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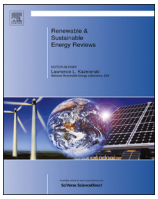

Optimal energy use of agricultural crop residues preserving soil organic carbon stocks in Europe[☆]

F. Monforti[a,*], E. Lugato[b], V. Motola[a], K. Bodis[a], N. Scarlat[a], J.-F. Dallemand[a]

[a] *European Commission, JRC—Institute for Energy and Transport, Via E. Fermi 2749, TP 450, I-21027 Ispra, VA, Italy*
[b] *Institute for Environment and Sustainability, Via E. Fermi 2749, TP 450, I-21027 Ispra, VA, Italy*

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ABSTRACT

The European Union has committed itself to ambitious targets of Renewable Energy and bioenergy is expected to play a major role, increasing its contribution to Gross Final Energy Consumption from 2458 PJ in 2005 to 4605 PJ by 2020.

Agricultural crop residues are considered a reliable resource for energy uses but important concerns still exist on the potential depletion of Soil Organic Carbon (SOC) stocks that may partially offset the environmental suitability and convenience of their large-scale exploitation.

This paper provides an estimate of available agricultural residues and related potential energy production obtainable without impacting the EU SOC stock showing how SOC content preservation imposes the application of different collection rates for agricultural residues across the EU, depending on factors such as climate, soil type, current farming practices and pre-existing cultivation history.

The results suggest that a potential amount of residues of 146,000 kt/year of dry matter leading to a potential gross energy production of about 2300 PJ/year could be obtained in EU-27[1] without impacting the current SOC stocks. Agricultural residues are then theoretically able to provide a substantial contribution to renewable energy targets in several EU-27 countries as well as accommodating competitive uses and SOC preservation. Nevertheless, the spatial pattern of results also clearly indicates regions and countries where residues exploitation should be handled with care and current practices on residues collection are risky in term of SOC content.

The estimate provided builds on results from previous studies (e.g., Scarlat et al. Waste Manage 2010;30:1889–1897, Monforti et al. Renewable Sustainable Energy Rev 2013;19:666–677) and on the analysis of future scenarios of SOC content obtained from an innovative pan-EU modelling platform (Lugato et al. Global Change Biol 2014;20:313–326. doi:10.1111/gcb.12292. Such an integrated approach, making use of soil, climate and energy transformation modelling, is unique and constitutes a substantial applied value for assessing the sustainability of crop residues use.

Contents

[☆] The views expressed in this paper are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

[*] Corresponding author. Tel.: +39 332 783996.
E-mail address: fabio.monforti-ferrario@ec.europa.eu (F. Monforti).

[1] Excluding Croatia.

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1. Introduction

The European Union (EU) has committed itself to ambitious targets for Renewable Energy Sources—RES thereafter [7]. According to the National Renewable Energy Action Plans presented by Member States, bioenergy is expected to play a major role in the deployment of RES throughout the current decade, increasing its absolute contribution from 2458 PJ in 2005 to 4605 PJ by 2020, both in solid, liquid and gaseous forms [2] with a relative increase of 87%.

Among the different feedstock available for bioenergy, agricultural crop residues are a reliable and readily exploitable resource for both the electricity and heating and cooling sector. In perspective, they are also expected to play a role in the production of second generation biofuels thus supporting the decarbonisation of the transport sector, without threatening food security or impacting on the land use [8].

Nevertheless, important concerns still exist on the potential depletion of soil organic carbon—SOC thereafter [3], that may partially offset the environmental suitability and convenience of a large-scale bioenergy production policy [19,5,9] involving agricultural residues. Obtaining reliable and relevant data on soil carbon stock change requires long-term experiments in different soils and farming practices over several decades. The effect of residue management on SOC balance is documented in some long-term experiments within the EU and in other parts of the world [20]. In the majority of cases, authors reported an increasing trend for SOC and total soil N content whenever straw was incorporated annually but with relative changes generally below 10%. However, pan-EU scenarios are still lacking primarily due to the uncertainty in upscaling local field data to such a broad territory.

In this context, biogeochemical models may provide useful information on SOC evolution because of their ability to simulate SOC turnover in different pedo-climatic conditions, and in interaction with specific management practices. Smith et al. [23] showed that widely used process-based models (e.g., CENTURY, DNDC) simulated values in the same uncertainty range as estimates derived from field experiments, where different residue removal rates were tested.

Given the large agricultural area in Europe (> 174 Mha according to Eurostat), even small SOC change at field level may translate into significant CO_2 losses that should be accounted for under a coherent policy aiming at reducing GHG emissions [11]. Moreover, a decrease of SOC content could deteriorate the soil physical properties and its nutrient cycling [4], leading to lower resilience of agroecosystems and requiring higher external input (fertilisers) for maintaining soil functions, with additional environmental and economic burdens.

Having these considerations in mind, policies aimed at exploiting the energy content of agricultural residues should carefully consider the issue of SOC content [1,10], in order to avoid excessive exploitations in areas where residues collection could become unsustainable from this perspective [25]. In this context, this study updates and re-assesses residues collection strategies discussed in previous works [21,15] by assessing the potential impact on SOC change.

Based on a pan-EU modelling platform [12], this paper aims to: (1) calculate the optimal collection rate of crop residues without depleting SOC stocks across the EU; (2) provide a reliable estimate of the primary energy potentially obtainable by this category of feedstock for fuelling crop residues-based electricity and/or Combined Heat and Power (CHP) plants.

2. Material and methods

2.1. Available agricultural crop residues in the EU-27

The potential gross energy production from agricultural crop residues in the 27 Members States of the EU until July 1st 2013 (EU-27 hereafter) has been estimated in several studies and summarized in Monforti et al. [15]. In the same paper, a geographical assessment of potential agricultural residues availability for energy uses was developed for 8 crops[2] at a 1×1 km (100 ha) resolution for the whole EU 27 territory. The amount of agricultural residues associated with crop production was estimated for each NUTS2 administrative region on the basis of Eurostat data for crops production and of the residues-to-crop ratios discussed in Scarlat et al. [21]. Then, based on analysis of available literature, collection rates for agricultural residues were assumed to be either 40% of the residues present on the ground for wheat, barley, oat and rye residues, while 50% was assumed for maize, rapeseed, rice and sunflower residues, irrespectively of the location. These collection rates are referred to as “Default Collection (DC) rates” in the following text.

Finally, competitive uses for some of the residues (e.g., straw for animal bedding, horticulture and mushrooms production) were also estimated for each category of crop residues in each NUTS2 administrative entity and subtracted from the exploitable pool of residues.

The resulting available residues were then spatially allocated on the basis of a GIS-based analysis combining different information layers such as relevant land cover (CORINE) [6], crop production (M3) [13] and land productivity [24]. The result of the overall procedure is shown in Fig. 1 in units of t/km^2.

2.2. Biomass removal and its effect on soil carbon stock content

As stated in the introduction, SOC changes under different residue collection rates are strongly dependent on cultivation practices but also on other parameters such as climate and soil characteristics; therefore, the estimation of the locally sustainable[3] collection rates needs to take into account all these factors.

