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How to enhance crop production and nitrogen fluxes? A result-oriented scheme to evaluate best agri-environmental measures in Veneto Region, Italy

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Abstract

The cost-effectiveness of adopting agri-environmental measures (AEMs) in Europe, which combine agricultural productions with reduced N losses, is debated due to poorly targeted site-specific funding that is allocated regardless of local variability. An integrated DAYCENT model-GIS platform was developed combining pedo-climatic and agricultural systems information. The aim was to evaluate best strategies to improve N fluxes of agro-ecosystems within a perspective of sustainable intensification. Indicators of agronomic efficiency and environmental quality were considered. The results showed that agronomic benefits were observed with a continuous soil cover (conservation agriculture and cover crops), which enhanced nitrogen use efficiency (+17%) and crop yields (+34%), although in some cases these might be overestimated due to modelling limitations. An overall environmental improvement was found with continuous soil cover and long-term change from mineral to organic inputs ($N_{Leach} < 10$ kg ha^{-1} a^{-1}, N-N_2O emissions < 1 kg ha^{-1} a^{-1}, soil C stock > 45 Mg ha^{-1}), which were effective in the sandy soils of western and eastern Veneto with low SOM, improving the soil-water balance and nutrients availability over time. Results suggest that AEM subsidies should be allocated at a site-specific level that includes pedo-climatic variability, following a result-oriented approach.

Keywords: Decision support system; modelling; SOC; nitrate; nitrous oxide

Introduction

Nitrogen (N) fluxes have changed greatly over the last four decades as a consequence of major artificial N inputs in agriculture to counter the yield-limiting factors of agro-ecosystems (Conant et al. 2013). At the same time, N-related atmospheric (increased N_2O emissions) and water (increased N leaching into surface and groundwater bodies) pollution has worsened. In this context, it is debated how to maximise biomass production and mitigate N losses, highlighting that the future challenge of sustainable intensification (Garbach et al. 2017) is still uncertain. The adoption of sustainable agricultural systems, in an attempt to combine competitive production with reduced N losses, is sustained by EU policy, especially through subsidies for agri-environmental measures (AEMs), which are specific land management practices included in the Rural Development Programme (RDP) (COM 2008). However, the cost-effectiveness of AEMs is questioned (Primdahl et al. 2010) because it is based on a "management-oriented" scheme where farmers are paid just for the adoption of AEMs, while the environmental benefits are not quantified (Uthes & Matzdorf 2013).

Several studies have proposed a "result-oriented" scheme (Burton & Schwarz 2013) to quantify outcomes of the adopted AEMs, supporting any specific measure with a scientifically-based evaluation. For instance, Ekholm et al. (2007) compiled relevant monitoring data to quantify the benefits of several AEMs (e.g., balanced use of manure, introduction of riparian zones, plant cover in winter and reduced tillage) adopted in Finland to reduce N leaching into surface water bodies. The authors found no consistent and systematic decrease in nutrients losses from agricultural catchments, attributing the AEMs ineffectiveness to poorly spatial-targeted adoption. Dal Ferro et al. (2016) quantified the environmental benefits of adopting AEMs in north-eastern Italy by using multiple indicators, underlying the site-specific effectiveness of AEMs as a result of both pedo-climatic variability and different environmental parameters that were used for evaluation. Nevertheless, these studies only evaluated the environmental impacts, omitting any agronomic outcome (e.g., crop yield requirements). As an example, environmental benefits of AEMs practices such as conservation and organic agriculture can be associated with reduced yields (Soane et al. 2012; Dal Ferro et al. 2017). This is especially important for the nitrogen cycle, N being the most important yield-limiting factor in agricultural systems as well as extremely reactive in the environment. Although it is possible to combine a minimisation of environmental N losses with a concurrent modest reduction in crop yields (Heumann et al. 2013), the mutual evaluation of agronomic and environmental aspects at landscape scale has not yet been studied in a comprehensive way (Uthes & Matzdorf 2013).

Veneto, a region of north-eastern Italy, is affected by high anthropogenic pressures due to increasing conflicts over natural resources. Highly intensive and productive agriculture on the floodplain coexists with one of the most densely populated and industrialised areas in Italy (about 355 inhabitants per km^2), leading to important environmental issues (e.g., water and air pollution, land take and decrease of soil fertility). Therefore, within the context of the RDP 2007-2013, the Veneto Region financed specific AEMs (about 22% of total rural development measures) to enhance water quality, protect soils from degradation and mitigate climate change. However, at site-specific level, we hypothesise that these changes in land use management have different effects on both N cycle regulation and crop production, so RDP subsidies should be allocated according to a result-oriented approach.

With the aim of evaluating their effectiveness, an integrated model-GIS platform was developed. By including both agronomic and environmental factors, we evaluated the most effective measures to improve the nitrogen cycle, enhancing N use by crops and reducing environmental pollution (water, soil and air quality) across the Veneto Region, Italy.

Material and methods

Study area

Veneto is a Region (NUTS-2) located in north-eastern Italy with a total area of about 18,400 km^2. The elevation varies from sea level in the south up to about 3200 m on the Dolomites in the north. The plain, which covers 55% of the regional area, is mainly flat and rarely exceeds 100 m above sea level. The area surrounding the Venice lagoon (1240 km^2) is even lower (around 2 m below sea level) and has been cultivated after land reclamation since the 1st century BC. Most of the low-lying plain in Veneto is covered by sandy and silty-clay deposits. According to the World Reference Base classification (WRB 2014), the main soils of the Veneto plain are Calcisols and Cambisols, characterised by medium natural fertility due to relatively low organic matter (around 15 g kg^{-1}) and cation exchange capacity from low (sandy) to high (silty-clay). Moving northwards, hilly areas (15-300 m above sea level) are composed of calcareous, skeletal (25-47%) loam and clay loam soils (Luvisols and Cambisols). Mountain areas generally comprise sandy/clay loam soils, with poorly differentiated profiles (Leptosols, sloping areas) alternating with deeper Cambisols (valleys).

