LIFE 20 PRE IT/017

CARBON FARMING CERTIFICATION SYSTEM

D.5 - METHODS AND APPROACHES TO CREATE GIS-FARMS AND IMPACT OF THE CARBON FARMING PRACTICES

ACTION A.4

BARBATI ANNA, GIULIARELLI DIEGO, OLAKUNLE JOSHUA

UNITUS, FLA, CMCC, TS, CGAI, CREA

TABLE OF CONTENTS

Introduction: aims of the High-resolution geographical information system GIS-FARMs

This report illustrates the output of the activities implemented under the Action 4 of C-Farms project, aiming at defining a methodology to integrate information from different data sources collected under Actions 1, 2, and 3 (farm-level statistical information, geospatial datasets on land cover and environment, statistical information on impacts of carbon farming practices) into a GIS-based infrastructure to support decision-making in Carbon Farming (GIS-FARMs). In particular the GIS-FARMs methodology focuses on a well-defined area of C-farming practices, i.e. farmland management practices capable of offsetting CO_2 emissions due to agricultural activities, through CO_2 sequestration in the topsoil layer (0-30 cm) and/or emissions reduction.

The GIS-FARMs platform is designed to support Regional Public Authorities and farmers in making informed decisions in the field of carbon farming by targeting two main information needs:

Regional scale (end-users: **Public Authorities)**; at this scale the main goal of GIS-FARMs is to provide reliable information with the highest possible spatial resolution on:

- **current soil organic carbon (SOC) stocks in the topsoil**, so as to display SOC spatial variation in the land under agricultural land use in the Region Lombardy territory;

- **soil C sequestration potential in relation to local environmental conditions**, so as to identify areas were carbon-farming activities should be prioritized in relation to distance to the level soil C storage saturation of agricultural soils;

Farm scale (end users: **single farmer** or land-owner); at this local scale, corresponding to a farm's block (one or more agricultural land parcels owned by a single farmer), the main goal of GIS-FARMs is providing robust values of **SOC change** at the scale of **single agricultural parcels,** based on the potential for **CO_2 sequestration and/or emissions reduction** of **carbon-farming practices** identified under project Actions 2-3.

The Report structure is organized into four main sections, conceived to explain step-by-step the methodological framework proposed to address the GIS Farm information needs above illustrated.

Section 1 *Regional scale delineation of homogeneous areas for mitigation potential of carbon farming* illustrates the **methodological steps** leading to the **environmental**

stratification of the territory under **agricultural land use** in Lombardy Region. The stratification acts as the foundation underlying subsequent analysis of both current spatial variability of SOC content in the topsoil (Section 2) and associated SOC sequestration potential (Section 3), and the assessment of the potential for CO_2 sequestration and/or emissions reduction of some carbon-farming practices (Section 4). The vector layer of environmental **stratification of the territory** under **agricultural land use** in Lombardy Region is provided with this Deliverable.

Section 2 *Characterization of Soil Organic Carbon (SOC) content of the strata* describes the **geoprocessing methodology** to associate **initial** levels of **SOC in the topsoil** to the **spatial units deriving from stratification** (*strata*); in addition, geospatial criteria are introduced to derive by descriptive statistics a quantitative characterization of variability in SOC content across strata.

Section 3 *SOC Sequestration Potential assessment* explains how geospatial information on current levels of SOC and strata descriptive statistics values can be integrated to calculate the *SOC Sequestration Potential* of agricultural soils in Lombardy. The resulting map is provided as vector layer with this Deliverable.

Section 4 *Carbon farming scenario analysis at the scale of agricultural parcel* illustrates a **methodological pathway** for integrating in a GIS environment, the data sources collected under project Actions 2-3 with the **SOC Sequestration Potential map of Lombardy Region** and with vector layers of the **Land Parcel Identification System (LPIS)** to enable **SOC change projections** to be made at the scale of **agricultural parcels**, in terms of **CO_2 sequestration and/or emissions reduction** potential of **carbon-farming practices.**

Section 5 *Conclusions and recommendations* offers main conclusions about the spatial information provided by the GIS Farm methodology to support decision making on carbon farming in Lombardy Region.

Two graphical abstracts are provided below for Section 1 to Section 3 and Section 4 to offer a concise and visual summary of the overall flowchart of the GIS-FARMs methodology.

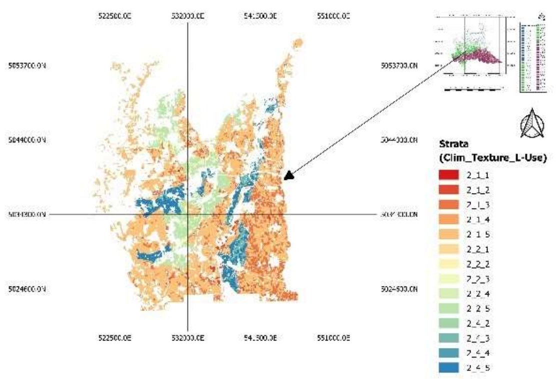
LIFE 20 PRE IT/017

C·FARMs
CARBON FARMING CERTIFICATION SYSTEM

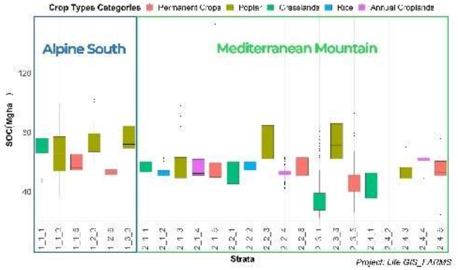
INPUT DATA	STRATIFICATION (Section 1)	CHARACTERIZATION OF SOC CONTENT OF THE STRATA (Section 2)	SOC SEQUESTRATION POTENTIAL (SOC_{SP}) (Section 3)
• Climate • Texture • Land Use • Initial Soil Carbon Content (SOC) from the FAO GSOC Map	Intersecting Climate, Texture and Land Use *(Map of 53 unique strata homogenous for climate, texture and land use)*	GSOC map vectorization for Lombardy region Extraction of SOC Statistics for Strata	Descriptive Statistics on SOC for Strata homogenous for climate and texture (11 Strata) Derivation of SOC Saturation level for the 11 strata (SOC_{SAT}) SOC SEQUESTRATION POTENTIAL $SOC_{SP} = SOC_{SAT} - SOC$

Climate Texture Land Use

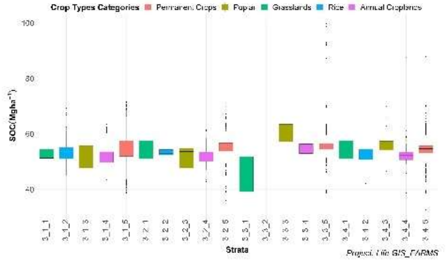
Extract from the map of the Strata

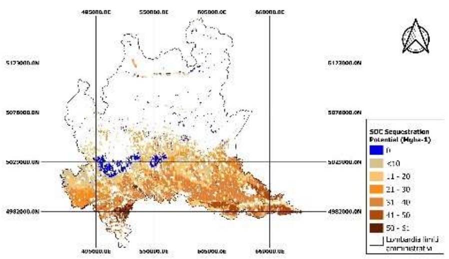


Alpine South & Mediterranean Mountain



Mediterranean North





SHAPEFILE GIS-FARMS

Strata_Section_1

SOC_Sequestration_Potential_Map

LIFE 20 PRE IT/017

C·FARMs CARBON FARMING CERTIFICATION SYSTEM

Carbon farming scenario analysis at the scale of agricultural parcel (Section 4)

INPUT DATA

Farm scale: Agricultural parcels

Regional scale: Climate, Texture, SOC Sequestration Potential Map

Agricultural parcels (AP)

(contiguous agricultural land homogeneous by cultivation type and management)

AP STRATIFICATION

Intersecting Climate and Texture with AP land use (derived from vector LP map)

Relational database

ID FARM	1
ID LAND PLOT	79884018
ID CADASTRAL PARCEL	116060
ID AGRIC PARCEL	92
AREA (m^2)	66928

Land plots (LP)

ID FARM	1
ID LAND PLOT	79884018
LAND USE	Sowable areas

Cadatstral parcel (CP)

ID CADASTRAL PARCEL	116060
PROVINCE	MI
MUNICIPALITY	Abbiategrasso
MAP SHEET	5
PARCEL	24

AP SOC SEQUESTRATION POTENTIAL

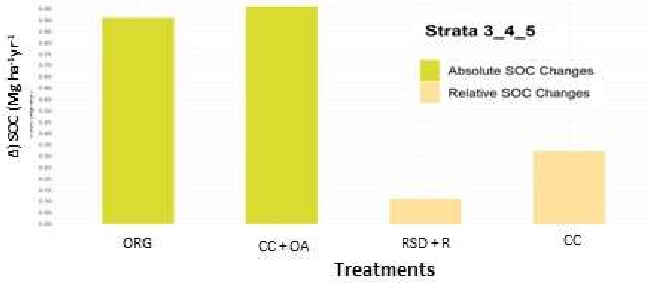
SOC sequestration potential data transfer (initial SOC level (SOC_0), saturation SOC level (SOC_{SAT}), SOC potential accumulation (SOC_{PA})) to the AP database via the identity tool

AP SOC CHANGE SCENARIOS

Merging the scenario database to the AP map via a table join based on the stratum code

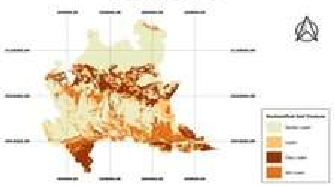
ID FARM	1
ID LAND PLOT	79884018
ID CADASTRAL PARCEL	116060
ID AGRIC PARCEL	71
AREA (m^2)	108945
CLIMATE	3
TEXTURE	4
LAND USE	5
STRATUM	3_4_5
ID SOC CELL	14806
SOC_0 (Mg ha^{-1})	47.79
SOC_{SAT} (Mg ha^{-1})	61.35
SOC_{PA} Mg ha^{-1})	13.35
ΔSOC_{ABS}	a) ORG; b) CC+OA
ΔSOC_{REL}	a) RSD+R; b) CC

Cover crops (CC) - Organic ammendant (OA) - Organic agriculture (ORG)
Maintanance of crop residues (R) - Reduced soil disturbance (RSD)

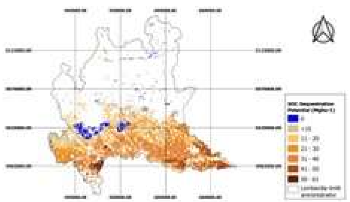


Climate

Texture



SOC SEQUESTRATION POTENTIAL



FLA FEDERLEGNOARREDO · PEFC · crea · Confagricoltura · rete clima · Università della Tuscia · TERRASYSTEM · cmcc Euro-Mediterranean Center on Climate Change

Section 1. Regional scale delineation of homogenous areas for mitigation potential of carbon farming

1.1 Introduction

The carbon sequestration capacity of agricultural soils depends on numerous factors such as the initial carbon content, texture, climate, type of use and agronomic management practices applied. Having said that, the information layers acquired and pre-processed during Action 1 (see Deliverable 1 & 3 for a description) are combined in a GIS environment in order to identify, on a regional scale, agricultural areas that are homogeneous in terms of biophysical characteristics (climatic zone and textural macro-class) and type of use (proxy of the management history at regional scale). The overarching goal of this activity is to understand the spatial distribution of soil organic carbon content among the unique strata, so as to provide useful information to decision makers capable of assisting them prioritize areas that require more attention in terms of potential SOC accumulation.

1.2 Method

Input data: Vector layers: Climate zones (3 classes); Soil texture macro-classes (4 classes); Crop-type categories (5 classes).

Geoprocessing tool: Intersect

The three input layers (climate zones, soil texture macro-classes and crop-type categories) were intersected in a GIS environment to form a shapefile of strata having the possible combinations of all the three layers. At the end of this process, 53 strata (combinations) were formed homogenous to both climate, texture and land use.

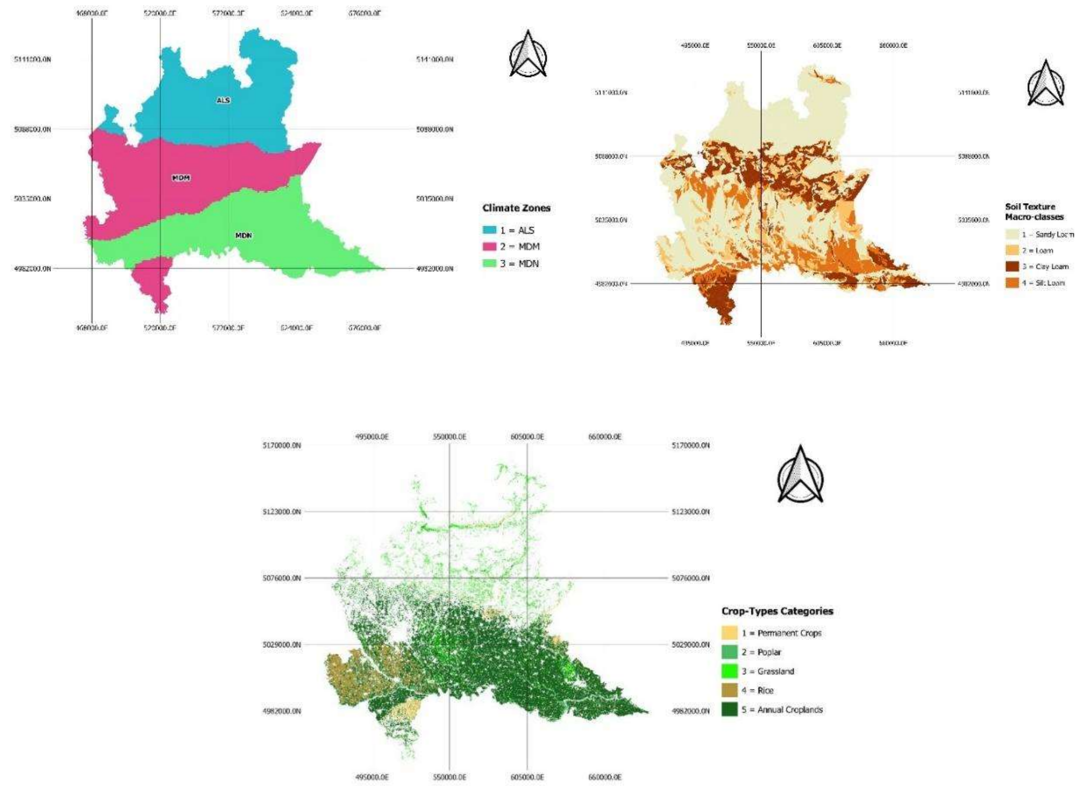


Figure 1. The three input layers with their respective legends and code (EPSG: WGS 84/UTM Zone 32N).

