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Evaluation of the Grey Water Footprint Comparing the Indirect Effects of Different Agricultural Practices

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Abstract: Increasing global food demand and economic growth result in increasing competition over scarce freshwater resources, worsened by climate change and pollution. The agricultural sector has the largest share in the water footprint of humanity. While most studies focus on estimating water footprints (WFs) of crops through modeling, there are only few experimental field studies. The current work aims to understand the effect of supposedly better agricultural practices, particularly precision agriculture (variable rate application of fertilizers and pesticides) and conservation agriculture (minimum, strip, or no-tillage), on water deterioration and water pollution. We analyzed the results from an experimental field study in the northeast of Italy, in which four different crops are grown across three years of crops rotation. We compared minimum, strip, and no-tillage systems undergoing variable to uniform rate application. Grey WFs are assessed based on a field dataset using yield maps data, soil texture, and crop operations field. Leaching and associated grey WFs are assessed based on application rates and various environmental factors. Yields are measured in the field and recorded in a precision map. The results illustrate how precision agriculture combined with soil conservation tillage systems can reduce the grey water footprint by the 10%. We assessed the grey Water Footprint for all the field operation processes during the three-year crop rotation.

Keywords: water footprint; conservation tillage systems; precision agriculture; sustainable management; agriculture soil practices; impact reduction

1. Introduction

Water degradation becomes an important problem when the territory is affected by a high risk of water scarcity and water pollution. Agriculture is the greater user of water resource that causes water depletion and degradation [1]. In this context, the impact of agriculture soil management on water resources and its effects on the environment are clearly shown by the indicator of Water Footprint (WF) [2]. Water Footprint is a concept introduced by Hoekstra and Hung (2002), and it is an indicator of quantitative and qualitative water use [3]. It is quantitative since it evaluates the consumption and the embedded water. It is qualitative since it evaluates the pollutants load into a water body as a dilution volume under the qualitative standard threshold [4]. Agriculture practices have direct and indirect effects on water pollution according to the amount of fertilizers and pesticides required during the process of crop production [5]. In Chukalla et al. (2017) different nitrogen rates and water management are analysed for different crops comparing conventional and no-tillage systems [6]. The proper nitrogen rate in combination with a suitable tillage system can reduce the water pollution without compromising the yield. In particular, a variable rate application of fertilizers improves the soil productivity and the fertilization efficiency [7,8]. In addition, Hirel et al., (2011) studied how precision agriculture can reduce the environmental impact for different nitrogen rates [9]. The variable nitrogen application can minimize differences in soil fertility between conservation tillage systems; especially, when the soil water storage is reduced and the fertilization is applied, there is a higher crop growth [10,11]. In this sense, precision farming is a technique able to indirectly minimize the water pollution because it improves the efficiency of agricultural processes without compromising the yield [12]. In addition, the combination of agriculture tillage practices and precision farming determines a good solution to reduce the impact on water resources [13]. In fact, the integration of precision farming with different soil tillage techniques enhances a secure farm income, including a sustainable ecosystem management [14,15], and a reduction in land use pressure. Therefore, the increased pressure in global crop productivity due to the increasing food demand involves the dilemma of intensification/extensification of crop systems that somehow affects the impact on the environment [16–18]. A sustainable agricultural system must decrease the environmental pollution. Moreover, an intensive farming system increases the yield productivity, while the extensive system requires reduced external inputs and reducing the yield [16,19,20]. In this way, a proper compromise between agriculture intensification and extensification must be found [21]. The Common Agricultural Policy has strongly encouraged conservation tillage practices or the set-aside of arable land [21,22] and maintains the food production without intensifying the land use [20]. Conservation tillage system ameliorates soil properties in different aspects [23–26]. This soil tillage technique was introduced to increase soil organic matter and soil biodiversity [23,24] and to maintain the physical soil structure that determines the soil health and quality [25,26]. For example, De Vita et al. (2007) shows how important a reduced tillage system is in a semi-arid environment that guarantees a good performance in wheat grain quality thanks to an acceptable and stable production [27]. On the other hand, conventional agriculture has positive aspects on soil properties: it mixes fertilizers and manures, it includes topsoil aeration, it reduces weeds competition with effective weeds control, and it drills soil crusts [28,29]. However, many research studies demonstrate how conventional tillage could increase soil degradation [26,30,31], it contributes to soil organic matter reduction and therefore to the loss of fertility [32].

The study focuses on the use of the indicator “grey water footprint” as a preliminary analysis of direct and indirect water deterioration during soil management and tillage. The study discusses how proper soil management and tillage system can reduce the grey water footprint, achieving a more sustainable soil practice without compromising the yield. The case study analyses the grey water footprint on different tillage systems, one conventional and three conservation tillage systems, undergoing Precision and Tradition Farming of a three-year crops rotation. A solution for which sustainable soil practices might be involved within the intensification or the extensification of agriculture is also provided.

2. Materials and Methods

2.1. Description of the Study Area and the Experimental Setup

The study area is situated in the Veneto Region plain, near the Venice Lagoon, 45.63° N and 12.95° E. The location has an extreme anthropogenic pressure; it is particularly vulnerable for its geomorphological variability. The proximity to the sea influences the salt-water intrusion, forced by the height of the water table that affects crop cultivation and can compromise the yield. The area of the test considers a total surface of 23.4 ha, divided into 16 plots of about 1.5 ha each one (Figure 1a). The experimental setup is built on four soil tillage techniques, with conservation and conventional soil tillage as described:

- The Minimum tillage (MT) refers to a cultivation system that consists in few non-inversion tillage passages with the use of tine and disc implements. The techniques were conducted with a tine cultivator at 25 cm depth. The seedbed preparation and the sowing were combined with the use of a combined power harrow planter. Crop residues remain on the surface and mixed on the topsoil or landfill at deeper depth (15–20 cm);

- No-tillage (NT) is a direct drilling system combined with the sowing crop on previous crop residues with no prior cultivation. Seeding was conducted using special discs that make a narrow and slight furrow on the soil for seed deposition. The tillage technique provides fast land preparation within the optimum period. The combination of the drilling system with the sowing system in a narrow band of soil avoids soil inversion and it provides minimum soil disturbance. Weeds have been controlled with herbicides;
- Strip tillage (ST) is a modified direct drilling system. It consists of a soil tillage technique with the combination of a knife tine and disc passage on a strip land. Strip tillage creates narrow tilled strips of 10–30 cm width and 55 cm inter row. Seeds are drilled into the cultivated strips. Crop residues are removed from cultivated strips and placed between rows;
- Conventional tillage (CT) concerns a primary operation of the topsoil inversion using a mouldboard plough at 35 cm deep. A secondary cultivation prepares the seedbed with a single passage of a tine cultivator at 25 cm and a power-harrow down to 10 cm. Conventional tillage prepares a seedbed without surface residues, interrupting weeds growth, pest and disease for the optimum condition of crop germination [33].

