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Operating performance of manual, semi-automatic, and automatic tractor guidance systems for precision farming

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Abstract: Precision agriculture is increasingly relying on tractor auto-steer systems to boost productivity and optimize crop inputs. Identifying field variations and performance, on the other hand, is necessary for giving site-specific recommendations. This study reports the field operating performance indicators of manual (MG), semi-automatic (SG), and automatic (AG) tractor guidance for weed control in wheat production in Southern Italy. Performance indicators include effective worked area, overall working time, effective field capacity, field efficiency, fuel consumption, and product usage. The SG tractor guidance working times were similar to the MG, but with significant savings in the herbicide spray solution and work quality. In terms of all parameters examined, the AG outperformed the SG and MG. The AG was 54% faster than the MG, resulting in an increased area worked and effective field capacity of 5 and 46%, respectively. The total time (effective time plus non-productive time) was reduced by 28%, while overlapped areas by 88.9%. Herbicide and fuel input was reduced by 30 and 11.5%, respectively. A streamlined environmental analysis indicated that AG could reduce the energy and carbon intensity of the one-time weed control process by 25 and 27% for each hectare. Our results confirm that auto guidance provides numerous benefits (e.g., machining uniformity, increased work quality, reduced resource use, and reduced environmental burdens), supporting the larger goal of agricultural production sustainability.

Keywords: automated guidance system; smart agriculture; self-steering tractors; variable rate technology

Global population growth, climate change, and increased competition for natural resources are influencing the overall sustainability of food and agricultural systems (Calicioglu et al. 2019). High-input, resource-intensive farming systems, on the other hand, put additional strain on already-strained natural resources by increasing greenhouse gas emissions, and deforestation, and land degradation (FAO 2017). As a result, the primary goal of contemporary agriculture is to dramatically increase agricultural output while remaining ecologically sound, economically viable, and socially just. Since 1962, the Common Agricultural Policy (CAP) has played a crucial role in assisting the EU's transition to sustainable farming. A new CAP set to start on January 1, 2023, is designed to shape the transition to a sustainable, resilient, and modern European agricultural sector. Under the reformed policy, farmers will be supported to take up innovations, from precision farming to agroecological production methods. Precision agriculture (PA), a whole-farm management approach, proposes emerging and modern technologies such

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as sensors, information systems, enhanced machinery, and informed management to help with production efficiency and stability (Erickson and Fausti 2021) by accounting for variability and uncertainties within agricultural systems. It contributes to the larger goal of ensuring agricultural production's sustainability by bringing benefits to both farmers and society through increased resource efficiency, profitability, and environmental protection.

The use of automated guidance for agricultural vehicles coupled with computer technology is one of the most widely used PA technologies. Guidance systems (mechanical or electronic) allow precision cultivation at greater speeds with a reduced risk of crop damage associated with operator steering errors (D'Antonio et al. 2015). Other potential benefits include increased productivity and accuracy, together with enhanced operational safety (Ünal and Topakci 2015).

Since 2011, there has been a surge in interest in automatic guidance systems for a variety of agricultural applications. Alonso-Garcia et al. (2011) developed an autonomous guidance system for a tractor and investigated the use of a low-cost GPS as the sole positioning sensor for guidance. Holpp et al. (2013) investigated the driving performance and ergonomic effects of automatic guidance systems in commercial farms across the Czech Republic for the operations of primary tillage, seedbed preparation, and sowing. Ünal and Topakci (2015) designed and built a GPS-guided, remote-controlled autonomous robot for use in precision farming applications in Turkey. Oksanen (2015) investigated the performance of a four-wheel-steered tractor used in an autonomous spring wheat sowing operation in southern Finland. Han et al. (2015) conducted field validation tests of auto-guided tractors for tillage operations in South Korean paddy fields. Lipiński et al. (2016) compared manual and automatic steering modes for farming operations in Poland to see if the benefits of automatic guidance outweighed the cost of paid GPS signal access. Marucci et al. (2017) investigated the use of network RTK in GNSS technology for weeding operations in wheat cultivation in hilly areas. Guo (2018) developed methodologies for improving and designing guidance features for operating guidance systems in contour and terrace fields in the USA. Radicioni et al. (2020) reported the results of an experimental campaign in Central Italy to optimize automatic and semi-automatic guidance systems for agricultural machinery based on real-time positioning services provided by GNSS Networks (NRTK). Scarfone et al. (2021) compared semi-automatic guidance with manual guidance in wheat sowing in Italy. Han et al. (2021) created a prototype of an autonomously driven agricultural vehicle and tested it in apple farming in South Korea. In the United States, Kharel et al. (2020) explored the relationships between tractor guidance systems and field shape and terrain attributes on tractor path overlap. Ashworth et al. (2022) assessed the environmental consequences of pasture management with and without the use of tractor guidance.