Model-GIS platform

This study aimed to model the N cycle in agro-ecosystems across Veneto Region and evaluate the impacts of different agri-environmental measures that have been adopted at local scale. Different AEMs were evaluated through the implementation of a model-GIS platform, by combining geographical and alphanumeric data that affected agronomic and environmental outcomes (Figure 1). Despite being a modelling approach, this integrated system is suitable to overcome the limits of monitoring field experiments that, for economic and organisational reasons, could not be conducted with a fine resolution at regional level. A total of 1343 polygonal units covered the territory's area by integrating the following data: soil, climate, land use, digital terrain model, fertiliser input and vulnerable nitrate leaching zones.

DAYCENT agro-ecosystem model

DAYCENT is a daily time-series version of the monthly-based ecosystem model CENTURY (Parton et al. 1994). Like CENTURY, DAYCENT simulates carbon (C), nitrogen (N), phosphorus (P) and sulphur (S) cycling in natural or cultivated systems associated with SOC dynamics. The model has also increased spatial resolution of soil layers to estimate trace gas fluxes from soils (e.g., N_2O) and water dynamics in the short-term. DAYCENT has been applied to many agro-ecosystem conditions (Parton et al. 1998). Required inputs include soil profile information (e.g. ~~soil~~ depth, organic carbon content), current and historical land use and management, climatic data etc. Significant sub-models include plant growth dynamics, decomposition rate of organic materials, water and nutrient fluxes, soil water and temperature dynamics. The water balance is computed considering the inputs (rainfall and irrigation) and outputs (evaporation, transpiration, drainage and runoff). For this study, DAYCENT was run with the C-N-P sub-models. To establish a baseline of C-N-P pools and stabilise SOC content, DAYCENT was spun up for 20 years to reach equilibrium at the beginning of each simulation. Some basic assumptions were necessary: in particular, it was assumed that agricultural areas in the past were only used for maize and permanent meadow~~.~~

DAYCENT model validation

Numerical modelling with DAYCENT has been conducted extensively for N cycle (e.g., Sansoulet et al. 2014), enabling the study of areas with different pedo-climatic conditions just by using previously calibrated site-specific parameters. Nevertheless, before modelling, the robustness of DAYCENT was assessed under different pedo-climatic and agronomic conditions for both carbon (with CENTURY model) (Lugato et al. 2007) and N cycles (with

DAYCENT model) (Dal Ferro et al. 2016). Data from field experiments (Morari et al. 2012) as well as those ~~coming~~ from a lysimeter experiment (Cocco et al. 2012) were used for validation of N uptake and N losses, comparing different cropping systems (e.g., conventional, organic) and field management practices (e.g., N inputs, water table level), indicating the model's ability to predict reliable data. DAYCENT was able to explain 69% of total N leaching variability from open field and lysimeter experiments, although with a tendency to overestimate N losses. Instead, no data relating to N_2O emissions were available under field conditions, while the model predicted higher emissions (+1.1 kg $N\text{-}N_2O$ ha^{-1} a^{-1}) than those measured at the lysimeter scale. In general, the model could accurately predict reliable data according to the EF index (> 0.01) (Nash & Sutcliffe 1970). Further details on N validation have already been reported in Dal Ferro et al. (2016).

Pedo-climatic database

The soil database refers to the Veneto Region 1:250,000 soil map (Regione Veneto 2005). Seventeen polygonal soil units across Veneto were linked to an alphanumeric database containing information on physico-chemical characteristics (e.g., depth, bulk density, gravel content, organic matter, pH etc.) through the soil profiles (Table 1). The database did not include hydraulic parameters that are required by DAYCENT, in particular the soil water content at -33 kPa and -1500 kPa, as well as saturated hydraulic conductivity. Pedotransfer functions for water retention (Rawls et al. 1982) and saturated hydraulic conductivity (Rawls et al. 1998) were used to estimate these since they are the most suitable for the soils of northern Italy (Morari et al. 2004). Soil-water dynamics as modelled by DAYCENT do not include the effect of gravel. As a result, a cascade method (Morari et al. 2004) was applied to proportionally reduce the depth of each soil horizon by its gravel content, while not changing the water content values at -33 kPa and -1500 kPa. The climatic database of Veneto Region is based on geostatistical processing of long-term temperature (maximum and minimum) and rainfall data from 35 meteorological stations, spread evenly over the territory. Following a fuzzy c-means classification of homogeneous areas with MZA software (Fridgen et al. 2004), the region was divided into seven homogeneous areas (Table 2). Each defined area was then associated with the meteorological station of the Veneto Region Environmental Protection Agency (ARPA Veneto) closest to its centroid. Reference crop evapotranspiration (ET_0) was calculated according to the Penman–Monteith equation (Allen et al. 1998).

Crop and management database

Agricultural crops and land use management in the region were provided by the Veneto Region (Regione Veneto 2012) at a municipal level, comprising a total of 579 polygonal units and referring to the year 2010. Eleven crops were simulated with DAYCENT: grain and silage maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), soybean (*Glycine max* L.), sunflower (*Heliantus annuus* L.), rapeseed (*Brassica napus* L.), potato (*Solanum tuberosum* L.), sugar beet (*Beta vulgaris* L.), pastures and meadows (permanent or in succession). The simulated crops represented most croplands and grasslands across the region, covering more than 60% of total used agricultural area (UAA). According to the last agricultural census by the National Institute of Statistics in 2010 (ISTAT 2010), the UAA covers about 44% of the region and is mostly concentrated on the plain (78%), comprising mainly cereals (e.g. maize, wheat), soybean and fodder crops (about 70%). In this study, only arable land areas were considered for analysis, thus excluding pastures and meadows. Field management information for the municipal units was also extracted from Veneto Region agricultural administration database (Regione Veneto 2012). Tillage practices include soil ploughing and standard seedbed preparation operations (e.g., harrowing) at different times according to crops. A fertilisation database was created including information on the type (organic or mineral) and quantity (kg ha^{-1}) of N and P input for each simulated crop. For arable lands, the same type of tillage operations (including ploughing 30 cm deep and seedbed preparation with a spring-tine harrow) were assumed. Irrigation was also included in the model by simulating irrigated and non-irrigated areas according to the ISTAT database (ISTAT 2010). Pesticides were ignored since DAYCENT cannot simulate them.