The CT was carried out only with the uniform rate technique, while the conservation soil tillage systems were applied to both the uniform and the variable rate application. Every plot was managed with variable (VRA) and uniform rate application (URA). The variable rate application consists in a variable application of nitrogen fertilization, in a reduced overlapping and in a more efficient application of pesticides. The experimentation considers a crop rotation with the most representative crops in Veneto plane: Maize (*Zea maize*), Soybean (*Glycine max*), Wheat (*Triticum aestivum*), and Rapeseed (*Brassica napus*) (Table 1). Data collection derives from a field dataset of a three-year crop rotation from 2014 to 2017.

Table 1. Crop rotation schedule of maize, soybean, rapeseed, and wheat during the 3-year experimentation.

Crop Rotation Fields	CT-MT-ST-NT	CT-MT-ST-NT	CT-MT-ST-NT	CT-MT-ST-NT
2014–15	MAIZE	SOYBEAN	WHEAT	RAPESEED
Seeding	01 April 2015	25 May 2015	02 November 2014	06 September 2014
Harvesting	05 October 2015	28 October 2015	06 July 2015	23 June 2015
2015–16	SOYBEAN	WHEAT	RAPESEED	MAIZE
Seeding	23 May 2016	31 October 2015	28 August 2015	31 March 2016
Harvesting	24 October 2016	30 June 2016	21 June 2016	03 October 2016
2016–17	WHEAT	RAPESEED	MAIZE	SOYBEAN
Seeding	31 October 2016	30 August 2016	02 April 2017	25 May 2017
Harvesting	02 July 2017	23 June 2017	30 September 2017	27 October 2017

The crop rotation was replicated in four plots per soil tillage system, where four different patterns of crop rotation were established during the 3 years (Figure 1). A cover crop was sown after the main crop to keep a permanent soil cover. The cover crop was established on plots undergoing conservation tillage systems, which was devitalized with the soil cultivation in strip and minimum tillage or with the use of herbicides in no-tillage [34,35]. The case study aims to assess the qualitative water footprint of the processes during different crop seasons and different soil tillage systems under precision (VRA) and tradition (URA) farming that are described in the experimentation pattern shown in Figure 1b.

