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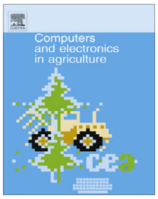

Soil tillage and residues management in wheat continuous cropping in Southern Italy: A model application for agronomic and soil fertility assessment

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ABSTRACT

The intensive agricultural practices are the main causes of soil organic matter decline that generates the desertification process, mainly in Mediterranean areas, characterized by a semi-desertic climate.

The central aim of this work was to simulate and assess the consequences of different crop residue management in durum wheat cultivation in Basilicata region (Southern Italy).

CropSyst model was applied in the 6 main traditional production areas of Basilicata of durum wheat for a total of 15 soil profiles. For this simulation study, 13 years of continuous wheat in 6 different management scenarios were simulated. The compared treatments were: Conventional, Conventional plus residues, Minimum Tillage, No-Tillage, Conservative and Conservative with rotation. The evaluated output variables were biomass and grain yield, water used and percolated, soil organic carbon content. Simulations covered a period over 13 years (from 2001 to 2013) using daily climatic data recorded by 6 weather stations located less than 30 km far from the soils used in the simulation.

The highest yield production resulted in Lavello site, the lowest in Potenza one. Conventional management (residues burning, ploughing and supplemental soil tillage) ensured the best crop performance (3430 kg ha^{-1}), comparable to the other treatments where the straw was left on the soil and highest if compared to the reduced input tillage and straw removal. Burning of straw caused a reduction of the soil organic carbon content (−137 kg ha^{-1} y^{-1}), whereas the other practices allowed an increase in the soil carbon stock, especially when straw was left on the soil and ranging from 1756 kg ha^{-1} y^{-1} in conservative management to 86 kg ha^{-1} y^{-1} in minimum tillage.

CropSyst model indicated an improvement in *SOC* under reduced and no tillage treatments, but the highest soil carbon stock enrichment was achieved when the straw was left on the soil. Anyway, the increment in *SOC* did not lead to an improvement in grain yield, and for this a financial support to the farmers is still necessary.

1. Introduction

Crop management can be adopted as mitigation strategy to take away CO_2 from the atmosphere and incorporate it in agricultural soils (Smith and Olesen, 2010). Indeed conventional soil management characterized by high energetic input on soils, release large amount of CO_2 as a consequence of soil carbon degradation. Increase in greenhouse gas emissions, impoverishment of soil fertility and desertification processes are the main consequences of the conventional soil practices (Reicosky, 2001; Six et al., 2000).

There are several ways to reverse this trend throughout alternative crop management such as: reduced or no-tillage soil management, organic instead of mineral fertilization, deep-rooting crops, adoption of crop rotation instead of intensive farming, residue left or incorporated into soil.

The latter is a simple way to increase soil organic carbon as underlined by Freibauer et al. (2004) who reported as the increment in the soil carbon stock could range from 0.21 to 0.69 t ha^{-1} y^{-1} depending on experimental conditions.

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Residue burning is the most common practice adopted by farmers in Southern Italy, including durum wheat cropping system, with the aforementioned environmental impact other than fire risk. The current environmental protection measures provided by New Common Agricultural Policy (CAP 2014–2020), states that the farmers have to align to Standards of Good Agricultural and Environmental Condition (GAEC) for claiming the founding. In GAEC guidelines, burning of wheat residues is prohibited to avoid the risk of fires and air pollution, keeping good soil organic carbon content to preserve soil fertility. GAEC were implemented via Regional Rural Development Plans (PSR) (EC Regulation No. 1782/03).

In Mediterranean area durum wheat (*Triticum durum* Desf.) cultivation is one of the main income source for farmers and Italy is one of the leader in the world with 1.2 million ha of cultivated surface and 4.2 million tons of grain production (ISTAT, 2013): Basilicata is the third region in Italy for durum wheat production. The growing season of this crop in this environment takes place during the autumn-winter period, for exploiting the rainfall of this period; no irrigation is scheduled, so moderate water stress, which is becoming more frequent because of global warming, can compromise the grain yield.

In Basilicata (Southern Italy), agricultural soils underwent continuous degradation during the last century due to the highly erodible nature of outcropping terrains and to the anthropic pressure favored by the introduction of Common Agricultural Policy (CAP) measures, which, especially in the last 30 years, has led to the reclamation of scrub lands and badlands for durum wheat cultivation (Capolongo et al., 2008). This practice of reclamation, known as 'remodelling', increases soil erosion, implying an enlargement of the surface area exposed to physical phenomena of erosion. An appropriate soil tillage and residues management could help to significantly reduce soil erosion.

With rising awareness of problems related to degradation of land and decreased production, efforts have been undertaken recently in Southern Italy to experience alternative crop management in order to replace the resource-depleting tillage and preserve the soil fertility. Conservation agriculture (*CA*), is seen as a promising way to address the issue facing three main issues: no tillage or zero tillage, crop residue management to preserve the soil organic matter as long as possible in the field, and crop diversification/rotation (Hobbs et al., 2008).

One key point of *CA* is the increment in plant available water of soil by increasing soil water infiltration, reduce runoff (Scopel et al., 2005; Thierfelder et al., 2005) and soil evaporation (Bescansa et al., 2006). Water scarcity, land degradation and soil erosion are issues that occur frequently in the semi-arid areas of Mediterranean countries; investigations are needed to assess the mitigation effects of *CA* in these areas.

The boosting on yield and soil fertility of *CA* is a "long-term" property and, therefore, studies that require long time must take in place for highlighting these effects. In addition, results obtained in a site could not be confirmed under different pedo-climatic conditions that can be encountered in other cultivation areas.

To overcome these issues the crop simulation models are tools that after the proper calibration and validation process can provide quick and reliable answers with low cost, even if with an approximation which must be previously put into account.

Crop growth simulation models have been widely used to simulate long-term responses of crops to different pedo-climatic conditions and crop management. A multitude of crop software models have been developed for wheat, as reported in the study of Asseng et al. (2013) for which were experienced 27 wheat crop growth models, with the most widely used DSSAT (Decision Support System for Agrotechnology Transfer), APSIM (Agricultural Production Systems Simulator), EPIC (Environmental Policy Integrated Climate model), STICS (Simulateur Multidisciplinaire pour les Cultures Standard) and CropSyst (Cropping Systems Simulation Model) to simulate the wheat response under different management and locations.

Simulation studies were performed also to investigate long-term dynamic of soil organic carbon in Mediterranean areas: Gabrielle et al. (2002) compared the response of four crop models on soil carbon dynamics, other studies were carried out to compare conventional and conservative soil management for several crop rotations (Lugato et al., 2006); other investigations were finalized to assess the consequences of residue removal on soil organic carbon content (Saffih-Hdadia and Mary, 2008; Alvaro-Fuentes et al., 2009).

