the spatial variability of
20 soil organic carbon in relation to the influence of human activities and land use; iii) assess the
21 temporal changes in soil organic carbon in agricultural soils after 10 years by setting the island
22 as an exploratory plot to know the translatable tendencies for Mediterranean areas.

23

24 **2. MATERIALS AND METHODS**

25 **2.1 Study area**

26 The Island of Majorca is located to the west of the Mediterranean Sea (Figure 1). It is the
27 largest (3,640 km²) of the Balearic Islands, formed mainly by calcareous lithologies (around 150
28 million years ago). Its climate is purely Mediterranean, with annual rainfall of 350–650 mm.
29 Traditional agriculture is based on cultivating dry land with the combination of trees, such as
30 almond (*Prunus dulcis* L.) and carob (*Ceratonia siliqua* L.), and winter cereals like wheat
31 (*Triticum aestivum* L.). Other types of agricultural activity include terraced farming, which
32 allows olive trees and vines to be grown in the Tramuntana Mountain Range. These are the
33 main agricultural crops on Majorca, along with citrus fruits. On Majorca, agriculture lost its
34 importance through the development of tourism in recent decades. The abandonment of
35 agricultural activity has been accompanied by a change in residential land use. The influx of

1 Northern Europeans as residents and speculation have increased agricultural land values. They
2 have spread to rural areas, and have settled down to live in farmhouses, known as the
3 agrotourism sector. This common situation is on the rise on the Mediterranean coast and
4 works against the economic feasibility of agricultural activity. Tourism and the development of
5 urban areas have created a huge demand for fresh vegetables, which has led to the intensive,
6 technical, irrigation-based cultivation methods being taken up in this sector. The flat plains in
7 the centre of the island represent the most important area for such agriculture.

9 **2.2 Soil sampling and laboratory analyses**

10 Soil samples were taken from the upper 25-30 cm of soil. One hundred and eight soil samples
11 from georeferenced localisations (Figure 1) were collected on the Majorca Island between
12 2016 and 2017. Thirty soil samples were used as Sentinel plots (Figure 1), which correspond to
13 the previous sampling done in 2006 (Rodríguez Martín et al., 2009). These plots were selected
14 according to a systematic grid (8 km × 8 km size) in agricultural areas (Rodríguez Martín et al.,
15 2009). The same field sampling methodology was used at both times to enable the evaluations
16 to be made of changes over time with no interferences from the field or laboratory. For each
17 sampling site, at least 10 soil subsamples were mixed in the field to select 3 kg of soil.

18
19 *Figure 1: Map of the Majorca Island showing the soil samples in 2016/2017 and the position of*
20 *the sentinel plots (sampling in 2006) in agricultural and forest areas.*

21
22 Soil N was determined by the Kjeldahl method (Bremner and Mulvaney, 1982) and available P
23 was established following the Olsen method (Olsen et al., 1954). Ammonium acetate was used
24 to extract and determine the exchangeable potassium content in soil (Helmke et al., 1996). Soil
25 reaction (pH) and carbonate concentration were carried out (Houba et al., 1995). To determine
26 coarse fragments (% mineral particles >2 mm in diameter), soil samples were sieved to obtain
27 two sections with rocky fragments, >6 mm, another section between 6 mm and 2 mm,
28 (Rodríguez Martín et al., 2013), and the fine soil sample, <2 mm. Part of the latter was ground
29 to determine organic carbon content (SOC). Organic carbon was analysed by oxidising carbon
30 with acidic dichromate (Walkley, 1935), which has been the “reference” method followed to
31 make comparisons with other methods in numerous studies (Schumacher, 2002). This
32 procedure has been widely used because it is simple and rapid, and equipment requirements
33 are minimal. Bulk density (BD) was measured by the core method according to (Black and
34 Hartge, 1986).

1 Soil organic carbon stock (SOCS) was calculated as:

$$2 \quad (1) \quad SOCS_{(i)} = SOC_{(i)} \times BD_{(i)} \times D \times (1 - S_{(i)})$$

3 where SOC is the soil organic carbon concentration percentage ($g \ 100^{-1}g$), BD is bulk density (g
4 cm^{-3}), D is the thickness of the layer (30 cm) and S is the proportion of the volumetric coarse
5 fragments fraction ($g \ 100^{-1}g$). This type of estimation has been widely used in Spain (Boix-Fayos
6 et al., 2009; Muñoz-Rojas et al., 2012; Rodríguez-Murillo, 2001; Rodríguez Martín et al., 2016).