1.3 Results

In figure 2, an extract of the stratification map is shown to provide an idea of the possible combinations for both climate zones, soil texture macro-classes and crop-types categories. **The first code on the legend represents the code for the three (3) climate zones** where:

1 = Alpine South

2 = Mediterranean Mountain

3 = Mediterranean North

The second code represents the four (4) soil-texture macro-classes where:

1 = Sandy Loam

2 = Loam

3 = Clay Loam

4 = Silt Loam

The last code on the legend represents the five (5) crop-types categories which are:

1 = Permanent Crops

2 = Poplar plantations

3 = Grasslands

4 = Rice

5 = Annual Croplands

Therefore, a stratum with a legend of 2_1_5 shows an area with a Mediterranean mountain climate, sandy loam as its soil texture and annual croplands as the crop-type category. **The vector shapefile of the 53 strata with the corresponding metadata is attached with this Deliverable (vector file: "Strata_Section_1.shp"; metadata: "Metadata for Strata Section 1").**

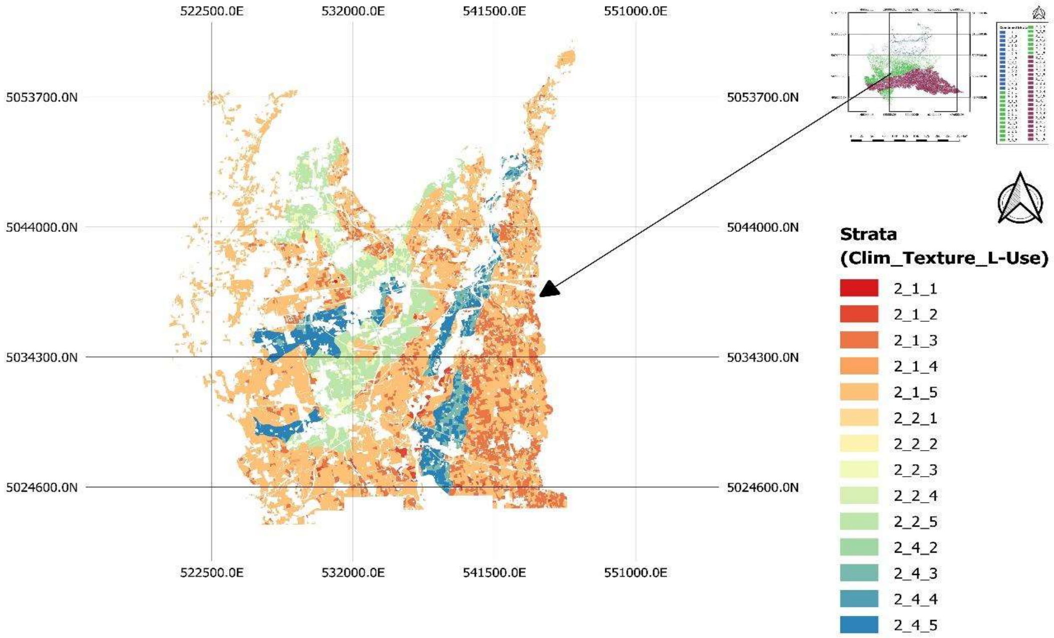


Figure 2. Map showing an extract of the agricultural territory in Lombardy region and its inner stratification into different combinations for both climate, texture and land use. (EPSG: WGS 84/UTM Zone 32N).

The allocation of total agricultural land to the 53 strata is summarized in Table 1, while Figure 3 provides a clear visual interpretation in terms of the surface covered by each stratum. At the end of the stratification, the strata formed ranged from the maximum area of 185014 ha attributed to stratum 3_1_5 (covering 18% of the total agricultural surface) to the less than 1 ha (stratum 1_4_1, representing just the 0.0001% of the total agricultural surface). The **first five (5) largest strata (3_1_5, 3_4_5, 2_1_5, 3_2_5 and 3_3_5)** cover the **61% of the total agricultural land** and are all associated to **annual croplands** mostly concentrated in the **Mediterranean north climate sector of the Lombardy Region**.

The only exception is stratum 2_1_5 belonging to the Mediterranean mountain climate. All the soil texture macro-classes are represented with the dominance of the sandy loam occurring at the largest strata 3_1_5 and the third largest strata 2_1_5.

Four out of five of the largest strata (3_1_5, 3_2_5, 3_3_5, 3_4_5) are those for which is **available from A2 Action knowledge** on a **set of carbon-farming practices** with their respective estimated **mitigation potential** (CO_2 sequestration and/or emissions reduction of carbon-farming practices). Section 4 will show how to incorporate this knowledge to GIS-Farms information layers to support decision-making in carbon farming.

A **second group** includes a set of **small strata**, each accounting for a **small percentage (1% to 3.5%) of the total agricultural surface** (2_4_5, 2_1_4, 1_1_3, 3_1_4, 2_2_5, 2_1_3, 2_3_5, 2_3_3, 3_1_3, 2_3_1, 3_1_3, 2_2_4, 3_2_4 and 1_3_3). For **two strata** in this group **(2_2_5, 2_3_5)** information **on estimated mitigation potential of carbon farming** practices is **available** from Action 2. The rest of the agricultural area is fragmented to very small strata covering less than 1% of limited significance.

Table 1. Strata surface statistics (expressed in hectares).

Strata	Total Area	Mean	Min	Max	Median	SD
1_1_1	2815.01	16.09	0.01	372.10	1.48	48.21
1_1_2	9.3	0.66	0.00	2.10	0.50	0.59
1_1_3	33323.11	37.07	0.00	788.35	14.26	71.36
1_1_5	2082.74	10.85	0.00	264.33	1.74	32.05
1_2_1	193.02	4.71	0.18	60.80	0.91	10.60
1_2_3	6345.11	43.76	0.00	292.33	21.94	55.47
1_2_5	246.49	7.70	0.02	94.02	1.17	20.45
1_3_1	208.02	4.43	0.11	42.49	0.65	9.57
1_3_2	1.82	1.82	1.82	1.82	1.82	NA
1_3_3	10049.18	42.40	0.02	506.28	25.35	59.21
1_3_5	227.12	4.06	0.01	88.36	0.90	12.32
1_4_1	0.84	0.42	0.07	0.77	0.42	0.49
1_4_3	133.66	12.15	0.33	61.99	9.22	17.33
1_4_5	8.16	2.72	0.98	4.72	2.45	1.88
2_1_1	2034.34	12.48	0.00	391.55	1.63	44.47
2_1_2	4931.46	36.00	0.00	777.54	5.60	86.98
2_1_3	22856.53	69.05	0.03	3360.53	19.83	210.96
2_1_4	35548.7	399.42	0.01	6586.50	207.56	811.99
2_1_5	120219.7	414.55	0.09	14005.93	93.71	1299.66
2_2_1	3785.18	39.84	0.03	767.59	3.97	96.07

Strata	Total Area	Mean	Min	Max	Median	SD
2_2_2	505.58	12.64	0.19	97.08	2.36	23.52
2_2_3	9737.38	53.50	0.12	600.97	18.22	90.19
2_2_4	11049.67	441.99	1.39	3262.34	131.90	797.58
2_2_5	24205.58	187.64	0.00	2231.01	47.31	336.23
2_3_1	15021.22	51.09	0.00	1448.90	7.30	140.68
2_3_2	65.86	2.00	0.00	15.35	0.75	3.20
2_3_3	18923.91	42.81	0.04	358.18	21.54	56.68
2_3_5	20507.83	62.14	0.00	1515.91	17.96	139.87
2_4_1	2426.29	34.66	0.23	312.92	7.67	60.13
2_4_2	226.4	6.29	0.04	60.01	1.64	11.39
2_4_3	6574.25	54.79	0.21	537.86	18.71	95.00
2_4_4	898.3	112.29	11.14	390.55	79.00	127.89
2_4_5	35619.84	291.97	0.06	3990.28	92.48	576.17
3_1_1	1526.49	13.88	0.01	283.09	1.99	37.20
3_1_2	17010.64	95.03	0.00	6621.58	7.94	527.10
3_1_3	14830.29	70.62	0.03	2153.10	14.91	201.06
3_1_4	32116.09	373.44	0.18	3708.30	146.54	647.32
3_1_5	185014.01	770.89	8.30	9390.66	271.28	1378.11
3_2_1	3948.17	49.35	0.04	994.69	4.43	134.16
3_2_2	1184.27	16.45	0.03	314.68	4.97	40.79
3_2_3	6135.94	58.44	0.01	1048.63	15.91	126.81

LIFE 20 PRE IT/017

C·FARMs CARBON FARMING CERTIFICATION SYSTEM

Strata	Total Area	Mean	Min	Max	Median	SD
3_2_4	10976.05	498.91	6.56	2219.31	129.05	649.16
3_2_5	75171.48	683.38	1.87	11218.76	285.28	1260.77
3_3_1	1314.78	23.07	0.00	455.01	3.83	65.00
3_3_2	944.77	18.90	0.00	163.01	3.48	31.66
3_3_3	1890.86	32.60	0.10	258.49	13.46	54.18
3_3_4	1059.5	105.95	3.89	417.94	64.86	141.57
3_3_5	62548.99	893.56	0.95	8868.10	302.13	1611.64
3_4_1	3193.1	28.51	0.00	1545.47	1.63	151.45
3_4_2	4752.08	34.69	0.00	858.01	10.05	88.34
3_4_3	8401.2	46.67	0.00	801.84	10.90	107.54
3_4_4	7464.7	133.30	0.00	976.19	67.73	193.14
3_4_5	174205.96	829.55	2.78	16721.28	304.18	1651.87
TOTAL	**1004470.97**					

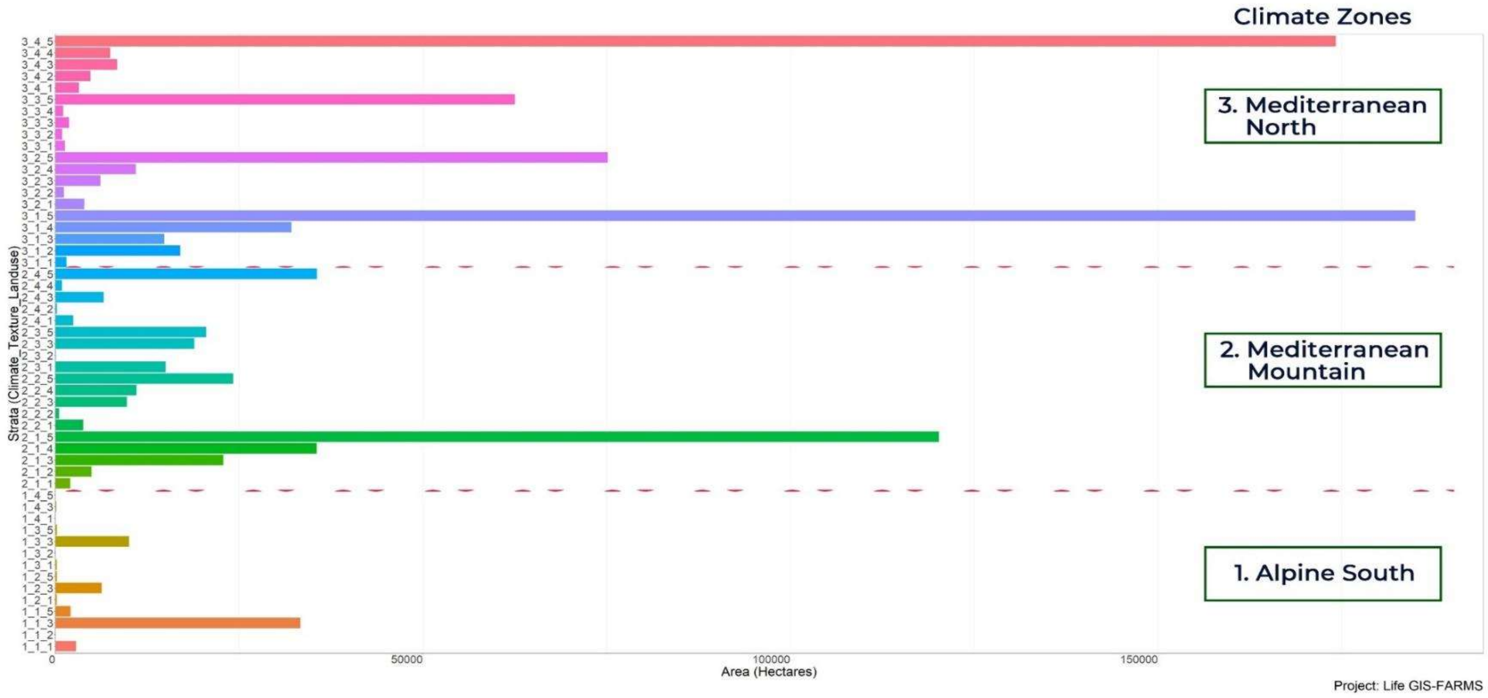


Figure 3. Total area covered by the 53 strata in Lombardy region.

SECTION 2. Characterization of the Soil Organic Carbon (SOC) content of the strata.

2.1 Method

Input data: vector layers (strata; regional administrative boundaries); raster layer (GSOC map)

Geoprocessing:

- Lombardy SOC map extraction (tool: clip raster)
- Lombardy SOC map vectorization (tools: Fishnet; Extract values to point; Join)
- SOC values assignment to strata (tool: Identity), (criterion: at least 50% of the SOC cell surface covered by one strata)

In managed ecosystems such as cropland and grazing land, the topsoil C stock dynamics (both the rate of C input as well as the rate of soil C loss through decomposition) are impacted by the soil and management practices applied. To characterize the **initial Soil Carbon Content of the topsoil layer of agricultural lands**, the FAO GSOC map available in raster format (see Deliverable 1 & 3.5) was deployed to extract **per hectar values of soil carbon stock** (Mg ha^{-1}), hereafter simply referred to as **SOC**.

The first step taken in this phase was therefore to vectorize, for the Lombardy Region territory, the FAO GSOC raster map (Grid at 30 arc-seconds resolution, approximately 1 x 1 km) previously converted to the WGS84/UTM32 projection, so as to combine it with the strata shapefile obtained in Section 1. For this purpose, the fishnet tool implemented in ArcGIS was deployed to create a polygon shapefile with the same geometrical properties of the Lombardy SOC map (spatial extent, number of rows and columns, cell size). The cells produced by fishnet were assigned with an identification code (ID) and transferred the respective SOC values from the SOC raster map.

The output from the identity tool was then used to derive **the descriptive statistics on the SOC content of the strata** by applying the following criterion 1:

SOC values are considered for the statistics only if they **belong to the cells in which more than 50% of the surface** (1km²) is occupied by **agricultural land** (i.e. agricultural land is the predominant land use of the cell).

The SOC value of the **cells that satisfy criterion 1 contribute only to the calculation of the statistics of the dominant stratum**, i.e. the stratum that **occupies the largest percentage of the agricultural area of the cell** (Figure 4).

With this approach, it is assumed that **the SOC value** of each cell is **attributed to an agricultural area only if it occupies more than half of the cell**. On the contrary, the SOC value is considered linked to a different type of land use (e.g. forest). Similarly, where criterion 1 is met, it is considered reasonable to use **SOC data** to compile only the **descriptive statistics** for the **dominant stratum** within the agricultural area. A visual example to explain the application of the criteria to subsample cell SOC values for calculating SOC statistics by strata is provided in Figure 4.

Figure 4. Criteria application example. The SOC values of the sample cells from A to C would be processed as follows: A. Cell without agricultural area. SOC value excluded from statistics (Criterion 1); B. Cell with agricultural area ("3_4_4" + "3_4_5") ≤ 50% of the total area of the cell. SOC value were excluded from the statistics (Criterion 1); C. Cell with agricultural area (("3_4_4" + "3_4_5") > 50% of the total area of the cell. SOC value considered for the statistics (Criterion 1) of the dominant stratum 3_4_5 (Criterion 2).

2.2 Results

As the original GSOC map covers most but not all the territory under agricultural land use in Lombardy (see Deliverable 1 & 3.5), not all the entire surface is covered by cells containing SOC data. This combined with the effect of the selection criteria presented in the previous section, resulted in a progressive decrease of the area with SOC data available for the calculation of the SOC statistics when compared to the original area of the strata as displayed in Tables 2 and 3.

Table 2. Comparison of the original area against the area remaining after SOC extraction for strata with the combination of climate, texture and land use (area values in hectares).