CropSyst model (Stöckle et al., 2003) has been applied on wheat in several environments, as Washington (USA) in response to different fallow and tillage management practices (including no-till; Pannkuk et al., 1998), Central Anatolia Plateau Turkey, (Benli et al., 2007), northwest Uzbekistan (Djumaniyazova et al., 2010) and northern Syria (Pala et al., 1996). Simulations with CropSyst took place for a wide range of purposes, such as: to estimate drainage and nitrogen leaching resulting from different soil-weather-management scenarios in Po Valley, Italy (Donatelli et al., 1999; Meinke et al., 2001); to develop a decision support system for nitrogen fertilization strategies (Ferrer-Alegre and Stockle, 1999); to evaluate the amount and dynamics of nitrate leaching from a typical irrigated potato-/winter wheat-/maize rotation in this area (Peralta and Stockle, 2001). Long-term simulations with CropSyst were carried out to explore the performance of several cropping systems with different input levels (Donatelli et al., 1997; Morari et al., 2000; Garofalo et al., 2009).

The most part of the simulation studies on long term simulation of soil organic carbon (*SOC*) have been focused in UK (Falloon et al., 2006), China (Guo et al., 2007) Australian (Skjemstad et al., 2004), France (Gabrielle et al., 2002) and African (Badini et al., 2007) pedo-climatic conditions, but scarce works are reported in Mediterranean environment as Southern Italy. In this area of Italy, CropSyst was previously calibrated and validated to simulate a wheat-faba bean rotation (Garofalo et al., 2009) and in view of this, this software was chosen as reference crop model in our study.

In this study, CropSyst was used with the aim of simulating durum wheat response to different straw and soil management, under the pedo-climatic conditions of Basilicata, in order to analyze the long-term effects on crop productivity and soil carbon stock dynamics.

2. Materials and methods

2.1. Locations

The study area is located in two provinces of "Basilicata" region (Southern Italy; 9992 km^2), Potenza and Matera (Fig. 1) in a predominantly mountainous area. The area consists of mountains (areas above 700 m a.s.l.) and hills (areas between 201 and 700 m a.s.l.) by 47% and 45% respectively, whereas the remaining area is flat surface.

Vegetation is strongly influenced by climatic conditions of the zone which can be divided in two parts. The Western part, along the strip of the Apennines, is characterized by soils plenty covered with vegetation, with many woods and fields cultivated with vineyards and olive groves. The Eastern part of the region, instead, is characterized by bare and arid soils where durum wheat is the predominant cultivated crop in the flat and hilly areas (Fig. 1). Lavello, Matera, Potenza, Val d'Agri, Vulture and medium basin of Agri-Sauro rivers were the inspected areas for this study.

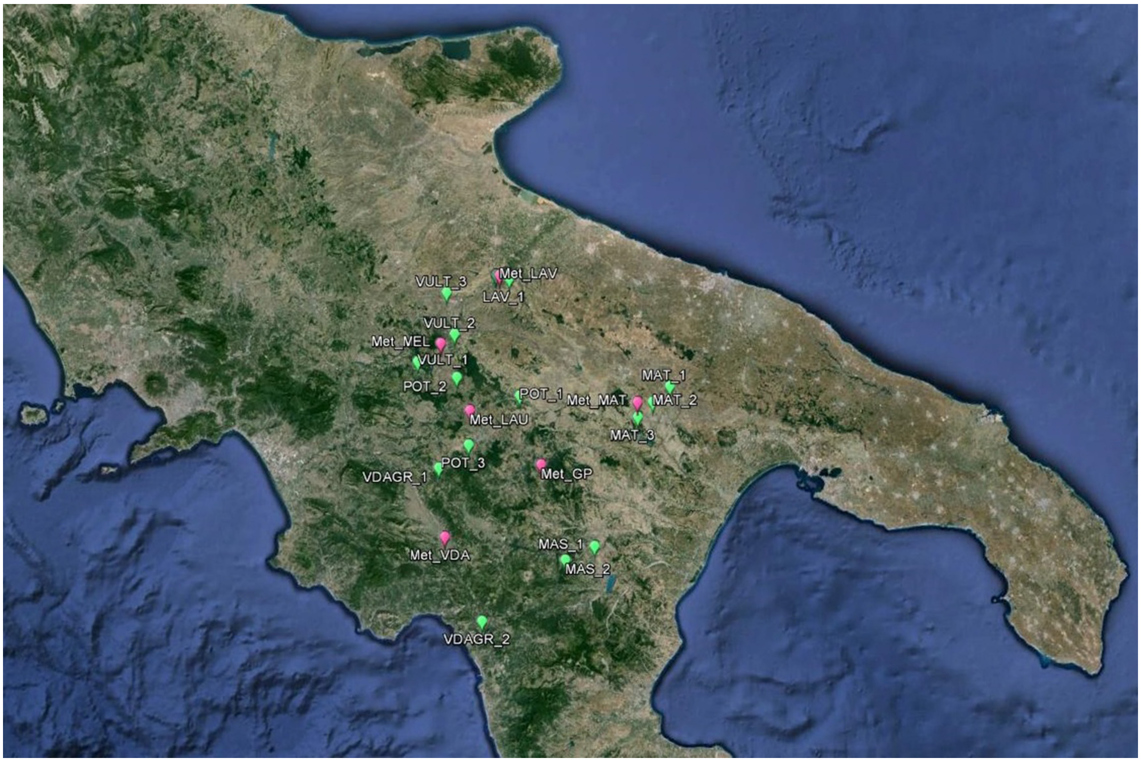

Fig. 1. Map of soils (green bookmarks) and meteorological stations (purple bookmarks) location, used in this modelling activity. Refer to Tables 1 and 2 for codification. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Climatic, soil and management data

Climatic data derived from a network of 38 agro-meteorological stations distributed within the region and managed by ALSIA (Agenzia Lucana di Sviluppo ed Innovazione in Agricoltura – Agriculture Development and Innovation Agency of Lucania) equipped with instruments for automatic and continuous measurements of the main meteorological parameters. Air temperature is measured by PT100 thermo-resistances with a precision of ±0.1 °C. Solar radiation is measured through a pyranometer working in the range 0.3–3 μm with an accuracy of ±2%. Six of these stations provided for the input of the model, as daily air temperature (minimum and maximum), global solar radiation, wind speed and precipitation. The list of the agro-meteorological stations used for the simulations is reported in Table 1 with some of the main climatic long term values.

Physical and chemical characteristics of the 15 soils used in this simulation resulted from the "Carta pedologica della Regione Basilicata" (2006) with the main information reported in Table 2.

2.3. CropSyst model

CropSyst (Cropping Systems Simulation Model) is a multi-year, multi-crop, daily time-step crop growth simulation model, designed to serve as an analytical tool to study the effect of cropping system management on crop productivity and on the environment (Stöckle et al., 2003). Simulates the soil-water budget, soil-plant nitrogen budget, canopy cover and root growth, crop phenology, biomass production, crop yield, residue production and decomposition, soil organic matter and soil carbon stock, and soil erosion according to soil characteristics, crop characteristics, and cropping system management, including crop rotation, irrigation and nitrogen scheduling, tillage operations and residue management.

The model can be considered a generic crop simulator, simulating different crops from a common set of parameters. Daily potential crop growth is a function of solar radiation and water transpiration. The duration of the phenological phase is calculated as the sum of heat units, modulated where necessary by photoperiod and vernalisation requirements; the accumulation of thermal

Table 1
Climatic main yearly data of the 6 meteorological stations used in this simulation application.