7

8 **2.3 Statistical and geostatistical analyses**

9 Descriptive statistics (mean, median, standard deviation, etc.) were calculated for the soil
10 parameters. The general linear model (GLM) was used to test the effects of Agricultural Crops
11 and Sampling year on SOCS in the sentinel plots (Takoutsing et al., 2018). The general linear
12 model included two-way and interactions between main effects. A simple geostatistical
13 analysis was used to generate kriging maps of the percentages of SOC, BD and coarse
14 fragments fraction (Goovaerts, 1997; Lv et al., 2015; Odumo et al., 2018; Rodríguez Martín et
15 al., 2014). Spherical models were used to fit the experimental semivariograms and ordinary
16 kriging (OK) was utilised to estimate SOC (%), BD ($g \ cm^{-3}$) and Stoniness (%) as a map grid of
17 $100 \times 100 \ m$ (1 ha). The total SOCS was calculated according to Equation 1 for all the grid map
18 cells. The prediction accuracy of the SOC, BD and stoniness maps was evaluated by the cross-
19 validation technique (Holy et al., 2009; Rodríguez Martín et al., 2007). The estimated standard
20 errors of the kriged values and the root mean square error (RMSE) were used to test the
21 accuracy of the kriging maps (Meersmans et al., 2012; Mishra et al., 2010). XLSTAT, ISATIS
22 V10.0 and ArcGis 10 were used.

23

24 **3. RESULTS AND DISCUSSION**

25 **3.1 Descriptive soil parameters**

26 The statistical summary of the studied soil parameters is presented in Table 1. The mean SOC
27 concentration was 2.64%, with values ranging from 0.84% to 12.51%. A previous study
28 estimated that the mean SOC concentration for the entire Spanish surface was 1.73%, with
29 values ranging from nearly 0% to 18.40% (Rodríguez Martín et al., 2016). Therefore, the mean
30 SOC value found herein for the Majorca Island was about 50% higher than the mean SOC value
31 for the entire Spanish territory. This same national assessment concluded that half the area of
32 Spain presented SOC values below 1%, which is the desertification limit proposed by Loveland
33 and Webb (2003). However for the particular case of Majorca, the majority of measured SOC
34 values were above 1%, and only one presented SOC values below 1%. The measured BD values
35 fell within the $0.38 - 1.69 \ g \ cm^{-3}$ range, with a mean value of $1.16 \ g \ cm^{-3}$ (Table 1). The mean

1 BD value obtained for the Majorca Island was low compared to the mean value of 1.38 g cm^{-3}
2 obtained for the entire Spanish surface (Rodríguez Martín et al., 2016). It is well established
3 that soil BD is negatively related with SOC (Heuscher et al., 2005). Thus the higher mean SOC
4 levels on Majorca, compared to the mean SOC value for Spain, could explain the observed
5 difference in soil BD. The mean stoniness value for the Majorca Island was about 20% higher
6 than the mean national value obtained for Spain (Rodríguez Martín et al., 2016). Other
7 measured soil properties generally showed soil to have relatively high CaCO_3 contents (mean
8 value above 34%), which results in soils with high pH values (within the 8.4-7.4 range; Table 1).
9 Soils rich in calcareous materials formed from sedimentary basins are typical from the Balearic
10 Islands.

11

12 The SOC concentrations for different land uses are presented in Table 2. One of the main
13 controlling factors for SOC changes is land use. In a global meta-analysis (Guo and Gifford,
14 2002), land use change from cropland to grassland or forest resulted in increased SOC levels. It
15 is well documented that historical agricultural activity, compared to natural land, has depleted
16 SOC levels (Assefa et al., 2017; Smith et al., 2008). A historical SOC change assessment
17 observed how SOC levels have continuously declined throughout the 20th century for the
18 entire Spanish surface (Aguilera et al., 2018). These authors concluded that the expansion of
19 cropland and the reduction in C inputs returned to soil were the two main explanations for the
20 declining SOC levels in Spain in the last century. In our study, the SOC levels found in the three
21 different sampled cropland types (annual crops, fruit trees and vineyards) showed the main
22 SOC concentration values to lie between 1.14% and 1.73% (Table 2). Fruit trees showed a SOC
23 concentration to be about 15% higher compared to annual crops. Interestingly, in a previous
24 national SOC assessment made for all peninsular Spain (the Majorca island was not included),
25 annual crops showed higher SOC levels than woody crops (Rodríguez Martín et al., 2016). The
26 difference in SOC levels found between tree crops and arable crops could be related with
27 differences in the soil management practices applied to each cropping system. According to
28 the National Survey for the Agriculture Sector published by the Spanish Government in 2012,
29 conventional tillage was performed on the Majorca Island on more than 95% of its total
30 surface, destined to annual crops (MAPAMA, 2012). In tree crops, however, conventional
31 management only affected 10% of the surface covered by tree crops. This value contrasts with
32 the tree crop area managed by intercropping which, according to the National Survey, was
33 40% on Majorca (MAPAMA, 2012). The use of cover crops between tree lines is a strategy that
34 successfully increases SOC levels under Mediterranean conditions (Almagro et al., 2017;
35 Vicente-Vicente et al., 2016). Furthermore, the use of cover crops in woody crops lowers soil

1 erosion rates and nutrient loss, which makes this technique a win-win strategy (Gómez et al.,
2 2011).