		Area after Identity with SOC vector map			
			With SOC data		
Strata	Area on a regional scale		Criteria for Statistics		
			Criterion 1		Criterion 2
		Without SOC data	Not satisfied	Satisfied	
1_1_1	2815.01	241.61	1222.06	1351.34	1099.38
1_1_2	9.30	1.39	2.87	5.04	
1_1_3	33323.11	5029.05	22541.06	5753.00	5341.90
1_1_5	2082.74	436.38	707.97	938.39	306.18
1_2_1	193.02	62.08	114.96	15.98	
1_2_3	6345.11	863.85	5065.38	415.88	386.59
1_2_5	246.49	58.79	101.71	85.99	53.84
1_3_1	208.03	60.24	141.68	6.11	

1_3_2	1.82	1.82			
1_3_3	10049.18	1744.79	7709.13	595.26	605.75
1_3_5	227.12	114.32	89.35	23.45	
1_4_1	0.84	0.84			
1_4_3	133.66	30.24	103.42		
1_4_5	8.16	4.12	4.04		
2_1_1	2034.34	836.63	341.76	855.95	509.52
2_1_2	4930.43	925.50	431.64	3573.29	997.10
2_1_3	22856.53	7788.06	6384.23	8684.24	2541.67
2_1_4	35542.01	4699.02	998.24	29844.75	25724.63
2_1_5	120217.91	40959.02	12299.05	66959.84	60341.27
2_2_1	3785.19	1115.31	1004.19	1665.69	1164.32
2_2_2	505.58	91.77	18.18	395.63	58.29
2_2_3	9737.38	2485.41	4538.46	2713.51	1193.07
2_2_4	11039.41	975.58	491.94	9571.89	8710.81
2_2_5	24205.10	9517.11	2489.01	12198.98	9973.30
2_3_1	15021.12	1793.03	2648.97	10579.12	9507.40
2_3_2	65.86	4.79	9.98	51.09	
2_3_3	18923.45	2972.83	13693.62	2257.00	1036.87
2_3_5	20507.16	2554.08	6230.79	11722.29	9846.86
2_4_1	2426.30	602.21	389.72	1434.37	988.90
2_4_2	226.40	34.14	27.24	165.02	41.63
2_4_3	6574.24	2683.46	1882.08	2008.70	428.57
2_4_4	898.29	196.89	8.69	692.71	572.24

2_4_5	35618.15	13903.06	5061.45	16653.64	15539.57
3_1_1	1526.49	257.02	55.79	1213.68	95.77
3_1_2	16945.56	3980.65	1949.18	11015.73	5323.88
3_1_3	14828.43	2722.99	858.67	11246.77	3232.17
3_1_4	32116.08	3219.63	451.76	28444.69	24250.97
3_1_5	185003.04	33779.39	6056.78	145166.87	135844.21
3_2_1	3947.27	892.89	304.19	2750.19	783.67
3_2_2	1184.28	198.65	48.31	937.32	123.71
3_2_3	6135.94	1414.40	390.14	4331.40	654.01
3_2_4	10976.05	1003.91	104.98	9867.16	8364.47
3_2_5	75167.08	10575.70	2109.68	62481.70	59844.47
3_3_1	1313.14	161.69	119.97	1031.48	252.56
3_3_2	944.78	81.59	48.63	814.56	41.88
3_3_3	1890.86	305.33	100.06	1485.47	108.51
3_3_4	1059.50	51.37	10.24	997.89	331.57
3_3_5	62504.83	5377.92	1758.36	55368.55	54962.86
3_4_1	3191.52	651.10	87.24	2453.18	1259.69
3_4_2	4752.08	774.75	143.19	3834.14	1271.61
3_4_3	8399.20	1176.00	273.92	6949.28	945.34
3_4_4	7464.70	1278.05	139.10	6047.55	3254.90
3_4_5	174177.07	20972.63	2920.98	150283.46	147209.48
	1004286.34	191663.07	114684.07	697939.22	605125.40

Overall, only the 19% of total agricultural surface is missing SOC information, while for the **81% of the total agricultural surface SOC data is available**. The area containing SOC data was then used to apply criteria previously explained in section 2.1. The **area for strata that meets Criterion 2 (dominant stratum)** amounts to 605125 ha **ca 60% of the total agricultural surface**. The **75%** of this area (Criterion 2) is represented by the **five (5) largest strata**.

As a result of the criterion 2 established, only 44 strata were left, the remaining 9 strata were dropped due to limitations as regards their original magnitude and inability to meet up with criterion 1 and 2. The **descriptive statistics on the SOC** was carried out using the remaining **44 strata (occupying 60% of the total agricultural surface)** that meet the criterion 2 that is, SOC value belonging to the cell that occupies the largest percentage of the agricultural area as explained visually in Figure 4. The statistics on the SOC of these dominant strata are provided in Table 3.

Table 3. SOC statistics for 44 strata that satisfy criterion 2 (SOC values in Mg ha^{-1})

Strata	Mean	Min	Max	Median	SDv	IQR
3_4_5	54.65	32.50	88.06	54.62	3.48	2.64
3_4_4	52.53	38.71	87.71	52.20	4.56	2.77
3_4_3	56.52	46.40	70.00	55.16	4.62	3.11
3_4_2	52.57	42.10	59.83	52.39	3.61	3.77
3_4_1	52.34	42.69	57.81	51.12	4.28	6.60
3_3_5	56.01	38.74	99.87	55.08	5.34	2.14
3_3_4	54.42	52.36	56.58	53.16	1.90	3.39
3_3_3	59.79	53.93	63.53	60.84	4.62	6.29
3_3_2	56.94	56.94	56.94	56.94	NA	0.00
3_3_1	45.41	38.92	51.85	45.91	6.30	12.73
3_2_5	55.33	36.02	87.33	54.85	3.74	2.97
3_2_4	52.24	42.83	61.47	52.84	2.54	3.44
3_2_3	51.93	39.47	58.19	53.6	5.05	7.08

3_2_2	53.43	51.68	55.73	52.95	1.60	1.80
3_2_1	53.57	50.71	62.21	51.26	3.46	6.45
3_1_5	55.11	38.72	71.60	54.89	4.93	5.73
3_1_4	51.86	43.48	63.46	50.83	3.86	3.79
3_1_3	52.58	35.96	66.20	54.09	4.77	8.12
3_1_2	53.27	45.07	69.30	53.53	3.66	4.12
3_1_1	53.42	51.14	57.90	51.23	3.88	3.38
2_4_5	54.96	24.37	75.84	52.92	6.59	9.81
2_4_4	60.14	48.79	62.67	61.60	4.65	1.51
2_4_3	54.02	48.30	70.03	52.44	6.01	7.28
2_4_2	71.11	71.11	71.11	71.11	NA	0.00
2_4_1	44.41	25.88	74.37	43.01	13.25	17.22
2_3_5	47.36	26.04	92.61	48.93	9.21	11.21
2_3_3	72.88	29.52	95.89	71.20	14.91	23.66
2_3_1	34.69	22.32	80.87	29.87	10.13	11.36
2_2_5	57.48	36.87	72.19	59.55	7.15	12.17
2_2_4	53.21	42.00	63.27	53.14	4.17	2.78
2_2_3	73.24	51.14	102.09	70.38	13.61	22.4
2_2_2	57.13	51.51	62.75	57.13	7.95	5.62
2_2_1	51.78	24.89	73.19	53.77	11.40	14.89
2_1_5	53.94	39.79	153.04	51.37	6.51	9.76
2_1_4	54.60	39.91	66.88	52.27	5.67	10.8
2_1_3	58.08	47.25	97.71	56.93	10.94	13.94
2_1_2	52.30	46.06	63.29	52.01	4.25	3.49

2_1_1	57.77	49.72	67.72	58.72	5.13	7.01
1_3_3	75.41	57.62	86.29	71.88	9.71	15.20
1_2_5	53.01	49.51	56.50	53.01	4.94	3.50
1_2_3	75.42	58.49	102.28	73.61	14.58	12.38
1_1_5	58.68	44.28	74.33	55.97	9.03	10.44
1_1_3	65.34	36.97	99.72	65.68	14.75	23.38
1_1_1	68.92	46.46	88.81	69.87	10.37	9.94

The first five (5) strata with the highest mean/median values are 1_2_3, 1_3_3, 2_3_3, 2_4_2 and 2_2_3 respectively. The associated climate are alpine south and Mediterranean mountain. Most of these **strata with the highest median value** lies within the **grassland crop-type categories** except for the strata 2_4_2 associated with the poplar crop-types category, though having only one single observation used for calculating its statistics.

Information on the variability of the SOC values by stratum is also very important and useful in identifying outliers and the maximum attainable level of SOC, under given climate and soil texture conditions, which is important for the subsequent estimation of the carbon storage potential of agricultural soils. Variability in SOC content is clearly shown using boxplots (Figure 5) providing a visual interpretation of the observed initial SOC levels within and between strata.

The initial SOC values mapped in Lombardy range from the minimum value of 22.32 Mg ha^{-1} (2_3_1) to a maximum value 153.04 Mg ha^{-1} (2_1_5). Table 3 also provides information on strata with the lowest SOC values which are strata 2_3_1, 2_4_5, 2_2_1, 2_4_1 and 2_3_5 respectively. On the opposite, strata 2_1_5, 1_2_3, 2_2_3, 3_3_5 and 1_1_3 are the first five (5) with the maximum SOC values. These results show that the **climate associated with the smallest SOC value** is the **Mediterranean mountain** and the associated **soil texture macro-classes are loam, clay loam and silt loam**. It also shows that most **permanent crops and annual croplands are strongly depleted in SOC**

(Sanderman et al., 2017) and that **grasslands have higher SOC content than croplands** (Guillaume et al., 2021).

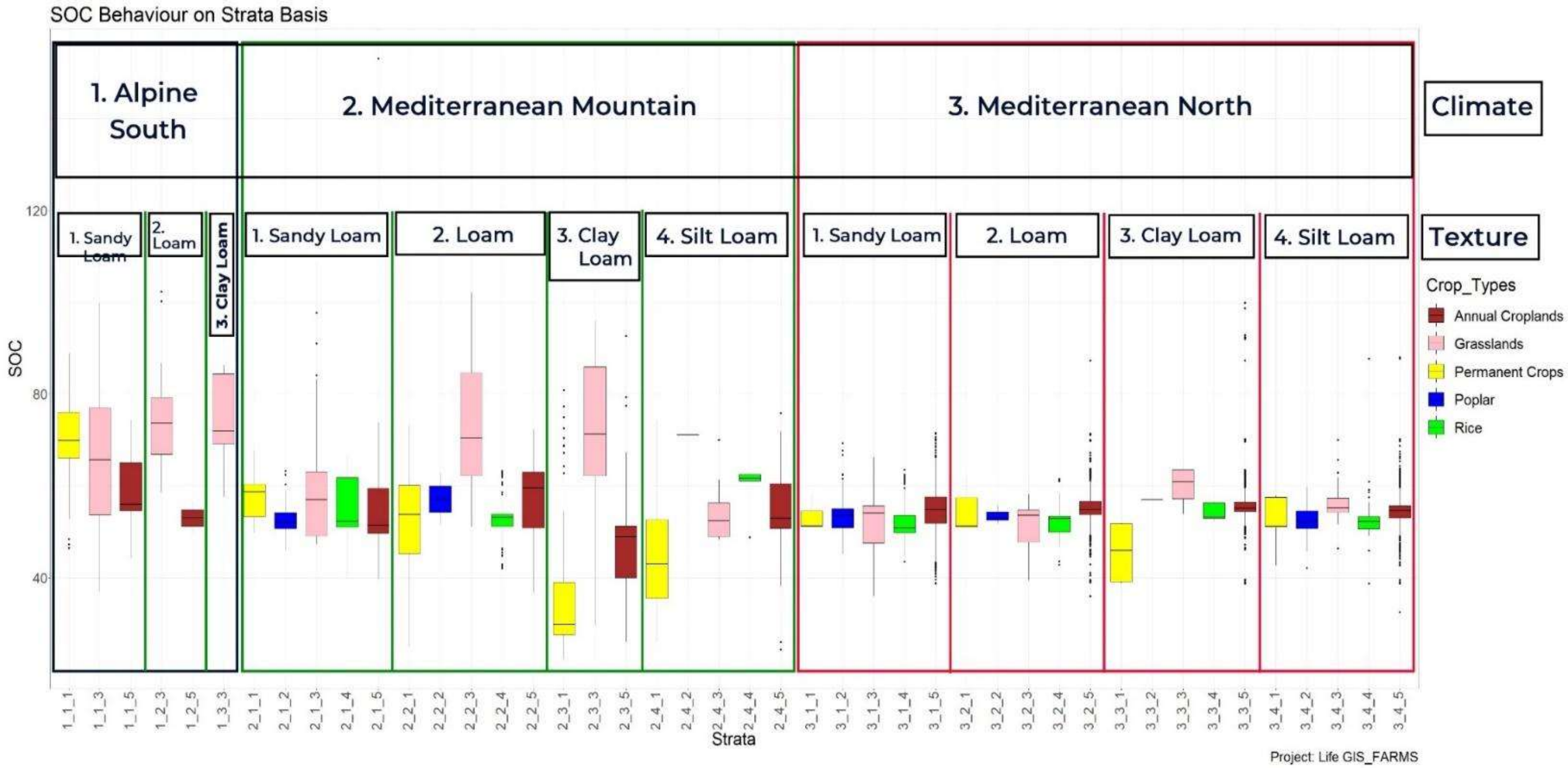


Figure 5. Boxplot of initial SOC values by dominant strata (Climate, texture and land use).

FLA FEDERLEGNOARREDO PEFC crea Confagricoltura rete clima Università Tuscia TERRASYSTEM cmcc

SECTION 3: SOC Sequestration Potential Assessment

3.1 Introduction

The goal of this section is to explain how the SOC sequestration potential of the agricultural area can be calculated from SOC statistics, thus producing a map capable of identifying surfaces that have the greatest potential on which to prioritize the implementation of sustainable soil management projects. In order to identify the SOC sequestration potential of the strata, emphasis is placed on biophysical properties (climate and texture conditions) affecting SOC accumulation dynamics in the topsoil of agricultural areas, while blocking the effect of land use as a varying factor that can change at any time depending on the farmer's management goals.

In fact, the carbon sequestration capacity of agricultural soils is related to various drivers including the initial carbon content, climate, soil properties, land use and management practices applied. A change in the land use (e.g conversion from arable land to grassland) or land management (e.g transition from conventional to organic farming) can cause a positive variation of the SOC sequestration rate, that generally follows a sigmoid curve with decreasing rates of C changes until a new SOC equilibrium (after 20 to 100 years) is reached (Lal, 2004; Sanderman et al., 2010).

The equilibrium at which SOC stabilizes depends mainly upon site-specific properties. In particular, the upper limit or "saturation level" of the amount of carbon in mineral soils that can be sequestered is regulated by intrinsic soil properties, such as clay content and carbon exchange capacity, and climatic characteristics such as soil and moisture and ambient temperature (Wiesmeier et al., 2019).

3.2 Methods

Input data: SOC strata database; vector layer (Lombardy SOC map)

Geoprocessing:

Delineation of strata homogeneous for climate and soil texture conditions only (11 strata);

SOC data selection by stratum (criterion: at least 50% of the SOC cell surface covered by one stratum)

SOC saturation level (stratum) =Q3+1.5IQR

SOC sequestration potential (cell)= SOC saturation level (stratum) –SOC (cell)

Since land use can affect only the sequestration rate but not the maximum level of carbon that can be accumulated in the soil, the agricultural areas' SOC sequestration potential assessment is carried out considering homogeneous surfaces for climate and texture conditions, excluding the crop type categories from the stratification.

Therefore, compared to the stratification proposed in section 1 (total of 53 strata and only 44 strata that satisfied criterion 2), the **number of strata** decreases on a regional scale **from 53 to 11**.

The identification code of each stratum is created using the same rules adopted in section 1. For each of the 11 strata we derived descriptive SOC statistics using the same criteria described in section 2. The stratum' maximum SOC value reflects the carbon threshold that has been actually attained in agricultural soils located in that climate and soil texture conditions. To identify realistic values, we first identified extremely high values of observed SOC stock for the 11 strata that could be considered as outliers.

The latter are identified through a non-parametric approach, based on interquartile range (IQR), considering outlier as a data over the threshold value (CAP) given by the sum of third quartile (Q3) and 1.5 times the IQR. We used the IQR method as a straightforward method for identifying outliers to set up a "fence" outside of the third quartile (Q3). Any values that fall outside of this fence are considered outliers and the CAP value was used to identify the level of SOC saturation (hereafter SOC_{SAT}) for the stratum:

$$\mathbf{SOC_{SAT} = CAP = Q3 + 1.5*IQR}$$

In **strata where there are no outliers**, the calculated CAP is higher than the maximum SOC value. Hence, the **observed maximum SOC** is used for as reference for $\mathbf{SOC_{SAT}}$ (see Table 5). Once the SOC_{SAT} values for the 11 strata were established, the **SOC sequestration**

FLA FEDERLEGNOARREDO PEFC crea Confagricoltura rete clima Università degli Studi della Tuscia TERRASYSTEM s.r.l. cmcc Euro-Mediterranean Center on Climate Change

potential (hereafter SOC_{SP}) map was produced on the basis of the SOC vector map: for each cell of the map meeting criterion 1 (more than 50% of the cell area covered by farmland), the sequestration potential was calculated as:

$$\mathbf{SOC_{SP} = SOC_{SAT} - SOC}$$

Where

SOC_{SAT} = SOC saturation content identified for the dominant stratum in the cell

SOC = SOC cell value

Reference values of SOC_{SAT} for strata, used for the calculation of **SOC_{SP}** are provided in Table 4.