Location	Meteorological stations	Altitude (m)	Air temperature		Solar Radiation (MJ m^{-2} d^{-1})	Cumulative Rainfall	
	Abbr.		Minimum (°C)	Maximum (°C)		Jan-Dec (mm)	Nov-May (mm)
Gaudiano/Lavello (PZ)	LAV	144	10.0	22.1	14.2	568.2	382.4
Melfi (PZ)	MEL	560	8.8	20.8	11.7	844.4	580.4
Guardia Perticara (PZ)	GP	553	9.4	20.1	11.6	674.4	479.6
Villa D'Agri (PZ)	VDA	598	5.7	20.3	12.9	869.2	622.6
Laurenzana (PZ)	LAU	917	6.5	16.5	12.1	729.0	560.8
Matera	MAT	401	9.4	22.2	12.5	597.2	397.2

PZ = sites located in province of Potenza.

Table 2
Soil characteristics per layer of each soil used in the simulation.

Soil	Location	Layer depth (cm)	Sand (%)	Silt (%)	Clay (%)	Wilting Point ($m^3\ m^{-3}$)	Field Capacity ($m^3\ m^{-3}$)	Bulk Density ($kg\ dm^{-3}$)	Weather Station
LAV_1	Iacovone	15	61.1	10	28.9	0.090	0.203	1.549	Gaudiano/Lavello
		22	45	32	23	0.180	0.296	1.348	
		21	56	16	28	0.112	0.226	1.471	
		40	62	13	25	0.101	0.209	1.513	
		88	92	6	2	0.062	0.134	1.684	
LAV_2	Vaccareccia	45	37	19	44	0.121	0.266	1.409	
		25	35	20	45	0.124	0.271	1.398	
		35	34	26	40	0.149	0.292	1.357	
		40	43	18	39	0.118	0.253	1.428	
MAS_1	Aliano	35	26.2	19.7	24.1	0.127	0.236	1.44	Guardia Perticara
		35	53.8	20.2	26	0.129	0.241	1.432	
		65	28.1	18.3	23.6	0.122	0.229	1.455	
MAS_2	Vaccuta	30	62	16	22	0.113	0.217	1.482	
		15	60	17	23	0.117	0.223	1.469	
		75	54	29	17	0.167	0.270	1.379	
MAT_1	Candida	45	52.4	22.6	25	0.139	0.251	1.413	Matera
		20	51.7	28.7	19.6	0.165	0.273	1.377	
		30	58.3	23	18.7	0.142	0.244	1.422	
		45	71.7	12	16.3	0.097	0.191	1.543	
MAT_2	Cipolla	30	12	38.7	49.3	0.217	0.385	1.256	
		45	11.2	44.8	44	0.256	0.418	1.233	
		45	3.7	51.7	44.6	0.304	0.462	1.198	
		37	4	53	43	0.313	0.469	1.195	
MAT_3	Timmari	22	62	24	14	0.147	0.242	1.423	
		48	66	20	14	0.130	0.224	1.457	
		23	85	6	9	0.065	0.146	1.670	
		47	90	5	5	0.058	0.132	1.707	
POT_1	Biscione	35	72.5	16.9	10.6	0.118	0.206	1.494	Laurenzana
		45	76.3	15	8.7	0.110	0.194	1.519	
		20	81.2	10.4	8.4	0.088	0.171	1.582	
		33	81.5	12.4	6.1	0.098	0.178	1.557	
POT_2	Caruso	45	25.7	49.7	24.6	0.281	0.416	1.246	
		20	21.9	45.7	32.4	0.259	0.405	1.251	
		30	17	56.1	26.9	0.327	0.467	1.211	
		45	19.8	57.2	23	0.332	0.466	1.214	
POT_3	La Pantanella	20	58	16	26	0.113	0.223	1.474	
		25	24	26	50	0.147	0.309	1.338	
		25	20	32	48	0.177	0.340	1.3	
		20	14	43	43	0.244	0.405	1.245	
VDAGR_1	Santoro	20	16	50	34	0.289	0.438	1.226	Villa D'Agri
		45	22	46	32	0.261	0.406	1.250	
		30	5	38	57	0.213	0.387	1.246	
		40	47	30	23	0.171	0.285	1.361	
VDAGR_2	Servino	50	21	29	50	0.162	0.325	1.316	
		22	48	19	33	0.123	0.247	1.430	
		40	78	8	14	0.078	0.167	1.615	
		85	94	5	1	0.056	0.125	1.714	
VULT_1	Arca Monaci	40	22.2	39.6	38.2	0.221	0.373	1.273	Melfi
		15	36.3	30.3	33.4	0.170	0.305	1.339	
		25	50.3	22.2	27.5	0.136	0.253	1.412	
		70	60.3	14.9	24.8	0.108	0.216	1.489	
VULT_2	Piano Duca	20	71	13	16	0.101	0.195	1.530	
		40	72	16	12	0.114	0.203	1.501	
VULT_3	Montelungo	45	20	44	36	0.249	0.40	1.253	
		30	19	50	31	0.287	0.432	1.232	
		50	25	43	32	0.241	0.385	1.266	
		25	32	24	44	0.140	0.289	1.365	

time may be accelerated by water stress. Crop yield production is calculated according to the harvest index (affected by water and nitrogen stress) and the translocation factor.

The water balance includes rainfall, irrigation, runoff, interception, infiltration, redistribution in the soil profile, crop transpiration and soil evaporation. Water dynamic in the soil is modelled by a simple cascading approach or by Richards' equation, the latter solved numerically using the finite difference technique.

Residue decomposition is based on Bristow et al. (1986) and Stroo et al. (1989) reports and rate decomposition is affected by soil tillage management, soil moisture, temperature and residue carbon-nitrogen ratio (C/N).

The modelling of C/N includes the description of decay and mineralization of organic residues incorporated into soil layers and dead roots. Decomposition and mineralization of organic residue resembles the approach proposed by Verbene et al. (1990), where residues are divided in three fractions with different decomposition rates. The pools included in the model are crop residues and roots Microbial Biomass (*MB*), Labile Active (*LA*), soil organic matter (*SOM*), Metastable Active (*MA*) *SOM* and Passive (*P*) *SOM*. A separate set of pools is defined for each soil layer.

Potential daily above-ground biomass production (*AGBpt*) is calculated as the minimum value between the approach for transpiration use efficiency (Tanner and Sinclair, 1983) and that for radiation use efficiency (Monteith, 1977).

On *AGBpt* occur water limiting conditions which magnitude is calculated as ratio between potential and actual transpiration to estimate actual above ground biomass (*AGBact*); consequently *AGBact* is corrected by a coefficient based on plant nitrogen concentration (Stöckle and Debaeke, 1997), the latter influenced by nitrogen uptake estimated as function of root nitrogen availability, maximum root nitrogen uptake and plant available water.