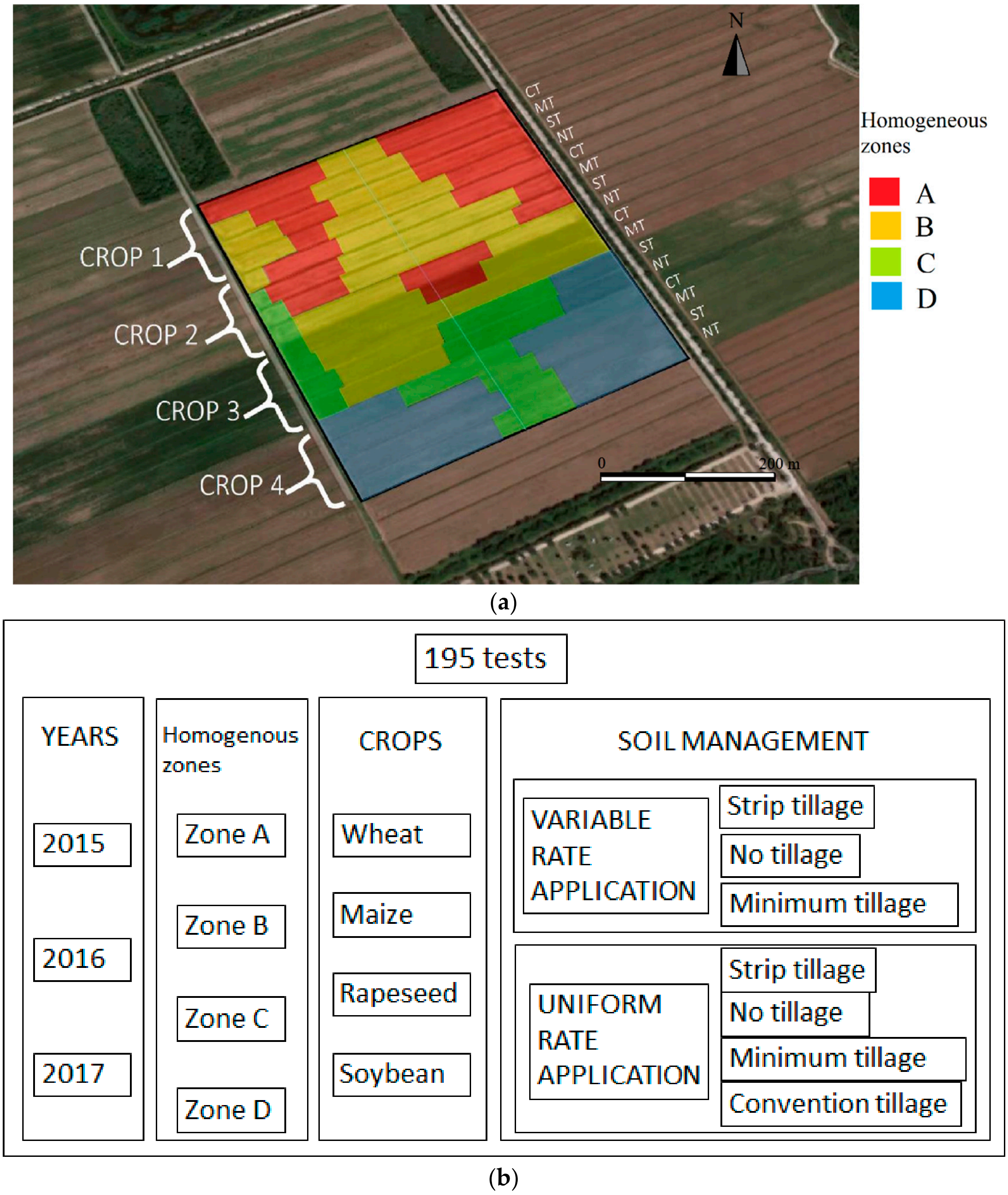

Figure 1. Experimental field pattern. In (**a**), the map shows the annual plots setup of maize, soybean, wheat, and rapeseed under different homogenous zones; while in (**b**), the experimental setup shows the field organization and the soil management involved in 3 years of crop rotation.

The variable rate application differs among four different homogeneous zones (Figure 1a). The homogenous zones are identified using the Salus model in a map of prescription as homogenous areas of soil spatial variability of soil productive potential [13,36]. The Salus model is designed to simulate crop production under different soil management, simulating the dynamics of nutrients with different atmospheric and soil conditions [34]. Using the Soil Texture Triangle Hydraulic Properties Calculator from Saxton et al. (1986) [37], three different soil textures were identified (Table 2): Sandy Loam Soil (Zones A and B), Loam Soil (Zone C), and Clay Loam Soil (Zone D).

Table 2. Soil properties of different homogeneous zones.

Soil Properties	Zone A	Zone B	Zone C	Zone D
Soil Electrical Conductivity (dS/m)	1.82	2.01	2.26	2.39
SAR (Sodium Adsorption Ratio)	0.46	0.50	0.35	0.32
pH	7.25	7.53	7.54	7.48
Total Nitrogen (%)	0.06	0.06	0.08	0.11
Organic matter (%)	1.22	1.23	1.71	2.38
P available (mg/kg)	32.83	30.0	30.9	29.5
K (mg/kg)	115.8	121.7	151.0	154.3
Clay (%)	15.17	16.33	22.14	32.00
Silt (%)	25.33	24.67	36.14	47.75
Sandy (%)	59.50	59.00	41.71	20.25

The fixed operation process for crop production are in order: ploughing, seeding, the use of herbicides, fertilizers and pesticides, and harvesting. The operation strategies applied in the field are shown in Table 3.

Table 3. Common soil management and operations during crops season.

OPERATIONS	MAIZE	SOYBEAN	WHEAT	RAPESEED
PLOUGHING AND SEEDBED PREPARATION	March	May	October	August
FERTILIZATION BEFORE SEEDING	Fertilizer 8-20-20 (400 kg ha^{-1})	Fertilizer 0-20-20 (400 kg ha^{-1})	Fertilizer 8-20-20 (400 kg ha^{-1})	Fertilizer 8-20-20 (400 kg ha^{-1})
HERBICIDES PRE SEEDLING EMERGENCE	Lumax (4.21 L ha^{-1})	Corum+Harmony+Dash (947+4.2+315 mL ha^{-1})	Caliban Top (0.42 L ha^{-1})	Sultan (1.579 L ha^{-1})
SEEDING	April	May	October	September
HERBICIDES POST SEEDLING EMERGENCE		Tuareg+Stratos ultra (947 + 4.2 L ha^{-1})		
1° FERTILIZATION DURING STEAM ELEVATION	Urea (120 kg ha^{-1})		Ammonium nitrate (211 kg ha^{-1})	Ammonium nitrate (211 kg ha^{-1})
2° FERTILIZATION DURING STEAM ELEVATION	Urea (230 kg ha^{-1})		Urea (211 kg ha^{-1})	Ammonium nitrate (211 kg ha^{-1})
FUNGICIDE TREATMENT			Prosaro (1.05 L ha^{-1})	
INSECTICIDE TREATMENT	Coragen (0.1053 L ha^{-1})		Karate (0.132 L ha^{-1})	Decis (0.526 L ha^{-1})
HARVESTING	October	November	July	June

The common soil management and operations were replicated during the three years of experimentation. The term of soil management includes the different soil tillage systems, with either the application of variable or uniform rate. There is no nitrogen application in the case of soybean since it is assumed that the nitrogen nutrient is provided by the nitrogen fixation. The Precision Agriculture applied in the field is based on a Variable Rate Application (VRA) of nitrogen and seed density among different homogeneous zones and tillage systems (Table 4). The map of yield variability was recorded during harvesting and it discriminates the variable crop productivity across the homogeneous zones and soil tillage systems (Table 5). The yield was summarized as the cumulative crop rotation yield under the common field plot. The cumulative yield also represents the yield from different homogeneous zones, which was previously normalized on the respective area [35]. The harvesting operation was made with a harvesting machine that recorded and integrated the entire points yield in a precision map. The experimental pattern of variable application is kept constant along the three years according to the prescription map. In Table 4, different rates of inputs are recorded.

Table 4. Variable rate of nitrogen during crop season and for each homogeneous zone.

Tillage System	Homogeneous Zone	Seed Density (seeds m^{-2})				Fertilization (Kg N ha^{-1})			
		MAIZE	SOYBEAN	WHEAT	RAPESEED	MAIZE	SOYBEAN	WHEAT	RAPESEED
CT	-	7.5	45	500	50	193	-	178	128
MT	A	6.0	55	500	50	180	-	150	140
	B	7.0	50	500	50	190	-	190	120
	C	8.5	40	500	50	180	-	140	100
	D	9.5	35	500	50	200	-	180	110
ST	A	6.5	55	260	55	190	-	150	140
	B	7.5	50	260	55	200	-	190	120
	C	8.5	40	260	55	170	-	130	110
	D	9.5	45	260	55	190	-	190	120
NT	A	6.5	55	550	55	200	-	150	150
	B	7.5	50	550	55	210	-	190	130
	C	8.5	40	550	55	200	-	130	140
	D	9.5	35	550	55	220	-	170	120

Table 5. Average yield (tons ha^{-1}) of three-year crop rotation of different crops, zones, and soil practices.