Application of agri-environmental measures

The impact of AEMs application on arable lands throughout the region was quantified by simulating two different scenarios: i) a scenario (hereafter called "standard") was simulated across Veneto without the adoption of any specific agri-environmental policy, highlighting the impact of conventional farming practices on the agro-ecosystems; ii) an AEM scenario (Table 3), based on the spatial distribution data of AEMs for the period 2007-2013, in response to the RDP (Regione Veneto 2013) and European Council Regulation (EC) No 1698/2005. AEMs were supported in the region to improve the environmental quality of agro-ecosystems by increasing, among other things, soil fertility (for instance, payments for organic farming – labelled as "OF", farmyard manure input – labelled as "FMY", conservation agriculture – labelled as "CA", etc.), decreasing water pollution (for instance, payments to reduce nutrients inputs – labelled as "$FERT_{Opt}$", or to enhance irrigation practices – labelled as "IRR_{Opt}", etc.) as well as mitigating greenhouse gases (for instance, payments to adopt conservation agriculture). Following the RDP regulation, organic farming was modelled in the long term, where already applied in the region (i.e. maintenance of OF practices, hereafter subscripted as "Maint"), and short term (i.e. new adoption, hereafter subscripted as "New") (Table 3). Therefore, in this particular case DAYCENT simulations were performed for a 21-year period rather than a 7-year one, both on a daily time-step. A total of 45,000 unique simulations, distributed over 1343 unique polygonal units covering the Veneto territory, were performed with DAYCENT as a result of the combination of pedo-climatic and AEMs information. Modelled UAA that was subjected to some AEMs accounted for a total of 44,065.3 ha.

Data analysis

Agronomic outcomes of N fluxes from the adoption of AEMs were evaluated in terms of:

a) standardised yields ($\Delta Yield$), quantified as the relative difference between agro-ecosystems that adopted ($Yield_m$) – and did not adopt ($Yield_0$) – AEMs:

$$\Delta Yield = \frac{Yield_m - Yield_0}{|Yield_0|}; \quad (1)$$

b) nitrogen use efficiency (NUE), here defined as the ratio between N removed as yield (kg N ha^{-1} a^{-1}) and the total amount of N fertiliser (mineral and organic, kg N ha^{-1} a^{-1}) (Oenema et al. 2015); NUE was also quantified as relative yearly average (ΔNUE) between agro-ecosystems that adopted (NUE_m) – and did not adopt (NUE_0) – AEMs, as follows:

$$\Delta NUE = \frac{NUE_m - NUE_0}{|NUE_0|}, \quad (2)$$

NUE was calculated only for N-fertilised crops; as a result, soybean and lucerne were excluded from analysis as well as the MEAD measure, which did not include any fertilisation. An overall evaluation of the agronomic performance of the different AEMs (compared to the standard scenario) was provided by integrating both yield and NUE results. From an agronomic point of view (Figure 2b), a “win-win” scenario includes increase of crop yields as well as optimisation of nitrogen use (top-right side of the graph); by contrast, a reduction of both yields and NUE (bottom-left side of the graph) would result in a worsening of the crop production system. Intermediate scenarios are of higher (or lower) yields Vs. lower (or higher) NUE.

Environmental outcomes on N fluxes from the adoption of AEMs were evaluated in terms of:

a) soil carbon stock (SOC, Mg ha^{-1}) within the 0-30 cm profile, as an indicator of organic N accumulation;

b) N leaching from all simulated agricultural fields into groundwater (N_{Leach}, kg N ha^{-1} a^{-1});

c) emissions of N_2O from all simulated agricultural fields (kg N-N_2O ha^{-1} a^{-1}).

The environmental indicators were then integrated to construct AEM performance maps in ArcGIS 10.2 (Esri Inc., Redlands, CA) and evaluate the overall effectiveness of AEMs in improving the agro-ecosystems quality. As a result, soil, water and air indicators were arbitrarily classified in each geographical unit as representing high (H), medium (M) or low (L) environmental quality (Table 4), although based on expert opinion and a literature review. Here it must be noted that national and regional data and classifications were available regarding SOC (ARPAV 2015) and N leaching (Regione Veneto & ARPAV 2005), whereas the classification for N_2O was based on international studies conducted in agricultural fields (Bouwman et al. 2002). The same weight was assigned to all indicators. Lastly, possible linear relationships between standardised NUE (ΔNUE) and environmental indicators (ΔSOC, ΔN_{Leach}, $\Delta N\text{-}N_2O$) were estimated through Pearson correlation coefficients ($p < 0.05$) using R software (R Development Core Team, Vienna, A).

Results

Crop yield and NUE

DAYCENT predictions of crop yields (dry matter) in the standard scenario (weighted average values of different simulated crops in each geographical unit) ranged between 3.3 and 21.4 Mg ha^{-1} a^{-1}, with a median of 7.7 of Mg ha^{-1} a^{-1}. The highest simulated yields were found where silage maize was highly fertilised in irrigated areas (> 20 Mg ha^{-1} a^{-1}), while the lowest were found when rapeseed and/or wheat were the main cultivated crops (< 3.5 Mg ha^{-1} a^{-1}). Agricultural systems that showed higher values were observed in the central-northern plain areas, where the interaction between pedo-climatic (e.g., rainfall) and management conditions (e.g., irrigated areas, high nutrients input) generally favoured optimal crop growth.