Decomposition of the different pools occurs according to first order kinetic with decompositions constants varying for each pool; the carbon/nitrogen ratio is fixed for each pool, excepted for the organic residue, specified by the user. Decomposition of *MB* takes into account the soil silt and clay trough specific coefficients, whereas the *MB* residue transferred to *MA* and *LA* is correlated to recently disturbed soil layers by tillage. Significant fraction of the carbon is lost as CO_2 from the decomposition of the different pools by specific constants and the rest is transferred to other pools; again, *MB* carbon loss is reliant on soil silty-clay fraction. From initial *SOM*, the model estimates the carbon allocated to each pool, by coefficients and clay fraction.

CropSyst includes net mineralization, nitrification and denitrification, simulated using first order kinetics (Stöckle and Campbell, 1989); net mineralization results in ammonium from organic matter nitrogen.

Fluxes between the carbon and nitrogen for each pool determines the nitrogen available for plants. Indeed, the carbon transferred among pools, as computed by the model, also determines the nitrogen transfer, which is equal to the amount of nitrogen required to preserve the carbon/nitrogen ratio of the receiving pools. In the carbon/nitrogen dynamics of soil, if the amount of nitrogen released by the decomposing pool is greater than the amount of nitrogen required by the receiving pools, mineral nitrogen in the form of ammonium is released to the soil layer (mineralization). If the opposite occurs, ammonium (first source) and nitrate (secondary source) from the soil layer is taken up for microbial consumption (immobilization).

Nitrification is the reverse process that transforms ammonium to nitrate. Finally, denitrification converts nitrate to gaseous

Table 3
CropSyst model crop parameters for durum wheat (cv. Simeto) and faba bean (cv. Chiaro Torre Lama); (C = Calibrated values; M = Measured values; D = Default values).

Parameter		Unit	Durum wheat	Faba Bean
Growth	Above ground biomass transpiration coefficient	kPa kg/m^3	6.5 C	8.5 C
	Unstressed light to above ground biomass	g/MJ	3.5 C	6.6 C
	Optimum mean daily temperature for growth	°C	+18 D	+20 D
Leaf	Maximum expected LAI	m^2/m^2	5 D	7 C
	Specific leaf area	m^2/kg	17 M	28 C
	Steam/Leaf partition coefficient		3.1 M	3.7 C
	Leaf duration	Degree-days	720 M	600 C
	Leaf duration sensitivity to water stress		1 M	1 D
	Fraction of max. LAI at maturity		0.8 D	0.8 D
Root	Maximum rooting depth	m	1.6 D	1.2 D
Transpiration	Extinction coefficient for solar radiation		0.48 D	0.45 D
	ET crop coefficient at full canopy		1.05 D	1.05 D
	Maximum water uptake	mm/day	10 D	9 D
	Critical leaf water potential	J/kg	−1500 C	−1000 D
	Wilting leaf water potential	J/kg	−2200 C	−1500 D
Phenology	Emergence	Degree-days	120 C	197 C
	Peak LAI	Degree-days	1400 C	1259 C
	Begin flowering	Degree-days	1500 C	854 C
	Begin filling	Degree-days	1756 C	1066 C
	Physiological maturity	Degree-days	2316 C	2183 C
	Base temperature	°C	0 D	+2 C
	Cut-off temperature	°C	+30 C	+25 D
	Unstressed harvest index		0.30 C	0.26 C
	Grain sensitivity to water and nitrogen stress			
	During flowering		0.10 D	0.05 C
	During grain filling		0.05 D	0.05 C
	Translocation to yield factor		0.30 D	0.26 D
Nitrogen	Nitrogen availability adjustment		1 D	1 D
	Amount of residual nitrogen per soil layer	kg ha^{-1}	1 D	10 C
	Max N concentration during early growth	kg N/kg DM	0.05 D	0.05 C
	Max N concentration at maturity	kg N/kg DM	0.015 D	0.07 C
	Min N concentration at maturity	kg N/kg DM	0.007 D	0.02 C
	Max N content of standing stubble	kg N/kg DM	0.007 D	0.03 C
Crop residues	Top and root carbon fraction	%	0.70 C	0.46 C
	Residue Top biomass fast cycling	%	0.1 C	0.5 D
	Residue Top biomass slow cycling	%	0.3 C	0.4 D
	Lignified biomass	%	0.6 C	0.1 D
	Residue Root biomass fast cycling	%	0.1 C	0.5 D
	Residue Root biomass slow cycling	%	0.3 C	0.3 D
	Lignified biomass	%	0.6 C	0.2 D

Table 4
Crop management scenarios simulated by CropSyst model.

Scenarios	Acronyms	Residues	Tillage
Conventional	*CV*	Burned	Plowing (35 cm) Disking (15 cm) Harrowing (5 cm)
Conventional + residues	*CVRS*	Residues incorporated with the following tillage	Plowing (35 cm) Disking (15 cm) Harrowing (5 cm)
Minimum Tillage	*MNT*	Only straw was removed	Disking (15 cm) Kongskilde vibro cultivator (8 cm)
No-Tillage	*NOT*	Only straw was removed	Direct seeding
Conservative	*CS*	All residues were chopped and left on the soil as mulch	Direct seeding
Conservative with rotation	*CSRT*	All residues were chopped and left on the soil as mulch	Direct seeding, but with a 3-year rotation "wheat-wheat-faba bean"

Table 5
Crop management scenarios implemented in CropSyst model for durum wheat.

Scenarios	Operation	Date	Amounts or depth
CV	Crop residue burning	5 days after harvest	
MNT, NOT	Crop residue removing	5 days after harvest	
All	Fertilization	21st October	60 kg ha^{-1} of N (Ammonium nitrate)
CV, CVRS	Ploughing	1st August	35 cm
CV, CVRS, MNT	Disking	1st September	15 cm
CV, CVRS, MNT	Harrowing	22nd October	5 cm
MNT	Kongskilde vibro cultivator	22nd October	8 cm
All	Sowing	1st November	350 seeds m^{-2}
All	Fertilization	1st March	60 kg ha^{-1} of N (Urea)
All	Harvest	2136 GDD (end of June)	

For scenarios abbreviations, see Table 4.

nitrogen, lost in the atmosphere. These processes are temperature and soil temperature dependent and estimated following the methodology reported by Sharpley and Williams (1990).

Previous model calibration and validation phases on durum wheat and faba bean provided for the phenological and physiological input of the crop files (Garofalo et al., 2009; Garofalo and Rinaldi, 2013). The crop parameters used are reported in Table 3 and referred to Simeto cultivar.

Water movement in the soil was simulated with the cascade approach and water infiltration/surface water runoff with the USDA curve number model. Penman–Monteith method (Allen et al., 1998) was chosen for estimating the reference crop evapotranspiration.

Multiple organic matter pools (microbial, labile, metastabile, passive) and residue with carbon decomposition was the model option set to assess the nitrogen and carbon soil dynamics.

2.4. Crop model simulations

The input files of 15 soil profiles, 6 climatic stations data and 6 crop management have been compiled before performing the simulations. The model has been run from 2001 to 2013 and one crop per year was considered in these simulations, with a total of 1170 yearly output (15 soil profiles x 6 crop management × 13 years).

The different crop management implemented in the input files are reported and described in Table 4 and Table 5: Conventional, Conventional + residues, Minimum Tillage, No-Tillage, Conservative and Conservative with a 3-year rotation with faba bean.