		Maize (tons ha^{-1})		Soybean (tons ha^{-1})		Wheat (tons ha^{-1})		Rapeseed (tons ha^{-1})	
		URA	VRA	URA	VRA	URA	VRA	URA	VRA
CT	A	8.77		1.43		4.35		2.47	
	B	9.60		2.91		5.00		2.48	
	C	10.26		3.84		6.18		3.02	
	D	10.06		3.73		7.47		3.03	
MT	A	8.48	7.44	1.52	1.64	4.78	4.38	2.70	2.58
	B	9.73	7.73	2.72	3.44	5.09	5.18	2.67	2.37
	C	10.38	10.63	3.85	4.20	5.74	5.93	2.95	2.85
	D	9.86	10.22	2.91	3.73	8.37	8.03	2.22	2.19
NT	A	7.79	9.12	2.64	2.89	4.32	5.77	1.82	2.04
	B	10.12	10.31	3.42	3.51	4.84	4.56	1.35	2.38
	C	7.53	9.47	3.80	3.40	6.70	6.11	2.26	2.20
	D	7.22	9.85	3.14	3.00	7.85	6.94	-	-
ST	A	6.18	6.87	1.71	2.06	3.84	3.88	2.03	2.06
	B	6.17	7.42	2.94	3.11	4.44	4.52	1.95	2.28
	C	8.78	9.36	3.62	3.85	5.36	6.03	2.14	3.22
	D	7.18	9.31	3.54	3.66	7.16	7.80	-	-

2.2. Description of the Methodology Applied to the Water Footprint Assessment

The Water Footprint Assessment ideated by Hoekstra et al. (2011) focuses on two components for the consumptive water use and one component for the water quality aspect [38]. In this study, we focus on the grey water footprint index. It is an environmental indicator of water degradation and pollution. It becomes useful when assessing the impact on water resource due to human activities. In the case of agriculture processes, the water quality index relies on the grey water that is the freshwater volume needed to assimilate pollutants under a standard threshold of water body quality. The grey WF considers the use of pesticides and fertilizers applied in the fields. The study compares the grey WF of the process of crop production within different soil tillage systems and soil management. The Water

Footprint is the relation between the volume of water to dilute pollutants, and the yield, in terms of m^3 per tons, or the surface, in terms of m^3 per hectares. In order to compare the effect of soil tillage systems across a crop rotation, we considered the grey Water Footprint (grey WF) of soil management as a sum of the process during the three years of crop rotation in a specific field plot. The grey WF is then compared undergoing variable or uniform soil management. In addition, the grey WF in terms of $m^3\ ha^{-1}$ is put in relation to the grey WF in terms of $m^3\ tons^{-1}$. The relation can explain which soil practice reduce the water pollution in a context of intensive or extensive agriculture.

2.3. Assessment of the Grey Water Footprint

The Grey water is the volumetric amount of water to dilute pollutants under an acceptable level of water quality. Agriculture production is the main actor in water body pollution. Since The Grey Water Footprint, Grey $WF_{[i,p]}$, is a qualitative indicator of water pollution, we assess the volume of water that dilutes the most critical pollutant (p) under a sufficient level of water quality, as given by Franke et al. (2013) [39], and for each crop production (i):

$$\mathrm{GreyWF}_{[i,p]} = \frac{\propto \times \mathrm{Appl}_{[t]}}{(C_{max} - C_{nat})} = \left[\frac{\mathrm{Volume}}{\mathrm{Area}}\right] \quad (1)$$

where $\mathrm{Appl}_{[t]}$ is the application rate at time [t], and α is the leaching-runoff coefficient improved by Franke et al. (2013) [39] as

$$\alpha = \alpha_{min} + \left[\frac{\sum_i (s_i * w_i)}{\sum_i (w_i)}\right] * (\alpha_{max} - \alpha_{min}) \quad (2)$$

where the α_{max} and α_{min} are respectively the maximum and the minimum leaching-runoff factors, while s_i is the leaching-runoff potential and w_i is a weighting factor, and they vary according to the properties of the chemical substance. The α_{max} for nitrogen is fixed at 0.25, at 0.05 for phosphorus, and 0.01 for pesticides, while the α_{min} is fixed at 0.01 for nitrogen, at 0.0001 for phosphorus and pesticides. The toxicity of the pesticide to the selected non-target organisms was assessed using data of eco-toxicological and toxicological parameters derived from databases (FOOTPRINT, 2006) [40]. The maximum acceptable concentration (C_{max}) is an ambient water quality standard for pollutants. We considered a C_{max} of 50 mg nitrate-N L^{-1}, or 11.3 mg N L^{-1} for nitrogen [6], the value of 0.02 mg P2O5 L^{-1} for Phosphorus [41]. We also considered a C_{max} of 0.1 µg L^{-1} for single application and 0.5 µg L^{-1} for total residues of pesticides, and according to the EU limits for pesticides in drinking water for individual substances [42,43]. For the specific chemicals included into the Franke et al. (2013) and Hamilton et al., (2003) guidelines we considered the reported C_{max} threshold (Table 6). The natural concentration (C_{nat}) applied following the guidelines concerns a value of 0.1 mg L^{-1} for nitrogen, 0.01 mg L^{-1} for Phosphorus, and zero for pesticides.

Table 6. Maximum acceptable concentration (µ L^{-1}) for pesticides in water and used in the field.