Table 4. Descriptive statistics on SOC for dominant strata (Mg ha^{-1}) and corresponding values for SOC_{SAT}. The symbol "" for the maximum SOC column value denotes strata with SOC outliers.*

Strata	Average	StdDev	Max	Min	Median	Q75	IQR	CAP	SOC_{SAT}
1_1	65.53	13.90	99.72*	36.97	66.37	57.06	6.27	66.46	66.46
1_2	72.22	15.75	102.28*	49.51	71.15	55.67	2.98	60.14	60.14
1_3	75.41	9.71	86.29*	57.62	71.88	60.03	10.1	75.18	75.18
2_1	54.28	6.54	153.04*	39.79	51.64	56.41	3.29	61.35	61.35
2_2	56.62	8.92	102.09*	24.89	53.72	56.48	2.15	59.71	59.71
2_3	43.29	14.26	95.89*	22.32	41.16	50.65	20.48	81.37	81.37
2_4	54.38	7.79	75.84	24.37	52.85	62.24	11.125	78.92	75.84
3_1	54.46	4.89	71.60	35.96	54.18	61.03	10.7	77.08	71.60
3_2	54.86	3.78	87.33	36.02	54.62	76.14	21.895	108.98	87.33
3_3	55.93	5.41	99.87	38.74	55.04	84.37	15.2	107.17	99.9

3_4	54.56	3.57	88.06	32.50	54.56	76.44	17.25	102.32	88.06

According to the criteria defined above, the SOC_{SP} can be calculated only for a selection of SOC cells, as exemplified in Fig. 6.

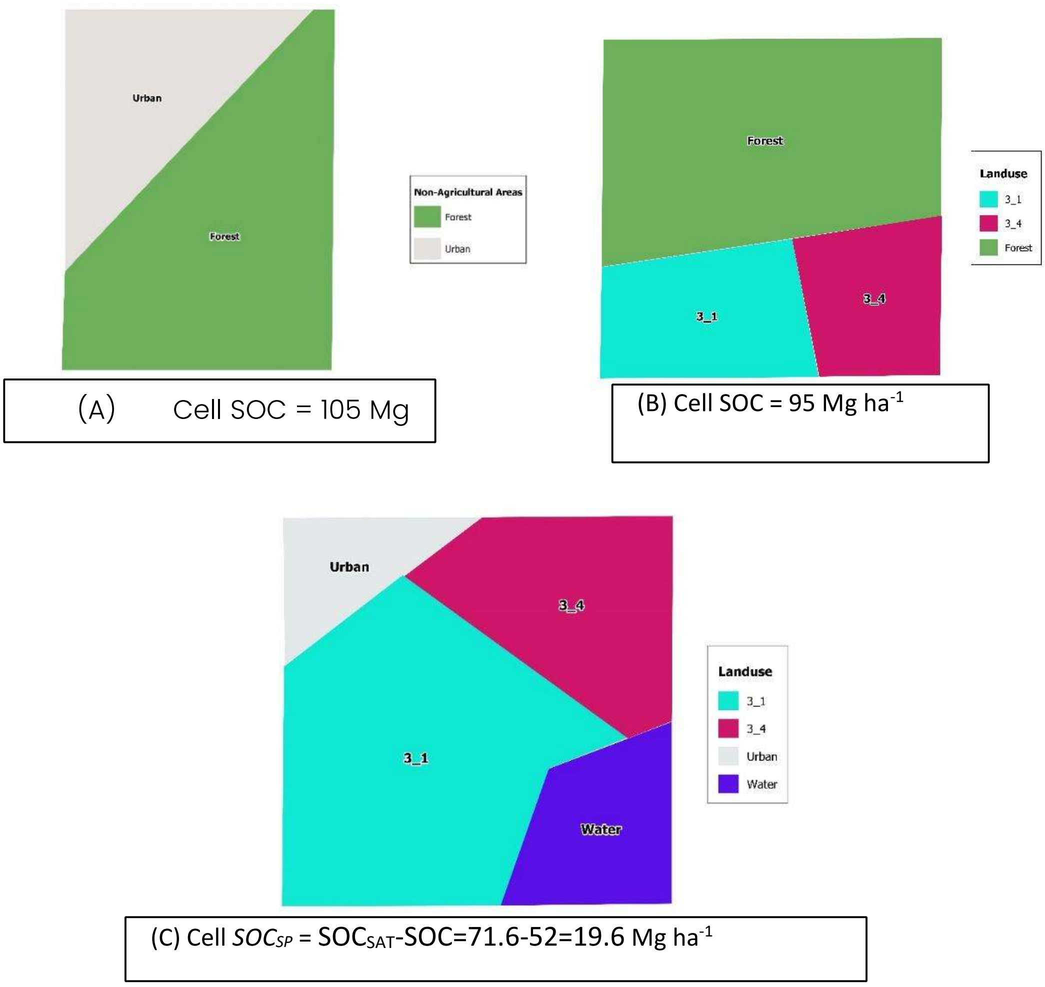


Figure 6. Examples of conditions for SOC_{SP} calculation. (A) Cell without agricultural area. SOC value excluded from statistics (criterion 1) of the strata and from the SOC_{SP} map; (B) Cell with agricultural area (3_1 + 3_4) ≤ 50% of the total cell surface. SOC value excluded from statistics (criterion 1) of the strata and from the SOC_{SP} map; (C) Cell with agricultural area (3_1 + 3_4) > 50% of the total cell surface. SOC value considered for the statistics (criterion 1) of the dominant stratum 3_1 (criterion

2). Cell included in the SOC_{SP} map with the value of 19.6 Mg ha-1 (SOCSAT of the dominant stratum (71.6) - SOC of the cell (52)).

The SOC_{SP} calculation when applied to cells corresponding to outliers for SOC values (SOC of the cell>SOC_{SAT} of dominant stratum) would provide negative values. For this reason, the SOC_{SP} of those cells corresponding to outliers were denoted by a default value equal to zero (0).

3.3 Results

Considering that not all the regional surface is covered by cells containing SOC data and given the criteria established for the derivation of SOC statistics, figures in Table 5 show the progressive decrease of the area of the strata involved during the steps of the workflow.

Table 5. Comparison of the original area against the area remaining after SOC extraction for strata with the combination of climate, texture and land use (area values in hectares).

			Area after Identity with SOC vector map			
				With SOC Data		
				Criteria for Statistics		
				Criterion 1		
Strata	Area on a regional scale	Area (%)	Without SOC Data	Not Satisfied	Satisfied	Criterion 2
1_1	38230.16	3.81	5708.43	24473.97	8047.76	8005.83
1_2	6784.62	0.68	984.72	5282.05	517.84	461.51
1_3	10486.14	1.04	1921.16	7940.16	624.82	592.40
1_4	142.65	0.01	35.20	107.46		
2_1	185581.23	18.48	55208.23	20454.93	109918.07	105323.73

2_2	49272.67	4.91	14185.18	8541.78	26545.70	22971.87
2_3	54517.59	5.43	7324.73	22583.37	24609.50	23040.08
2_4	45743.39	4.55	17419.76	7369.18	20954.44	18192.70
3_1	250419.62	24.94	43959.68	9372.19	197087.75	183118.13
3_2	97410.61	9.70	14085.55	2957.29	80367.77	69673.76
3_3	67713.10	6.74	5977.89	2037.27	59697.94	53639.47
3_4	197984.59	19.71	24852.54	3564.43	169567.62	154855.13
Total	1004286.36	100.00	191663.07	114684.07	697939.22	639874.61

As shown in the Table 5 above, out of the 12 strata formed as a result of the combination between climate and texture, only 11 strata satisfy the criterion 2. The only stratum (1_4) omitted has the least value in terms of surface and does not meet up with both criterion 1 and criterion 2. The largest stratum (3_1) covering 25% of the agricultural area is from the Mediterranean north climate and sandy loam soil texture macro-classes, followed by stratum 3_4 from the Mediterranean north and silt loam soil texture macro-classes covering 20% of the agricultural area and lastly stratum 2_1 covering 18% of the agricultural area and belongs to the Mediterranean Mountain climate and sandy loam soil texture macro-classes respectively.

The **vector shapefile providing the set of values for the assessment of SOC content properties** of the topsoil of agricultural lands in Lombardy Region (**SOC, $\mathbf{SOC_{SAT}}$, $\mathbf{SOC_{SP}}$**) is attached with this Deliverable with the corresponding metadata file (Vector file: **SOC_Sequestration_Potential_Map**, metadata: Metadata for Sequestration Potential SOC Map). An example of layout of SOC_{SP} for the Lombardy Region is shown in Figure 7.

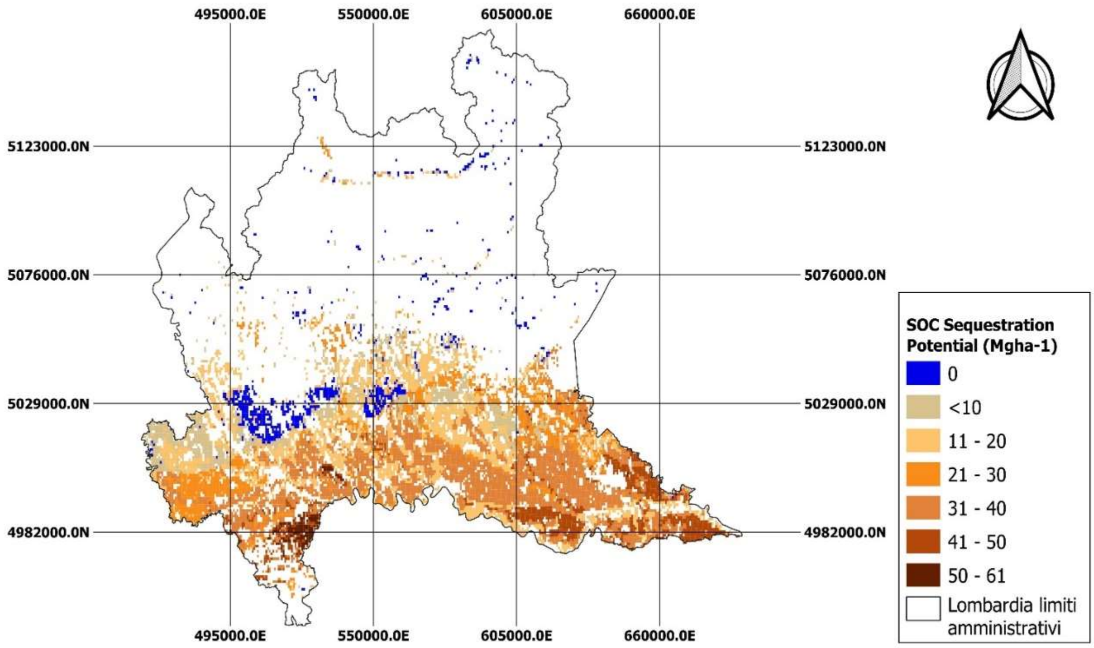


Figure 7. Map of SOC Sequestration Potential in agricultural land in Lombardy (EPSG: WGS 84/UTM Zone 32N).

The Figure 8 below, shows instead an example of the fields of the attribute table of the vector shapefile of the sequestration potential map.

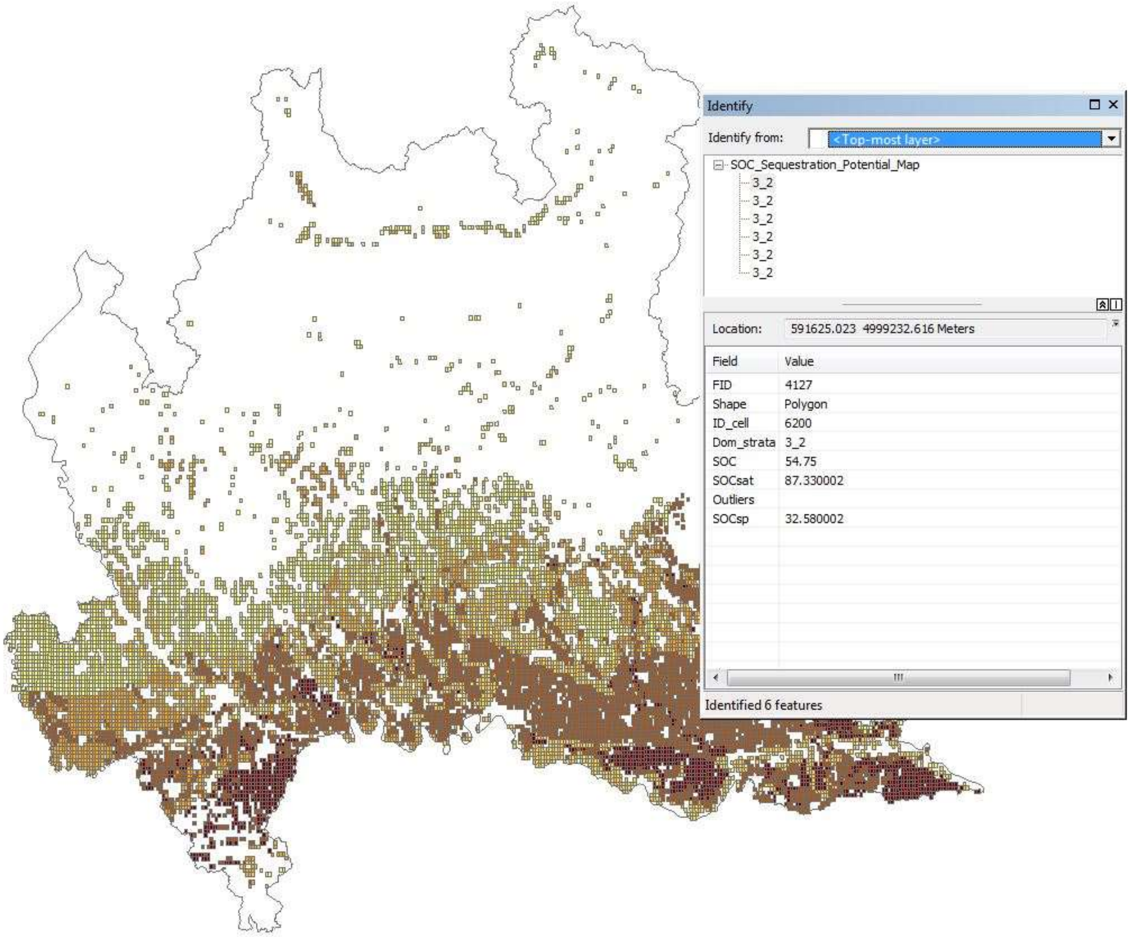


Figure 8. Example of the attribute table of the SOC Sequestration Potential map (EPSG: WGS 84/UTM Zone 32N).

The descriptive statistics on the SOC sequestration potential associated to the five crop types categories is presented in Table 6.

Table 6. Sequestration Potential on the basis of crop types (Mg ha^{-1})

Crop Types	Area (Ha)	SOC_{SP} Mean	SOC_{SP} Min	SOC_{SP} Max	SOC_{SP} Median	SOC_{SP} StDv	SOC_{SP} IQR
Annual Croplands	503518.24	24.92	0	61.13	26.56	12.56	19.24
Grasslands	20749.25	11.96	0	51.85	11.52	11.82	20.87
Permanent crops	19157.04	35.43	0	60.95	40.09	18.75	29.45

Poplar	10726.03	19.81	0	45.96	18.323	8.96	6.01
Rice	85724.05	16.51	0	49.35	15.34	11.29	13.22

From Table 6, the **median value of the SOC_{SP} peculiar to permanent crops (40 Mg ha^{-1})** is the highest compared to all other crop types categories. This value is approximately **3.5 times the median for grassland and 2 to 2.5 times the value observed for poplar and rice and 1.5 times the value observed for annual croplands**. This implies that permanent crops have a higher SOC_{SP} compared to the other crop types categories followed by annual croplands, poplar, rice and grasslands respectively. It also confirms that most **permanent crops and annual croplands are strongly depleted in SOC compared to grassland and, therefore, carbon-farming activities should be prioritized in this crop types**.