Initial field condition (water and nitrogen content in the soil layers), planting depth and date, plant population, fertilizer application, soil tillage, harvest schedule, soil characteristics were collected and then set as input for the simulations.

The harvest time was set when the sum of the thermal units accumulated by the plant and computed by Growing Degree Days (GDD; °C days) reached the physiological maturity. For winter durum wheat GDD were set to 2316 °C days or the average values necessary for the physiological maturity of seeds as observed in field trials (Garofalo et al., 2009) close to the examined area.

Aboveground plant dry matter yield, grain yield, percolated water, actual evapotranspiration, soil organic carbon content in the 0–100 cm soil depth, were the model output taken into account to compare the different soil and straw management.

Statistical analysis was performed with GLM procedure of SAS/STAT package with a model of Area, and "Area × Management" interaction. The homogeneity of variance was checked by means of the Levene test, whereas the Shapiro-Wilk test analysis was applied to verify assumptions about the normality of the data. Soils and Years have been considered as replications. Upon corroborating the lack of both the homogeneity and the normality of the data, the Wilkoxon test was applied for the mean separation of main effects, using the test at 0.05 probability level.

3. Results

Comparing the output of the six analyzed areas (Table 6), the highest yield was simulated for Lavello site, the lowest for Potenza site (−1143 kg ha^{-1}). Comparable performances were observed for the remaining sites with an average yield of 3137 kg ha^{-1}. Same path was recorded for the total dry biomass with values oscillating from 10,073 to 6992 kg ha^{-1} passing from the best to the worst scenario. Can be argued that higher water consumption resulted in higher grain yield, whereas reduced water use caused slight yield loss (see correlation in Fig. 2a); alike, was observed a fair matching between nitrogen uptake and grain yield (Fig. 2b).

Table 6
Average values of durum wheat grain and biomass yield, percolated and used water and crop nitrogen uptaken (13 years) simulated by CropSyst model in the 6 main cereal areas of Basilicata region. Different letters indicate significant differences (Wilkoxon test, $P < 0.05$). In parentheses, the coefficient of variation (%).

Location area	Grain yield (kg ha^{-1})	Above ground biomass (kg ha^{-1})	Percolated water (mm)	ET actual[a] (mm)	Nitrogen uptake (kg ha^{-1})
Lavello	3769 (33.5) A	10073 (31.4) A	87 (67.5) C	280 (15.4) C	121 (41.9) A
Matera	3271 (33.9) B	8773 (35.2) B	75 (54) C	277 (19.3) C	129 (50.1) A
Val D'Agri	3168 (39.8) BC	8406 (40) B	219 (54.1) A	355 (17.5) A	96 (54.2) B
Vulture	3162 (33.4) BC	8532 (33.8) B	138 (63.2) B	313 (15.8) B	104 (44.3) B
Medio Agri-Sauro	2947 (26.1) C	8167 (24.6) B	131 (80) B	283 (17.6) C	100 (33.8) B
Potenza	2653 (34.4) D	6992 (36.4) C	230 (47.6) A	312 (17.2) B	79 (52.1) C

The averages presented in this table include all the simulations for all the different scenarios.
[a] ET = evapotranspiration.

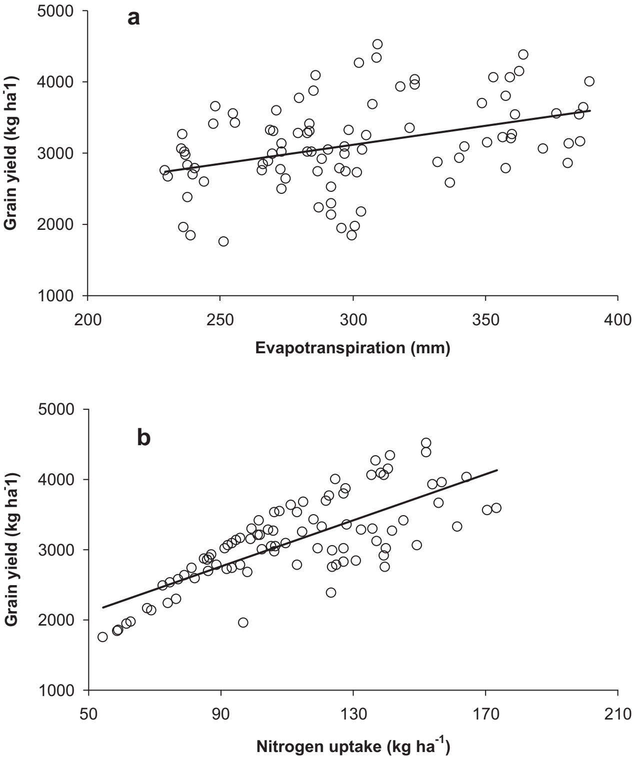

Fig. 2. Correlation between grain yield, evapotranspiration (a) and nitrogen uptake (b). Points represent the simulation outputs for the different soils and straw management as averaged values for the growing seasons (2001–2013).

However, it must be pointed out that sites characterized by higher elevation and amount of rainfall (i.e. Vulture and Potenza) showed worse crop performances compared to other sites; this was due to the higher N leaching of these areas that reduced the amount of soil nitrogen availability and uptake by plants.

Basically, the most productive sites are located in flat areas (Lavello, Northern Basilicata) and low hill (Eastern Basilicata) areas, while as elevation raised the yield decreased (central-west area of region).

Conventional and minimum tillage provided for the highest wheat productivity if compared with the other soil practices (9220 and 3421 kg ha^{-1} for the total dry biomass and grain yield respectively; Table 7). No tillage guaranteed crop performance slightly lower compared to the most productive management (*CV*), with a reduction of 5% for both biomass and grain yield.

On the other side, conventional tillage with residue left on the field, as well as conservative soil practice decreased the yield and the total dry biomass of 21% compared to conventional tillage scenario.

This is due to immobilization of nitrogen in the soil following the incorporation of straw; in this condition (especially at beginning of straw management diversification, before reaching the equilibrium) microbial population needs to take the nitrogen readily available for its activity, subtracting the mineral nitrogen supplied with fertilization to the crop. Therefore, to re-establish the yield level simulated for the scenarios involving straw removal from soil it would be required an extra amount of mineral at least in the short-term (Jeffrey et al., 2001) when the straw are retained on the soil.

However, legume crop (faba bean) in rotation with durum wheat (*CSRT*) guaranteed a higher nitrogen availability (due to nitrogen fixation, as simulated by the model) and uptake by wheat compared to *CS* (92 vs 86 kg ha^{-1}) with a small yield improvement in terms of grain yield (+161 kg ha^{-1}).

Another interesting aspect that emerged from simulations was the water lost by deep percolation (Table 7). Indeed the sum of crop water consumption and percolation was comparable among treatments; significant differences could be found out for the percentage of water lost by percolation on total water consumed (percolation plus evapotranspiration), that in the case of straw left on the soil (conservative or conventional tillage) was equal to 42% far above to the others practices (29% as mean). This is explained by the increased water infiltration and reduced evaporation

Table 7
Average values of durum wheat grain and biomass yield, percolated and used water and crop nitrogen uptaken (13 years) simulated by CropSyst model in the six crop management scenarios. Different letters indicate significant differences (Wilkoxon test, $P < 0.05$). In parenthesis, the coefficient of variation (%).