Chemicals	Type of Chemical	C_{max} (µ L^{-1})	Source
Bentazon	Herbicide	30	[43]
Chlorsulfuron	Herbicide	100	[43]
Deltamethrin	Insecticide	0.4×10^{-3}	[39]
Glyphosate	Herbicide	800	[39]
Metolachlor	Herbicide	7.8	[39]
Metribuzin	Herbicide	1	[39]
Terbuthylazine	Herbicide	7	[43]

The Grey Water Footprint, Grey $WF_{[i,p]}$, can be assessed according to the quantitative production of the crop process in every management package (y):

$$\text{Grey } WF_{[i,p,y]} = \frac{\text{Grey Water Footprint}_{p,i}}{\text{Yield}_i} = \left[\frac{\text{Volume}}{\text{Weight}}\right] \tag{3}$$

The Grey Water Footprint stands on the concept of the critical load for water pollution, which concerns the assimilation capacity of a water body and the acceptable concentration of pollutants receiving in the water body. The resulting grey WF is the maximum value of the critical pollutant on each process under different methods of crop production and soil management. The present methodology considers only the indirect effect of using different soil tillage systems can have on the environment. Some limitation can be found on the interpretation of the volumetric value of grey WF, which is a volumetric indication of the water pollution magnitude of the different soil management. The main limit on the analysis of soil management effects on water pollution is the limited studies on the soil management effects on chemicals fate, and the scarcity of soil models availability. Another limitation during the field activities was to conduct a groundwater survey able to detect chemical residues for the different methods of soil management since the groundwater quality might be affected by the leaching from one plot to another. Therefore, we implement the aforementioned methodology of the grey WF assessment. The absolute value is to be considered as a mere indication of water pollution and not a real volume. A further improvement of the case study can analyze not only the grey WF, but also different indicators of water quality or the environmental effects of using different tillage systems on soil moisture increase and on irrigation water saving.

3. Results

The study analyses the grey WFs of crop rotation under different soil tillage systems with the variable and uniform rate of input applied. For that reason, the grey WF of crop rotation under the same soil variability was considered. The yield of crop rotation under different soil tillage systems differs among the soil productivity. The soil productivity is the result of three years of crops rotation under the same soil variability. Yield variability considers different soil type, different plant density, and different fertilizers application. The dataset presents a high statistical variability among the tests; therefore, a crop rotation analysis was assessed. The main outcomes show an of yield variation from uniform rate application (URA) to the variable rate application (VRA), where, generally, the conservation soil practices benefit from a greater yield under VRA. In the case of Minimum Tillage (MT), the production is reduced within the use of precision agriculture, where only 2% yield reduction is recorded from URA to VRA. In the others conservation tillage systems, the yield records a better trend and it gains a positive effect by an increase of 6% and 8% under Strip (ST) and No-tillage (NT) respectively.

The indirect effects of soil management under different tillage systems on water pollution are, most of the time, the indirect consequences of the applied inputs during the operational phases. The effect of precision agriculture with VRA is more effective and it shows a grey WF reduction for every soil management practice. In Figure 2, the grey WF of the process of crop rotation is shown in terms of m^3 ton^{-1}. ST VRA and NT VRA reduce the grey WF by the 10% and 11% from ST URA and NT URA respectively, while MT VRA reduces only by the 1.3%. Nevertheless, MT VRA has a 6% reduction compared to CT. Generally, the higher level of water pollution in ST and NT, with respect to MT, is generally due to the higher number of treatments for weeds control. The use of VRA has a higher reduction in the grey WF in relation to the crop yield. The technique of precision agriculture permits to reach a lower grey WF with a more efficient application of inputs, thanks to a smaller amount of pesticides and fertilizers and the higher effective rate spread in the field that reduces the impact on water pollution. In other terms, the water pollution can be reduced by the use of suitable soil management without compromising the yield.

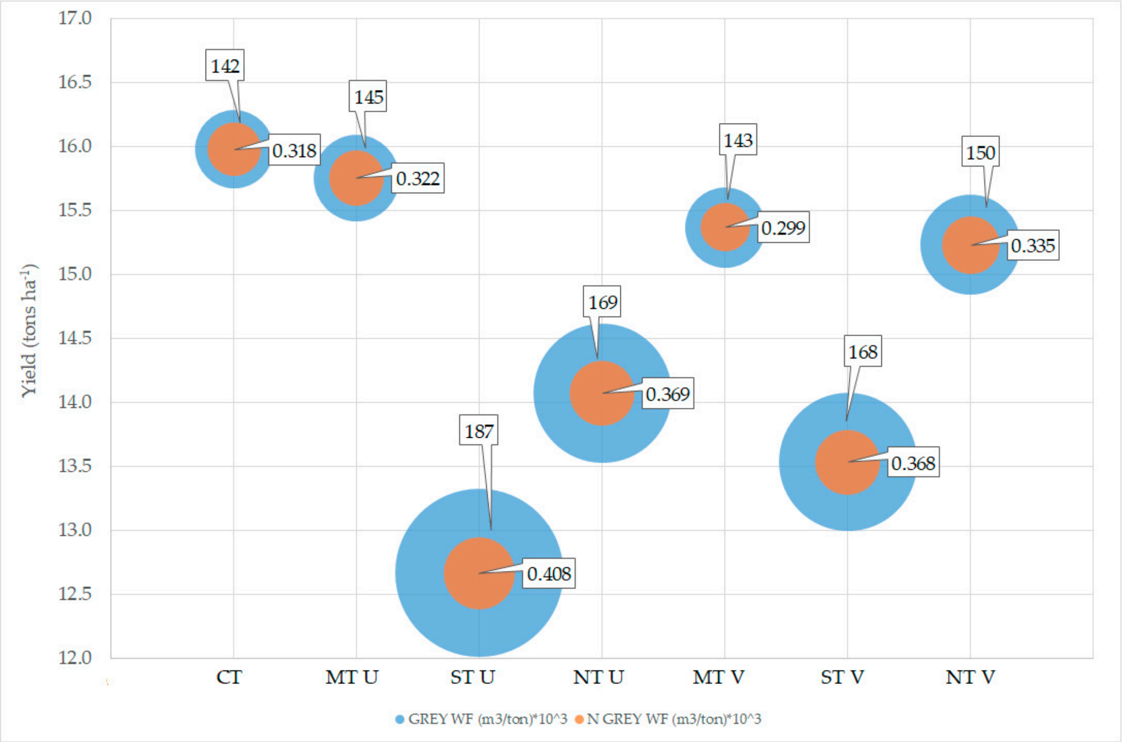

Figure 2. Relation of the three-year yield of crop rotation under different soil tillage systems (tons ha^{-1}), with the Grey Water Footprint (WF) and N Grey WF (m^3 ton^{-1})·10^3 of soil tillage systems undergoing variable (VRA) and uniform application rate (URA) per unit of production.