From the map shown in Figure 7, the maximum SOC_{SP} in Lombardy Region lies within the "51-61" class and is mainly localized in agricultural lands of the Mediterranean north climate. The minimum SOC_{SP} is distributed across the three (3) climates but with much occurrence only in the Mediterranean mountain climate. It can also be deduced from the map that the most widespread class of SOC_{SP} is 31 – 40 Mg ha^{-1}.

In order to better quantify the area covered by different levels of **SOC_{SP}** in Lombardy, Figure 9 provides a comparison by the 6 SOC_{SP} mapped in Figure 7. The classes occupying the largest area are "**31-40 Mg ha^{-1}" (20% of the total agricultural surface)** followed by the class **"11-20 Mg ha^{-1}" (just 16% of the total agricultural area)**. This is followed by the class "<10", "21-30", "41-50" and "Greater than 51" respectively.

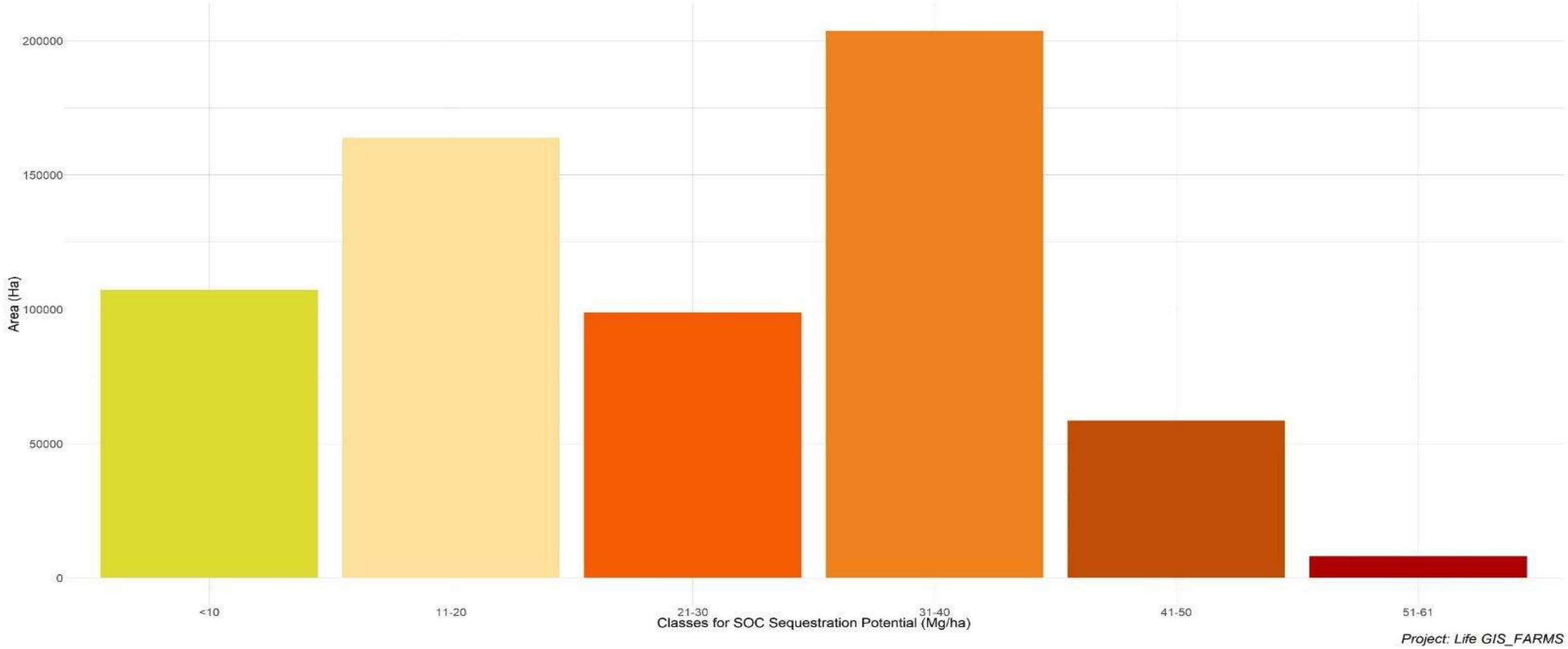


Figure 9. Bar Chart showing SOC Sequestration Potential classes against area covered by class.

SECTION 4. Carbon farming scenario analysis at the scale of agricultural parcel

4.1 Introduction: Land Parcel Identification System (LPIS) and links with GIS-Farms high resolution layers

This chapter sets out a **geoprocessing methodological pathway** to integrate the GIS-FARMS vector layers produced for Lombardy Region (Strata & SOC Sequestration Potential) with the SOC change estimates, available for a selection of carbon farming practices in Lombardy Region from findings of Action 2 and Action 3, so as **to enable SOC change projections** to be made at **farm level scale**.

The main target of the methodology is to geolocate at farm level scale lands cultivated as annual croplands and make available to farmers information on the **CO_2 sequestration and/or emissions reduction** potential of **carbon-farming practices** applicable to **croplands** (including conversion to poplar plantations).

In view of the development of a prototype demonstration IT tool for the management of Carbon Farming, foreseen under Action 6, and of carbon farming certification schemes it is essential to establish what reference surfaces are to be used for **SOC change projections** at **farm level scale.** To this end, the solution proposed is to rely on the Land Parcel Identification System (LPIS). The LPIS is the geographic information system, containing diverse spatial data sets from multiple sources (e.g. cadastral maps, high resolution layers on land use) that allows the Integrated Administration and Control System (IACS) to geo-locate and display records of all agricultural areas in the Member State, so as to assess eligible areas under different EU aid schemes in Pillars 1 and 2 of the **Common Agricultural Policy** (CAP). The LPIS operates based on reference parcels. A **reference parcel** is a **uniquely identified and geographically delimited agricultural area**. The reference parcel is currently used as **spatial unit** to **verify the eligibility for area-based subsidies** requested by farmers **under the CAP**. The same approach can be also suggested for future schemes of payments in carbon farming (either action- or result-based).

The LPIS's technical specifications vary from one Member State to another. In Italy the LIPS is implemented by the National IACS, i.e. *Agenzia per le erogazioni in agricoltura* - AGEA (https://www.agea.gov.it), in compliance with European Union and national regulations (Ministerial Decree n. 99707 of 1 March 2021, Italian Ministry of agricultural food and forestry policies). The **LIPS reference parcel in Italy** is a delimited **area consisting of contiguous portions of agricultural land, managed by a single farmer, homogeneous for land cover and management practices** applied. This reference parcel is referred to as **Agricultural Parcel (AP)**. The technical specifications set out by AGEA to delineate Agricultural Parcels are illustrated in Annex 1, with examples of delineation of APs in the Lombardy Region.

The SOC change scenario analysis at farm-scale presented in this Section is developed in compliance with the AGEA rules for APs delineation. It is important to emphasize that the LIPS databases are managed in Italy by the Regional Agencies of AGEA, that in Lombardy Region is *Direzione Organismo Pagatore Regionale Gestione sviluppo rurale – misure a superficie*. For the scope of the LIFE C-Farms project a sample of LIPS datasets was provided by the *Direzione Organismo Pagatore Regionale Gestione sviluppo rurale – misure a superficie* for six municipalities. Based on this information APs were delineated for a sample of farms to provide examples of SOC change scenarios at farm scale that are presented in § 4.3.

4.2 Linking SOC change scenarios to GIS-FARMs

The starting point for the carbon farming scenario analysis presented in this Section are findings from Action 2 and Action 3, leading to the identification of the potential for CO_2 sequestration and/or emissions reduction associated to some carbon-farming practices applicable to annual croplands of Lombardy Region.

The use of the environmental stratification (climate, texture, crop type) as data harmonization procedure to classify carbon farming scenarios makes it possible to map their "domain of applicability" both on regional scale, through the vector layer of the strata (§ Section 2.2), and on farm scale, via the APs map previously integrated with climate and soil texture information (see § 4.4.1). Accordingly, 6 strata (2_2_5, 2_3_5, 3_1_5, 3_2_5, 3_3_5 and 3_4_5) associated to the annual croplands were identified as areas of agricultural land where information for SOC change scenario assessment is available (Figure 10).

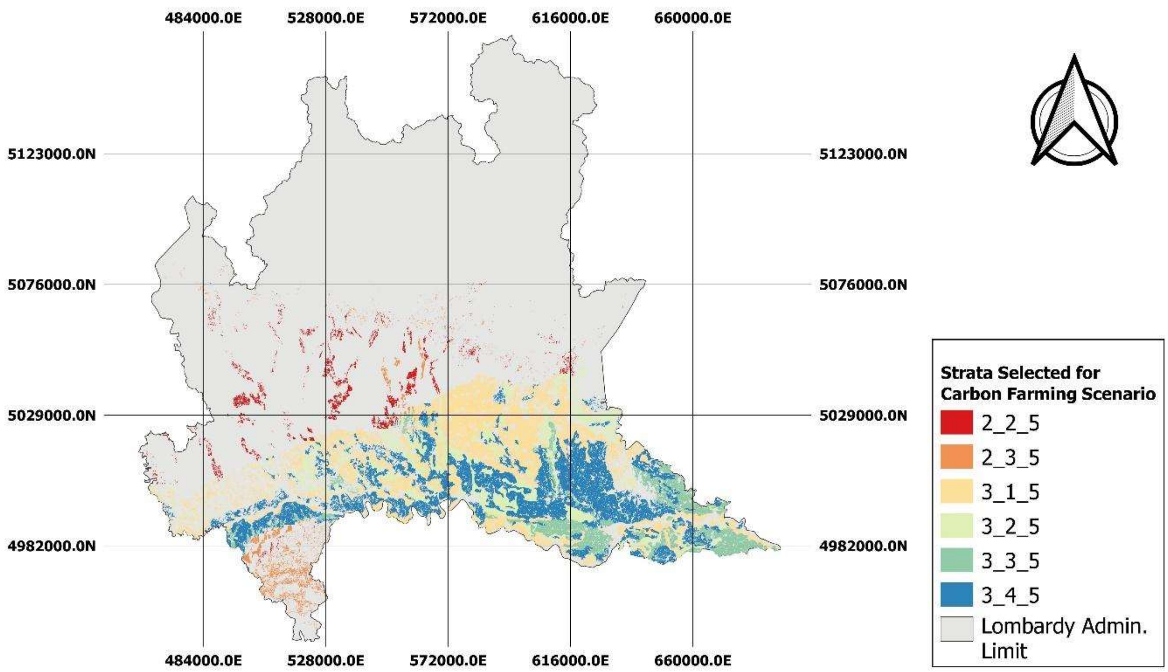


Figure 10. Map of the strata available for carbon farming scenario analysis (EPSG: WGS 84/UTM Zone 32N).

The statistics for the 6 selected strata according to their respective area (ha) are provided in Table 7, along with the share of regional agricultural surface covered (Relative %). Overall, the share of agricultural land for which scenarios are available amounts to nearly 54% of total agricultural area. As anticipated in § 1.3 four strata (3_1_5, 3_2_5, 3_3_5, 3_4_5) correspond to the largest strata in Lombardy Region while the other two (2_2_5, 2_3_5) account for a small percentage of total agricultural land (around 2%).

Table 7. *Surface statistics (expressed in hectares) of strata available for carbon farming scenario analysis.*

Strata	Number of polygons	Total_Area	Mean	Max	Median	SDv	Relative area (% out strata total area)
2_2_5	3774	24205.58	6.41	841.15	0.92	31.15	2.41
2_3_5	4917	20507.83	4.17	611.46	0.74	24.22	2.04
3_1_5	4837	185014.01	38.25	31336.49	1.81	559.03	18.42
3_2_5	2738	75171.48	27.45	4298.26	0.93	184.45	7.48
3_3_5	843	62548.99	74.20	10386.43	1.01	515.83	6.23
3_4_5	2511	174205.96	69.38	37183.44	1.18	821.22	17.34
Subtotal		541653.85					
Total Strata		1004470.97					53.92

The surface statistics also suggest that the median size of polygons of the strata is relatively small (around 1 ha), although there is a wide variability in size among polygons of the same stratum (standard deviation 31-821 ha).

On a farm scale, the stratification of agricultural parcels takes place through their spatial overlay with the map of the 11 homogeneous strata for climatic and soil texture conditions (see Section 3).

The stratification of the agricultural parcels enables the connection with the databases of actions 2 and 3 and the identification of the available SOC change scenarios.

At the same time, the overlay of AP units with cells of **the SOC sequestration potential map** allows to transfer SOC data to APs, in those agricultural areas covered by this dataset.

A detailed explanation of these geoprocessing operations is provided in § 4.4.1.

4.3 SOC change assessment of carbon farming scenarios annual crops

SOC storage is governed by the balance between the rate of C added to the soil from plant residues (including roots) and organic amendments (e.g. manure, compost, biochar), and the rate of C lost from the soils, which is mainly emitted as CO_2 from decomposition processes (i.e. heterotrophic soil respiration).

In agro-ecosystems such as cropland and grazing land both the rate of C input as well as the rate of soil C loss via decomposition are impacted by the soil and crop management practices applied.

The main management practices that affect soil C stocks in croplands are the type of residue management, tillage management, fertilizer management (both mineral fertilizers and organic amendments), choice of crop and intensity of cropping management (e.g. continuous cropping versus cropping rotations with periods of bare fallow), irrigation management, and mixed systems with cropping and pasture or hay in rotating sequences. In addition, conversion of annual croplands into poplar plantations allows to sequester C in above ground biomass, while modifying the rates of soil C input and soil C loss.

The state of the art obtained from the literature review conducted under Actions 2 and 3 leads to quantify the potential for carbon sequestration or mitigation of CO_2 emissions for some of the sustainable soil management (SSM) practices indicated above, namely for SSM applicable to croplands. Based on this knowledge, scenarios can be developed to return SOC change annual rates expected from the transition from business as usual (BAU[1]) to SSM practices. Based on the methodology followed to calculate SOC change two different types scenarios are available:

A. **SOC sequestration scenarios**, derived from experiments based on the "stock difference method" (IPCC, 2006), in which an "absolute SOC change" is computed after the adoption of SSM practices for a defined period of time (e.g. 20 years) as the difference between the final SOC stocks (SOC_{SSM}) and the initial SOC stock ($SOCt_0$)

[1] BAU refers to a kind of agriculture that does not evidence any kind of soil carbon stock technical maintenance: conventional tillage, monoculture and mono-succession, application of synthetic fertilizer, bare soil during crop rotation.

$$\Delta SOC_{ABS}\ (Mg\ C\ ha^{-1}) = SOC_{SSM} - SOC_{t0}$$

B. **SOC retention scenarios** derived from experiments implementing the "pair comparison method", in which changes in SOC stocks after the adoption of SSM practices for a defined period of time (e.g. 20 years) are computed as "relative SOC change" compared to BAU SOC stocks.

$$\Delta SOC_{REL}\ (Mg\ C\ ha^{-1}) = SOC_{SSM} - SOC_{BAU}$$

In these studies, the initial SOC is not measured and is assumed to be equivalent between adjacent plots undergoing SSM (treatment) and BAU practices (control).

Mean annual SOC sequestration rates (Mg C ha^{-1} yr^{-1}) and mean annual SOC retention rates (Mg C ha^{-1} yr^{-1}) were determined by dividing absolute and relative SOC changes by the duration of the experiments, respectively.

Table 8 summarizes the **twelve (12) scenarios that can be developed for annual croplands** in Lombardy Region, according to the current state of knowledge provided by Actions 2 and 3. Four **(4) are SOC sequestration scenarios** and eight **(8) SOC retention scenarios**. The scenarios involve the six (6) strata mapped in Figure 10, distributed in 2 different environmental zones (Mediterranean mountain and Mediterranean north) and in all soil macro-classes considered.

For the other strata there is no sufficient information available for the development of carbon farming scenarios. It is not currently possible namely to develop scenarios for permanent crops, poplar plantations, grassland, rice crops, and in general for the agricultural areas of the Lombardy Alpine South environmental zone.

Table 8. Annual SOC change rates (expressed as Mg C $ha^{-1}yr^{-1}$) of the treatments considered for the scenarios. Each scenario is identified by a unique code consisting of the indicator type used and the stratum code to which the scenario is applicable. If alternative scenarios are available for a stratum using the same indicator (stratum 3_2_5 and 3_4_5), these are distinguished with a last letter added to the scenario code.