Positioning systems on a tractor with automatic guidance systems are exploited to optimize processes of conventional farming, such as the distribution of fertilizers, herbicides, and pesticides, to reduce soil erosion and preserve the soil's organic matter. Although automated guidance systems are widely used in precision agriculture, determining field performance and variations is critical for precision farming applications to better select the most suitable option for a given farm operation. This study aims to compare the field operating performance of manual (MG), semi-automatic (SG), and automatic (AG) tractor guidance systems for optimal weed control in cereal crop production in southern Italy. Site-specific pest control is important for both economic and environmental reasons, as extensive pesticide applications incur unnecessary costs and harm the environment.

MATERIALS AND METHODS

Experimental site. The experiment was conducted in a durum wheat field located near Melfi (Potenza, Italy). Figure 1 shows (highlighted in yellow) the boundaries of the study field. The total experimental surface was about 18 ha (41°01'04.4" N 15°43'30.5" E). Within the field, three contiguous test plots were chosen (Figure 1A – highlighted in red, blue, and green). The sub-plots were approximately 3 hectares in size (rectangular with sides of 417 and 72 m) and were appropriately delimited by signal poles along the borders. Altitude ranged from 220 to 290 m or more above sea level. The study area was flat, as shown in Figure 1B, with an average slope of 5.5%, except for a strip of land with an average slope of just over 15%.

Before field testing, the chemical and physical properties of the soil were investigated. Spatial variations of electrical resistivities were assessed

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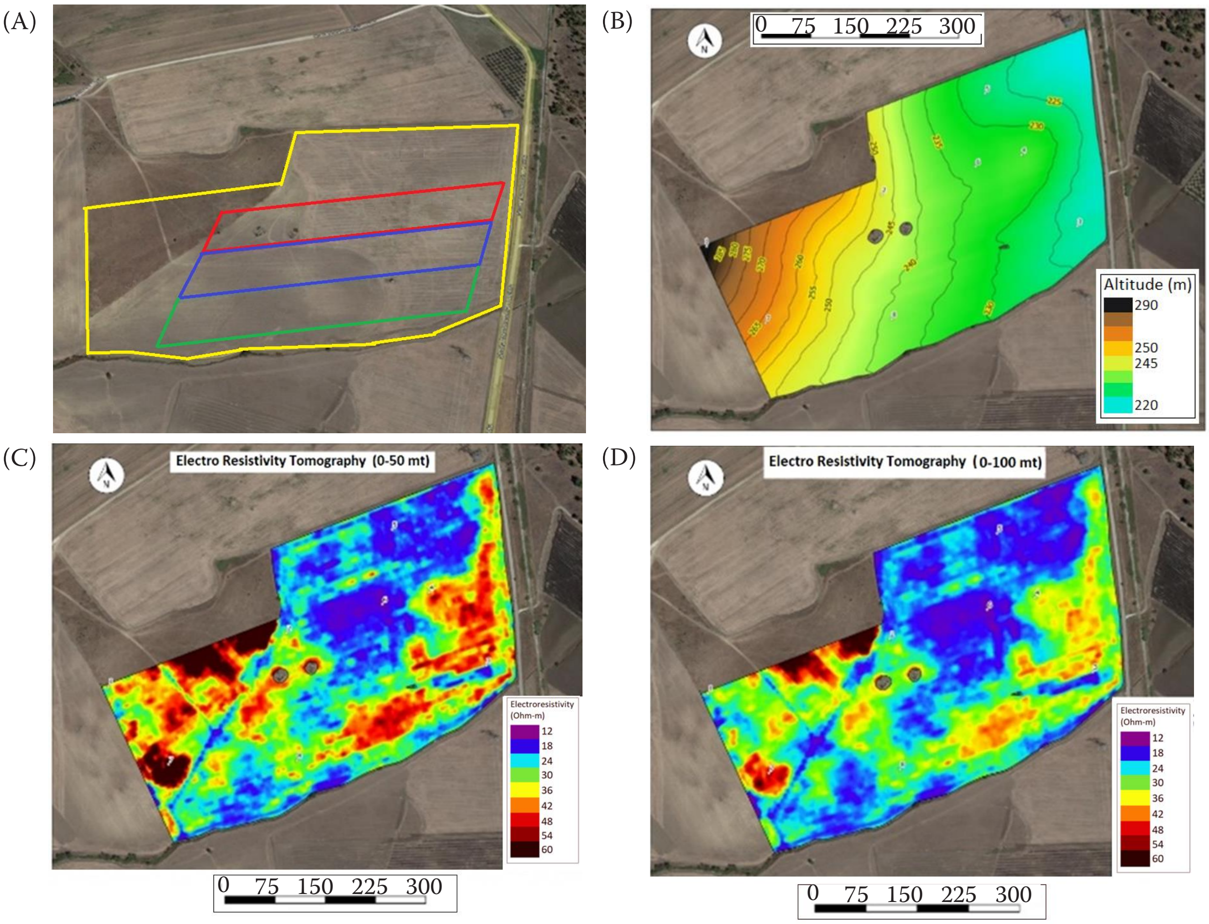

