ENVIRONMENTAL IMPACT ASSESSMENT OF TRACTOR GUIDANCE SYSTEMS BASED ON PASTURE MANAGEMENT SCENARIOS

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HIGHLIGHTS

- Tractor guidance (TG) reduced the overlaps and gaps during fertilizer and herbicide applications.
- Production gains with TG on were 2.7% to 6.5% relative to TG off; however, fuel consumption increased.
- A 5% increase in yield is needed to make tractor guidance environmentally remunerating.

ABSTRACT. *The use of auto-guidance on tractors and self-propelled machinery improves agricultural production efficiencies by reportedly avoiding negative environmental impacts from over-applying fertilizers and herbicides. Environmental impacts from auto-tractor guidance systems have not been systematically quantified and are difficult to assess at the farm system level. Therefore, this study uses a life cycle-based assessment to quantify the environmental impacts of deploying tractor guidance (TG) over a range of fertility rates, fertilizer sources (organic and inorganic), equipment, and pasture crops through scenarios based on in-field data (collected with and without TG). The use of TG reduced gaps by 7.6% and 10.1% and reduced absolute overlaps by 32.5% and 4.2% during herbicide and fertilizer application, respectively. Estimated production gains with TG on ranged from 2.7% to 6.5% over the baseline (TG off); however, tractor fuel consumption increased when TG was employed. There was high uncertainty for productivity gain estimates; however, under scenario testing with an assumed 15% yield gain, TG resulted in 8% to 12% reduced environmental impacts across all impact categories relative to non-GPS enabled technologies. Future research should be focused on actual yield-based responses from TG, as well as field emissions, operator experience, and resulting water quality. Overall, yield gains were crucial for improved pasture-based system sustainability when using TG because TG results in fewer gaps and overlaps, thereby resulting in greater input use across pasture landscapes. Consequently, more targeted applications of inputs during production may lead to fewer nutrients in water systems and more sustainable production of food.*

Keywords. *Auto-guidance, Forage systems, Life cycle assessment, Poultry litter, Precision agriculture, Small farms.*

Tractor guidance (TG) is a precision agriculture technology that is reported to enable more spatially precise applications of seed, fertilizer, and agrochemicals when compared to field operations conducted without Global Navigation Satellite System (GNSS) guidance (Ashworth et al., 2018). Consequently, TG may reduce environmental impacts associated with inefficient agricultural input usage (Shockley et al., 2012a, 2012b; Velandia et al., 2013; Vellidis et al., 2014). These TG systems function through real-time kinematic correction based on GNSS signals and can either be added to existing equipment or included as a stock item in new equipment (USDA-NRCS, 2007). In-depth field studies and subsequent environmental analyses are lacking and yet are needed for identifying TG adoption impacts on environmental outcomes, prior to best management practice (BMP) designation.

Based on a USDA report on conservation trends on working lands in the U.S., GNSS-guided autosteer system adoption for corn (*Zea mays* L.) increased from 2005 to 2016 in all regions, except for the Southeast, which decreased its use from 2010 to 2016 (USDA, 2018). Specifically, corn acres grown using TG increased from 13% to 47% to 56% in the

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Corn Belt from 2005 to 2010 to 2016, respectively (USDA, 2018; Schimmelpfennig, 2019). In addition, adoption of TG in soybean (*Glycine max* L.) and wheat (*Triticum aestivum* L.) increased by 25% and 26% over six and four years, respectively (USDA, 2018). Overall, larger farms are more likely to adopt precision agriculture technologies compared to small farms, despite research suggesting the economic feasibility of its adoption on small farms (Lindsay et al., 2018). Therefore, adoption of TG among small-scale forage and cattle producers is largely non-existent and research on the environmental enumeration of TG in pasture systems is needed.

Spatially precise applications of nitrogen (N) and phosphorus (P), through the use of auto-guidance systems, reportedly improves crop production and reduces nonpoint-source pollution across agricultural landscapes (Ashworth et al., 2018; Lindsay et al., 2018). Nutrient runoff and volatilization from soils are associated with negative impacts on atmospheric and water quality (Ashworth et al., 2021). Poultry litter (combination of bedding and excreta) is a common nutrient source for pastures in regions with poultry production because of its abundance and the proximity of broiler houses to pastures where fertilizer is needed to enhance cow-calf profitability in comparison to synthetic fertilizers. Broiler litter typically consists of approximately 3% N, 1.5% P, and 2.5% K (Ashworth et al., 2020). Applications targeting N requirements for forages often exceed the amount of usable P, resulting in higher P concentrations in runoff and increased eutrophication potential (de Koff et al., 2011). Over-application has led to environmental issues and litigation over deteriorating water quality (Moore and Barrentine, 2004; Sharpley et al., 2003). At the same time, environmental impact comparisons of poultry litter and inorganic fertilizers, with and without TG, are nonexistent.