Nitrogen use efficiency (NUE, Figure 2a) under conventional management practices covered a wide range of values as a result of different management (e.g. crops, nutrients, irrigation) and pedo-climatic conditions (e.g. soil texture, soil water holding capacity, rainfall) that were simulated across Veneto. Indeed, the median value of standard NUE was 0.51, including results between 0.3 and 0.7. A reduction of NUE was observed after a change from mineral to organic N fertilisation until median values of 0.47, 0.45 and 0.42 in FMY (introduction of farmyard manure input), OF_{Maint} and OF_{New} (organic farming), respectively. By contrast, the effectiveness of crop N use was increased by the provision of continuous soil cover (CA, median NUE = 0.61; CC, median NUE = 0.59) as well as the reduction of N mineral input ($FERT_{Opt}$, median NUE = 0.61), with values rarely observed below 0.50. A general overview of the agronomic effects of single AEMs on regional agro-ecosystems was provided by intersecting normalised crop yields and NUEs (Figure 2b). The distribution of AEMs showed a significant differentiation along both the x-axis and y-axis. Only crop management practices including continuous soil cover (i.e. CA and CC) were able to improve yields (right side of the graph), especially in areas that were managed according to green manure (i.e., CC) practices (lower quartile = +40.4%, upper quartile = +65.2%). By contrast, FMY showed a generally lower production than the standard scenario (median = -7.4%), as well as the adoption of organic farming practices (both in the short and long term; -16.4% and -27.5%), MEAD (conversion from cropland to pasture; -13.3%) and IRR_{Opt} (irrigation optimisation; -27.2%). Optimising N mineral fertilisation ($FERT_{Opt}$) slightly affected crop yields, with a median of -2.9% and minimum values no lower than -20% (Figure 2b). Instead, both CA and CC as well as $FERT_{Opt}$ were strategies that generally improved the system efficiency by increasing NUE (y-axis). Conversely, practices involving only the use of organic fertilisation (OF_{Maint} and OF_{New}) reduced both yields and NUE compared to the standard scenario (bottom-left side of the graph), while the partial conversion of mineral to mixed input systems (FMY) showed more inconsistent (both positive and negative) results. Several factors across Veneto significantly affected the spatial distribution of NUE in the different measures: for example, NUE gradually decreased from north to south in IRR_{Opt} (only applied to maize), where a change from silty to sandy soils likely depressed N uptake due to unfavourable soil-water conditions. Better results were provided by $FERT_{Opt}$, especially in south-western areas, which most benefited from the optimisation of mineral fertilisation practices. By contrast, an opposite behaviour was observed in FMY, where the interaction between crop management and pedo-climatic conditions led to the increase of NUE from north to south, following the same trend as that found in the standard scenario.

Nitrogen in agro-ecosystems and environmental quality

After a 7-year simulation of conventional practices in the Veneto Region, soil organic carbon (SOC) stock (as an indicator of organic nitrogen accumulation) was 33.3 Mg ha^{-1} on average in arable lands (0-30 cm layer), with lower and upper quartiles of 31.2 Mg ha^{-1} and 35.6 Mg ha^{-1}, respectively (Figure 3a). Similar results were found in FMY, IRR$_{Opt}$ and FERT$_{Opt}$, 35.8 Mg ha^{-1} on average. By contrast, the conversion from croplands to meadows (MEAD), as well as the maintenance of organic farming in the long-term (OF$_{Maint}$), were effective measures to improve soil C stocks, with median values above 50 Mg ha^{-1} and maximum peaks up to 75.3 Mg ha^{-1}. Also CA and CC improved the soil C content, although with a lower performance (Figure 3a).

Strong improvements in N water quality were provided by MEAD, CA and CC, which were characterised by a continuous soil cover (3.4 kg N ha^{-1} a^{-1} on average) (Figure 3b). Also OF$_{Maint}$ reduced N leaching below 10 kg ha^{-1} a^{-1}, suggesting consistent differences between stabilised (long-term OF application) and not-stabilised (short-term OF application) systems adopting organic amendments, which conversely showed results similar to the standard scenario (OF$_{New}$ = 25.3 kg N ha^{-1} a^{-1}; standard = 28.8 kg N ha^{-1} a^{-1}).

Simulations of nitrous oxide emissions into the atmosphere (Figure 3c) showed median values between 0.33 kg N-N_2O ha^{-1} a^{-1} (CA) and 1.59 kg N-N_2O ha^{-1} a^{-1} (standard), although with a high variability, especially in OF$_{Maint}$ and MEAD (N-N_2O = 0-5 kg ha^{-1} a^{-1}). By contrast, negligible changes were observed in CA and CC, which always showed values < 1.0 kg N-N_2O ha^{-1} a^{-1}. Water (IRR$_{Opt}$) and nitrogen (FERT$_{Opt}$) optimisation slightly reduced N_2O emissions (1.33 kg N-N_2O ha^{-1} a^{-1}).

The spatial visualisation of agro-ecosystems environmental quality in the standard and AEM scenarios (Figure 4) showed different results, both in terms of effectiveness of adopted measures and their spatial variability. It was noticed that the standard scenario as well as IRR_{Opt} and $FERT_{Opt}$ measures generally produced “medium” environmental quality (yellow-domain maps). By contrast, ensuring continuous soil cover (MEAD, CA, CC) generally improved the environment (green-domain maps). Good environmental performances were also provided by long-term organic farming (21 years), while intermediate results were observed in OF_{New} and FMY. The standard scenario showed a decrease of environmental quality from plain (yellow polygons) to hilly (orange polygons) areas, that increased again in the most northern hilly and mountain areas (light green polygons). By contrast, environmental quality did not follow the same spatial distribution when adopting AEMs, which were more or less effective depending on local pedo-climatic variability. Significant correlations were found between agronomic (NUE) and environmental indicators (Table 5): increasing NUE led to reductions in N leaching ($p < 0.05$), although with differences among adopted measures ($r = -0.56$ in $FERT_{Opt}$; $r = -0.30$ in FMY and CA). Increasing the system efficiency was positively correlated with air quality improvement (less N_2O emissions) in OF_{New} ($r = -0.47$), $FERT_{Opt}$ ($r = -0.46$), CC ($r = -0.44$) and IRR_{Opt} ($r = -0.34$), while negatively with soil C content in OF_{New} ($r = -0.50$), $FERT_{Opt}$ ($r = -0.44$), IRR_{Opt} ($r = -0.40$) and FMY ($r = -0.16$).