3

4 *Table 1: Statistical summary of the descriptive soil parameters (n=108).*

5 *Table 2: Statistical summary of SOC according to the land use classes sampling finished in*
6 *2017.*

7

8 **3.2 Spatial variability and assessment of SOC stocks on Majorca**

9 The spatial distribution of the SOC percentage ($\text{g } 100^{-1}\text{g}$), BD (g cm^{-3}) and the proportion of the
10 volumetric coarse fragments fraction ($\text{g } 100^{-1}\text{g}$) are shown in Figure 2. From the geostatistical
11 analysis, OK was used for the spatial interpolation according to the spherical isotropic model in
12 the experimental semivariograms (Figure S1 in the Supplementary Material). The quality of the
13 prediction map of SOC, BD and Stoniness was examined by cross-validation statistics
14 (Meersmans et al., 2011; Mishra et al., 2010). Standard errors map showed minor errors on
15 the uncertainty kriging maps (Table S1 in the Supplementary Material).

16

17 There was considerable spatial variability in the SOCS on the Majorca Island. SOCS tended to
18 be higher in the north-westerly part of the island, while the lowest contents were located in
19 the south (Figure 2). This was particularly evident in the mountainous areas of the Tramuntana
20 Mountain Range, where the highest SOCS (above 100 tC ha^{-1}) value was found for the forest
21 samples which contained high percentages of organic matter (more than 3%). In general, these
22 areas corresponded to forest lands with Aleppo pine (*Pinus halepensis* Mill.) and holm oak
23 (*Quercus ilex* L.). However, equally high values were also found in abandoned olive crops (*Olea*
24 *europaea* L.) and grasslands. Olive crop-growing has been practiced as terrace cultivation in
25 the Tramuntana Mountain Range. Nevertheless, many agricultural terraces have gradually
26 been abandoned due to low economic benefits. In 1979, only 28% of terraced fields were
27 already abandoned, while this figure currently exceeds 90% (Martínez et al., 2013). The
28 abandonment of agricultural terraces has triggered the growth and expansion of bush and
29 forest species (Deng et al., 2018; Martínez et al., 2013). This secondary succession, which is
30 covered by vegetation, develops higher SOC, especially in the Mediterranean region. The
31 conversion of arable land into grassland for the same reason to the north-west of Majorca has
32 had similar consequences for soil carbon storage. This circumstance has reduced tillage and,
33 according to other studies, can increase sequestration rates between $0.4\text{-}0.8 \text{ tC ha}^{-1} \text{ yr}^{-1}$
34 (Lugato et al., 2014). On the contrary, low organic carbon contents were observed in the
35 central and southern areas of the island, with values below 70 tC ha^{-1} (Figure 2). This mean

1 value is similar to other Mediterranean agricultural areas in Europe (de Brogniez et al., 2015),
2 such as Italy with 58.7 tC ha⁻¹ or France with 78.3 tC ha⁻¹ (Lugato et al., 2014). Nonetheless, the
3 agricultural SOCS on the island is above the Spanish national mean, with 56.6 tC ha⁻¹ (Rodríguez
4 Martín et al., 2016).

5

6 According to the grid map statistics for the whole study area, Table 3 shows the total SOCS for
7 the two main land uses: forest and agricultural areas. As expected, the highest carbon content
8 was concentrated in the forest areas to the north of the island (Tramuntana Mountain Range),
9 with a mean value of 100.49 tC ha⁻¹. Under Mediterranean climate conditions with calcareous
10 substrates, forest ecosystems are the most important reservoirs of carbon pools (González
11 González et al., 2012). However, the agricultural area of the Majorca Island (2331 km²) showed
12 higher soil carbon storage with more than 18 Mill Tons of C (Table 3). The contribution of
13 agroecosystems to the global carbon budget of Mediterranean soil (Álvaro-Fuentes et al.,
14 2009; Jebari et al., 2018; Pardo et al., 2016) and the importance of preserving or increasing
15 SOC in these soils through several agricultural practices were particularly obvious (Álvaro-
16 Fuentes et al., 2014). In short, today the total organic carbon stock stored in Majorca topsoil
17 was estimated to be 31.23 Tg C.