Scenario code	Control	Treatment	n*	mean	median	min	max	sd
ΔSOC_{ABS}_3_2_5	$SOCt_0$	OA	4	0.5	0.36	0.1	1.2	0.42
ΔSOC_{ABS}_2_3_5	$SOCt_0$	CONS	5	0.73	0.84	0.15	1.26	0.45

$\Delta SOC_{ABS}\_3\_4\_5\_a$	$SOCt_0$	ORG	4	0.85	0.91	0.37	1.19	0.3
$\Delta SOC_{ABS}\_3\_4\_5\_b$	$SOCt_0$	CC + OA	3	1	0.96	0.86	1.19	0.14
$\Delta SOC_{REL}\_3\_2\_5\_a$	SOC_{BAU}	RSD + R	4	0.15	0.14	0.08	0.25	0.06
$\Delta SOC_{REL}\_3\_3\_5$	SOC_{BAU}	R	5	0.16	0.15	0.12	0.2	0.03
$\Delta SOC_{REL}\_3\_4\_5\_a$	SOC_{BAU}	RSD + R	6	0.24	0.11	-0.36	1.54	0.61
$\Delta SOC_{REL}\_3\_4\_5\_b$	SOC_{BAU}	CC	3	0.28	0.32	0.18	0.33	0.07
$\Delta SOC_{REL}\_2\_2\_5$	SOC_{BAU}	CC	3	0.34	0.41	0.17	0.43	0.12
$\Delta SOC_{REL}\_3\_2\_5\_b$	SOC_{BAU}	CC	3	0.37	0.49	0.1	0.52	0.19
$\Delta SOC_{REL}\_3\_1\_5$	SOC_{BAU}	LUC/SET-A-SIDE	4	1.04	1.01	0.45	1.71	0.48
$\Delta SOC_{REL}\_3\_4\_5\_c$	SOC_{BAU}	LUC-PP	3	1.23	1.6	0.33	1.75	0.78

Code	**Description**
$\Delta SOC_X\_Y\_Z\_A\_\beta$	X = absolute or relative SOC change Y = environmental zone (2 = Mediterranean mountain; 3 = Mediterranean north) Z = soil macro-class (1 = sandy loam, sandy and loamy sand soils; 2 = loam soils; 3 = clay loam, clay, sandy clay loam and sandy clay soils; 4 = silt loam, silty clay loam and silty clay soils A = crop type category (5 = annual crops) β = scenario option
CC	introduction of green manure or mulch cover crops to avoid bare soil and bare fallow
CONS	conservative practices consist in the combination of zero tillage or minimum tillage, maintenance of crop residues, crop rotation, cover crops
LUC/SET-A-SIDE	land use change from annual cropland to perennial crops (e.g vineyards, olive groves, orchards) or set-a-side of cropland

LUC-PP	land use change from annual crops to poplar plantations
OA	application of organic amendments (farmyard manure / compost / anaerobic digestate)
ORG	the organic agriculture includes conventional tillage, maintenance of crop residues, organic manure, extended crop rotation, cover crops, selection of better crop varieties, absence of synthetic fertilizer and herbicides
R	maintenance of crop residues in the field
RSD	reduced soil disturbance includes zero tillage or minimum tillage or reduced tillage at depths less than 25 cm, without inversion of the soil layers

**n stands for number of data entries*

4.4 Farm-scale SOC change scenarios

4.4.1 Methodology

In this chapter the workflow to enable SOC change projections to be carried out at farm level scale is outlined, along with examples of application in Lombardy Region. The main steps of the workflow are summarized in the flowchart presented in the introduction.

The development of SOC change scenarios of carbon farming at farm scale calls for the preliminary acquisition of the agricultural parcels (APs) vector layer of the Land Parcel Identification System (LPIS). As explained in § 4.1, such a vector layer was not directly provided by the Regional Agency of AGEA for Lombardy Region. However, the Regional Agency made available for 6 municipalities (Abbiategrasso, Besate, Inverno e Monteleone, Motta Visconti, Rosate, Vigevano) the vector layers of the cadastral map and of the land plot map, that are required to delineate APs at farm-scale. Therefore, in order to exemplify the steps required to generate SOC change scenarios of carbon farming at farm scale, a sample of three (3) farms located in the strata shown in Figure 10 was selected and the corresponding APs were obtained following the methodology illustrated in Annex 1.

The APs of the sample farms were combined with the following GIS-FARMS shapefiles using the "identity" tool integrated in ArcGis:

1) Map of the strata homogeneous for climatic and soil texture conditions (retrieved from the Strata_Section_1 shapefile);
2) Map of the SOC sequestration potential (SOC_Sequestration_Potential_Map shapefile)

The first geoprocessing step allowed to stratify the APs by environmental zone, soil texture macro-class and type of land use, the latter derived from the land plot map which provides detailed information on the cultivated crops.

The second geoprocessing step established the spatial association between APs and the cells containing data on initial SOC level (SOC), the SOC saturation level (SOC_{SAT}) and the SOC sequestration potential (SOC_{SP}).

The APs extending over different strata or cells of the SOC sequestration potential map were assigned with the data of the stratum/cell covering the largest proportion of the AP surface.

As APs and SOC cells cover different spatial extents, it may occur that the combination of climate and soil texture conditions characterizing the AP does not match with the dominant stratum of the SOC cell (see section 3) that contains AP; in this case, the following procedure was applied:

- the SOC_{SAT} is attributed to the AP through a join with table 4 based on stratum code;
- the SOC of the cell is considered not applicable to the environmental conditions of the AP. The latter consequently lacks the data on the initial SOC level (SOC = no data) and on the SOC sequestration potential (SOC_{SP} = no data).

Finally, the SOC change scenarios are assigned to APs via a join with Table 8 using the stratum code as primary key.

4.4.2 Examples of scenario analysis at farm scale

The application of the methodology presented in § 4.4.1 to the sample farms, leads to the results presented in this chapter. An extract of the agricultural parcels map developed for the sample farms and the related information associated with each single AP is provided in Figure 11.

The integration of spatial data sets from LIPS and GIS-Farms, makes it possible to retrieve the following key data from the AP attribute table:

- the "cadastral parcel ID", allowing to connect to the land cadaster archive, so as to reconstruct a complete cadastral identification of the APs (name of the municipality and province, section code, map sheet number, parcel number)

- the "land plot ID", that guarantees the connection to the land plots database from which it is possible to obtain detailed information on the land use, the intended use of the land, the cultivated variety etc.

- the "Stratum", returning the code of the stratum characterizing the AP surface; acts as hinge to join information on SOC_{SAT} (Figure 14) of the AP and on the applicable SOC change scenarios (fields: SCENARIO_ABS & ABS_SOC_CHA; SCENARIO_REL & REL_SOC_CHA; returned data are median values reported in Table 8).

The scale at which SOC data are available makes it impossible for some APs to retrieve information on the initial level of the resource (Figure 13) and, consequently, on the SOC quantities that could be accumulated over time through sustainable management practices (Figure 15).

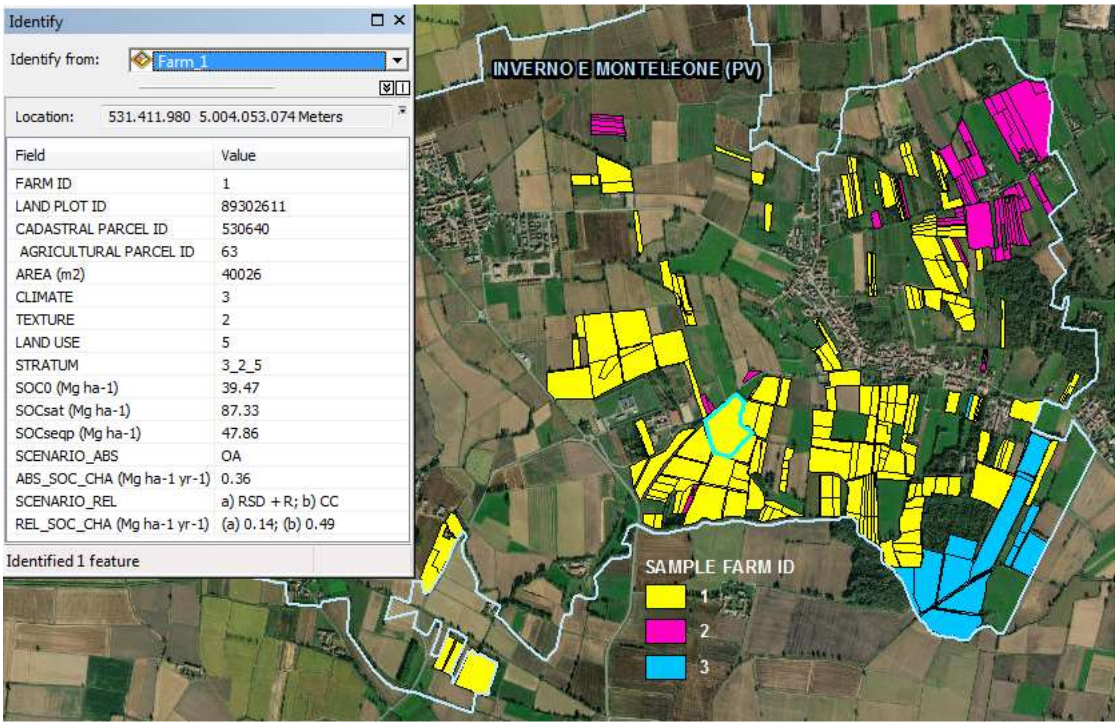


Figure 11. Attributes table associated with the agricultural parcels vector layer.

The possibility to return information on carbon-farming scenarios primarily depends on the membership of the APs to one of the strata listed in Table 8; consequently, the information that can be currently provided is inevitably heterogeneous and incomplete, even within the same farm. A complete exemplification of this issue is provided for Farm 1 (Figure 12), that includes APs covering 3 out of the 6 strata in Figure 10 (3_2_5, 3_3_5, 3_4_5). As the type of scenarios (SOC_{ABS} or SOC_{REL}) and the number of associated treatments vary from stratum to stratum (Table 8), it is possible to assess the effect of one or two specific treatments on the same AP (Figures 16 & 17). In addition, for the APs associated to strata other than those listed in Table 8, no scenario is available (e.g. stratum 3_3_1 in Farm 1).

Therefore, depending on the type of SOC change assessment (SOC_{ABS} or SOC_{REL}) the information that can be associated to APs of a given farm can vary from "no scenario" to maximum three scenarios that can be compared in terms of SOC changes (i.e. SOC_{REL} of stratum 3_4_5). The performance of different carbon farming options applicable at farm scale, can be made explicit through graphs reporting absolute and relative SOC change value (Figures 18-19). However, the SOC changes projections associated to each management option are valid, in strict terms, only for the environmental conditions (stratum) that characterize that scenario.

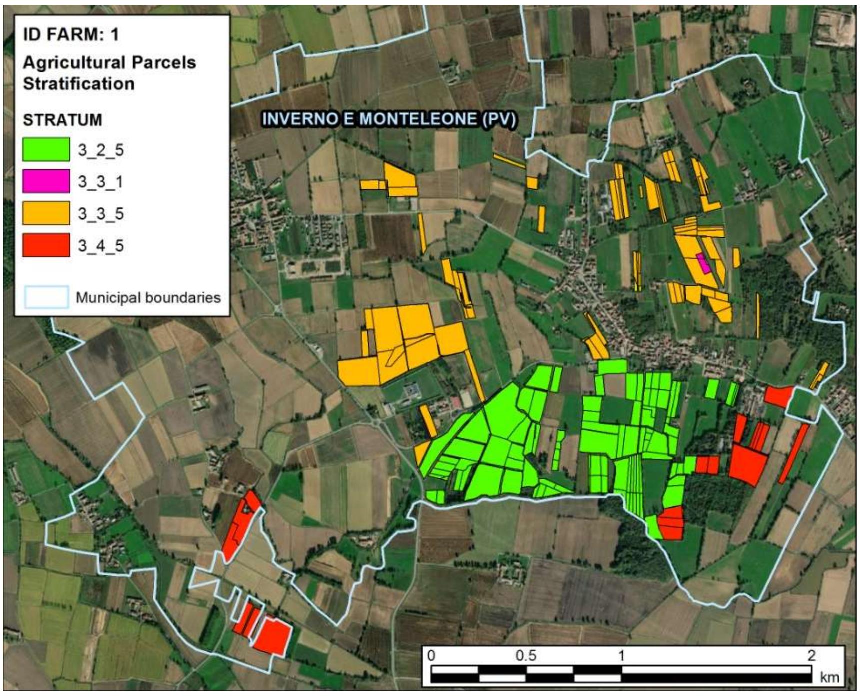


Figure 12. Agricultural parcels stratification of sample farm n. 1

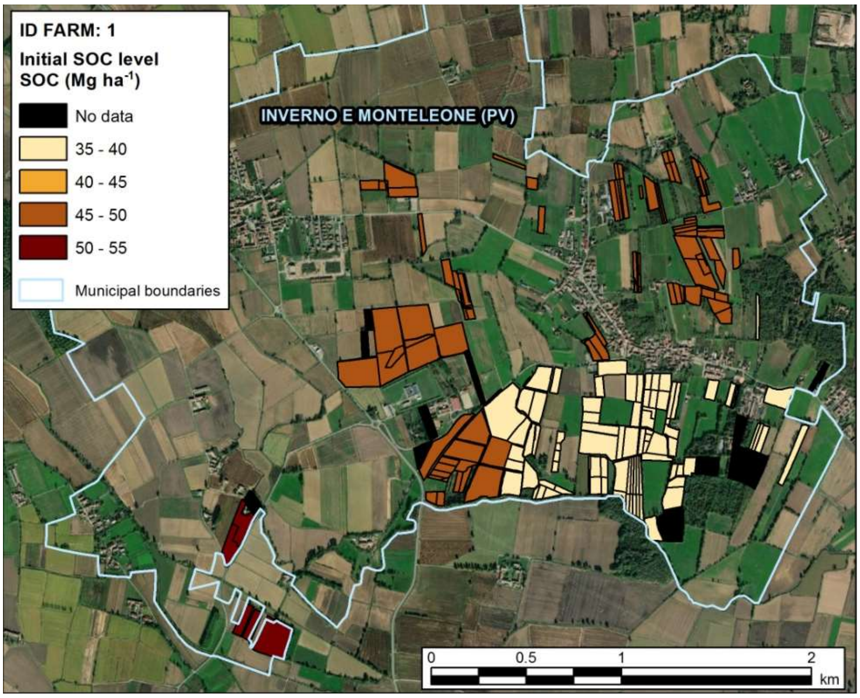


Figure 13. Initial SOC level (SOC) of the agricultural parcels of sample farm n. 1

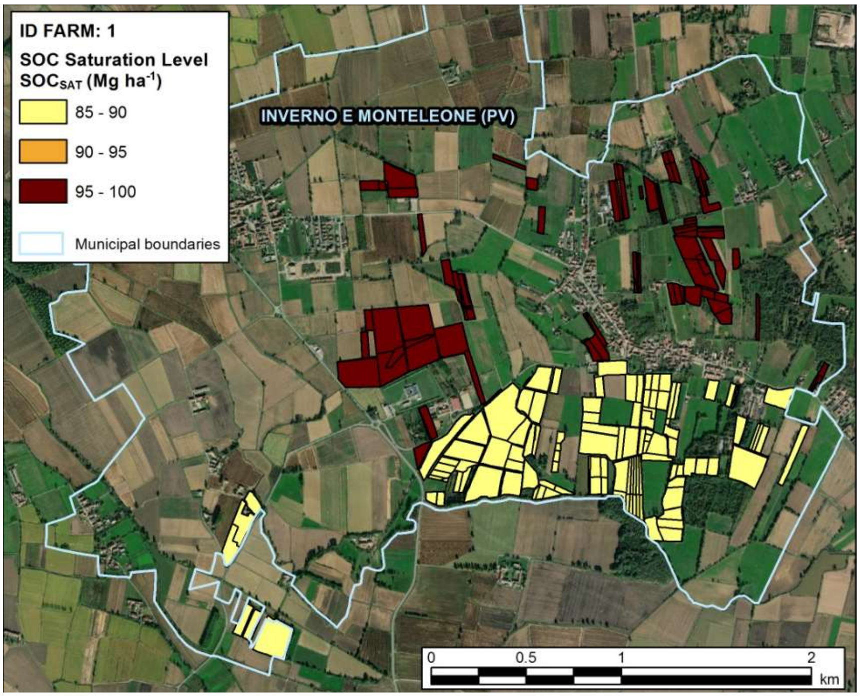


Figure 14. SOC Saturation level (SOC_{SAT}) of the agricultural parcels of sample farm n. 1.