Discussion

Simulations comparing standard and AEM scenarios predicted contrasting agronomic and environmental outcomes in the agro-ecosystems. Results suggested agronomic benefits when adopting continuous soil cover with conservation agriculture (CA, with no-till soil management) and cover crops (CC) because they both showed an increase of system efficiency (i.e., NUE) and crop yields. Benefits provided by CC in agro-ecosystems have already been reported by Cherr et al. (2006), who found a slow N release from decomposition of cover crops and following the increase of crop N availability. Similarly, a general increase of crop production was observed in CA systems during the 7-year simulation period, although some studies reported contrasting results (Figure 2b). For example, Soane et al. (2012), reviewing problems and opportunities of no-till practices in south-western Europe, found that crop yields with no-till varied between -77% and +200% with respect to those obtained with ploughing. The authors identified soil compaction and weed control as two of the main mechanisms that negatively affected crop production, although other factors, such as fertilisation management and changes in soil-water dynamics, can influence the CA system performance. By contrast, win-win outcomes for enhanced yields and ecosystem services in CA have largely been reported in other studies (e.g., Naderi et al. 2015; Garbach et al. 2017). As a consequence, the agronomic effects modelled here might be partially and locally overestimated because DAYCENT cannot simulate the negative impacts of weeds or soil compaction on crop production in CA systems, whereas it is generally able to predict benefits. Only in a few other cases was crop productivity higher with AEMs than with conventional practices (e.g., OF_{Maint}, FMY). According to Oenema et al. (2015), who reported reference European NUE values as guidelines to optimise production and environmental quality (Figure 2a), the agronomic efficiency of AEMs reduced NUE leading to risks of inefficient N use when applying only organic amendments. However, differences in NUE were observed between winter (mainly wheat, with a lower NUE) and summer (mainly maize, with higher NUE) crops, suggesting that more detailed evaluations are required to define crop-specific guidelines. A combination of organic and mineral fertilisers (Pang & Letey 2000) as well as their integration with cover crops may be strategies to improve AEMs, especially on the low-lying Venetian plain that often has loose soils and shallow water table, vulnerable to N leaching. However, here the intention of spatial modelling with DAYCENT was to cover all N fluxes to also evaluate the environmental aspects related to AEMs. In spite of the lower NUE in OF and FMY than standard scenarios, an improvement of N fluxes was also observed in terms of soil, water and air quality (Figure 3). The effectiveness of such measures was only significant after long-term application (OF_{Maint}), with a minor role that could be attributed to the spatial variability (Figure 4). Instead, higher NUE was frequently associated with an improvement of air and water quality (Table 4), while in some cases an N uptake increase led to changes in soil organic C (therefore soil organic N) dynamics. The long-term effects of organic amendments in the N balance were also reported by Lin et al. (2016) in a comparison between organic and conventional farming systems, observing an accumulation of soil organic matter in organically fertilised systems with respect to the conventional ones. A legacy-induced effect may be hypothesised on nutrients availability to crops, especially in sandy soils with low-organic matter, and a consequent improvement of N cycling with reduced leaching (Aguilera et al. 2013). Conversely, short-term organic application did not provide evidence of significant environmental improvements in all application areas, suggesting the need to target local strategies (Heumann et al. 2013) (e.g. improved fertilisation timing, crop varieties with slow growth), especially in the long term. Lastly, care should be taken over increased N_2O emissions as a result of high organic inputs in irrigated systems, which might provide much more anaerobic conditions with labile C substrates (that is needed for denitrification) than in rainfed systems (López-Fernández et al. 2007). Accordingly, our N_2O emissions variability in organically fertilised soils (Figure 3c) was likely affected by a complex interaction between soil water holding capacity, management and climatic conditions. In this context, modelling the optimisation of irrigation (IRR_{Opt}) and mineral fertilisation ($FERT_{Opt}$) techniques showed median decreases in N_2O emissions and strong reductions in data variability, partly because simulations were performed on simplified conditions (only irrigated in IRR_{Opt}, only rainfed in $FERT_{Opt}$), but simultaneously disentangling the benefits of the different strategies. Indeed, in IRR_{Opt}, anaerobic conditions were likely time-limited for denitrification processes, while the high NUE efficiency in $FERT_{Opt}$ involved low N_2O cumulative emissions (Barton et al. 2011). Nevertheless, an overall environmental quality improvement with IRR_{Opt} and $FERT_{Opt}$ was hardly obtained with respect to the standard scenario and contemporarily associated with a reduction in crop yields (Figure 4). In contrast, the maintenance of a continuous soil cover was much more effective in improving the N cycle, both in arable lands (CC) and with minimum soil disturbance (MEAD and CA). On the one hand, a conversion to permanent meadows led to substantial reductions in N fluxes (especially N_{Leach}) as also observed by others (Bilošová et al. 2017). On the other, cover crops emphasised their potential for increasing N retention in cropping systems, thereby reducing N fluxes to the atmosphere and water bodies through N immobilisation and soil protection (Aguilera et al. 2013). These measures (as for IRR_{Opt} and $FERT_{Opt}$) were the most promising to improve the environment in the short/medium term, although their actual application only covered 10% of modelled AEMs. More specifically, CA and CC were mainly adopted in the south/south-eastern areas of Veneto, while on the central and northern plains, where N loads are generally higher due mostly to livestock concentrations, they were rare or completely absent, minimising the benefits at regional scale. This was likely due to the main differences in cropping systems management. Indeed, silage maize monoculture and ryegrass are typical crops of the central and northern plains where they are commonly used as livestock feed. By contrast, their inclusion in crop rotations is difficult due to farmers' management constraints. As a consequence, these practices were adopted in just 1.2% of total hectares under conventional practices, despite DAYCENT predictions suggesting both agronomic and environmental improvements. Several other factors likely hindered their application (especially with regards to CA and CC which do not imply a significant change in growing crops): i) little investments due to relatively small size of the farms (55% < 5 ha; 5% > 30 ha); ii) little innovation as a result of low generational change (50% of Veneto farmers are more than 60 years old); iii) uncertainties on farm incomes (in CA), especially in the short term. As a result, the lack of application of most conservation practices to improve the N balance should be better sustained and addressed following a result-oriented approach that would establish a closer link between the payments and the outcomes achieved (Burton & Schwarz 2013).

Conclusions

The proposed DAYCENT model-GIS platform proved its feasibility for a spatial evaluation of AEMs to provide crop productivity and regulate N fluxes in agro-ecosystems in the Veneto Region. As a decision support system, this method was able to evaluate different AEMs at the local scale with a result-oriented approach, disentangling agronomic and environmental benefits of different adopted strategies. In particular, modelled results showed that some AEM scenarios (e.g., CA, CC) were able to improve the agricultural system efficiency as they increased NUE and crop yield with respect to the standard scenario, while others increased only NUE (e.g., $FERT_{Opt}$, IRR_{Opt}). These measures also improved environmental quality by, in some cases reducing N leaching and N_2O emissions, in others by also increasing soil C stocks, although with differences that associated local pedo-climatic variability and management approaches. However, an overall contribution to enhanced environmental quality was only observed with continuous soil cover and after the long-term adoption of organic instead of mineral inputs, although only partly combined with better crop yields. In this context, better agronomic and environmental performances were obtained with CC across Veneto, while OF_{Maint} was particularly effective in the sandy soils of western and eastern Veneto with low SOM content, likely improving soil-water conditions and nutrients availability over the years. This suggests the need to target local strategies, especially within a long-term perspective, which should provide equal environmental standards across Veneto Region and simultaneously guarantee decent farm incomes. Nevertheless, these modelling results should be carefully evaluated and further validated under a larger pedo-climatic variability to reinforce predicted outcomes.