Scenario	Grain yield (kg ha^{-1})	Aboveground biomass (kg ha^{-1})	Percolated water (mm)	ET actual[a] (mm)	Nitrogen uptake (kg ha^{-1})	ΔSOC[b] (t ha^{-1})
CV	3531 (18.3) A	9509 (17.0) A	127 (49.5) C	326 (11.8) A	124 (21.7) A	-1.78 E
MNT	3312 (16.9) A	8931 (15.6) A	132 (47.7) C	322 (11.7) A	113 (19.9) AB	1.12 D
NOT	3254 (19.8) A	8773 (18.5) A	140 (48.2) BC	317 (11.7) A	110 (23.1) B	1.9 D
CVRS	2913 (19.7) B	7893 (18.4) B	133 (45.9) C	322 (11.3) A	97 (23.1) C	20.6 B
CSRT	2891 (17.8) B	7807 (16.7) B	167 (35.6) AB	257 (7.7) B	92 (20) CD	17.2 C
CS	2730 (15.5) B	7371 (14.7) C	188 (36.2) A	256 (7.7) B	86 (14.5) D	22.8 A

The averages presented in this table include all the simulations for all the different locations.
[a] ET = evapotranspiration.
[b] ΔSOC = Differences in soil organic carbon content in the 0–0 cm soil depth, from the start to end of simulation period (2001–2013). For scenarios abbreviations, see Table 4.

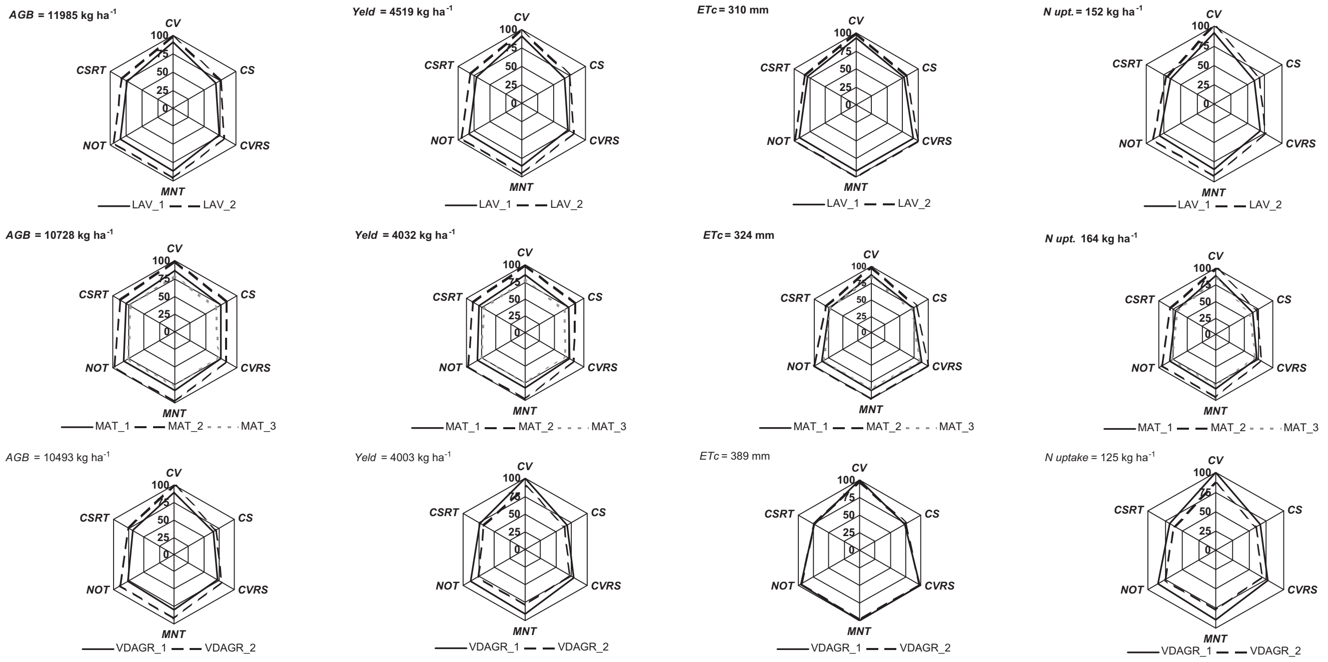

Fig. 3. Difference expressed in term of percentage with respect to the maximum value simulated for the main crop characteristics at Lavello (LAV), Matera (Mat) and Val D'Agri (VDAGR) sites, as resulting from the different management scenarios. The value reported for each figure represents the best simulated output.

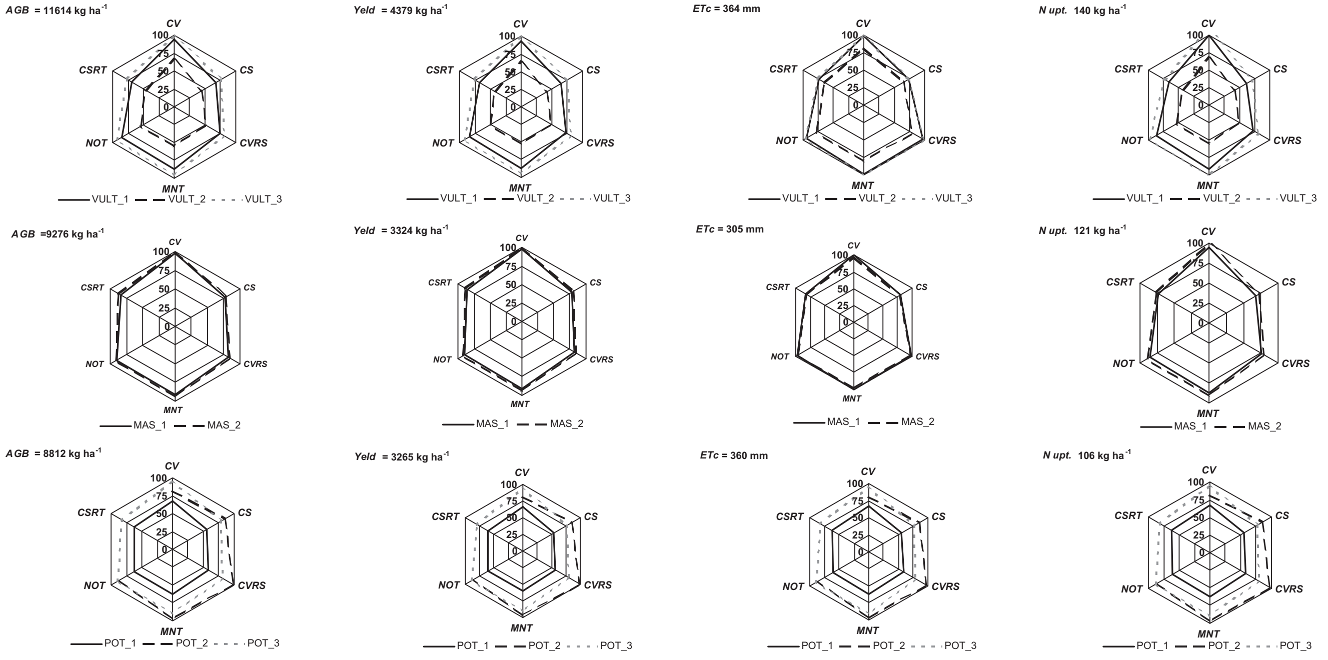

Fig. 4. Difference expressed in term of percentage with respect to the maximum value simulated for the main crop characteristics at Vulture (VULT), Medio Agri Sauro (MAS) and Potenza (POT) sites, as resulting from the different management scenarios. The value reported for each figure represents the best simulated output.

consequent to the straw retention on the soil, as measured by Rinaldi et al. (2000). The impact of straw left on the soil on deep percolation is remarkable in hilly areas contributing to reduce erosion phenomena that frequently occur in Basilicata.