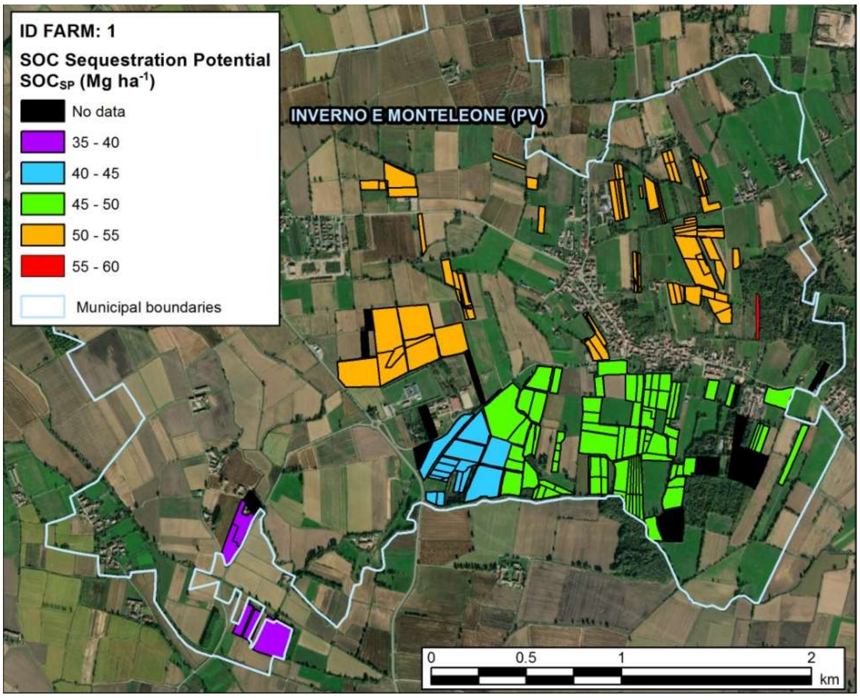


Figure 15. SOC Sequestration Potential (SOC_{SP}) of the agricultural parcels of sample farm n. 1

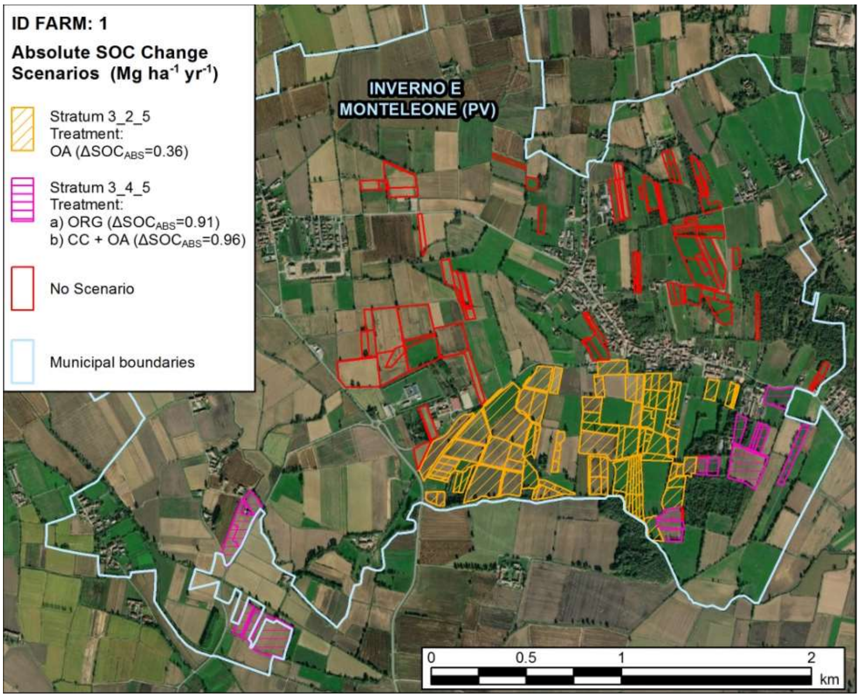


Figure 16. Absolute SOC change scenarios for the agricultural parcels of sample farm n. 1. Treatments: ORG = organic agriculture; CC = cover crops; OA = organic amendments.

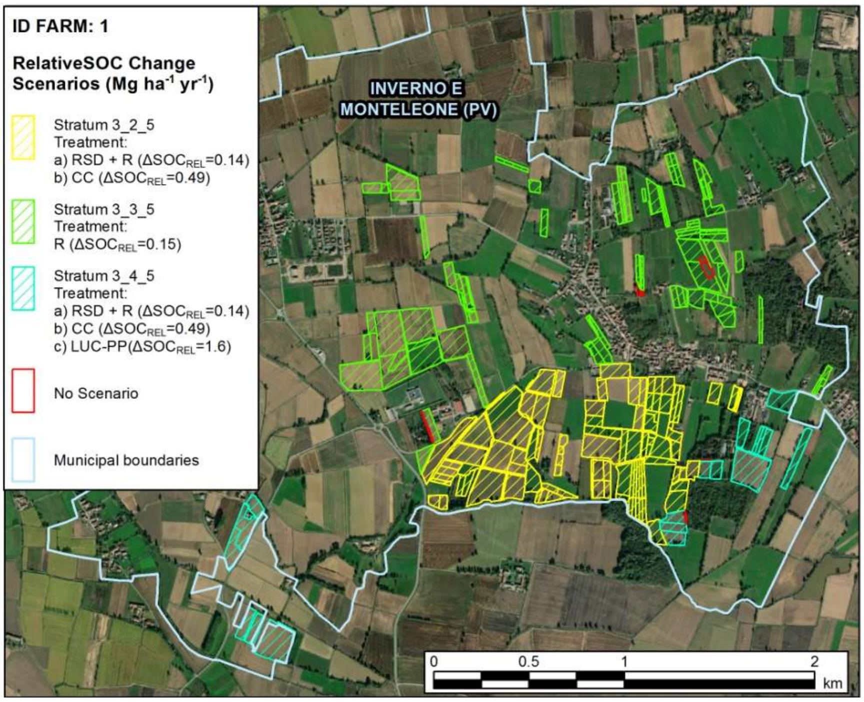


Figure 17. Relative SOC change scenarios for the agricultural parcels of sample farm n. 1. Treatments: RSD = reduced soil disturbance; R = maintenance of crop residues; CC = cover crops; OA = organic amendments; LUC-PP = land use change from annual crops to poplar plantations.

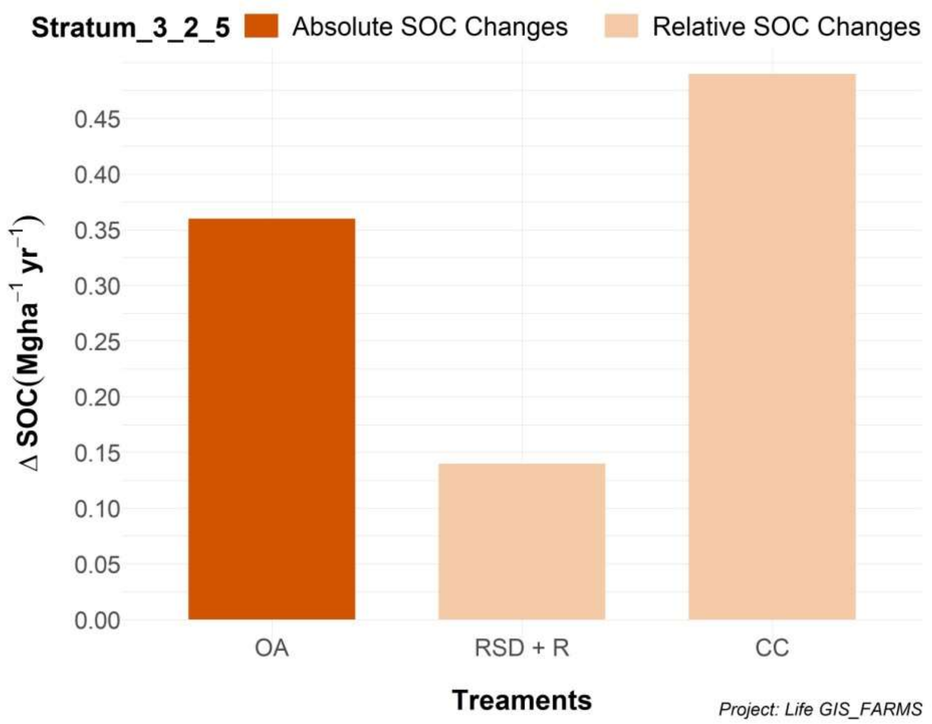


Figure 18. Absolute and relative SOC changes scenarios for the stratum 3_2_5 (annual crops on loam soils located in the Mediterranean north environment zone). Treatments: RSD = reduced soil disturbance; R = maintenance of crop residues; CC = cover crops; OA = organic amendments.

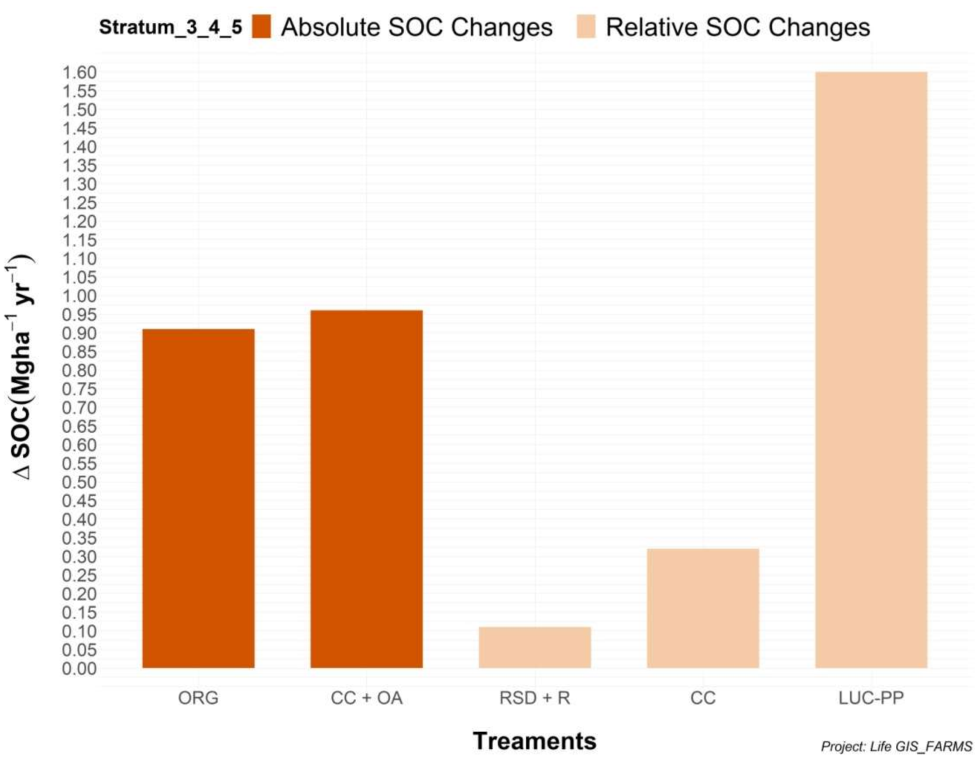


Figure 19. Absolute and relative SOC changes scenarios for the stratum 3_4_5 (annual crops on silt loam, silty clay loam and silty clay soils located in the Mediterranean north environment zone). Treatments: ORG = organic agriculture; CC = cover crops; OA = organic amendments; RSD = reduced soil disturbance; R = maintenance of crop residues; LUC-PP = land use change from annual crops to poplar plantations.

SECTION 5. Conclusions and recommendations

A GIS-based platform capable of integrating spatial data from different sources, so as to allow users to geo-locate agricultural lands and display their relevant characteristics for carbon farming, is a powerful tool to inform Regional Public Authorities and farmers interested to take action in carbon farming.

The GIS-FARMs architecture developed during Action 4 is designed to make the most out of the spatial integration of existing geodatabases (FAO GSOC map, Climatic stratification of the Environment of Europe, Land use and pedological map of the Lombardy Region) to generate new and reliable information, with the highest possible spatial resolution, on initial SOC level of agricultural soils and their associated soil C sequestration potential.

The keystone of the GIS-FARM workflow is the use of strata (the 53 classes homogeneous for environmental climate/soil texture/land use or the 11 classes homogeneous for environmental climate/soil texture) as the basic units to which the information on SOC properties and SOC change carbon farming scenarios is to be referred to. To translate this condition into geoprocessing tasks, criteria for robustly selecting or generalizing data to the scale of the mapped units (SOC cells, Agricultural Parcels) had to be introduced.

Building on this approach, the following key findings have been gained during Action 4:

1. **SOIL C SEQUESTRATION POTENTIAL OF AGRICULTURAL LANDS IN LOMBARDY REGION**

- a realistic assessment of **soil C sequestration potential (SOC_{SP}) in the topsoil of agricultural lands** (i.e. distance to SOC saturation content defined in relation to local environmental conditions) **can be provided by** the sequestration potential map for the **60% ca of the total agricultural surface;**

- most of the surface of permanent crops and annual croplands is strongly depleted in SOC; the **median value** of the Soil Carbon Sequestration potential (SOC_{SP}) peculiar to

permanent crops (40 Mg ha^{-1}) turned out to be the highest compared to all other crop types categories: 3.5 times the median for **grassland (11.5 Mg ha^{-1})** and 2 to 2.5 times the value observed for **poplar (18 Mg ha^{-1})** and **rice (15 Mg ha^{-1})** and 1.5 times the value observed for **annual croplands (26.5 Mg ha^{-1})**.

- overall, the sequestration potential map allows to figure out the allocation of the agricultural areas by classes of carbon sequestration potential:

- 1-10 Mg ha^{-1} 100K ha
- 11-20 Mg ha^{-1} 160K ha
- 21-30 Mg ha^{-1} 100K ha
- 31-40 Mg ha^{-1} 200K ha
- 41-50 Mg ha^{-1} 50K ha
- 51-61 Mg ha^{-1} < 10K

The mapped and statistical information provided by GIS-FARMs will be useful to land owners, agencies and other decision makers to display and prioritize areas that require much attention for the implementation of carbon farming activities.

2. SOC CHANGE CARBON FARMING SCENARIOS AT FARM SCALE

- The simulation of SOC change carbon farming scenarios has encountered limitations due to the availability of data and its wide heterogeneity in terms of treatments. Overall, the share of agricultural land for which **SOC change carbon farming scenarios** are available amounts to **nearly 54% of total agricultural area**.

- **twelve (12) SOC change carbon farming scenarios can be currently proposed for annual croplands** only in Lombardy Region. Four **(4) are SOC sequestration scenarios** and eight **(8) SOC retention scenarios**. These scenarios are applicable to **annual croplands** located in the **Mediterranean North Region** (all soil texture classes) or in the **Mediterranean Mountain Region** (texture classes 2 = loam soils; 3 = clay loam, clay, sandy clay loam and sandy clay soils).

-for the strata indicated above, the SOC sequestration scenarios evaluate **gains in SOC stock in the topsoil of annual croplands** in the range of **0.36** (treatment: organic amendments (OA)) to **0.84 to 0.96 Mg ha $^{-1}$ yr^{-1}** (treatments: conservative (CONS) or organic agriculture (ORG) or organic amendments and green manure or mulch cover crops OA+CC).