Figure 1. (A) The study field and soil sample points, (B) map of soil elevation above the sea level with contour lines, (C) electrical resistivity tomography map at 50 m depth, and (D) electrical resistivity tomography map at 100 m depth the three different managed plots are shown in different colors (in Figrue 1A)

through Electrical Resistivity Tomography Electroresistivity maps (Figures 1C and 1D). The maps in Figure 1C and D show that the resistive areas are mostly concentrated in the southeast and northwest of the field, while an area of low resistivity is distinguishable in the northeast of the field. The soil has a clay texture and vertex characteristics (high potential for swelling and contraction of clays). The soil is a sandy clay loam, with: 61.2% of sand, 16.3% silt, and 22.5% of clay (Fiorentino et al. 2020). The soil appears dark in color; this is due to the high fraction of organic matter, which is very well-humified and strongly linked to the mineral part. Along the vertical profile, the soils are very homogeneous in terms of texture and organic carbon content. This aspect is typical of vertisols because the expandable clays create a continuous mixing of materials. The skeleton present in moderate quantities is useful for ensuring better soil drainage. Even a moderate content of fine sand (around 20%) to the detriment of silt is useful for improving the structure and consequently drainage. This type of soil benefits greatly from minimal tillage. In the field, for the last few years, only direct drilling has been adopted, recording a very high level of organic substance and having positive effects on yields generally higher than the average of neighboring farms.

Guiding strategies. The experimental design was devised to compare the MG, SG, and AG guidance systems for the same agricultural operation (herbicide application for weed control). In the MG strategy, the operator carried out the required field operation by manually guiding and controlling the tractor and herbicide application. The precision of the operation was influenced by the operator's experience and knowledge of the operations, as well as all of the limitations associated with manual driving (overlaps, failures, conditions of poor visibility, fatigue, speed limits in advance, etc.). In the SG mode, the operator used an X30 (Topcon Precision Agriculture USA) console with an LCD and touchscreen to assist the field operation (Figure 2). The X30 helped the operator guide the machine along the desired path. When traveling along the set waylines, an LED lightbar is displayed at the top of the console, and the LED lights display the direction and amount of inaccuracy (guidelines).

Despite the presence of an operator on board (as required by Italian law), all operations (including turning at the end of the field) in the AG were fully automated and performed using Topcon's System 350 (auto steering with the X30 console, the AGI-4 receiver/steering controller, and an AES-25 electric steering system) supported by Real-Time Kinematic-Global Navigation Satellite System (RTK-GNSS)-related corrections. According to the maps imported into the system, the tractor moved autonomously using a differential global positioning system (DGPS) signal via the RTK system. In theory, the operator must disengage only if an obstacle (people, livestock, or others) is in or moves into the path of travel.

Machinery equipment. Firstly, the three experimental plots were identified in the field, and all management strategies have been performed in four replications. The maps were imported on the tractor console before field operations. A GPS receiver was used to analyze real-time tractor operation data. The sensor signals were acquired using a data acquisition module, and the data were processed using Topcon's SGISfarm Data Management software (version 3.1). Following that, using vector data, it was possible to draw the tractor's maps and trajectories on a CAD spreadsheet, allowing the differences between guidance systems to be evaluated. The machine unit under test (Figure 2) was a 102 HP (75 kW) Massey-Ferguson 5435 tractor (France). It is powered by a diesel Perkins 1104C-44 with a maximum torque reserve of 380 Nm at 1 400 rpm and a fuel tank capacity of 150 L. The transmission features a gearbox 16FW + 16R with a top speed of 40 km h^{-1}, four-speed groups, and two ranges with electro-hydraulic selection and two-speed power shift transmission. The speed ratio of the engine to the PTO is 540/1 000 rpm. The 1 000 Kuhn Deltis tractor-mounted sprayer was coupled to the tractor using an automatic Easy Hitch attachment system for herbicide application. The machine has an 18-meter spraying width and a piston pump version of 125 L min^{-1} that is controlled by dynamic pressure regulators and variable speed controllers.. The sprayer tank is made of polyethylene and has a perfectly smooth interior and exterior walls to facilitate cleaning. The work pressure can range from 1–4 bars. The spray system was modified for variable rate application, allowing herbicide solution to be applied site-specifically based on prescription maps for SG and AG. A spraying electronic control unit such as Topcon ASC-10 was used as a liquid rate controller. ASC-10 allowed automatic control of the wedding tank spraying based on position or prescription maps, as well as variable rate control (VRC).