In order to account for this spatial variability, a recently developed simulation platform was used to assess the effect of different residue removal rates on SOC stock change at pan-EU level. The simulation platform is based on the integration of the

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[2] Namely wheat, barley, oat, rye, maize, rapeseed, rice and sunflower.

[3] It is worth noticing how in this study the term “sustainable” refers to the preservation of the SOC content of soil parcels. In this sense, a “sustainable collection rate” has to be considered as “the maximum collection of residues that could ensure the preservation of SOC content”. Other aspects of the wider sustainability concepts such as protection from soil erosion or from excessive water runoff are not considered here.

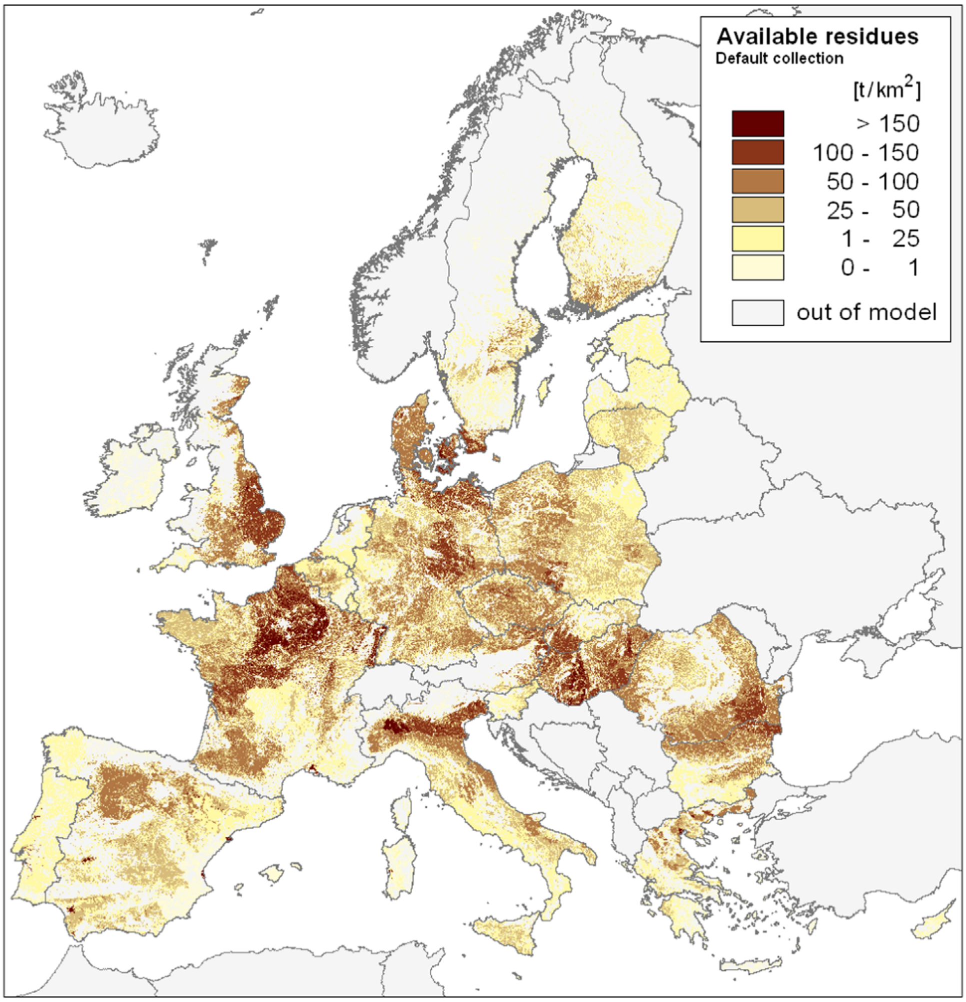

Fig. 1. Agricultural residues available for energy use in EU-27 as calculated in Monforti et al. [15] based on default collection rates of 40% or 50%. data in tonnes of dry matter per square kilometre (t/km^2)

agro-ecosystem CENTURY model [18] and several spatial and numerical databases developed at the EU level.

The CENTURY model is designed to simulate Carbon, Nitrogen, Phosphorus and Sulphur dynamics in natural and cultivated soils, using a monthly time step. CENTURY considers two litter (fresh residues) pools: metabolic and structural, and three SOC pools: active, slow and passive. Metabolic litters represent easily decomposable parts of plant residues, while structural litter contains ligno-cellulosic material, more recalcitrant to decomposition. Active SOC represents the microbial mass with rapid turnover (months to few years) while slow and passive SOC decompose with longer turnover (decades and centuries, respectively). The dynamics of SOC in CENTURY is influenced by soil texture, soil moisture and soil temperature and by the cultivation practices (type of tillage, rotation schemes, nutrients input, etc.).

As inputs, the simulation platform used soil data derived from the European Soil Database-ESDB available at the European Soil Data Centre (ESDAC) [17]. Climate data were taken from a 10′ × 10′ cell climate dataset provided by the Climate Research Unit, University of East Anglia, UK [14]. Monthly values of rainfall and maximum and minimum temperature were provided for the interval 1900–2000, based on interpolated observed data. For the period 2001–2100, corresponding values were derived from four different Global Climate Models (GCMs) forced by the four Intergovernmental Panel on Climate Change (IPCC) CO_2 emissions scenarios, as reported in the Special Report on Emissions Scenarios (SRES) [16]. In this study, the projected SOC values were run with two contrasting scenarios, namely HadCM3-A1FI (‘world markets-fossil fuel intensive’) and PCM-B1 (‘global sustainability’) as they encompass a wide range of climatic variations.

The spatial extension of agricultural land use was derived from the Corine Land Cover 2006 from the European Environment Agency [6]. Crop distributions within the arable class were calculated according to the statistics on crop production area for NUTS2 regions, from the EU Statistical Office (Eurostat[4]). Finally, 163,924 Soil–Climate–Land use (SCL) combinations were identified and simulated, but only the arable land class is utilized in this work (76,200 SCL). A full description of input data management, model structure and initialization, as well as model performance and uncertainty can be found in Lugato et al. [12].

For the specific purposes of this study, three residue management scenarios were considered for the arable land class:

- Business as usual (BAU): represents the baseline management regime according to the most recent spatial and numerical databases. For the residue management, 50% of cereal straw was assumed to have been removed from fields, except for

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[4] http://epp.eurostat.ec.europa.eu/portal/page/portal/agri_environmental_indicators/data/database〉.