In order to understand which soil tillage can reduce or minimize the grey WF in certain circumstances; we address the evaluation of the grey WF for the nitrogen (N) application (Figure 2). The use of VRA decreases the grey WF by the 7% in MT, 10% in ST, and 9% in NT. Also in the case of Nitrogen, the water pollution can be reduced by the use of suitable soil practices. Comparing different soil tillage systems under VRA, ST and NT have a higher grey WF value, in terms of m^3 ton^{-1}, by 19% and 11% than MT respectively. The use of suitable soil tillage can indirectly reduce the water pollution from nitrogen losses; especially, MT minimizes the grey WF without compromising the yield. In Figure 2, MT VRA reduces the N grey WF (m^3 ton^{-1}) by 6% more than CT. The VRA practices decrease the N leaching loss and increase the crop N uptake. ST VRA and NT VRA, on the other hand, have a greater grey WF reduction than MT VRA.

The effect of soil management on the grey WF of the process for the crop rotation per unit of area is described in Figure 3. The graph shows the variability between soil tillage systems in terms of volume of grey WF per hectare (m^3 ha^{-1}). There is a clear picture that VRA reduces the grey WF of field process for every soil tillage system. The reduction changes between 3.7% and 3.8% undergoing the use of VRA, where the MT VRA has the lower grey WF. The URA has the highest grey WF in all the soil tillage practices, and every soil tillage benefits from a reduction in water pollution using the VRA. Looking in detail at the VRA management, the comparison between tillage practices shows that the MT technique has the lowest grey WF with a decrease of 3.4% more than CT. Therefore, the use of VRA reduces the grey WF on conservation tillage systems in terms of water pollution per unit of surface. The MT VRA performed a better grey WF (m^3 ha^{-1}) reduction comparing the others conservation tillage by the 3.6% and 4% from ST VRA and NT VRA respectively. In Figure 3, soil tillage systems can affect the grey N WF in terms of m^3 ha^{-1}. In fact, the use of the VRA management reduces the grey WF by the 9.5% under MT, 3.6% under ST and NT, with 1.8% from uniform rate application. MT VRA reduces the grey WF by 8% and 10% more than ST VRA and NT VRA respectively. MT VRA reduces also the N grey WF by 9.6% more than CT. In this circumstance, MT VRA represents the most sustainable soil practice with the lowest N grey WF (m^3 ha^{-1}) value and the greater grey WF reduction.

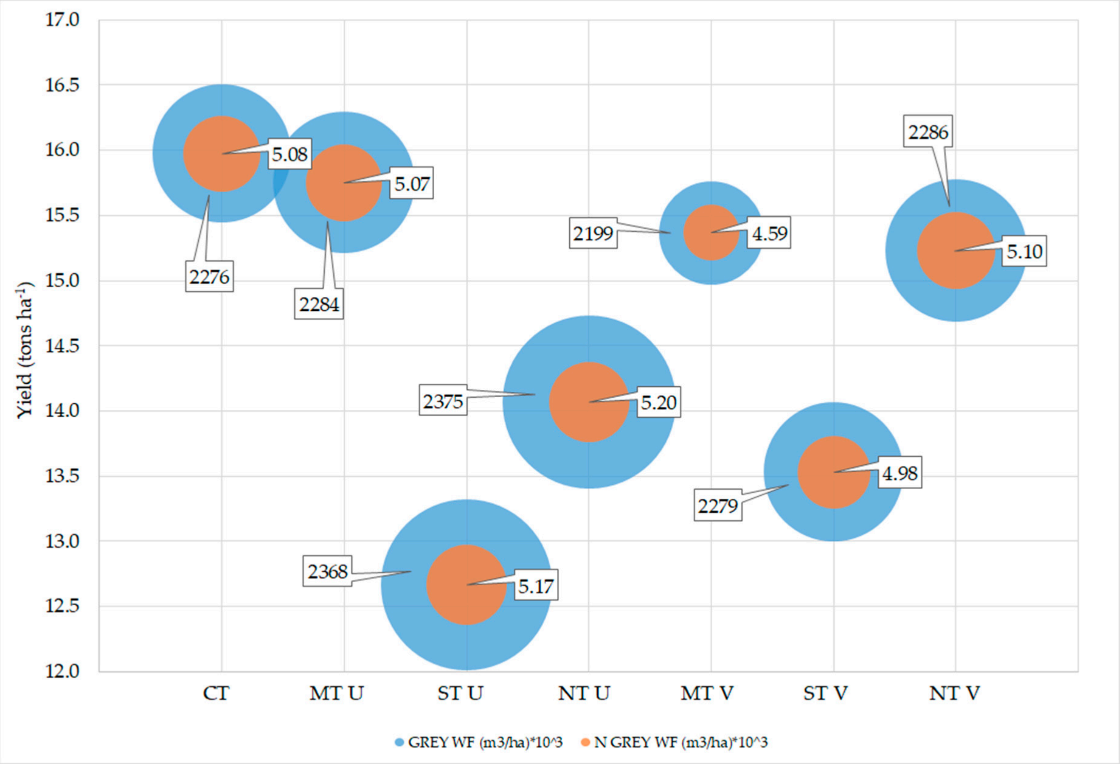

Figure 3. Relation of three-year yield of crop rotation under different soil tillage systems (tons ha^{-1}), with the Grey WF and N Grey WF (m^3 ha^{-1})·10^3 of soil tillage systems undergoing variable (VRA) and uniform application rate (URA) per unit of surface.