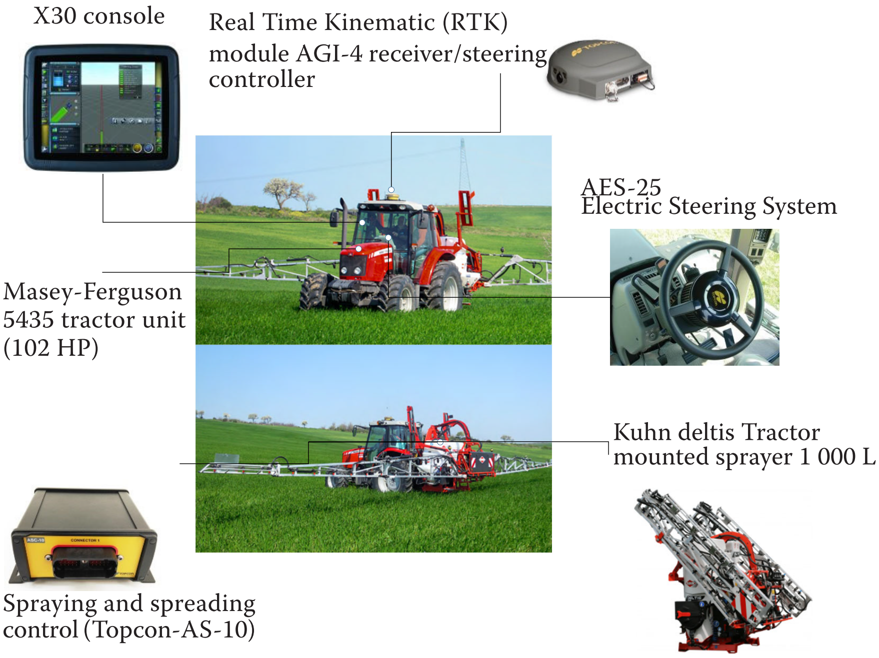

Figure 2. Tractor unit and equipment used in the field experiment

Key performance parameters and indicators. A series of parameters and performance indicators were used for performance comparison (Table 1). Parameters such as area worked, missed area (failures), overlapped area (overlaps), tractor forward speed, the total time (effective time plus non-productive time) taken to complete the operation, fuel consumption, and product usage were acquired during the field test. The effective field capacity (*EFC*), theoretical field capacity (*TFC*), field efficiency (*FE*), and energy and environmental indices were estimated using the field test data. *TFC*, *EFC*, and *FE* are shown in Equations (1–3), respectively.

$$TFC = W_t \times V_t \tag{1}$$

$$EFC = \frac{A}{T_e + T_t} \tag{2}$$

$$FE = \frac{EFC}{TFC} \times 100 \tag{3}$$

where: W_t – the theoretical working width (m); V_t – the tractor's theoretical operation speed (km·h^{-1}); A – the worked area (m^2); T_e – the effective time taken to perform its intended functions (min); T_t – the time to complete turning at the end of the field i.e. non-productive time including row-ends, stops for equipment adjustments, driver breaks, and cleaning various parts of the machine (min).

We further computed life cycle energy, carbon footprint, toxicity potential, and total environmental impact intensity for the one-time weed control process using cumulative energy demand (Frischknecht et al. 2015) and ReCiPe 2016 (Huijbregts et al. 2017) models. Impacts were computed for 1 ha of weeding operation. Environmental impacts were tracked by translating changes in fuel, herbicide solution (including mixing), and machinery inputs. Thus, the impact accounted for fuel production and combustion, pesticide (glyphosate) production and application, spray solution mix, and the production, amortization, and maintenance of farm machinery. The GHG emission factors of gasoline and diesel fuel combustion are reported (Nemecek et al. 2007) as 3 kg CO_2·kg^{-1} for gasoline and 3.12 kg CO_2 ·kg^{-1} for diesel, respectively. The production of 1 kg of farm machinery requires 126.5 MJ and releases around 6.1 kg CO_2-eq and 34 kg 1,4-DCB-eq. For each kilogram of pesticide produced and transported at the farm gate, around 205.3 MJ are consumed and 11.48 kg CO_2-eq and 52 kg 1,4-DCB-eq are released. The OpenLCA software (version 1.11) (GreenDelta 2022) was used to calculate the impacts.

Table 1. List of the key physical performance indicators

Parameter	Unit	Definition/Remarks
Area	ha; m^2	the effective area where the desired field operation was performed
Overlapped area	ha; m^2	the part of the total area where the desired operation was performed more than once by the machinery
Missed area	ha; m^2	the part of the total area that was left undisturbed by the tractor, i.e. areas where the desired operation did not occur
Tractor forward speed	km·h^{-1}	travel speed of the tractor to perform the desired field operation
Turning time	min	the time needed for turning the tractor at the end of the field. It is accounted as non-productive time. It includes turning times at row-ends, stops for equipment adjustments, driver breaks, and cleaning various parts of the machine
Effective operating time	min	time is taken to perform its intended functions, i.e desired field operation within field boundaries
Total time	min	total time (including turning time) taken to perform the desired field operation within field boundaries
Effective field capacity	ha·h^{-1}	it's the actual average rate of coverage by the machine. It is easily calculated by dividing the surface area completed by the hours of actual field time
Field efficiency	%	the ratio of actual or effective field capacity to theoretical field capacity is called the machine's field efficiency
Fuel consumption	L·ha^{-1}	the rate at which an engine uses fuel. It is quoted in kg·h^{-1} or L·h^{-1}
Herbicide rate	L·ha^{-1}	the volume of spray mixture (herbicide and water) applied per unit area

RESULTS

Forward speed and area covered. The three driving systems performed differently, as evidenced by the analysis of speeds and operating times. During operation, the average tractor forward speed (*TFS*) ranged from 7.65 km·h^{-1} in manual mode to 11.6 km·h^{-1} in automatic mode (Figure 3A). The latter enabled accurate, precise automatic control of the tractor or implementation along the predefined trajectory, resulting in higher speeds with values ranging from 10.7 to 12.6 km·h^{-1}.