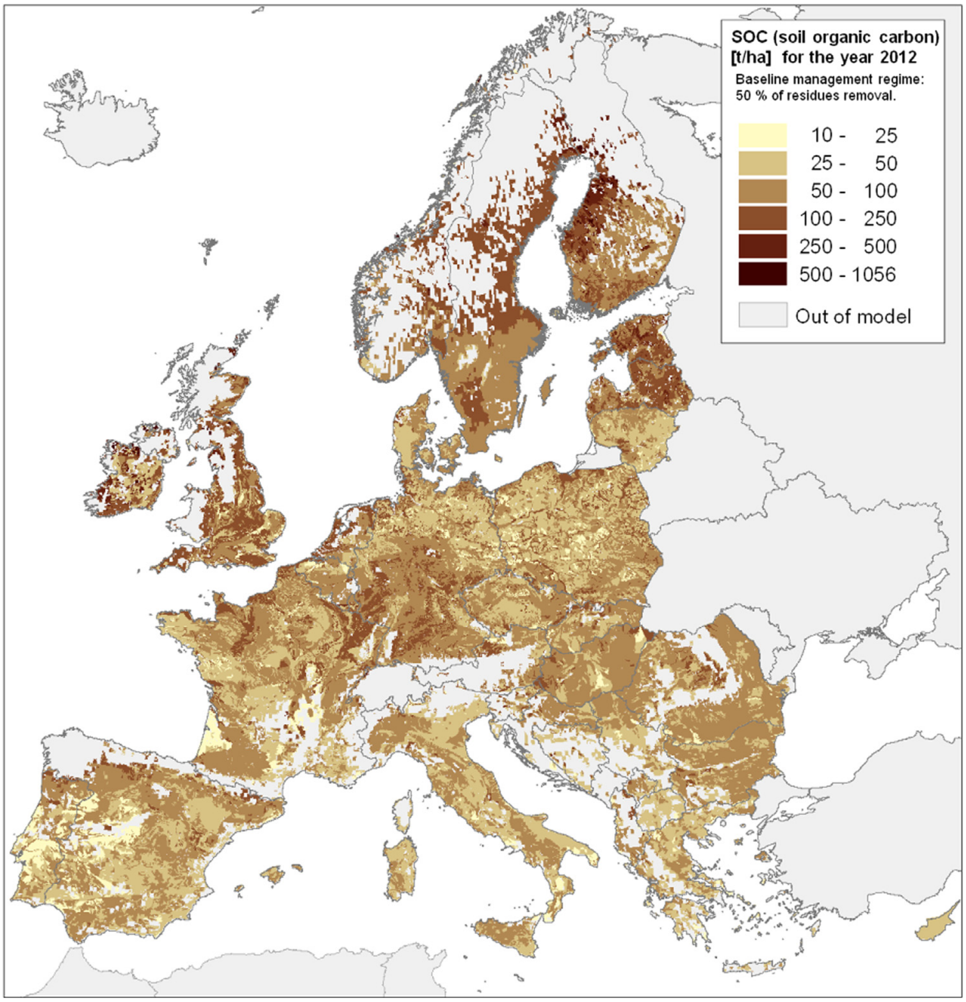

Fig. 2. Absolute content of SOC (t C/ha) in the arable soils in Europe in 2012 as modelled following the methodology described in Lugato et al. [12].

fodder crops, silage maize (all aboveground biomass removed) and grain maize (only grain removed).

- No crop residue removal (R_0): all cereal straw were left on the field and incorporated into the soil after the harvest by the successive tillage operations.
- Total crop residue removal (R_{100}): all cereal straw were removed from the field, except for grain maize.

All scenarios were run from the year 2013 and projected until 2050. The SOC content in 2012, then, represents the common SOC baseline and it is shown in Fig. 2.

2.3. *Calculation of the optimal collection rate of crop residues*

The SOC stock changes found for SCL units described in the previous paragraph were spatially reallocated on the same 1 × 1 km grid covering the EU-27 on which the residues potential map obtained in [15] are based.[5]

For each 1 × 1 km "pixel" simulated, the results of the three scenarios were used to build a piece-wise linear function relating SOC content to the amount of residues removed, considering R_0 as the scenario with the maximum C input. This function was computed for both the 2020 and 2050 scenarios. On the basis of this function, it is possible to identify the maximum biomass collection rate (i.e., C removed with residues) allowing the preservation of a given defined carbon stock (see Appendix A for mathematical details).

In the present study, the SOC level to be preserved was set equal to the SOC content of 2012, underlying the concept that whatever bioenergy policy may be planned, it should not deplete the present SOC stock.

Following the methodology detailed in Appendix A, the maximum possible amount of residues that can be collected assuring SOC stock preservation were computed for both 2020 and 2050 time horizons and denoted as OC_{2020} and OC_{2050} respectively for each 1 × 1 km parcel of the EU-27 territory.

Keeping the collection of residues below OC_{2020} should assure SOC preservation up to 2020 while keeping residues collection below OC_{2050} should assure SOC preservation in 2050. Keeping residues collection below the minimum between OC_{2020} and OC_{2050} should assure the SOC preservation along both the shorter and longer time horizons.

For this reason, the minimum of the two values was chosen as the Optimal Collection (OC) associated to the land parcel, i.e., the maximum amount of residues possible to be collected for each 1 × 1 km parcel without putting SOC stocks under pressure whatever the time horizon considered.

Optimal collection values were then converted from tonnes of carbon per hectare to tonnes of dry biomass per hectare and an

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[5] The SOC changes dataset and the straw potential map were found to be spatially compatible at 98% level, the slight differences being caused by the use of partially different CORINE versions. For the few pixels excluded from the SOC model providing agricultural residues, the standard collection rates were supposed.