Evapotranspiration, nitrogen uptake by plants and growth were the consequence of several factors (other than rainfall and nitrogen supply) such as soil texture, temperature and solar radiation. Interactions among anthropogenic (soil tillage and straw management) and endogenous factors (climatic conditions and soil characteristics) are remarked in Figs. 3 and 4. Although different sites shared the same climatic dataset, the different soils-treatments-weather assets provided outputs that largely varied. These divergences were less accentuated for the central-southern Basilicata, for which the differences in term of grain yield ranged from a minimum of 2% in Medio Agri Sauro area to a maximum of 16% in Val D'Agri area. Vice versa, other areas such as Vulture, Potenza and Lavello showed differences in term of grain yield up to 40% when comparing the different soil sites. This trend followed the variation in soil texture, the more they were pronounced, the higher the yield disagreement among sites was observed (Fig. 4).

SOC (0–30 cm depth) was more related to the straw management rather than the soil practices. Indeed, simulation outputs indicated that straw removed from the soil coupled with minimum or no tillage, resulted in a fairly good carbon stock enrichment (86 and 143 kg ha^{-1} y^{-1} for *MNT* and *NOT*, respectively). Vice versa, straw retention accounted for *CVRS*, *CS* and *CSRT* led to remarkable and comparable accumulation of *SOC* (despite different soil tillage among the different scenarios), equal to 1554 kg ha^{-1} y^{-1} as mean (Table 7).

As for the crop performances, interactions among soil type, soil and straw management, gave different response in terms of *SOC* at different sites. Analyzing the scenarios where higher improvement of *SOC* were simulated (*CVRS*, *CS* and *CSRT*), emerged as the same straw management and practices applied on soils with different characteristics but located in the same area provided for different *SOC* changing compared to the initial simulation condition. For instance, under Lavello, Medio Agri Sauro and Val D'Agri pedoclimatic conditions, *CVRS* and *CSRT* ensured the best *SOC* improvement when compared to *CS* (about +7%) whereas a mixed response was observed for the other sites under the different treatment, with the absence of an univocal path for *SOC* changing (Fig. 5).

4. Discussion

In Basilicata, the simulation outputs indicated as cropping systems characterized by wheat in monoculture caused a decrement of *SOC* storage with an average rate of 116 kg ha^{-1} y^{-1} over 13 years. This trend was slightly higher than the data reported by Monteleone et al. (2015) in Mediterranean environment under conventional tillage and straw removal. The authors indeed indicated *SOC* loss rate equal to −42 kg ha^{-1} y^{-1} after 20 years, emphasizing as this rate was higher in the first 10 years, but decreased over time, as the new equilibrium value was progressively approached.

The purpose of changing tillage and straw practices is to preserve/increase the *SOC* stock keeping grain yield comparable to the conventional tillage. CropSyst outputs showed that in soils with low initial organic matter content (1.1% as mean for the analyzed sites), reduced soil input systems (*NOT* and *MNT*) were capable to slightly increase *SOC* after 13 years. Indeed, comparing the difference between the starting time and the end of simulations the improvement in terms of soil carbon organic content was +4.2% for *MNT* and +7.0% for *NOT*, respectively.

Simulations performed by other authors (Alvaro-Fuentes et al., 2009) with Century model, showed that soil carbon content increased when tillage intensity decreased; the variation of *SOC* content after 16 years was +462.5 kg ha^{-1} y^{-1} for no-tillage practice in the 0–30 cm soil depth with a starting value of SOC of about 32,000 kg ha^{-1}.

In field experiments, *SOC* loss in conventional practice with straw removal was due to the high energy input that disrupted the soil aggregates, generating a soil aeration and microbial degradation of the former physically protected SOM by oxidative processes (Madejón et al., 2009; Laudicina et al., 2011). Franko and Spiegel, 2016 indicated the reduced turnover activity with depth in top soil, the main reason for the increased *SOM* storage under minimum tillage. Again, *NOT* and *MNT* induced improvement of soil aggregates size (McVay et al., 2006) and stability to wind erosion (Singh and Malhi, 2006), especially in poorer structured soils (Alvarez and Steinbach, 2009). In the light of that, there was an agreement between *SOC* changing among different soils and the literature evidences; as aforementioned in the model description, CropSyst takes into account the fraction of non-protected soil volume, which is zero or low for consolidated and undisturbed soil layers, and higher for layers recently disturbed by tillage. This, together with the constant of degradation of soil organic matter and the soil silty and clayey fractions, determines the amount of carbon transferred among microbial pools.

However, CropSyst outputs indicated as the straw left or incorporated in the soil led to dramatic enhancement in term of soil carbon stock in the first 0–30 cm depth. Many studies proved that straw incorporation resulted in a significantly more *SOC* concentration and storage than straw removal (Campbell et al., 1998; Malhi et al., 2011). Zhang et al. (2015), in an experimental trial, found out that incorporation of maize residues at a rate of 4.5 t ha^{-1} y^{-1}, led to an increase in *SOC* equal to 34 t ha^{-1} after 4 year, compared to stover removal. Our simulation study confirmed that straw