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Table 1. Main physico-chemical properties (0-30 cm) of soil units in the Veneto Region study area.

Soil units	Soil units representativeness (%)	Texture classification	Sand (%)	Silt (%)	Clay (%)	Gravel (%)	BD[a] (g cm^{-3})	SOC[b] (g 100 g^{-1})	SWC[c] -33 kPa	SWC -1500 kPa	K_s[d] (m s^{-1})
AP1	7.5	Clay loam	35.0	31.3	33.7	32.5	1.33	1.41	0.32	0.19	$5.76\ 10^{-7}$
AP2	3.6	Sandi clay loam	55.3	25.7	19.0	47.5	1.46	1.22	0.24	0.12	$9.70\ 10^{-7}$
AP3	1.8	Clay loam	33.0	34.0	33.0	25.0	1.32	1.18	0.32	0.18	$5.35\ 10^{-7}$
BP01	0.8	Sandy	93.0	5.0	2.0	0.0	1.83	0.79	0.11	0.04	$4.52\ 10^{-5}$
BP02	2.0	Sandi clay loam	59.0	19.0	22.0	0.0	1.35	0.59	0.30	0.13	$5.81\ 10^{-6}$
BP03	6.1	Sandy loam	68.0	20.0	12.0	0.0	1.54	0.59	0.20	0.10	$5.61\ 10^{-6}$
BP04	13.4	Silt loam	21.0	59.0	20.0	0.0	1.37	0.79	0.29	0.12	$6.53\ 10^{-6}$
BP11	1.8	Loam	47.0	39.0	14.0	0.0	1.48	0.79	0.25	0.10	$4.28\ 10^{-6}$
BP12	2.5	Silt loam	30.0	55.0	15.0	0.0	1.51	0.89	0.32	0.10	$6.12\ 10^{-6}$
BP13	5.1	Sandy loam	65.0	24.0	11.0	0.0	1.54	0.89	0.20	0.09	$8.05\ 10^{-6}$
BP14	14.4	Silt loam	24.0	57.0	19.0	0.0	1.38	0.79	0.29	0.12	$3.05\ 10^{-6}$
CC1	3.6	Loam	40.0	40.0	20.0	25.0	1.41	0.57	0.26	0.13	$1.36\ 10^{-6}$
CC2	5.1	Clay loam	27.0	37.0	36.0	3.0	1.39	0.76	0.41	0.21	$4.52\ 10^{-6}$
MM1	1.9	Clay loam	32.0	40.0	28.0	15.0	1.16	2.64	0.43	0.19	$2.93\ 10^{-6}$
MM2	0.9	Loamy sand	80.0	16.7	3.3	25.3	0.74	3.67	0.30	0.14	$3.25\ 10^{-3}$
MM3	3.8	Sandy loam	70.0	26.7	3.3	48.7	0.76	2.76	0.27	0.12	$2.39\ 10^{-3}$
MM4	25.7	Clay loam	30.8	39.3	29.8	29.0	1.03	1.63	0.47	0.26	$8.08\ 10^{-5}$

[a]BD: bulk density; [b]SOC: soil organic carbon; [c]SWC: soil water content; [d]K_s: saturated hydraulic conductivity.

Table 2. Mean annual temperature, absolute maximum (July) and minimum (January) temperature, rainfall (P), reference evapotranspiration (ET_0) and precipitation deficit (PD = P−ET_0) in the homogeneous climatic zones during the 7-year simulation with DAYCENT (2007-2013).

Meteorological station	Temperature (°C)			P (mm a^{-1})	ET_0 (mm a^{-1})	PD (mm a^{-1})
	Mean	Max (July)	Min (January)			
Auronzo di Cadore	8.2 (0.4)	30.9 (1.4)	-13.9 (2.2)	1320.3 (21.0)	920.2 (33.4)	400.1 (222.8)
Rosà	14.5 (0.4)	35.3 (1.7)	-4.2 (1.7)	1307.9 (29.1)	1024.9 (33.8)	283.0 (307.3)
Chioggia	14.1 (0.5)	33.5 (0.8)	-3.8 (1.8)	840.7 (23.3)	951.8 (35.4)	-111.1 (264.1)
Cortinad'Ampezzo	7.3 (0.6)	27.3 (1.7)	-12.0 (1.5)	1196.4 (18.6)	779.5 (28.4)	416.9 (207.1)
Gosaldo	7.3 (0.6)	25.7 (1.5)	-10.5 (1.3)	1905.9 (43.7)	718.3 (20.8)	1187.6 (453.3)
Villafranca di Verona	13.9 (0.5)	35.2 (1.7)	-5.3 (1.6)	927.6 (27.7)	1061.2 (47.0)	-133.6 (318.8)
Quinto Vicentino	14.0 (0.5)	35.4 (1.7)	-5.2 (1.7)	1140.5 (32.6)	1066.4 (49.4)	74.1 (365.1)

Table 3**.** Agri-environment measures (AEMs) simulated using DAYCENT model.

Agri-environment measure	Main management aspects	ID	Simulated hectares (ha)
Increase of SOM through farmyard manure input or other biosolids.	Organic input = 130 kg N ha^{-1} a^{-1} + mineral. 7-a simulation.	FMY	4760.7
Organic farming – new systems.	Only organic instead of mineral input. Same N-input quantity. 7-a simulation	OF_{New}	1373.9
Organic farming – maintenance of existing systems.	Only organic instead of mineral input. Same N-input quantity. 21-a simulation.	OF_{Maint}	5151.1
Permanent meadows in arable lands – new systems.	No fertilisation. 7-a simulation	MEAD	821.6
Conservation agriculture – new systems.	No tillage, permanent soil cover, maintenance of residues on soil surface, crop rotations. 7-a simulation	CA	2300.1
Continuous soil cover – new systems.	Permanent soil cover, green manure	CC	1466.7
Optimisation of irrigation in irrigated systems (maize).	Irrigation -25%.7-a simulation	IRR_{Opt}	7705.5
Optimisation of fertilisation in rainfed systems.	Mineral fertilisation -30% compared to benchmark values. 7-a simulation	$FERT_{Opt}$	20485.7

Table 4. Classification of soil (SOC stock), water (N leaching) and air (N_2O emissions) indicators representing high (H), medium (M) or low (L) environmental quality, based on expert opinion and literature review (Bouwman et al. 2002; Regione Veneto 2005; Fantappiè et al. 2010; ARPAV 2015).