18

19 *Figure S1: Experimental variogram and spatial models for SOC, stoniness and BD.*

20 *Figure 2: Spatial distribution of SOC, stoniness and BD interpolated by OK. Estimate map of the*
21 *SOC stock on the Majorca Island. Values in ton ha⁻¹.*

22 *Table S1: The root mean square error (RMSE) validation indices of soil parameters in spatial*
23 *analysis accuracy.*

24 *Table 3: SOCS in the main land use categories according to the SOC stock map in 2017.*

25

26 **3.3 Temporal change in agricultural SOCS.**

27 Figure 3 shows a SOCS content ratio map between samplings years 2006 and 2017 only in the
28 agricultural area. Decreasing soil carbon storage may be considered when the ratio is below 1.
29 The present study shows a major reduction for SOCS in the central and south zones of this
30 island. Nonetheless, this ratio is 1.5- and more than 2-fold higher in the agricultural zones
31 located on mountain slopes, which are associated with abandoned crops, mainly olive in
32 terrace cultivation. Land abandonment has been the main land use change in rural
33 Mediterranean areas in recent decades (Gabarrón-Galeote et al., 2015). Over the last 11 years,
34 agricultural soils on Majorca have sequestered 11.26 tC ha⁻¹ in the 0-30 cm soil layer (Table 4).
35 When considering the total agricultural surface of the Island, the total C stored from 2006 to

1 2017 reached 2.62 Tg C, which is an increase of about 15% (Table 4). According to the GLM
2 analysis using the sentinel plots (Table 5), no significant differences between both sampling
3 years were shown. This lack of statistical significance was due to the interaction between two
4 variables, year x agricultural use, which was statistically significant. We observed that in the
5 last 11 years, SOCS has decreased agricultural soils (annual crops and fruit trees), but has also
6 increased in grasslands soil to compensate for the balance between 2006 and 2017. The
7 difference in SOCS between years is particularly noticeable in the spatial variability of the ratio
8 map (Figure 3), which depends on the distribution of plots. As previously mentioned, to the
9 north of the island SOCS has increased due to abandonment of crops. However, grassland
10 systems have also increased from 1.998 tC ha⁻¹ to 2.311 tC ha⁻¹ (16.7%). Light grazing,
11 prolonged grass duration and the introduction of legumes could potentially contribute to
12 increase the soil C levels on Majorca. Several studies (Alidoust et al., 2018; Smith et al., 2014;
13 Song et al., 2018) have suggested that optimal grassland management may allow soil C gains.

14

15 In contrast, agricultural soils (both annual and tree crops) showed a decrease in SOC between
16 2006 and 2017, and was more pronounced in annual crops (-14.5%) than in tree crops (-4.7%)
17 (Table 4). This SOC reduction has been shown mainly in the centre of the island (Figure 3). The
18 reduction in SOC levels could be related to the proliferation of irrigated crops and changes in
19 the agricultural management practices that have taken place in the last decade in the annual
20 cropping systems on Majorca. The drop observed in SOC levels in annual crops could be
21 attributed to the typical intensive soil management of these zones. The use of intensive tillage
22 has been associated with SOC losses due to the boost of C decomposition after tillage
23 operations (Chen et al., 2018; Morell et al., 2011). Tillage breaks up soil aggregates, which
24 favours the release of aggregate-associated C occluded within soil aggregates (Plaza-Bonilla et
25 al., 2013). Furthermore, tillage creates better soil conditions for microbial activity, which
26 favours contact between soil microbes and crop residue, and also enhances soil profile
27 aeration (Álvaro-Fuentes et al., 2008). As mineralisation is limited by lack of soil moisture in
28 Mediterranean cropping systems during the dry season, the transformation into irrigated lands
29 could reduce SOCS, even when crop residue increases (Quemada and Gabriel, 2016). Besides,
30 changes in management would imply either the stimulation of microbial decomposition or the
31 reduction in the amount of C inputs returned to soil. However, changes in soil management
32 affect SOC levels for a limited period of time. After a period of fast increments or decreases,
33 SOC tends to strike an equilibrium in which C inputs are counterbalanced with C outputs (West
34 and Six, 2007).