4. Discussion

The use of one or the other soil tillage systems might have an indirect benefit on the reduction of water pollution [44]. Different rate applications affect the grey WF that provides a trade-off on the decision-making level [45]. Conventional Tillage (CT) is generally the common technique applied in the fields. In this case study, CT was compared with conservation tillage systems. Minimum Tillage (MT) minimizes and decreases the grey WF in comparison either with CT both with Strip Tillage (ST) and with No-Tillage (NT). Conservation tillage could have some environmental benefits and indirect effects on water pollution [26,44]. The increase of soil organic content permits decreasing the carbon oxide emissions and having a greater energetic efficiency [36]. In this study, a preliminary grey WF assessment on the field dataset is made to understand the effects of conservation tillage and precision agriculture on water pollution.

4.1. Effects of Soil Management to the Grey Water Footprint Reduction

Conservation tillage provides better outcomes if combined with precision agriculture. The MT VRA technique delivers the greater trend on grey WF reduction even if the yield decrease by 2%. The operation phases in MT VRA positively affects the environmental performance compared to the others tillage systems. Especially in the case of N grey WF, the MT VRA system gives a better reduction both in terms of m^3 $tons^{-1}$ or m^3 ha^{-1}. In any case, MT VRA minimizes and reduce the water pollution under the level of the referenced CT. Similarly, ST VRA and NT VRA have a greater reduction of water pollution combining with the URA management in terms of m^3 $tons^{-1}$. The low reduction of water degradation per unit of area is due to change in inputs application during the operations phases. In detail, a different application of fertilizers and pesticides affects the value of water pollution according to soil parameters and the chemical features of the substances. In order to understand which active substance mostly affects the grey WF, a list of chemicals applied in the field was made for the four herbaceous annual crops. In Table 7, different values of the grey WF were considered. The interval of grey WF refers to the minimum and the maximum amount of chemicals suggested in the label indications, while the field value is the grey WF for chemicals applied in the field study. The table ranks the substances with a decreasing order of the grey WF of the interval. The value is considered as the sum of the three-year crop rotation. The assumption of having a three-year value is due mostly to the magnification of the grey WF variability among crops and soil management. It is interesting to have a look to which insecticides and herbicides present the higher grey WF value and which could be used with caution. In the ranking list, herbicides are the most critical group of substances for water pollution. The grey WF and therefore the water degradation might be decreased by the use of different chemical substances with a lower impact on water pollution, or with the use of the lower application rate.

Table 7. Grey WF of chemicals applied in the field. The minimum and the maximum grey WF rely on the minimum and maximum amount of chemicals applicable according to the label.

TYPE OF SUBSTANCE	CROP CONCERNED	CHEMICAL OR ACTIVE SUBSTANCE	FIELD GREY WF (M3 HA−1)	INTERVAL OF GREY WF (M3 HA−1)
INSECTICIDES	Rapeseed	Deltamethrin	14.5×10^6	17×10^6–27×10^6
HERBICIDES	Rapeseed	Metazachlor	3.56×10^5	4.75×10^5–9.95×10^5
FERTILIZERS	All crops	P2O5 (phosphorus)	3.08×10^5	1.59×10^5–3.82×10^5
HERBICIDES	Soybean	Imazamox	2.75×10^5	3.61×10^5–7.77×10^5
HERBICIDES	Soybean	Cycloxydim	2.48×10^5	3.54×10^5–4.51×10^5
HERBICIDES	Soybean	Flufenacet	2.26×10^5	2.71×10^5–6.03×10^5
HERBICIDES	Maize	Mesotrione	0.86×10^5	0.86×10^5–1.78×10^5
FUNGICIDES	Wheat	Tebuconazole	0.61×10^5	0.63×10^5–1.54×10^5
HERBICIDES	Maize	Terbuthylazine	0.61×10^5	0.61×10^5–1.27×10^5
HERBICIDES	Rapeseed	Propaquizafop	0.03×10^5	0.57×10^5–0.91×10^5
HERBICIDES	Wheat	Propoxycarbadone sodium	0.39×10^5	0.39×10^5–0.81×10^5
FUNGICIDES	Wheat	Prothioconazole	0.38×10^5	0.38×10^5–0.99×10^5
INSECTICIDES	Maize	Chlorantraniliprole	0.13×10^5	0.19×10^5–0.38×10^5
HERBICIDES	Wheat	Amidosulfuron	0.15×10^5	0.15×10^5–0.30×10^5
HERBICIDES	Wheat	Mefenpir-diethyl	0.12×10^5	0.12×10^5–0.26×10^5
HERBICIDES	Soybean	Metribuzin	0.10×10^5	0.12×10^5–0.26×10^5
INSECTICIDES	Wheat	Lambda-cialotrina	0.07×10^5	0.11×10^5–0.18×10^5
HERBICIDES	Maize	S-metolachlor	0.07×10^5	0.07×10^5–0.14×10^5
HERBICIDES	Wheat	Tribenuron methyl	0.06×10^5	0.06×10^5–0.14×10^5
HERBICIDES	Soybean	Tifensulfuron methyl	0.01×10^5	0.03×10^5–0.06×10^5
FERTILIZERS	All crops	N (nitrogen)	0.04×10^5	0.02×10^5–0.06×10^5
HERBICIDES	Wheat	Iodosulfuron-methyl-sodium	0.02×10^5	0.01×10^5–0.03×10^5
HERBICIDES	Soybean	Bentazon	0.007×10^5	0.01×10^5–0.02×10^5
HERBICIDES	All crops	Glyphosate	0.0006×10^5	0.0016×10^5–0.0017×10^5
HERBICIDES	Wheat	Chlorsulfuron	0.0001×10^5	0.0001×10^5–0.0002×10^5

The most critical substance in the field is Deltamethrin, an insecticide applied to Rapeseed that is highly affecting the water pollution according to its chemical features. Table 7 shows the Rapeseed is the crop having the highest grey WF value during the crop rotation due to the chemical substances required in the field.