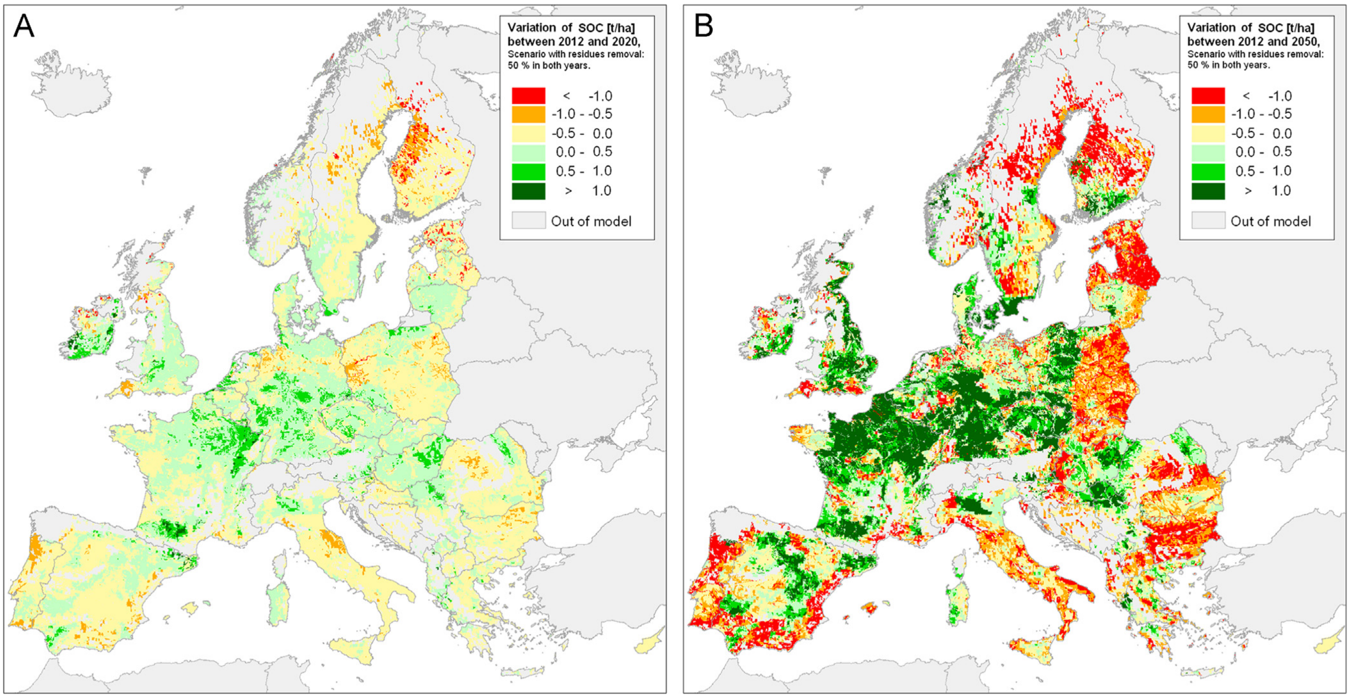

Fig. 3. Absolute variation of SOC (t C/ha) in BAU scenario for 2020 time horizon (left) and for the 2050 time horizon (right) in Europe. Future SOC predictions are the average of the two climatic scenarios (HadCM3-A1FI and PCM-B1).

additional residues collection threshold was finally applied in each pixel, in order to not overtake the theoretical available residues as computed in Scarlat et al. [21].

3. Results

3.1. Current and projected SOC stock in Europe in next decades

Fig. 2 shows the baseline SOC stocks in 2012 as modelled following the methodology described in Lugato et al. [12]. SOC content varies across Europe, with lowest values in the Mediterranean area, while higher SOC values are estimated for north, and especially north-eastern regions. Overall, the interaction of diverse pedo-climatic and agronomic conditions resulted in a complex SOC distribution for the EU, with eastern countries showing a particularly irregular pattern.

Fig. 3 shows the modelled changes in SOC content (t C/ha) under BAU scenario between 2012 and 2020 (left panel) and between 2012 and 2050 (right panel). From the maps it is evident how different areas in Europe are expected to react in a different way to BAU residues collection scenario in interaction with climate change: for some areas, such as northern France, central Germany, the Po Valley, central Spain and most of the UK, the BAU collection rate is not expected to cause any depletion of the existing SOC pool. In comparison, in areas such as eastern Poland, Portugal, central Romania and northern Baltic countries, the BAU scenario is expected to lead to SOC depletion even beyond 1 t/ha especially for the 2050 time horizon.

Fig. 4 shows SOC changes expected on the basis of R_0 (no collection) and R_{100} (full collection) scenarios in the 2020 horizon. The comparison of the two scenarios for 2020 shows that no collection is expected to end up in a constant or increasing SOC content almost everywhere in Europe, even if in some areas (e.g., northern Portugal) SOC is not maintained even leaving the totality of residues on the ground. Conversely, the full collection of residues is expected to negatively affect the SOC content almost everywhere in Europe, except for a few small areas (e.g., in Austria, Hungary and the Po valley) where even a full collection of residues is expected not to decrease SOC content. A similar pattern was found for the same two scenarios in the 2050 time horizon (not shown here).

3.2. Available residues in EU-27

Fig. 5 (left panel) shows the amount of residues available for energy uses in EU-27 with a 1 × 1 km resolution, based on the application of Optimal Collection (OC) described in Section 2.3 and after subtracting residues diverted to competitive uses [21]. The right panel in Fig. 5 reports the optimal collection rates as a percentage of produced residues.

A comparison between Figs. 1 and 5 show how the SOC preservation clearly impacts the overall picture of residues availability. For a better analysis, Fig. 6 shows the absolute difference between the amount of agricultural residues possible to be collected applying the Optimal Collection (OC) rate and the Default Collection (DC) rate in units of t/km^2 with 1 × 1 km resolution covering the whole EU-27 territory. Red colours identify areas where the optimal residues collection discussed in this study provides values lower than the default collection rate (i.e., areas where the removal of agricultural residues from land should be lowered in order to prevent SOC depletion). On the contrary, blue colours correspond to areas where agricultural residues collection could in principle be safely increased in comparison with the default scenario investigated in Monforti et al. [15].

It is evident that the distribution patterns shown in Fig. 6 are complex as several factors are involved in determining SOC balance: soil characteristics, climatic zones, land cover and the agricultural production itself. Generally, every country contains both red and blue areas, with some cases of predominantly red areas (e.g., Estonia, Romania and Hungary) and others with a dominance of blue zones (e.g., Denmark and UK). In addition to the soil characteristics, this situation is explained by the fact that

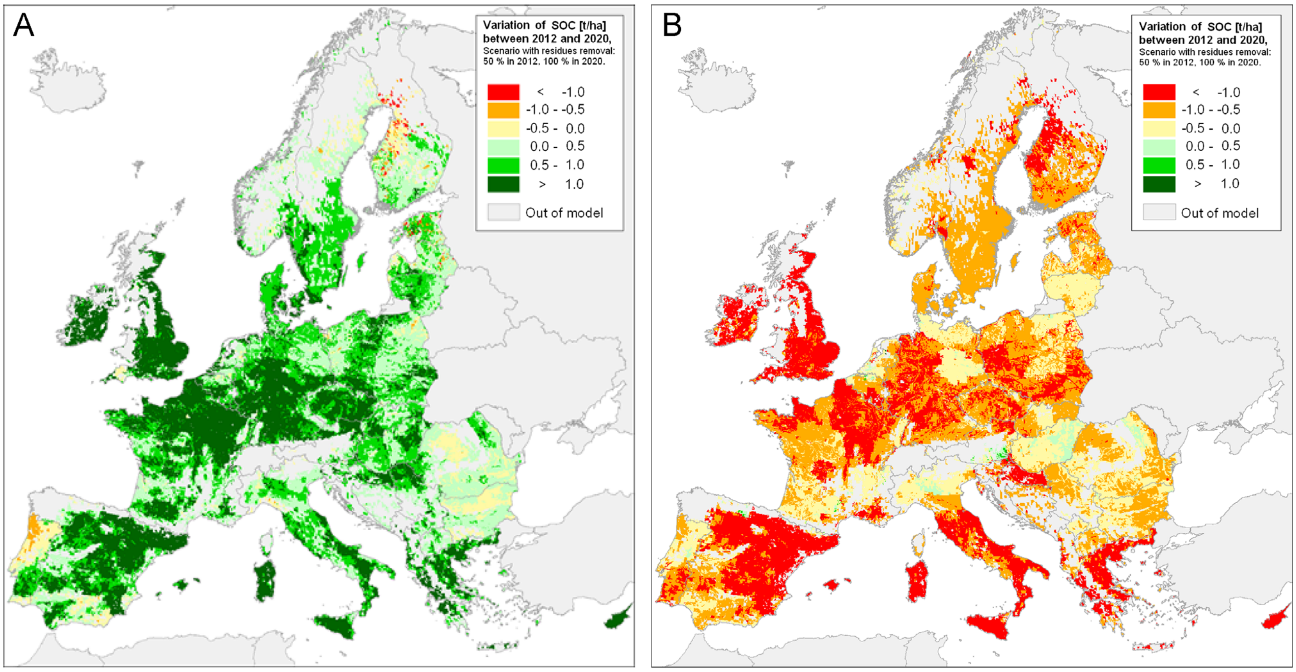

Fig. 4. Absolute variation of SOC (t C/ha) expected between 2012 and 2020 in the no residues collection scenario (left) and in the full residues collection scenario (right). Future SOC predictions are the average of the two climatic scenarios (HadCM3-A1FI and PCM-B1).