Agro-ecosystem quality	Environmental indicators		
	SOC stock ($Mg\ ha^{-1}$)	N leaching ($kg\ ha^{-1}\ a^{-1}$)	$N\text{-}N_2O$ emissions ($kg\ ha^{-1}\ a^{-1}$)
High (H)	>65	<10	<1
Medium (M)	40-65	10-35	1-3
Low (L)	<40	>35	>3

Table 5. Correlation matrix of ΔNUE and environmental parameters (ΔSOC, ΔN_{Leach}, $\Delta N\text{-}N_2O$) as a result of adoption of AEMs. Correlation coefficients are significant at $p < 0.05$ (bold values).

	ΔNUE						
	FMY	OF_{Maint}	OF_{New}	CA	CC	IRR_{Opt}	$FERT_{Opt}$
ΔSOC	**-0.16**	0.08	**-0.50**	-0.13	0.07	**-0.40**	**-0.44**
ΔN_{Leach}	**-0.30**	-0.31	**-0.36**	**-0.30**	**-0.31**	**-0.39**	**-0.56**
$\Delta N\text{-}N_2O$	-0.26	-0.01	**-0.47**	-0.08	**-0.44**	**-0.34**	**-0.46**

Figure 1. Workflow of steps and processes for spatial modelling standard and agri-environmental measure (AEM) scenarios.

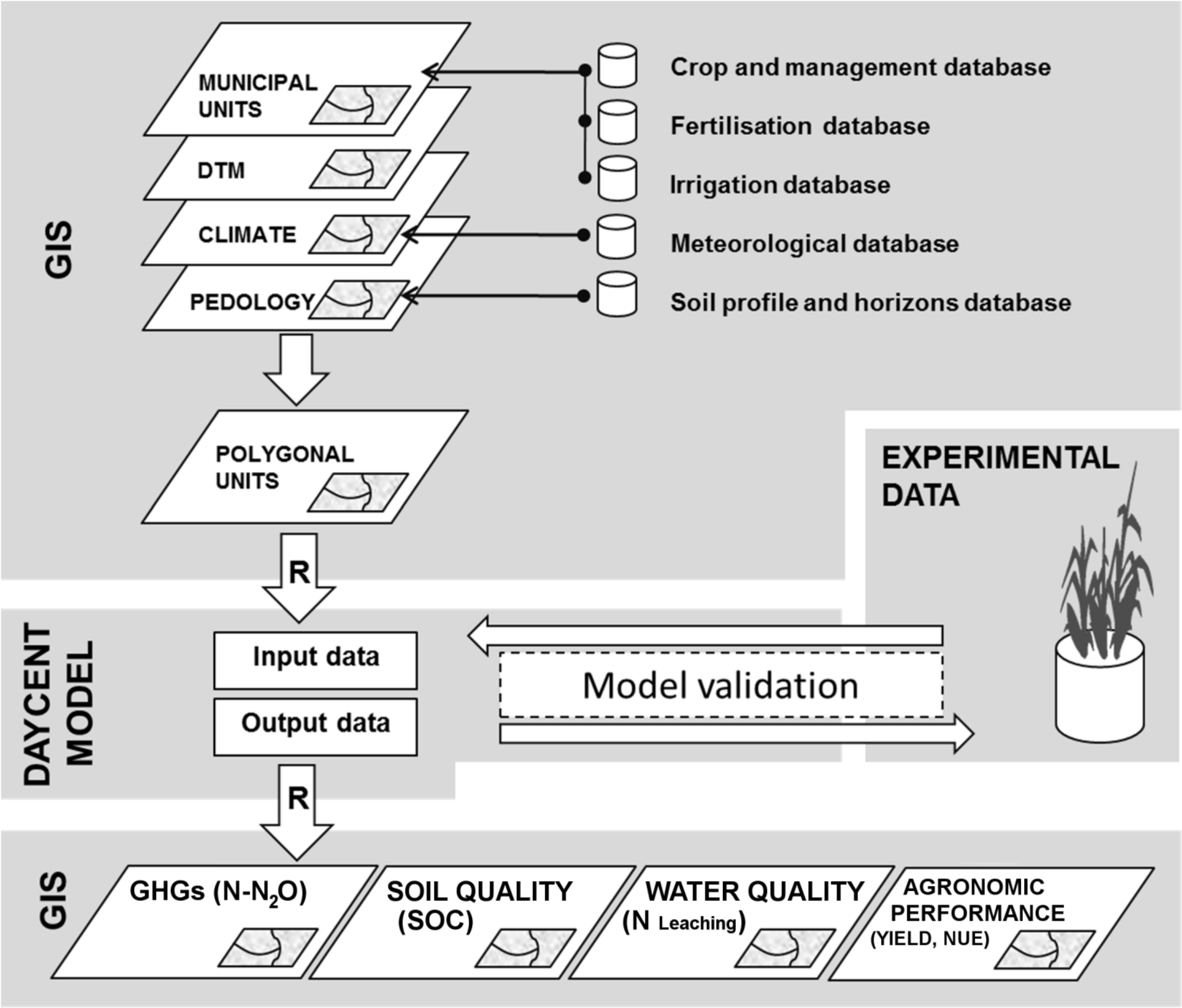

Figure 2. Boxplots of a) NUE of standard and AEM scenarios and b) relationship between standardised yields (x-axis) and standardised NUE (y-axis) of AEM and standard scenarios. Dashed lines in the left side graph indicate reference values of NUE for cropping systems across Europe in an attempt to define possible agronomic and environmental target values (Oenema et al. 2015).