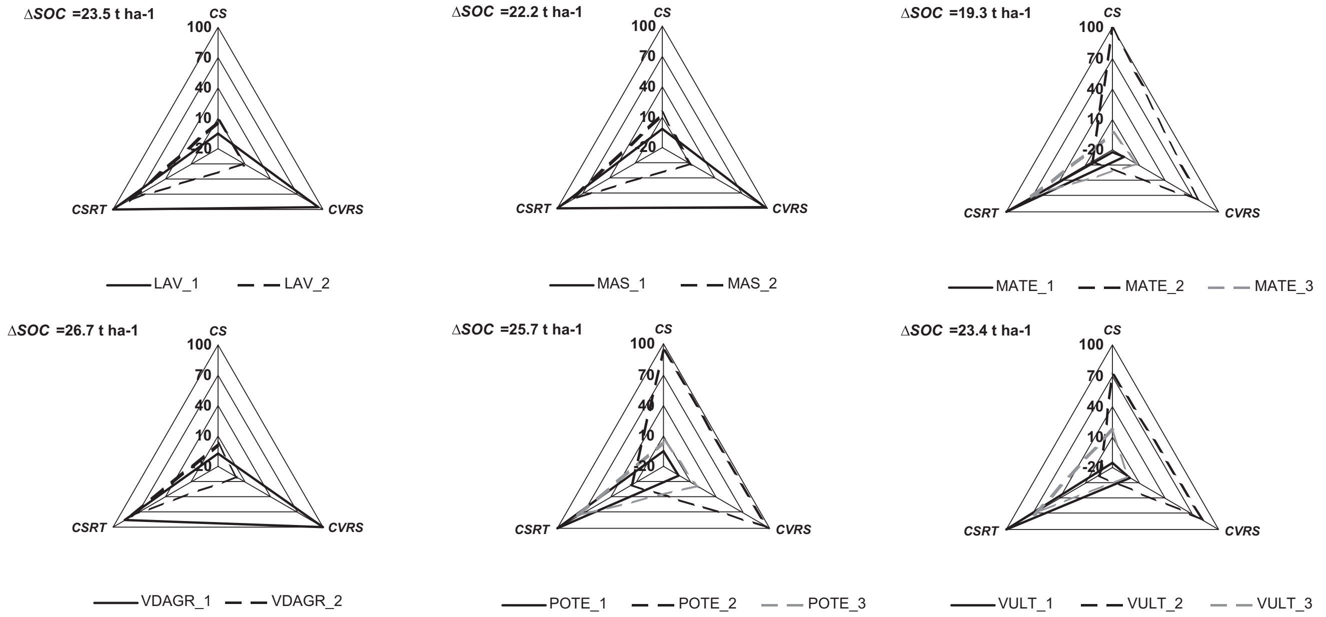

Fig. 5. Difference expressed in term of percentage with respect to the maximum value simulated for ΔSOC at different sites, as resulting from the different s. The value reported for each figure represents the best simulated output.

retention was capable to reduce or compensate the loss of *SOC* in continuous traditional tillage with straw removal, in line with the indication of Dolan et al. (2006). The enrichment of *SOC* with straw retention in experimental trials was due to the improvement of the soil physico-chemical properties that have been degraded by traditional tillage (Blanco-Canqui and Lal, 2007). As aforementioned in Section 2.3, CropSyst estimated the increased *SOC* trough the residue carbon/nitrogen ratio of residue. Indeed, computing of the portion of residue loss by decomposition is inversely correlated to a function depending by the carbon/nitrogen ratio of soil layer and residues and for the latter, the biomass subject to fast, medium and slow cycling (Table 3). In the model, C/N values of the different layer pools are kept constant whereas that for the organic matter added with residue was directly proportional to the carbon content of straw (see Table 3) but inversely correlated to the N content. This meant that the introduction of wheat straw led to an increment of carbon with respect to nitrogen for the different pools and consequently ammonium and nitrate supplied with mineral fertilization were taken away from microbial activity to keep their C/N value constant.

If soil nitrogen content was not enough to satisfy the microbial demand, decomposition of residues resulted reduced proportionally to the amount of nitrogen not available to meet the microbial demand (immobilization). This explained the improvement in terms of soil carbon stock simulated by the model when straw was left in the soil, indicating that immobilization prevailed over the mineralization process; as reported by Shaffer et al. (2001), at higher carbon/nitrogen ratio of crop residue corresponds slower mineralization cycle of the organic matter.

This led us to discuss about crop productivity. The fairly good relationship ($R^2 = 0.57$) existing between nitrogen uptake and grain yield, confirmed the lower grain yield in regime of straw left on the soil (Fig. 2b). As previously discussed, immobilization of nitrogen by microbial pools results in a lower N uptake in treatments that involved straw retention on the soil. Indeed nitrogen uptake was statistically lower in *CVRS*, *CS* and *CSRT* compared to *CV*, *NOT* and *MNT*, with grain yield proportionally decreased. Our results are consistent with data reported by Monteleone et al. (2015) in a long-term simulated effects of straw removal or left on the field in the Apulia Region (Southern Italy) and with an experimental trials carried out by Grahmann et al. (2014) in an arid site in Mexico. These authors showed as it was likely that the residue left on the field resulted in temporary N immobilization and reduced N efficiency, resulting in lower grain yield compared to residue removal. Again, Ventrella et al. (2016) in a long-term experimental trial (from 1977 to 2005) on the effect of different straw management on grain yield in a site belonging to Apulia Region, demonstrated as the residue burning in absence of supplementary mineral nitrogen supply, provided for higher grain yield compared to residue incorporation into soil. On the other hand, the authors underlined that straw incorporated into soil led to a decrement in terms of grain yield, as a result of immobilization process.

However other field investigations in a semiarid region of China (Zhang et al., 2015), determining the effects on maize and millet performances under straw removal and incorporation into the soil, found out an increasing grain production as the amount of straw incorporated into soil increased.

These contrasting results can be explained by the different amount of nitrogen and soil organic matter at beginning of the changed straw management. In degraded lands of Basilicata, the initial soil organic matter content (value at the beginning of simulations) was not enough to meet the increased nitrogen demand by the microbial pools after straw retained on the soil at least in the short-time of transition. As aforementioned, this led to subtraction of mineral nitrogen supplied with fertilizer by the different pools, triggering the immobilization process, resulting in lower grain yield due to the lower nitrogen availability for the plants.

However, should be underlined the slight but positive effect on increased soil nitrogen availability (and uptake) for plants under wheat-faba bean rotation, thanks to nitrogen fixation of the legume crop in rotation with durum wheat (Table 6).

5. Conclusions

In this simulation study, effects of different soil and straw management on soil organic stock and wheat productivity in wheat cropping systems of Southern Italy (Basilicata region) were assessed. CropSyst model indicated an improvement in *SOC* under reduced and no tillage treatments, but the highest soil carbon stock enrichment was achieved when the straw was left on the soil. Anyway, the increment in *SOC* did not lead to an improvement in grain yield. Conventional tillage coupled with residue burning, was the best choice for maximizing the crop productivity; reduced input management ensured yield statistically comparable with *CV*, albeit with straw removal. Immobilization process, due to the high carbon/nitrogen ratio of straw determined reduced nitrogen uptake by plants, which implied a yield reduction of 18%, when comparing straw left on the soil versus straw removal. This would require a supplementary amount of mineral nitrogen fertilizer at least in the short-middle term of transition (from straw removal to straw retention) to obtain comparable grain yield.

However, from an environmental and sustainable perspective of alternative wheat cropping systems, the benefit from enhanced *SOC* from straw left on the soil can be considered double. Indeed, straw left on the soil means carbon sequestration by plant from atmosphere and stored into soil, other than positive effects on soil aggregates, structure and water infiltration to prevent erosion process typical in hilly and degraded areas of Basilicata. Moreover, direct seeding as managed for *CS* requires less energy expenditure, or lubricants and fuel consumption with further reduction of direct (combustion) and indirect (manufacturing) greenhouse gas emissions into atmosphere.

Other studies should be performed to extend the period of simulation for assessing the effect of improved soil organic matter on crop productivity in the long term, even in reduced input (energy and fertilizer) systems.

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