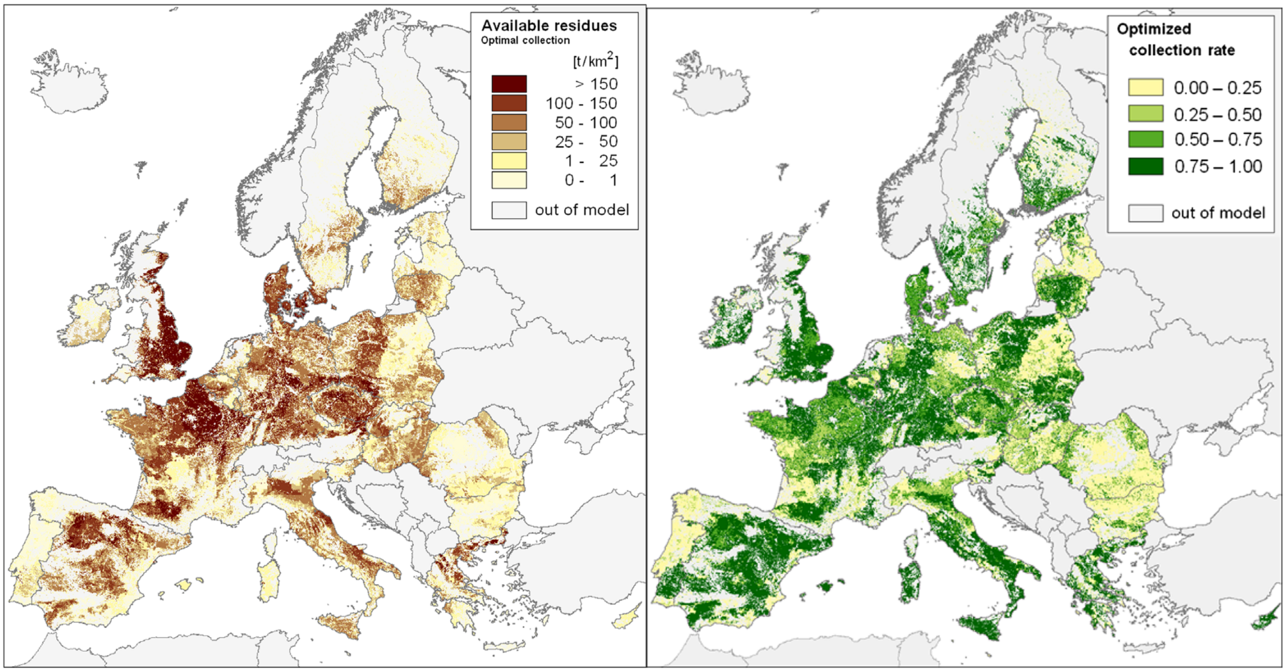

Fig. 5. Agricultural residues available for energy use in EU-27 in the assumption of optimal collection in t/km^2 (left) and OC rates in terms of maximum fraction of residues available for collection (right). The resolution of both maps is 1 × 1 km.

higher crop yields are associated with higher amounts of crop residues. Thus, in areas with higher agricultural yields, a higher amount of crop residues is produced, which provides higher C input into soils; crop residues could be partially removed from land, while enough biomass remains to maintain the carbon stock in soil.

In order to provide a country-based view, Fig. 7 shows the total amount of agricultural residues potentially available for energy production for the EU-27 countries in both DC (left bars) and OC (right bars) approaches. For each country the potentially available residues estimated in Monforti et al. [15] are shown in comparison with the corresponding values found in this study. It is interesting to notice that in some countries the overall amount of available residues increases moving from the default to optimal collection, while in others decreases. National percentage changes range between +150% for the Netherlands and −80% in Bulgaria, while in absolute terms the change in estimates of available residues applying the optimal collection approach can range