4.2. Soil Tillage Solutions to Reduce the Impact on Water Pollution throughout the Dilemma of Intensification or Extensification in Agriculture

Soil tillage systems have different effects on water pollution in terms of intensive or extensive agriculture [44]. As mentioned in the results part, only the MT VRA technique provides a good compromise between grey WF reduction in terms of m^3 $tons^{-1}$ or m^3 ha^{-1}. The further use of VRA management delivers a better choice in grey WF reduction. ST VRA and NT VRA, especially, have a high grey WF reduction for an intensive agriculture. This is more visible in Figure 4, where the graph describes a different pattern of grey WF undergoing precision or no-precision agriculture and regarding different possible solutions to achieve yield productivity without increasing the water pollution. The direct and indirect water pollution of a crop rotation under different tillage practices can be considered for agricultural extensification or intensification proposal. Different soil tillage techniques are addressed in different perspectives for the water pollution impact across an intensive or an extensive agriculture [46]. As shown in Figure 4, the MT has the lower grey WF in terms of m^3 ton^{-1} and m^3 ha^{-1}. This means that MT practice can minimize both in an extensive and in an intensive agriculture. MT can be assumed as the referenced tillage system for further case studies like the more sustainable tillage system in terms of indirect effects on water pollution. MT compromises the perspective of an intensive or an extensive agriculture reducing the grey WF in both of the cases. When precision agriculture is addressed on ST and NT, the impact is reduced either on the extensification or on the intensification perspective. Precision agriculture decreases the grey WF of MT on the only extensification perspective. In other hands, the use of a more efficient soil management like the precision agriculture with a variable rate application can reduce the impact of water pollution. The VRA management decreases the effects of extensification of water pollution for all the tillage practices, while it decreases also the effects of intensification on water pollution for the ST and NT practices.

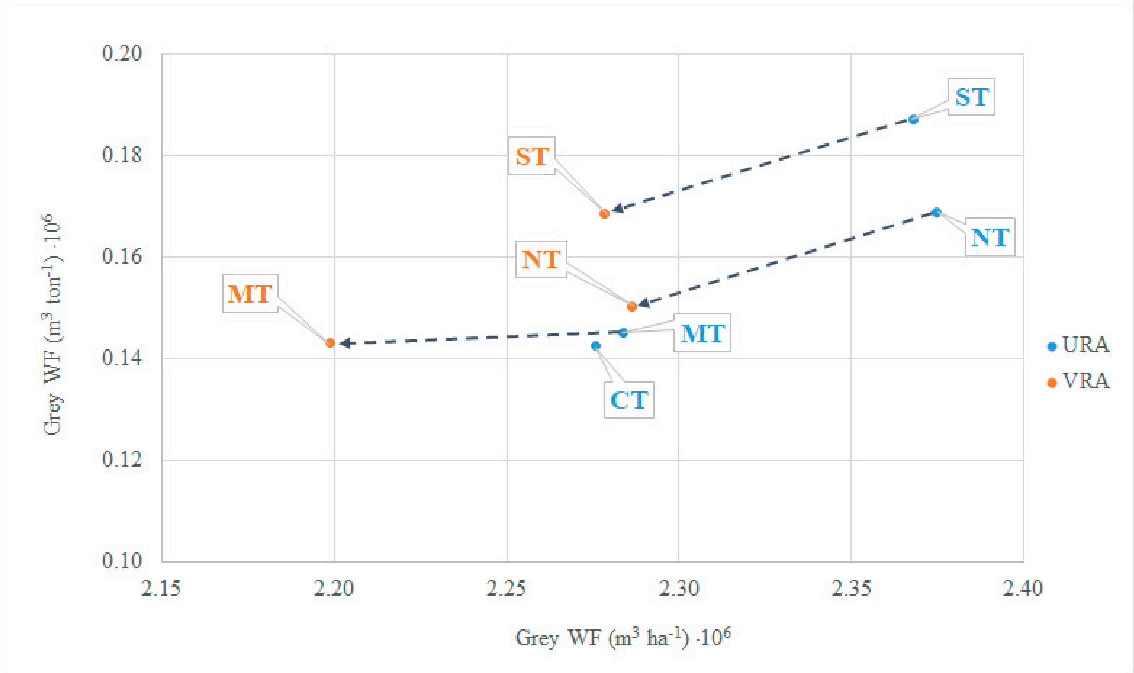

Figure 4. The pattern for suitable soil tillage practices under precision agriculture and over a three-year crop rotation, regarding the grey WF in terms of m^3 ton^{-1} and m^3 ha^{-1}.

The grey WF estimated in this paper does not consider more than three years of crop rotation. A further study might be done for a future scenario for more than ten years in order to understand the long-term effects of tillage systems for multiple crop rotation. The field dataset could calibrate the models for the long-term scenario in order to replicate the experiment in other location, climate, and different soil condition. A statistical analysis of variability is not shown since there is not a clear trend between variables in all the tests. The number of tests does not permit to having a clear picture of the variance.

5. Conclusions

The case study describes how different methods of soil management enhance a grey water footprint reduction. The study focuses on the synergetic effects of different soil practices as different soil tillage systems and the use of variable rate application, which have a positive grey WF reduction. Accordingly, the grey water footprint pattern is shown considering an extensive or intensive farming system. The results highlight which interaction between soil tillage systems and soil management reduces the grey WF of soil practices. The variable rate application consistently decreases the impact on water in terms of water pollution and chemical soil degradation. The Minimum Tillage presents a lower WF, both in terms of m^3 ton^{-1} and in m^3 ha^{-1} with the use of Precision Farming. ST VRA and NT VRA have a higher grey WF reduction in terms of m^3 ton^{-1} with a 10% and 11% of reduction respectively. The grey WF of Nitrogen application is better reduced within MT VRA in terms of m^3 ha^{-1} by the 9.5%. In order to decrease the water pollution and following agronomical best practices, we should prioritize the reduction, for example, of the amount of insecticides and herbicides more than fertilizers, or choose chemicals with a lower grey WF, or use an aforementioned sustainable soil management, or the interaction of all of these solutions. The case study provides suggestions for suitable soil management in order to reduce the water pollution. Further improvements of the study should consider the consumptive impact on water resource using different soil practices, in order to analyze the water saving through the soil moisture available for the crop. Furthermore, the study considers a three-year crop rotation; an additional work could consider a longer-term effect of tillage systems.

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