Because the total test area was the same (3 ha), the effective field area varied between driving modes. A total working area of 30 400 m^2 was recorded in MG (Figure 3B). The total worked areas were found to be 30 170 m^2 and 30 180 m^2 for SG and AG, respectively. The MG produced 454.15 m^2 of the overlapped area (1.5% of the total worked area) and 1 208.16 m^2 of the missed area (4% of the total worked area). SG reduced the overlapped area to 183.06 m^2 (0.6%) and the missed area to 420.65 m^2 (1.4%). The performance of AG was found to be better than SG, with 50.45 m^2 (0.2%) of the overlapped area and almost none of the missing area (Figures 3C and D). Similar findings were obtained from Singh et al. (2021), which demonstrated that missed areas were reduced from 15 to 3.75% and overlapped areas were reduced from 12 to 3% when navigator systems were used as compared to without navigator assistance. Ashworth et al. (2022) found that the use of tractor guidance compared to manual tractor guidance reduced gaps by 7.6 and 10.1%, and reduced absolute overlaps by 32.5 and 4.2% during herbicide and fertilizer application. Tractor overlaps and gaps during field operations cause additional wear as well as fuel and time consumption (Heiß et al. 2019), time loss, and reduced production efficiencies (Kharel et al. 2020; Singh et al. 2021), resulting in additional economic losses and environmental impacts. In particular, intensive agricultural management reduces fertility while increasing compaction and erosion, increasing the risk of desertification in the long run. The risk associated with intensive soil tillage

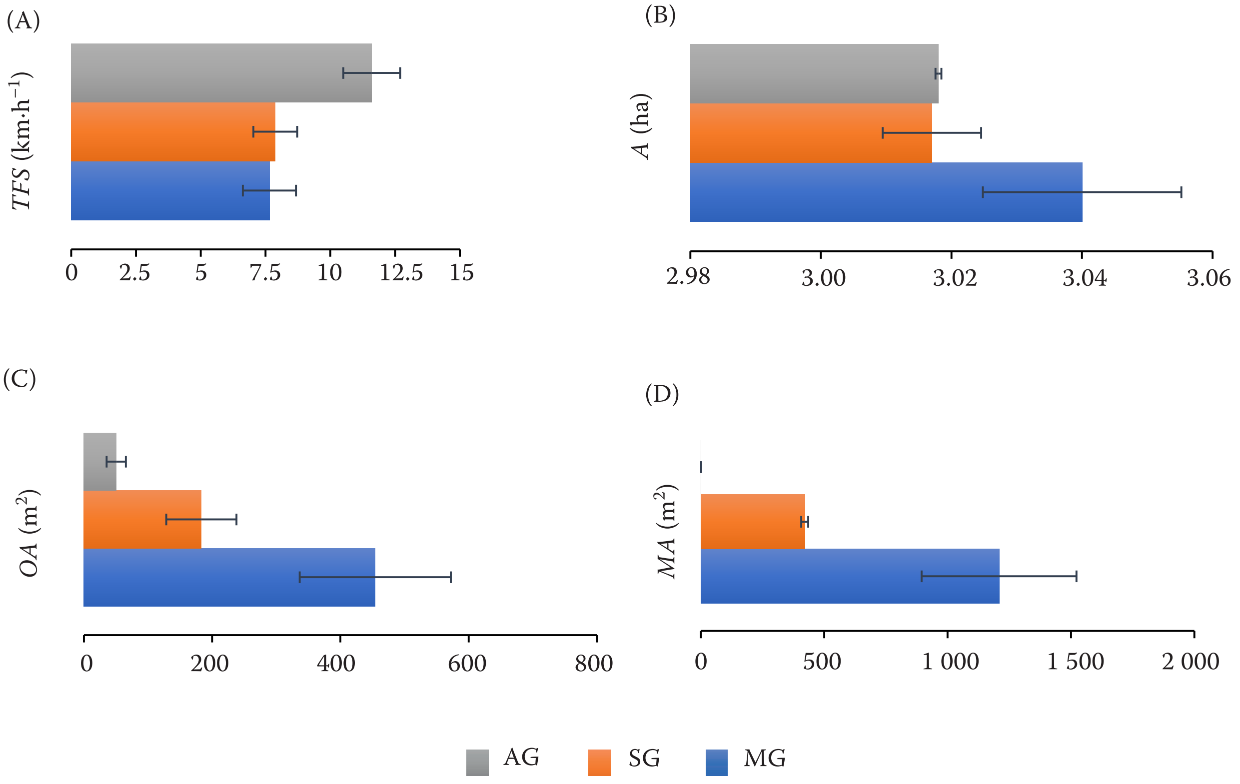

Figure 3. Field performance evaluation for manual (MG), semi-automatic (SG), and automatic (AG) tractor guidance in terms of the (A) average tractor forward speed (*TFS*); (B) total area worked (*A*); (C) overlapped area (*OA*); and (D) missed area (*MA*)