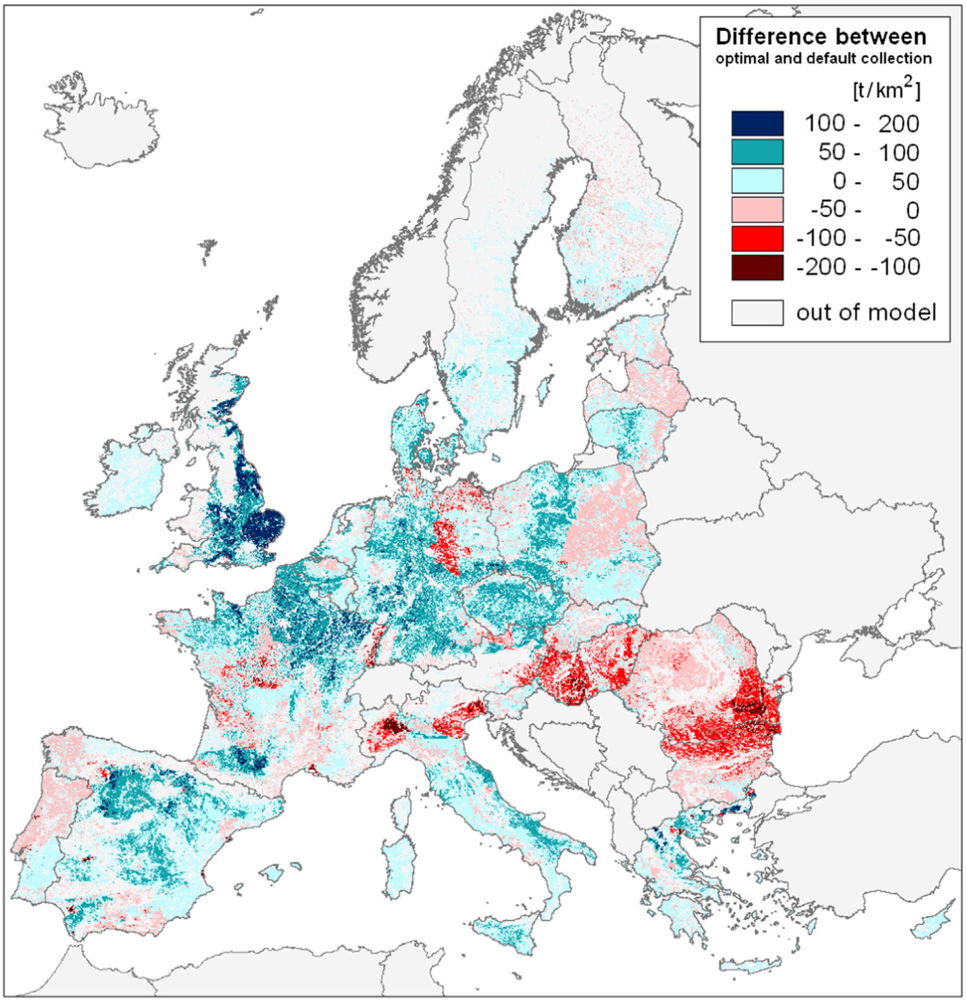

Fig. 6. Difference (OC–DC) between the estimates of available crop residues for energy uses, based on optimal (OC) or default collection (DC) rates. Blue colours identify areas where OC > DC while red colours correspond to areas where OC < DC. Unit is tonnes of dry crop residues /km^2 and resolution is 1 × 1 km. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

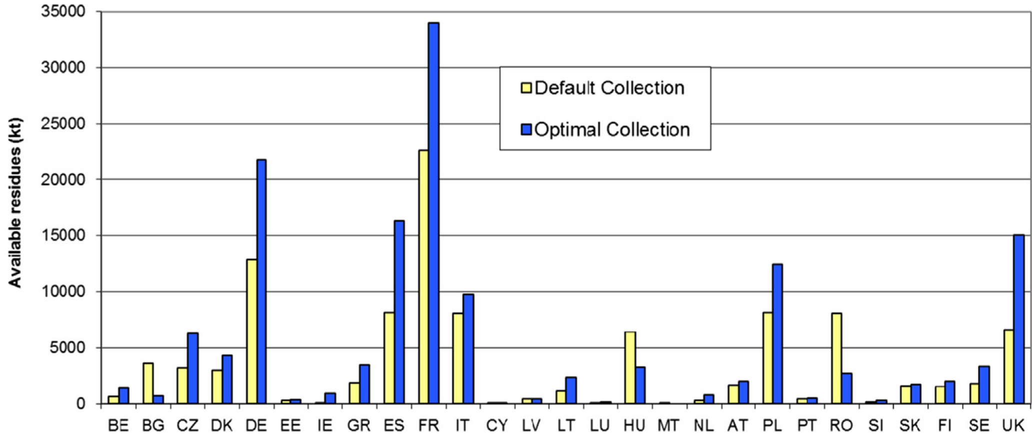

Fig. 7. Amount of agricultural residues available for energy production in EU-27 countries when default collection (left bars) or optimal collection (right bars) is applied. Data in thousands of tonnes of dry matter.

between about +11,500 kt in France and about −5300 kt in Romania.

In total, a value of 146,067 kt of available agricultural residues is estimated for the whole EU-27 when optimal collection is considered, to be compared with 102,186 kt estimated when default collection rates are supposed, with a relative difference of 42.9% between the two values.

3.3. Collection and transformation

Even if theoretically available on the ground, agricultural residues are not necessarily optimally distributed in order to be profitably exploitable for energy production. On the contrary, their distribution on the ground could be not dense enough for allowing an economically feasible exploitation. For this reason, a spatially

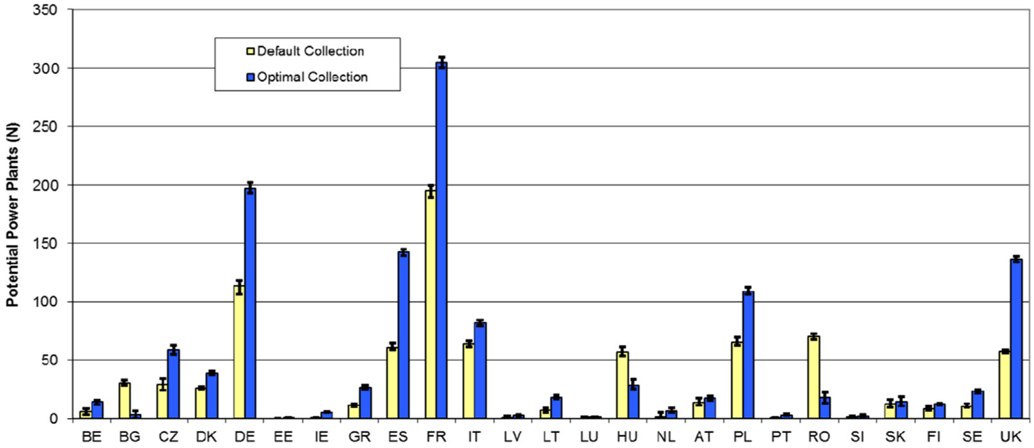

Fig. 8. Potential number of 'typical' power plants in each country of EU-27 supposing default collection rates (left bars) or optimal collection rates (right bars). Bars represent the average value found among the 20 Monte Carlo runs, while error bars show the minimum and the maximum values found. No plants are allocated in Cyprus and Malta in both scenarios.

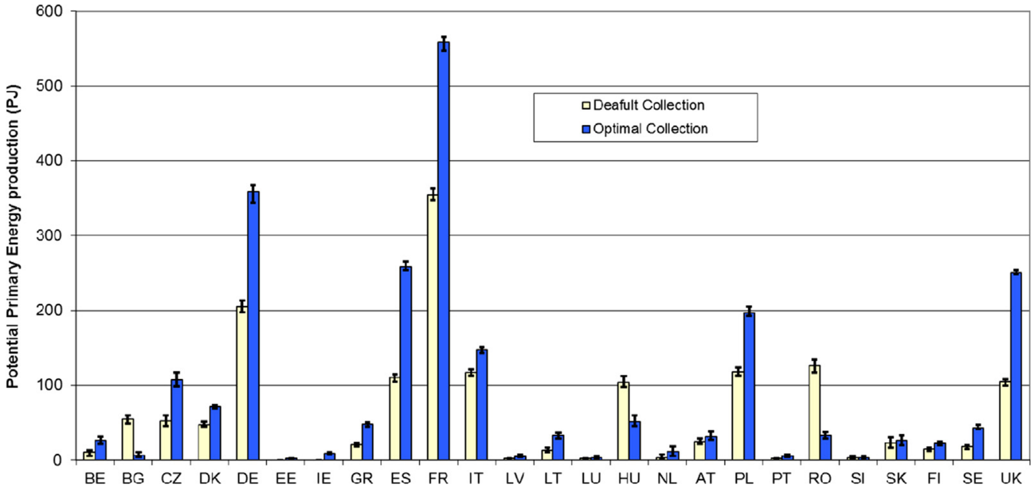

Fig. 9. Potential primary energy production from the 'typical' power plants shown in Fig. 8, supposing default collection rates (left bars) or optimal collection rates (right bars). Bars represent the average vale found among the 20 Monte Carlo runs, while error bars show the minimum and the maximum values found.

explicit model for the collection of raw material into energy was developed and applied in Monforti et al. [15]. In order to move from residues that are theoretically available on the field to the actual collectable residues, a model describing a "typical" biomass-fed power plant and its optimal allocation has been developed. A plant with a capacity of 50 MW of thermal input, needing about 100 kt/year of raw material was considered "typical" for the upcoming EU bioenergy market, providing a good balance between operational costs and revenues given the logistic and feasibility constraints related to the mobilization of a low-density energy source such as crop residues.