35

1 As mentioned in the previous section, the use of intensive tillage is a representative trait of the
2 annual cropping systems under Mediterranean Spanish conditions (MAPAMA, 2012). However,
3 several experiments performed in Mediterranean dryland agro-ecosystems have reported that
4 SOC contents did not vary 11 years after not adopting tillage (Álvaro-Fuentes et al., 2014). In
5 this context, we think that other factors have also been involved in the Majorcan agricultural
6 soils temporal changes. For example, the drop in the SOC levels in annual cropping systems
7 could be related to the increase in surfaces left to fallow observed in the last 20 years on the
8 Majorca Island. The Annual National Agricultural Survey reported that the agricultural surface
9 occupied by fallow increased from around 20,000 to 27,500 ha for the 1996-2014 period on
10 Majorca. This 35% increase in the agricultural surface covered by fallow in the last 12 years
11 could imply a drastic drop in the amount of C inputs returning to soil. Under Mediterranean
12 conditions, using long-fallowing periods (16-18 months) between cereal seasons is
13 commonplace in rain-fed systems. The principal impact of long-fallowing on C dynamics is
14 lowering C inputs as crop residue only returns to soils once every two seasons. The
15 intensification of the cropping system by suppressing long-fallow phases can more than double
16 the amount of C inputs returned to soil (Álvaro-Fuentes et al., 2009).

17

18 *Figure 3: Maps of change in SOCS in agricultural areas (2017/2006 ratio).*

19 *Table 4: Change in SOCS in the agricultural area of Majorca.*

20 *Table 5: GLM and Multiple Range Tests for agricultural use and sampling year in sentinel plots.*

21

22 **4 CONCLUSIONS**

23 This study has provided valuable information to quantify and rebuild trends in SOCS on the
24 Majorca Island, particularly land use variations due to human activities. The spatial analysis
25 and interpolated maps have proved essential to detect and evaluate temporal changes in
26 SOCS. From this study, as expected we conclude that soil organic carbon is higher in forest
27 areas than in arable land. However, total soil carbon storage is higher in agricultural uses as it
28 represents a bigger area on the island, which suggests that actions on agricultural land may
29 more strongly impact soil carbon stock. As a general trend, the carbon stock on this island
30 increased after 11 years. A marked increase in SOCS was quantified in the grassland areas and
31 abandoned crops located on mountain slopes due to lack of agricultural economic profits, a
32 common situation that has arisen in Mediterranean rural areas in recent decades. We provide
33 evidence for a marked decrease in SOCS in some agricultural zones located in the centre of the
34 island, which are associated with the conversion rain-fed crops into irrigated crops and with

1 intensive soil management practises. We conclude that alternative cropping techniques should
2 be considered to lower land degradation and to promote SOC sequestration.

3

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Table 1[Click here to download Table: Table 1.docx](#)

Table 1: Statistical summary of the descriptive soil parameters (n=108).

Soil parameter	Mean	Median	SD	Min	Max	3rd Qu
SOC (%)	2.64	2.00	1.84	0.84	12.51	3.22
Bulk density (BD)	1.16	1.17	0.21	0.38	1.69	1.26
Stoniness (%)	24.81	22.26	15.46	0.34	59.73	33.38
pH	8.17	8.22	0.17	7.43	8.42	8.28
CaCO ₃ (%)	34.08	33.50	20.82	4.00	87.00	46.00
N (%)	0.23	0.20	0.11	0.09	0.69	0.26
P (mgkg ⁻¹)	14.87	8.15	24.28	1.60	171.30	13.50
K (mgkg ⁻¹)	411.8	355.5	234.5	38.0	1414.0	520.0
A.W (%)	10.31	10.00	2.78	3.00	22.00	12.00

Table 2[Click here to download Table: Table 2.docx](#)

Table 2: Statistical summary of SOC according to the land use classes sampling finished in 2017.

Landuse	No. Samples	Mean	Median	SD	Min	Max	3rd Qu
Annual crops	32	1.49	1.35	0.52	0.84	2.87	1.84
Fruit trees	20	1.73	1.78	0.41	1.12	2.61	1.95
Vineyard	2	1.14	1.14	0.25	0.96	1.32	1.23
Grassland	10	2.31	1.88	0.88	1.32	3.79	3.07
Forest (holm oak)	9	3.90	3.20	1.67	2.06	6.11	5.19
Forest (pinewood)	31	4.20	3.84	2.33	1.01	12.51	5.21
Wetland (natural Park)	4	2.99	2.79	0.91	2.12	4.25	3.29
Total	108	2.64	2.00	1.84	0.84	12.51	3.22

Table 3[Click here to download Table: Table 3.docx](#)

Table 3: SOCS in the main land use categories according to the SOC stock map in 2017.