- as to SOC retention scenarios the estimated **SOC change due to the introduction of the carbon farming practice,** compared to levels of SOC associated to BAU agriculture, is in the order of:

- **0.11 to 0.15 Mg ha $^{-1}$ yr^{-1}** for **reduced soil disturbance (RSD) and/or residues (R) treatments**,
- **0.32 to 0.49 Mg ha $^{-1}$ yr^{-1}** for **green manure or mulch cover crops (CC)**
- **1 to 1.6 Mg ha $^{-1}$ yr^{-1}** for **land use change with set-aside** or conversion to **poplar plantations**.

- the possibility to return information on carbon-farming scenarios at farm-scale, using Agricultural Parcels (APs) as basic spatial units for the simulation, depends on the cultivation of these with annual crops and on the membership of the APs to the combination of climate and soil texture conditions indicated above; consequently, the **possible outputs of carbon farming scenario analysis** are **heterogeneous** and **incomplete**: depending on the type of SOC change assessment (SOC_{ABS} or SOC_{REL}) the information that can be associated to **APs of a given farm can vary from "no scenario" to maximum three scenarios that can be compared in terms of relative SOC changes**;

- the **performances of different carbon farming options** applicable at farm scale, **can be compared in terms of absolute and relative SOC change values**, but the SOC changes projections associated to each scenario option are valid, in strict terms, only for the environmental conditions characterizing that scenario.

3) TECHNICAL REMARKS on GIS-FARMS DATA COMPLETENESS

In general, the partial coverage of data currently offered by GIS-FARMs platform at Regional and farm scale, is largely related to the quality and availability of input data.

In particular, the **significant proportion of agricultural surfaces** currently remained **excluded** from the areas covered by GIS-FARMs **soil C sequestration potential (SOC_{SP})** is mainly due a bottleneck caused by the large size of the spatial units used to map initial SOC values, that are internally heterogeneous as to land use and strata (see Figure 6). This type of **limitation** could be solved if (regional/national) spatial data with **higher spatial resolution were available to map SOC content in the topsoil**.

The limited availability of SOC change carbon farming scenarios applicable to the climatic and pedological conditions of Lombardy Region, is another major weakness. This makes it difficult to provide an exhaustive evaluation of the potential of carbon-farming practices for sequestration or mitigation of CO_2 emissions from agro-ecosystems at the Regional and Farm scale, from scenarios devised from the literature review analysis conducted under Actions 2 and 3. In the perspective of developing a prototype demonstration IT tool, web oriented, for the management of carbon Farming in Lombardy Region this drawback needs to be addressed. A possible solution is to rely on more general, but presumably less accurate, methodologies to display the SOC changes due to changes in management practices applied to APs of a given farm, like methods provided by IPCC Guidelines (IPCC, 2006) and currently applied by the Italian National Greenhouse Gas Inventory.

SECTION 6. References

Guillaume, T., Makowski, D., Libohova, Z., Bragazza, L., Sallaku, F., Sinaj, S., 2022. Soil organic carbon saturation in cropland-grassland systems: Storage potential and soil quality. Geoderma, Volume 406, 2022, 115529, ISSN 0016-7061. https://doi.org/10.1016/j.geoderma.2021.115529

Intergovernmental Panel on Climate Change (IPCC), 2006. In: Eggleston. HS., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.). Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Program. vol. 4. Published: IGES. Japan. AFOLU. 2006. Chapter 2 P. 2.29.

Lal, R., 2004. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science 304 (5677), 1623–1627

Sanderman, J., Farquharson, R., Baldock, J., 2010. Soil Carbon Sequestration Potential: A review for Australian agriculture. A report prepared for Department of Climate Change and Energy Efficiency. https://doi.org/10.4225/08/58518c66c3ab1

Wiesmeier, M., Urbanski, L., Hobley, E., Lang, B., von Lützow, M., Marin-Spiotta, E., van Wesemael, B., Rabot, E., Ließ, M., Garcia-Franco, N., Wollschl¨ager, U., Vogel, H.-J., K¨ogel-Knabner, I., 2019. Soil organic carbon storage as a key function of soils – A review of drivers and indicators at various scales. Geoderma 333, 149–162. https://doi.org/10.1016/j.geoderma.2018.07.026.

Annex 1 – Example of agricultural land parcel identification in Lombardy Region

The LIPS reference parcel in Italy is the Agricultural Parcel (AP), consisting of contiguous portions of agricultural land, managed by a single farmer, homogeneous for land cover and management practices applied. The AP contributes to the determination of the maximum eligible area for each regional, national and Union support scheme, as well as for any declaration, communication and any other administrative procedure depending on area-based calculation.

For the scope of the LIFE C-Farms project two LIPS datasets were provided by the *Direzione Organismo Pagatore Regionale Gestione sviluppo rurale – misure a superficie* for six municipalities that have been used as input data to delineate APs, in accordance with rules set out by AGEA:

- Vector **cadastral map** of the farms (Figure 20);

- Vector map of the **land plots** (Figure 21); in this map any feature represents contiguous and homogeneous areas for land use according to the classification system adopted by AGEA (Table). The land use class is assigned to land plots by photo-interpretation of remote sensing images at very high spatial resolution (0.5 m), as well as based on the outcome of the administrative authorization procedures and on-site checks. In addition to differences in land use, permanent limits are also considered for the demarcation of a land plot, such as: roads and railways; rivers and streams; ditches and irrigation canals, embankments, buildings, courtyards, walls (with a width greater than 2 meters). Farmers are required to carefully examine the map of agricultural plots, as well as to identify and exclude from the application for financial support all uncultivated and ineligible elements.

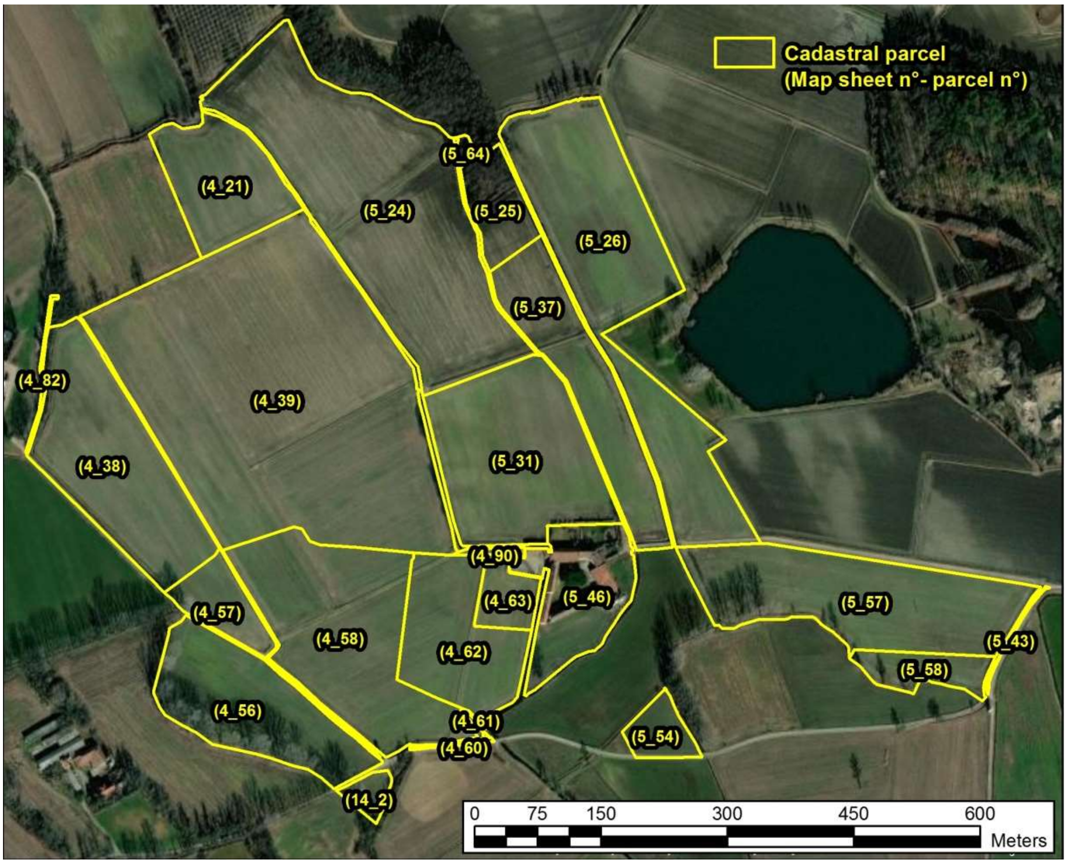


Figure 20. Cadastral parcels mosaic of a farm

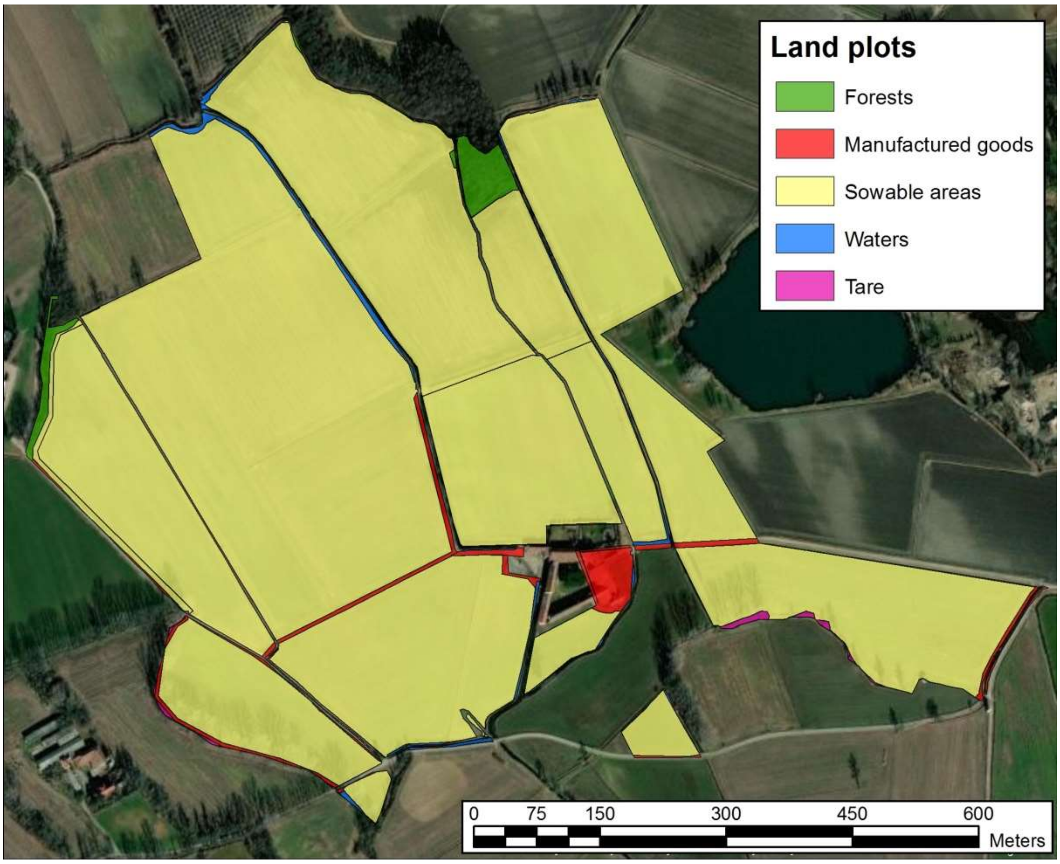


Figure 21. Land plots mosaic of a farm

Table 9. Land use legend adopted by AGEA for the land plots classification

CODE	Class description
410	Vineyards
420	Olive groves
430	Citrus fruits
491	Carob
493	Almond
494	Hazelnut
495	Walnut groves
497	Pistachio
557	Fixed greenhouses

638	Mountain pastures (without tare)
650	Forests
651	Specialized tree crops
654	Lean pasture (tare up to 50%)
655	Associated arboretum (with herbaceous crops)
659	Lean pasture (tare up to 20%)
660	Manufactured goods
666	Sowable areas
685	Promiscuous tree crops (multiple tree species)
690	Waters
770	Non-arable areas
780	Tare

Other information available from the land plot shapefile are descriptive codes of the crop type, variety and intended use.

The spatial relationship between the features of the land plot and the cadastral map can be:

- 1 to 1: a land plot corresponds to a cadastral parcel;
- 1 to many: a land plot includes several cadastral parcels or parcels parts;
- many to 1: different land plots are included in the same cadastral parcel (e.g. a cadastral parcel that includes also elements that are not eligible for contribution or that includes different crop types)

The spatial overlay (identity tool in ArcGIS) of the cadastral parcels layer with the land plots allow to generate the **agricultural parcels** shapefile (Figure 22).
The quality of AP delineation is affected by the quality of the cadastral data and by the co-registration level with the orthophotos used for the delimitation of the agricultural plots. These factors determine geometry problems and the possible creation of numerous polygons per cadastral parcels, most of which with an area equal to a few

square meters (sliver polygons). Geometry problems can be solved using the "repair geometry" tool in ArcGIS, while sliver polygons can be easily removed based on their size.

At the end of this process the obtained shapefile allows the graphic representation of the agricultural parcels and the quantification of the corresponding surface within the respective cadastral parcel.

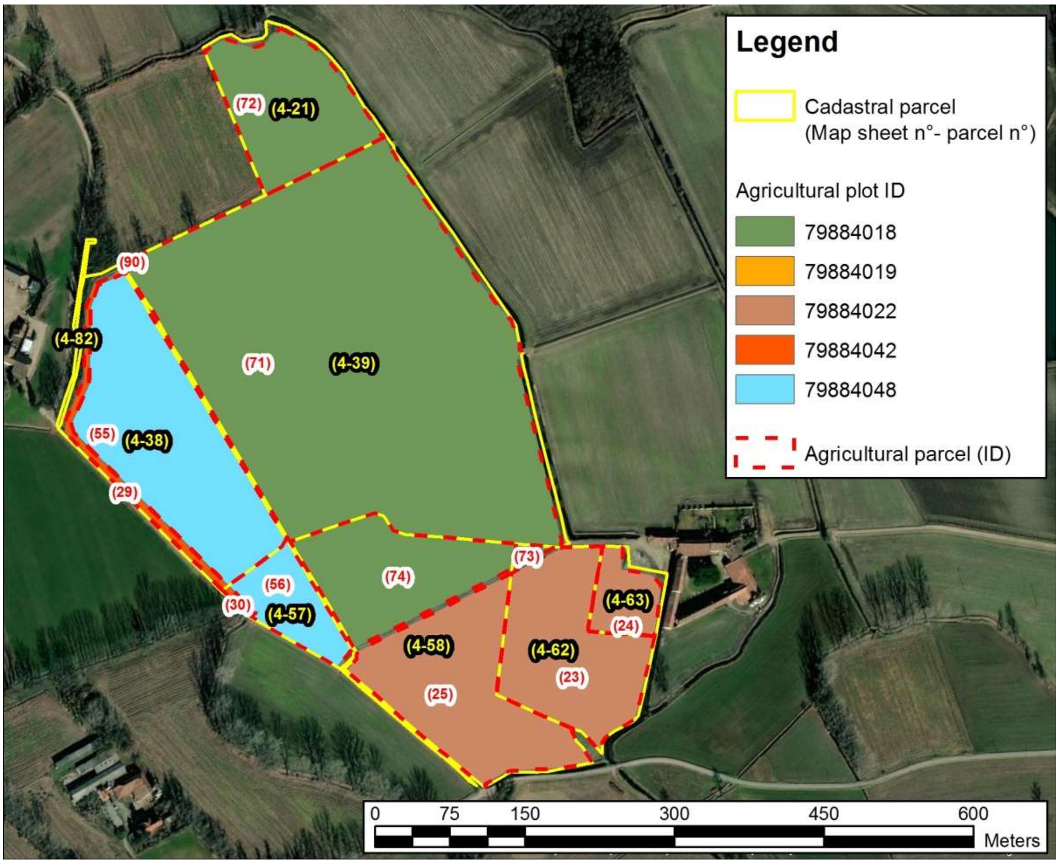


Figure 22. Example of agricultural parcels derived from the overlay of agricultural plots with cadastral parcels. The plot with ID 79884018 extends over three different cadastral parcels (n ° 21, 39 and 58 of sheet 4) consequently generating three different agricultural parcels (ID: 71; 72; 74); cadastral parcel 58 of sheet 4 is covered by two plots (ID: 79884018; 79884022) consequently generating two agricultural parcels (ID: 25; 74); etc.