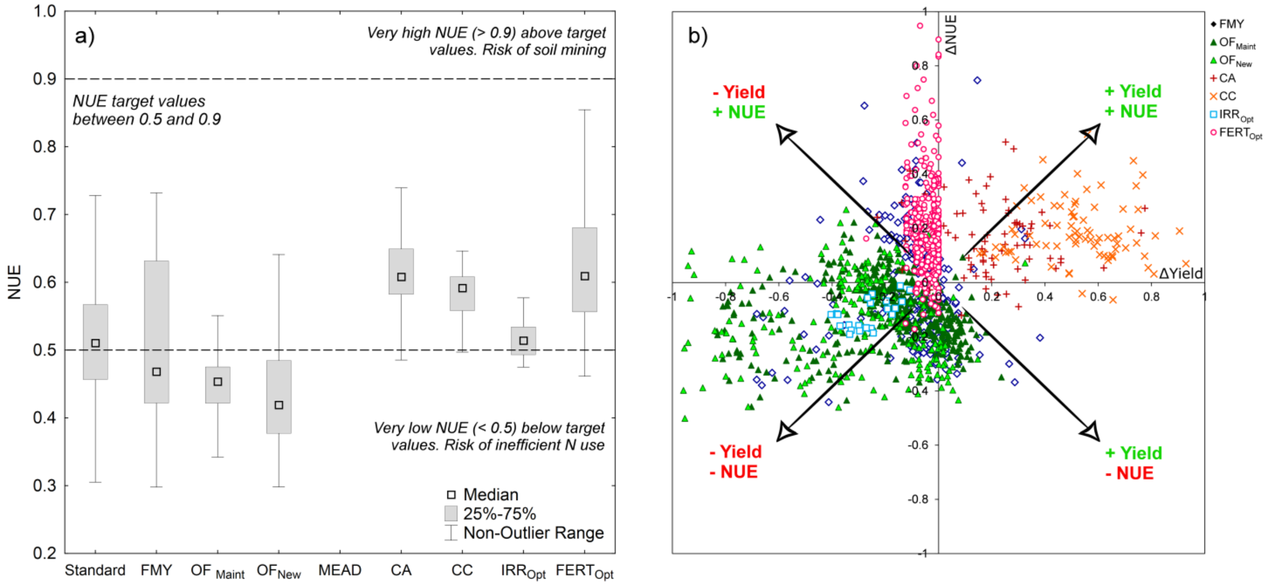

Figure 3. Boxplots of a) SOC content (Mg ha^{-1}) in the 0-30 cm soil profile, b) N leaching (kg ha^{-1} a^{-1}) and c) N-N$_2$O emissions (kg ha^{-1} a^{-1}) in the standard and AEM scenarios.

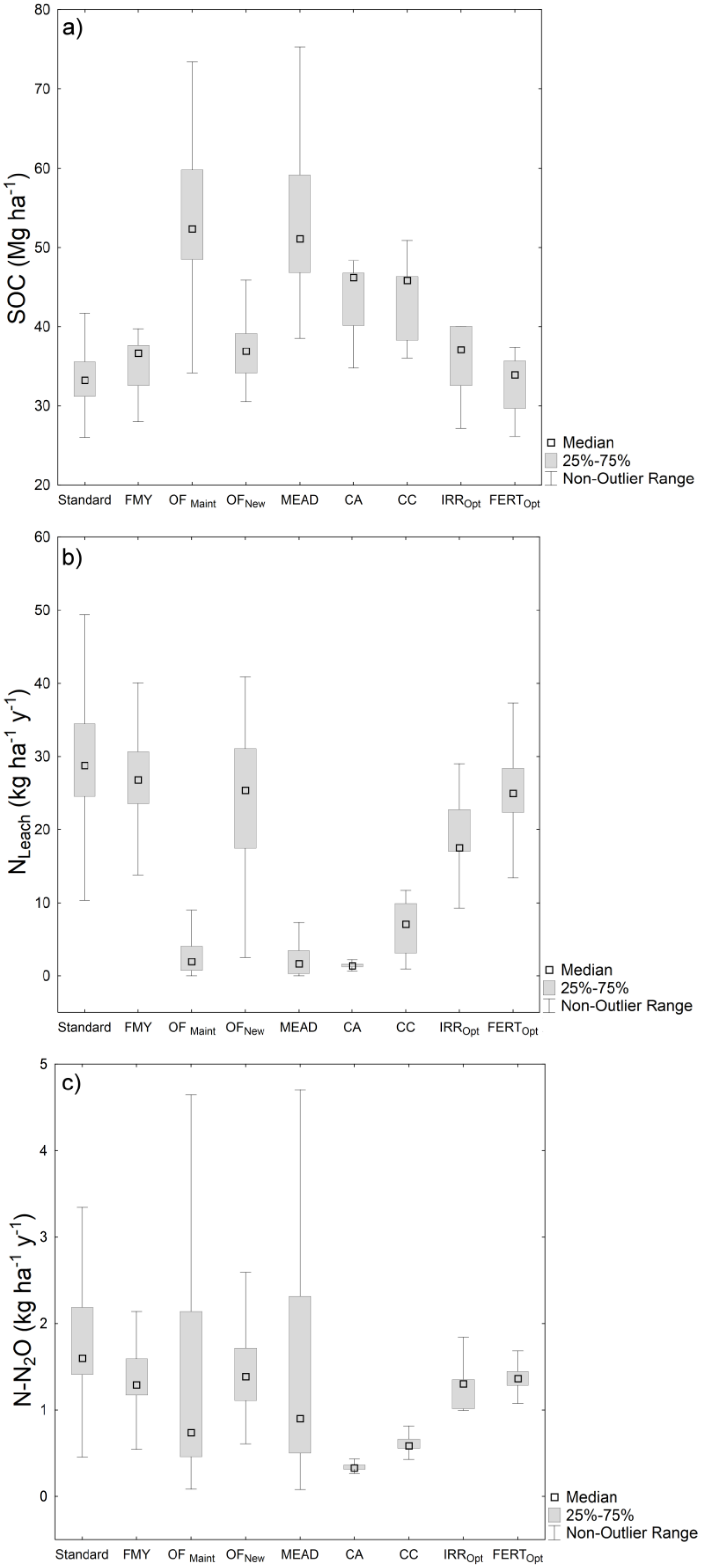

Figure 4. Spatial visualisation of agroecosystems environmental quality (H = high, M = medium, L = low) in the standard and AEM scenarios, evaluated in terms of integrated indicators of soil (SOC content), water (N leaching) and air ($N\text{-}N_2O$ emissions) quality. Stippled and hatched spatial units indicate an increase and decrease of crop yields with respect to the standard scenario respectively.