SOC Stock	Surface (Km²)	Mean (tC/ha)	SD	min	max	Amount of C (Tg)
Forest Area	1272	100.49	28.11	49.25	160.48	12.78
Agricultural Area	2331	79.29	23.29	48.96	157.46	18.48
Total	3603	86.77	27.08			31.26

Table 4[Click here to download Table: Table 4.docx](#)

Table 4: Change in SOCS in the agricultural area of Majorca.

Agricultural SOC Stock	Mean (tC/ha)	SD	min	max	Amount of C (Tg)
Year 2006	68.03	8.26	45.04	96.81	15.85
Year 2017	79.29	23.29	48.96	157.46	18.48
Agricultural Change	11.26				2.62
2017 versus 2006	14.20%				

Table 5[Click here to download Table: Table 5.docx](#)

Table 5: GLM and Multiple Range Tests for agricultural use and sampling year in sentinel plots.

Source	Df	Sum of squares	Mean square	F	Pr > F
Agricultural use	2	4.5748	2.2874	10.96	0.000
Sampling year	1	0.0006	0.0006	0.00	0.957
Crops x year	2	1.0205	0.5102	2.45	0.091

Agricultural crops	Total mean	H.Group	Mean 2017	H.Group	Mean 2006	H.Group
Annual crops	1.599	A	1.491	A	1.707	A
Fruit trees	1.771	A	1.731	A	1.812	AB
Grassland	2.155	B	2.311	B	1.998	B

Significant differences amongst the two sampling periods are indicated by different letters in homogeneous groups. The two samples in vineyards have not been considered for statistical analysis.

Figure 1
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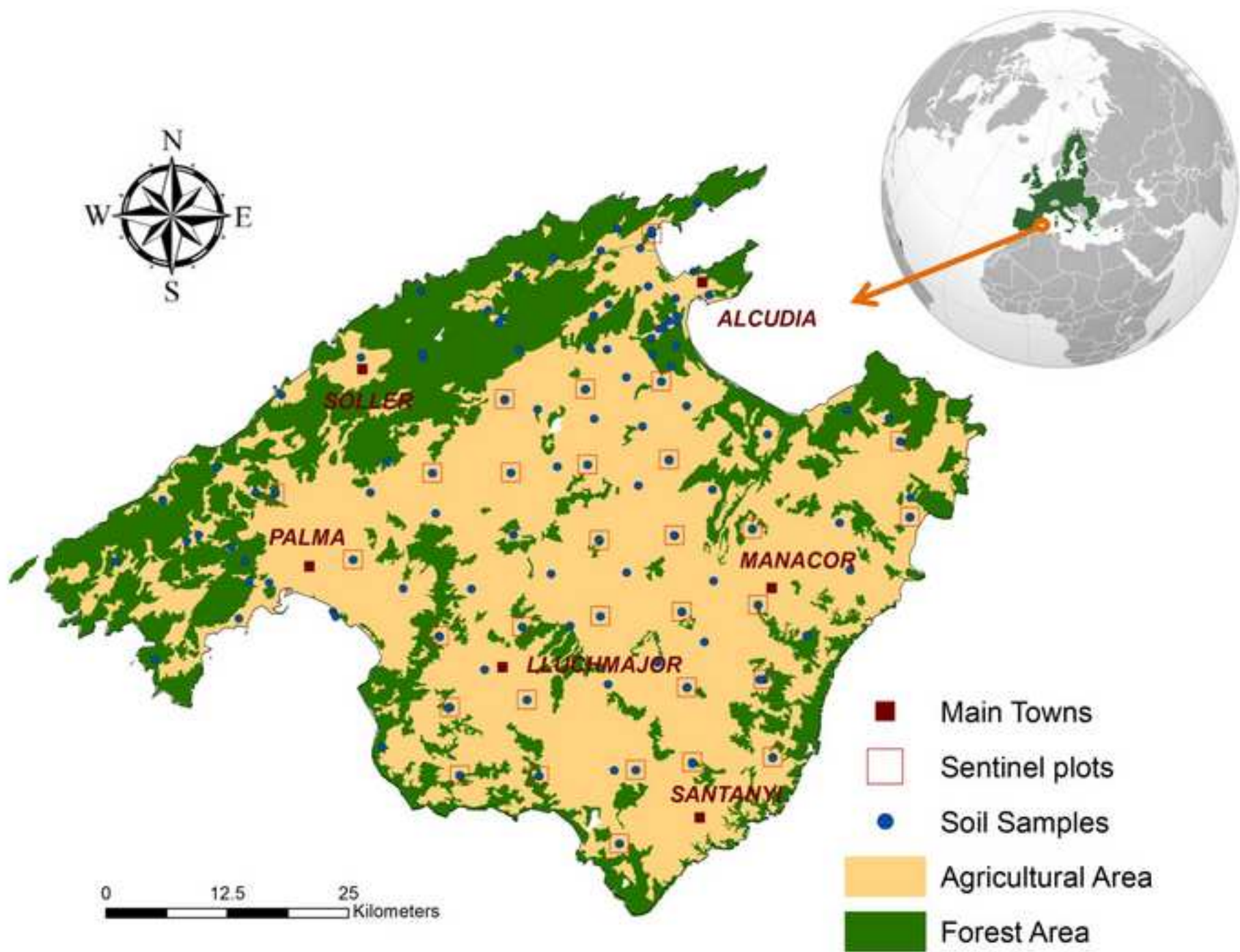