Suitable locations for placing such a "typical" power plant are governed by the presence of necessary resources within a radius of 50 km[6] and by the fulfilling of other geographical constraints (e.g., gentle terrain slope). Once a set of suitable geographical locations for power plants location have been selected, they have to be ranked to prioritize their exploitation potential. In the present study a *randomized* procedure, described in Appendix A of Monforti et al. [15], was applied where a Monte Carlo method based on randomized exploitation priority is applied and the whole randomized procedure is repeated 20 times in order to allow the analysis of the results variability.

Fig. 8 shows the number of plants allocated in the EU-27 countries in both OC or DC scenarios while Fig. 9 provides a view of the potential yearly amount of primary energy produced by these power plants.

At the EU-27 level, the DC scenario has led to a range of 834 to 852 plants producing between 1510 and 1540 PJ of primary energy per year, while the OC scenario provides a range of 1260 to 1276 power plants producing between 2290 and 2320 EJ of primary energy, with an increase of 51.6% in comparison with DC hypothesis.

It is worth noticing that applying OC instead of DC does not only make more residues available (+42.9%) but, as the spatial density of residues is also increased on average, a larger share of them can be efficiently collected and transformed into energy. For this reason, the increase in the generated energy (+51.6%) is larger than the increase in the amount of available raw material (+42.9%) as the efficiency of the collection process is on average enhanced.

In Table 1 the same results of Figs. 7–9 for the optimal collection approach are reported in a tabular format.

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[6] This distance corresponds to a maximum travel distance of about 70 km, given the typical European road deviousness factor of 1.4.

3.4. Mobilization needs

A consequence of the increased residues density is also shown in Fig. 10, where the mobilization needs (in t km) are reported as a function of the overall primary energy production in both hypotheses of optimal and default collection for all the 20 runs of both cases. Because of the increased overall areal density of residues, the same amount of raw material is generally available in a smaller area and its transportation needs are on average smaller in the case of optimal collection than in the default collection case: detailed computations show a value of about 1260 t km/GJ in the OC case to be compared with a value of about 1380 t km/GJ in the DC case.

Table 1
Available residues, potential number of typical power plants and potential primary energy production in EU-27.

	Available residues (kt dry matter)	Potential number of "typical" power plants	Potential primary energy production (PJ)
BE	1,389	12–17	21.5–31.1
BG	715	2–6	3.5–10.8
CZ	6,224	54–64	98.5–116.9
DK	4,342	38–40	68.6–72.9
DE	21,771	190–202	343.7–367.1
EE	363	1	1.8
IE	909	4–6	7.2–10.8
GR	3,421	25–28	45.0–50.4
ES	16,337	140–146	254.0–264.9
FR	33,994	299–309	547.2–565.9
IT	9,756	79–84	142.6–151.1
LV	378	2–4	3.6–7.4
LT	2,314	16–20	28.7–36.2
LU	105	1–3	1.8–5.4
HU	3,201	25–33	45.1–59.4
NL	771	3–10	5.4–17.9
AT	2,017	15–21	27.0–38.1
PL	12,438	106–113	192.2–205.1
PT	494	2–4	3.5–7.2
RO	2,688	16–21	28.9–37.2
SI	277	1–3	1.8–5.3
SK	1,713	11–18	19.7–32.5
FI	1,977	11–14	19.7–24.9
SE	3,323	23–26	41.3–46.7
UK	15,067	135–138	248.2–254.2
EU-27	146,067	1260–1276	2290.8–2319.8

4. Discussion and conclusions

The expected future evolution of SOC stock of agricultural land in EU-27 countries has been assessed for 2020 and 2050 by means of a modelling platform based on the agro-ecosystem CENTURY model [18] run under the climate evolution predicted by different Global Climate Models (GCMs) for two Intergovernmental Panel on Climate Change (IPCC) CO_2 emissions scenarios. The consequences of three different crop residues management on scenarios on total SOC stocks were assessed: 50% of removal, no crop residue removal and 100% cereal straw removal. On the basis of the results obtained, an optimal value for agricultural residues collection was obtained for each 1 × 1 km parcel of agricultural land in EU-27 with the hypothesis of preserving the current SOC content (2012) both in 2020 and 2050 time horizons.

The optimal collection rates found in this study were compared with the default collection rates proposed in Scarlat et al. [21] in order to provide an updated estimate of the amount of residues potentially available and their possible exploitation for energy production. The results show how the application of the optimal collection can make about 146,000 kt of raw agricultural residues potentially available for energy uses per year, in comparison with the estimated 102,000 kt if default collection is implemented. Nevertheless, this result has to be handled carefully at local level, as the study also clearly shows that there are countries and geographical areas where the actual exploitation of residues needs strict capping in order not to put SOC stocks at risk.

The collection and transportation model developed in Monforti et al. [15] was also applied in order to calculate the energy possible to be efficiently produced in "typical" European CHP plants leading to an overall range of potential gross energy production between 2290 and 2320 PJ/year in the whole EU-27, again to be compared with the corresponding 1510–1540 PJ/year coming from standard collection rate use application.

Finally the mobilization needs for residues-to-energy chain were estimated to about 1260 t km/GJ. These results redefine the amount potential availability and exploitability of agriculture residues in EU-27 countries taking into account the preservation of SOC stocks and could provide an overall guidance in dimensioning the European expectation about energy production from current crop residues.

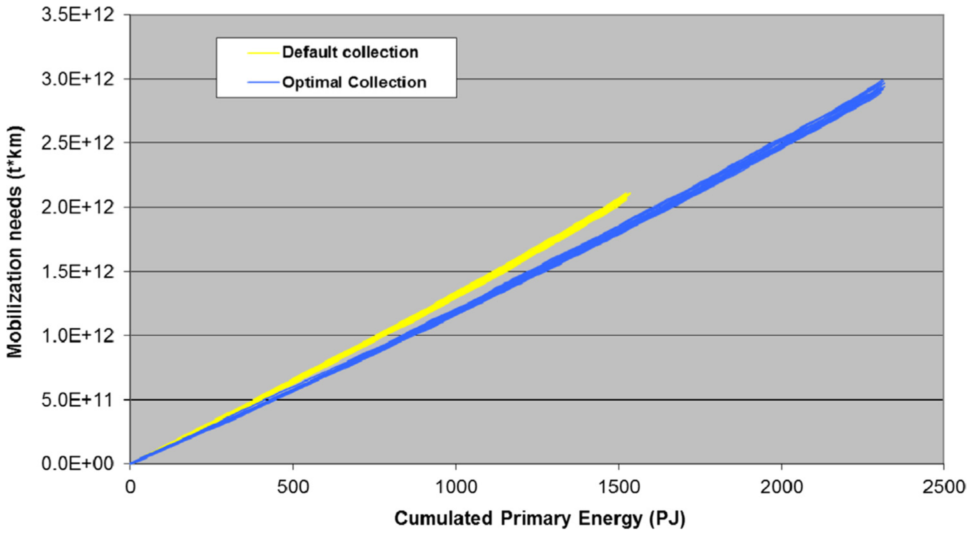

Fig. 10. Raw material mobilization needs (t km) as a function of cumulated primary energy production in EU-27 (PJ) for the 20 runs of both optimal and default collection rate hypothesis.