vertical bars indicate standard deviation

and heavy machinery traffic penalizes the roles of soil porosity and structural stability as essential elements for maintaining agricultural land fertility. Thus, land management based on conservative agriculture principles and techniques, implemented with operating machines equipped with the most advanced mechatronic innovations such as GNSS, has a significant potential for reducing greenhouse gas (GHG) emissions and protecting soils from potential threats to their fertility (Furlan et al. 2018).

Time, field capacity, and field efficiency. The effective operating time of the field operation (Figure 4A) was 12.72 min in MG, 12.67 min in SG, and 8.58 min in AG. The turning times for MG, SG, and AG at the end of the field were 44 s (0.73 min), 44.5 s (0.74 min), and 39.25 s (0.65 min), respectively. As a result, MG worked 15.65 min, SG 15.63 min, and AG 11.2 min.

For MG, SG, and AG, the corresponding effective field capacity values (Figure 4C) were 11.65, 12.15, and 17.01 ha·h^{-1}, respectively. The field efficiencies of the operation (Figure 4D) were then calculated to be 58, 58, and 80%, respectively. Field efficiency is directly related to the operating system's economic performance (Zhou et al. 2020). Typical average values for field efficiency of agricultural operations ranged from 50 to 90% (Zhou et al. 2020). Our findings regarding field efficiency are consistent with earlier observations on the field operating performance of automatic guidance. Topcuer and Keskin (2019) found that GNSS-based automatic steering (AS) systems were beneficial in reducing the overlap and spacing errors in parallel adjacent passes in spraying as compared to manual steering. Scarfone et al. (2021) found that SG resulted in a 6.6% reduction in working time and 19.2% higher effective field capacity compared to manual mode. The authors estimated that SG gives the farmers the possibility to sow 1.2 additional hectares per day, and reduce the sowing cost by 2.4%, corresponding to net savings of EUR 3.79 ha^{-1}. The findings of Holpp et al. (2013) showed guidance systems increased the average steering accuracy and delivered a lower heart rate. While driving speeds, turning times, and working-width utilization were in some cases more advantageous with a guidance system but did not differ statistically significantly