Figure 2
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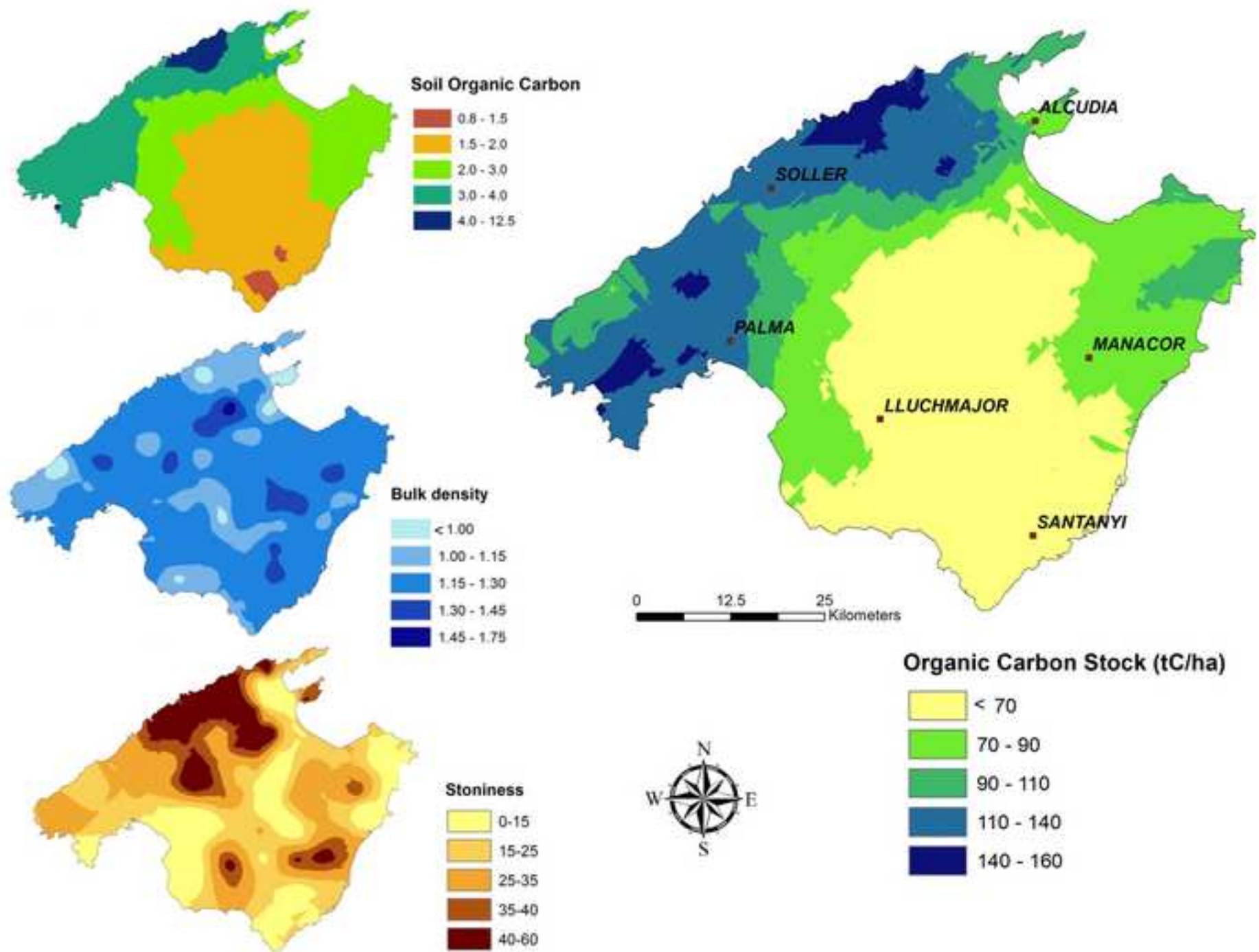