Again, it is worth emphasizing that the results provided here should be interpreted very carefully whenever actual exploitation plans are developed and should not substitute feasibility and sustainability studies to be developed at local scale.

It is also important to notice the assumptions and the boundaries of this study: in particular it has to be underlined that this study did not take into consideration other environmental or economic aspects possibly leading to further constraints for the actual exploitation of the available raw material. For instance, the overall cost in terms of t km is estimated at EU-27 scale, but it is obvious how the burden of residues transportation is not equally distributed: zones with higher potential are expected to experience higher traffic and local authorities could decide to cap such a pressure on the environment, resulting in a residues exploitation lower than the potential estimated here. Similarly, a regional or national government could decide to limit the number of biomass-fed power plants on its territory for environmental or social reasons, or even to impose special taxes (or incentives) in order to change the framework conditions supposed here. All these aspects, together with many others such as soil protection of agricultural soil form erosion or excessive water runoff, are not considered here, where "sustainability" is meant mainly in the sense of tuning the collection rates in order to assure the preservation of the current SOC stocks under the expected climate evolution for the next decades.

The actual collection of agricultural crop residue will ultimately depend on the farmers' decision, in function of market conditions, such as the price of straw or fertilisers they need to use to compensate for the export of nutrients, and could be based to a limited extent on environmental considerations, such as SOC balance.

Moreover, future SOC changes predicted by models have important margins of uncertainty. SOC accumulation under BAU conditions in large areas of the EU (Fig. 3) is partly related to the positive vegetation response to atmospheric CO_2 increase, as predicted by the IPCC Special Report on Emission Scenarios. Indeed, recent evidences of acclimation under elevated CO_2 conditions [22] indicate an overestimation of modelled plant responses to CO_2 concentration and, as consequence, of the resulting SOC stock.

Finally, it is also worth mentioning that also the underlying hypothesis of SOC preservation could in principle be better specified or even changed. Indeed, in areas showing an initial "low" carbon content (which still needs to be defined) it could be appropriate to further decrease the collection rates in order to make SOC increasing in time for the double purpose of improving the soil quality and let the soil acting a sink in the overall CO_2 balance. This more complex approach could be investigated in future studies, provided that a robust approach for setting meaningful threshold SOC content would be available.

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Appendix A

Starting from the base year 2012, the evolution of the SOC stock for each 1 × 1 km parcel of agricultural land in Europe was forecasted for 2020 and 2050 under the three different scenarios assuming full cereal straw collection, 50% cereal straw collection (BAU) and no residues removal. For each land parcel three alternative situations can arise:

(1) The "no collection" scenario leads to a SOC decrease either in 2020 or 2050 → even no residue collection will result into SOC depletion → the land in this pixel is very sensitive, so no residues should be collected at all here and the only possible optimal sustainable collection rate is 0.

(2) The "full collection" scenario leads to a SOC increase both in 2020 and 2050 → the SOC increases even when agricultural residues are fully collected → the land in this pixel is very resilient and residues can be fully collected: the optimal sustainable collection rate is 100%.

(3) The "full collection" leads to a SOC decrease, while the "no collection" leads to a SOC increase, either in 2020 or 2050 → this is an intermediate situation, in which the full residues collection is going to threaten the SOC stock, but some residue collection could be applied without reducing the SOC. In these cases, two values for optimal collection (OC) of residues for both 2020 and 2050 are computed by linearly interpolating the values of SOC and residues collected in the different scenarios in 2020 and 2050 in order to keep the value of

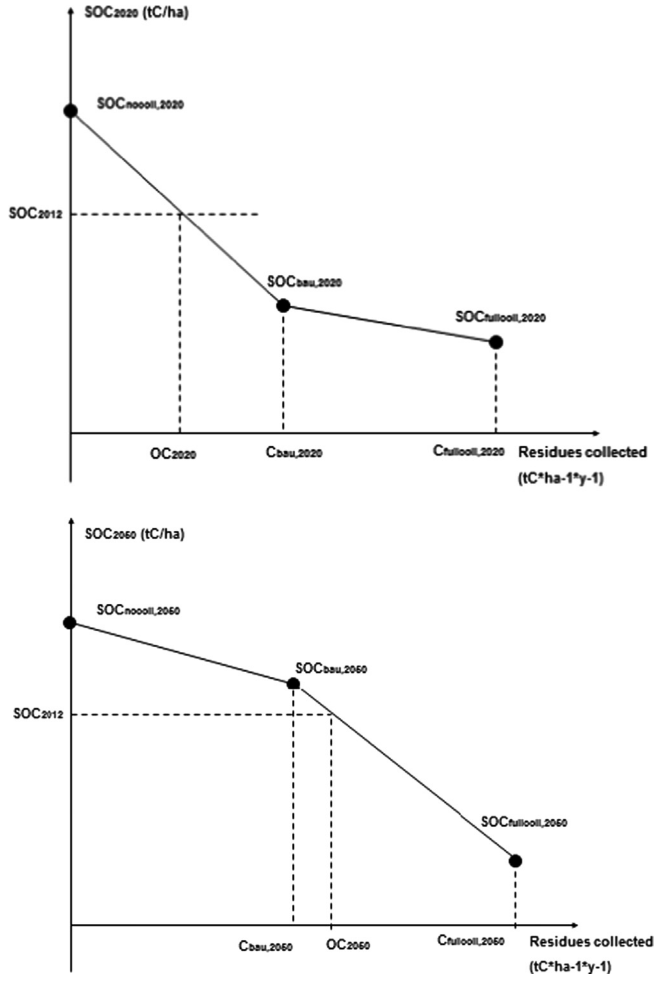

Fig. A.1. Evaluation of the Optimal Collection (OC) by means of linear interpolation for the 2020 (top panel) and 2050 (bottom panel) scenarios. Interpolation procedure involves the values of SOC and residues collected (C) in the scenarios of no collection (R_0), business as usual (BAU) and full collection (R_{100}). The values of OC identified in this way correspond to the highest collected residues amount that guarantees SOC to be kept at the 2012 level in 2020 and 2050, respectively.

SOC in 2020 and 2050 at least at the level of SOC found in the 2012 base year (see Fig. A.1 for details).

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