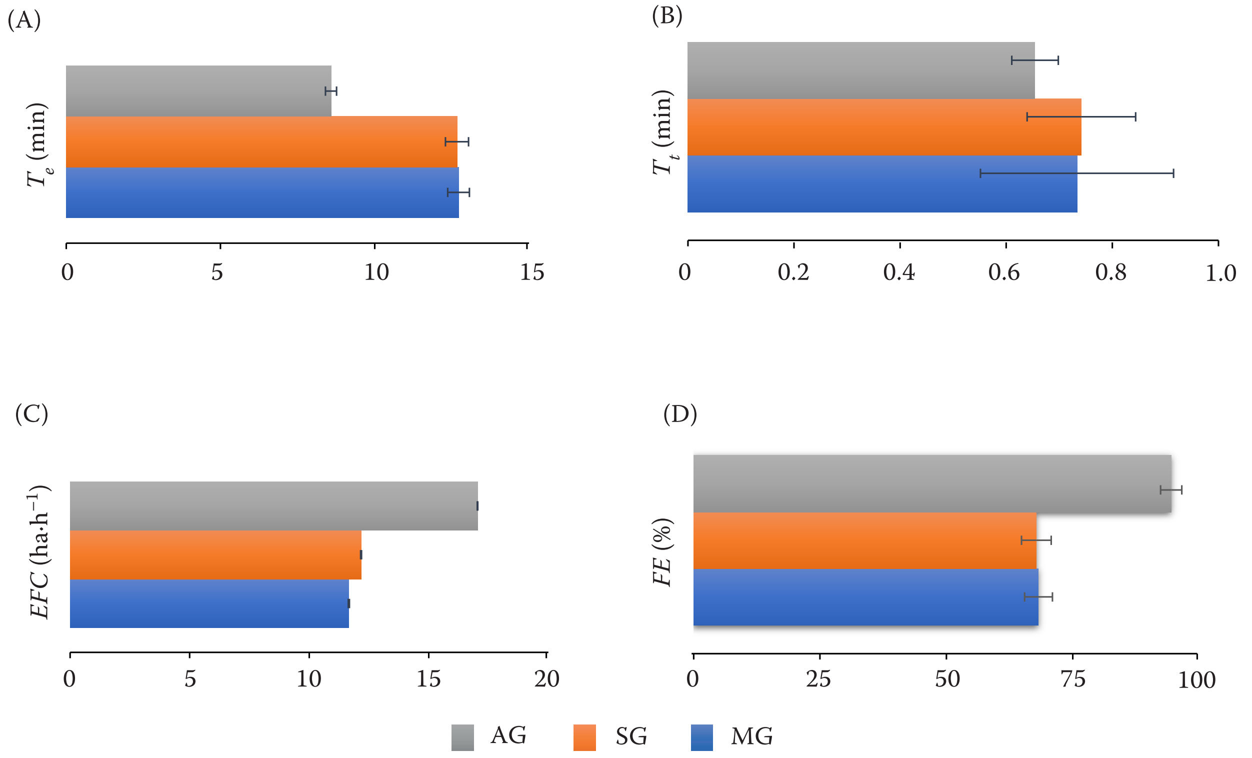

Figure 4. Evaluation of field performance for manual (MG), semi-automatic (SG), and automatic (AG) tractor guidance in terms of (A) effective operating time (T_e); (B) turning time at the end of the field (T_t); (C) effective field capacity (*EFC*); and (D) field efficiency (*FE*)

vertical bars indicate standard deviation

without the use of guidance systems. Han et al. (2021) found that autonomously driven agricultural vehicles using low-cost navigation sensors follows with minimum errors the desired trajectories.

Resource and product usage. Figure 5A depicts the rate of fuel consumption. During the experimental trials, 2.37, 2.35, and 2.19 L of fuel were consumed for MG, SG, and AG, respectively. As a result, the fuel consumption per hectare for MG, SG, and AG was 0.78, 0.74, and 0.69 L, respectively. The fuel consumption per hectare decreased as the tractor's forward speed increased. The tractor's increased forward speed shortens the time required to complete the operation, resulting in lower fuel consumption.

For MG, SG, and AG, the tractor implementation and maintenance (mass of tractor manufacture and amount of materials required for maintenance) are 0.059, 0.06, and 0.043 kg·ha^{-1}, respectively. The total herbicide spray solution (Figure 5B) in MG was 720 L, 530 L in SG, and 527 L in AG. These values were 236.8 L·ha^{-1} for MG, 167.2 L·ha^{-1} for SG, and 166.2 L·ha^{-1} for AG. As a result, the use of AG has the potential to improve agricultural sustainability by optimizing crop inputs while decreasing fuel consumption. Scarfone et al. (2021) found that SG resulted in a 6.3% fuel savings compared to manual mode. Sartori et al. (2014) demonstrated that assisted steering could reduce fuel consumption by 25 to 44% (17.4 to 44 kg·ha^{-1}) in comparison with manual mode. Conversely, Ashworth et al. (2022) found that tractor guidance systems translated to greater fuel usage due to the combination of more effective coverage (of agrochemicals), sloped terrain in these pasture systems, and automated speed, all culminating in reducing fuel efficiency gains. In general, is well-accepted that fuel economy improves with semi-automatic and automatic guidance systems.

Energy and environmental impact intensity. The energy required per ha for one-time weeding using MG was found to be 287.5 MJ·ha^{-1}, 222.4 MJ·ha^{-1} for SG, and 217 MJ·ha^{-1} for AG (Table 2). Global warming (GWP) was estimated to be 16.46 kg CO_2-eq ha^{-1}, 12.79 kg CO_2-eq ha^{-1}, and 12.48 kg CO_2-eq ha^{-1}. When SG and MG are compared, the estimated energy and carbon footprint savings are 23% (65 MJ·ha^{-1}) and 25% (3.67 kg CO_2-eq ha^{-1}). With AG these benefits are 25% (70.5 MJ·ha^{-1}) and 27% (3.98 kg CO_2-eq ha^{-1}), respectively. Ashworth et al. (2022), found that the use of tractor guidance compared to manual tractor guida nce resulted in an 8 to 12% reduced environmental impact on pasture management scenarios.

The range of glyphosate dose per hectare in Italy is 0.3 kg a.i. ha^{-1} while for EU28+4 level is 0.2 kg a.i. ha^{-1} (Antier et al. 2020). For wheat, the glyphosate rate is 0.5–2 kg a.i. ha^{-1} (Antier et al. 2020). Despite policy recommendations, high-input practices are often implemented by farmers, thus, the use of variable-rate equipment and technology allows savings

Table 2. Energy and environmental impact intensity of one-time weed control (1 ha) using manual (MG), semi-automatic (SG), and automatic (AG) tractor guidance

Indicator	Unit	MG	AG	SG
CED	MJ·ha^{-1}	287.50	222.40	217.00
GWP	kg CO_2-eq·ha^{-1}	16.28	12.27	11.93
Toxicities	kg 1,4-DCB-eq·ha^{-1}	65.72	47.55	46.57
TEI	point	3.93	3.09	2.97