Figure 3
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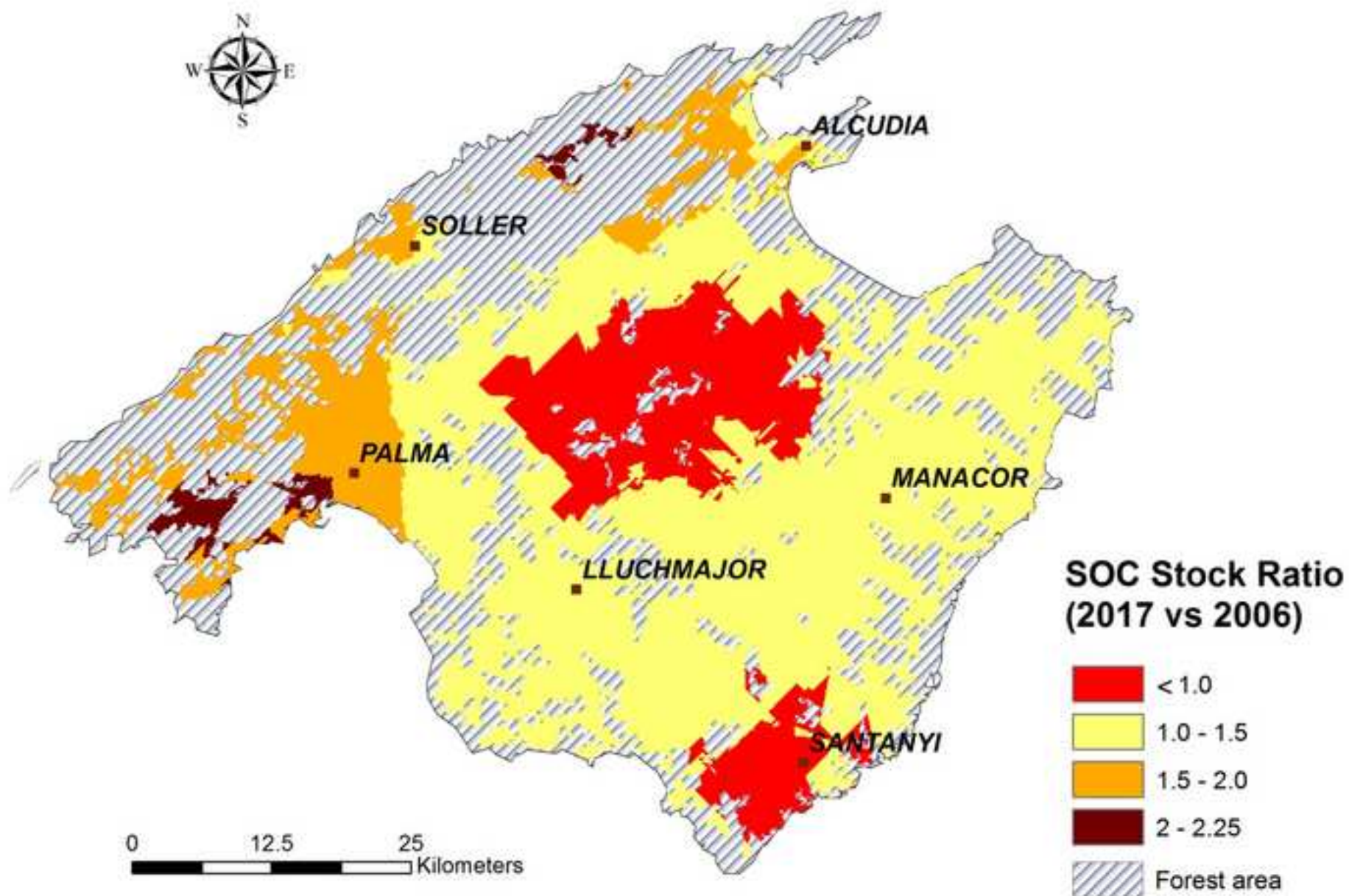


Figure Captions

Figure 1: Map of the Majorca Island showing the soil samples in 2016/2017 and the position of the sentinel plots (sampling in 2006) in agricultural and forest areas.

Figure 2: Spatial distribution of SOC, stoniness and BD interpolated by OK. Estimate map of the SOC stock on the Majorca Island. Values in ton ha^{-1} .

Figure 3: Maps of change in SOCS in agricultural areas (2017/2006 ratio).

Supplementary material

Figure S1: Experimental variogram and spatial models for SOC, stoniness and BD.