CED – cumulative energy demand; GWP – global warming; TEI – total environmental impact; toxicity potential include human, freshwater, marine and terrestrial sources

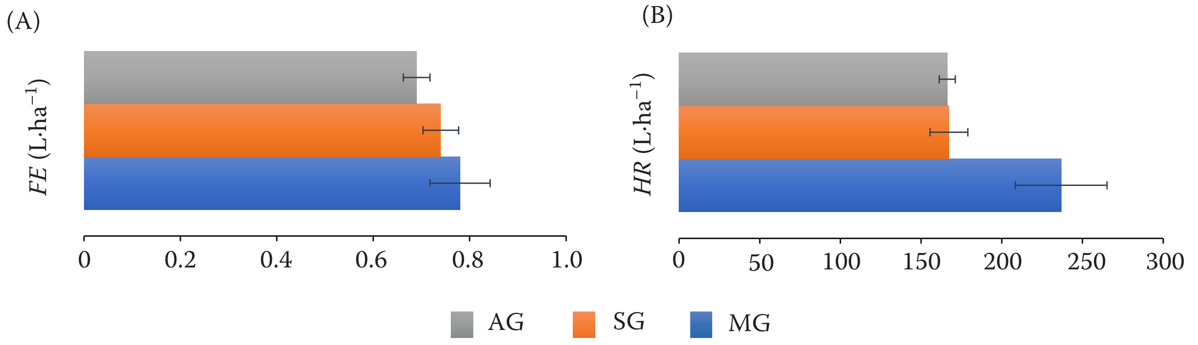

Figure 5. Evaluation of field performance for manual (MG), semi-automatic (SG), and automatic (AG) tractor guidance in terms of (A) fuel consumption (*FE*) and (B) herbicide spray solution rate (*HR*)
vertical bars indicate standard deviation

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in the use of herbicides, better weed control, and lower environmental impact. The savings in the use of herbicides due to AG in wheat production could range from 0.15 to 0.6 kg a.i. ha^{-1} and carbon footprint from 1.7 to 6.88 kg·CO_2-eq ha^{-1}. Pesticide manufacturing represents only a small portion of energy and GWP from arable crops as fertilizers and related-field emissions of nitrous oxide from the soil play a major role. Nevertheless, pesticide (fungicide, herbicide, insecticide) application is considered one of the primary sources of diffuse pollution contributing to environmental impacts in various ways, including human toxicity, terrestrial toxicity, freshwater toxicity, and aquatic toxicity. Thus, further benefits in terms of reduced toxicity impacts during or after the application of herbicides can be expected. The final benefits will vary by crop type and cropping system as well as the frequency of the fieldwork process and level of mechanization.

CONCLUSION

Agricultural vehicle autonomous guidance systems are an essential technology for precision autonomous farming. However, understanding tractor field performance in real-world settings is critical for understanding the differences between different driving strategies. This study reported the field operating performance indicators of the MG, SG, and AG tractor guidance for weed control in cereal crop production in Southern Italy. The results contribute to the determination of the field operating performance data of agricultural tractors on crop operations and provide empirical evidence of whether and to what extent smart farming technologies can provide advantages for farming applications.

Our test results showed that the automatic tractor guidance was 54% faster than manual mode (12.6 *vs.* 8.2 km·h^{-1}) and resulted in an increase in surface area and field capacity by 5% (1.06 ha *vs.* 1.01 ha) and 46% (17.03 *vs.* 11.65 ha·h^{-1}), respectively. The total time required to complete the field operation was reduced by 28% (0.062 *vs.* 0.087 h·ha^{-1}), while overlapped areas were reduced by 88.9% (15.86 m^2 ha^{-1} *vs.* 149.4 m^2·ha^{-1}). In terms of missed areas, there has been a significant reduction. Herbicide and fuel consumption was reduced by 30% (166.2 *vs.* 236.8 L·ha^{-1}) and 11.5% (0.69 *vs.* 0.78 L·ha^{-1}), respectively. The resource efficiency of using AG allows a theoretical reduction of cumulative energy demand by 25% and a carbon footprint by 27% for a one-time weed application. SA tractor guide production times were comparable to MG production times but with significant herbicide and work quality savings. In terms of all parameters examined, the automatic guide outperformed the semi-automatic and manual guides. This study confirms that automatic guidance in agricultural machines provides numerous benefits (e.g., machining uniformity, reduced working time, increased work quality, reduced resource use, and thus reduced environmental burdens), contributing to the larger goal of agricultural production sustainability. The investigations carried out constitute the starting point for subsequent precision agriculture applications. Starting from the optimization of the trajectories and the study of the soil parameters, further agronomic practices such as sowing and variable rate fertilization will be tested. The high investment cost is one major barrier to the adoption of precision farming technologies. As a result, additional research and studies are required to improve field knowledge, assess potential environmental impacts, and investigate the cost-benefit aspects of precision agriculture management strategies.

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