Several authors have highlighted the advantages of tractor guidance through reductions in gaps and overlaps between passes (Balafoutis et al., 2017b; Jensen et al., 2012; Batte and Ehsani, 2006; Kharel et al., 2020a), which may reduce eutrophication of water bodies across agricultural landscapes. This also can increase efficiency of agricultural production; however, empirical field studies are limited. The lack of empirical evidence is likely a contributing factor to the reluctance of pasture managers to adopt TG technologies, despite the potential for improved economic efficiencies and input-use savings. Producers and policymakers need information on potential environmental gains, especially in pastures, which account for 46.8% of all agricultural land in the U.S. and comprise the single largest land-use category of farmland (USDA-NASS, 2017). Hence, increased adoption of precision guided technologies (for applications of poultry litter, fertilizer, herbicides, and seed) on pastures may result in economic benefits for grassland managers as well as more efficient and environmentally sound applications of agrochemicals. However, the environmental impacts associated with the adoption of TG systems are not well established in the literature. Consequently, this study was conducted to assess the environmental consequences of pasture management with and without the use of TG. This study combines experimental data collected during field trials on pasture systems with life cycle assessment (LCA)-based methodologies to quantify the potential environmental costs and benefits of performing pasture management operations, and to evaluate these effects for an average year of pasture management with and without TG (cradle to gate). Simulation archetypes were established with varying nutrient sources (organic and inorganic), equipment, and pasture species to determine the conditions by which environmental impact reductions associated with grassland management could be achieved by adopting TG systems.

MATERIALS AND METHODS

FIELD DATA COLLECTION

Complete documentation of the field data collection and geospatial analysis supporting this assessment can be found in the publications by Kharel et al. (2020a, 2020b). Field trials were conducted during 2018 at the USDA-ARS Dale Bumpers Small Farms Research Center in Booneville, Arkansas, located at approximately 35.087723° N and -93.993740° W.

An experiment was implemented to quantify differences in fertilizer and herbicide application due to TG compared to manual tractor guidance. A New Holland 7040 (NH7040) tractor was used to test TG (both on and off) in six fields (11.7 to 22.5 ha) with a 10 m fertilizer spreader and in four fields (14.7 to 22.5 ha) with a 13 m boom sprayer. The NH7040 tractor was equipped with a 372 receiver, RTX signal (annual subscription), Intelliview IV display, and autosteer option. The autosteer option, 372 receiver, and RTX signal (Trimble Navigation Ltd.) with 15 cm pass-to-pass accuracy were used as a navigation and guidance system on the NH7040 tractor to apply synthetic fertilizer (ammonium nitrate, 168 kg ha^{-1}) and herbicide (Grazon P+D, a.i. picloram and 2,4-dichlorophenoxyacetic acid, Corteva Agriscience, 3.5 L ha^{-1}). Manual tractor operation was used to determine the manually steered baseline using the data collection system without the autosteer feature activated, e.g., the default outcome of overlapped areas and coverage gaps without TG when operating with a fertilizer spreader and sprayer, respectively (Kharel et al., 2020a). Autosteering TG (TG on) was then used to gather data for treatments on the fertilizer spreader and sprayer following a simple A-B line (reference line set for each field for the tractor/sprayer guidance system to follow) on the edge of each field. A single experienced operator (+10 years of professional experience) was used for all the field operations (with and without TG).

After collecting the fertilizer spreader and sprayer data with TG on and off, geospatial analysis was conducted in R software to determine the total covered area, absolute overlapped (double coverage) area, and gaps (no coverage) per implement and field. The data derived from the TG software gave the point (latitude and longitude) location of the tractor as it moved across the field, which were used to generate a polyline. The polyline was separated into individual tracks where turns were detected over 35° from the track. For each polyline track, a swath was generated using a buffer analysis with the respective implement widths. From the swaths, the total covered areas and gaps were determined. Overlapped areas were quantified based on the intersection of independent swaths crossing the field. The total covered area, overlapped areas, and gaps were determined for each field and implement, in addition to their respective fuel efficiencies during operation.

LIFE CYCLE ASSESSMENT

The goal of the life cycle assessment was to evaluate the environmental impacts associated with forage production under various pasture management regimes with and without the use of TG systems. Because the function of the system is to produce hay, the functional unit chosen for this assessment was 1 kg of unharvested forage (dry matter) produced during one year per hectare. The scope encompassed fertilizer and pesticide applications typical of established grassland management practices in the region and did not include initial seeding (assumed identical across scenarios) or forage harvesting (an activity following the established functional unit production). The system boundary encompassed the necessary inputs to provide the functional unit, including upstream activities for production of fuels and fertilizer, but excluded TG infrastructure (i.e., guidance system production). The unit process used for diesel combustion for field activities included an amortized estimate for tractor and ancillary equipment production, as well as combustion and other emissions associated with the operation of field equipment. The operating parameters were designed to be representative of typical pasture operations performed throughout a given year in Arkansas and were informed by experienced grassland managers and extension agents at the University of Arkansas. These parameters informed the simulation constraints, such as the number of fertilizer and pesticide applications in a typical year for a given forage species (Ashworth et al., 2015). Fuel efficiencies associated with each implement with TG on and off were collected during field trials and used in estimates of annual fuel and agrochemical use. Average annual yields were adapted from data presented by Huneycutt et al. (1988), which may present additional uncertainly based on the data pedigree matrix (Weidema et al., 1999). Emissions resulting from applied N were calculated using IPCC Tier 1 methods and included environmental releases of ammonia, nitrous oxide, and N losses via leaching and runoff (IPCC, 2006). Phosphorus lost via runoff and leaching was assumed to be 10% of P applied (Sharpley et al., 2010). The fractions of pesticides applied and emitted to surface water, air, and soil were determined using the methods described by Berthoud et al. (2011) in which the authors relate the vapor pressure of the active ingredient (a.i.) to the proportion emitted to air, water, and soil. Upstream burdens attributable to the production of material and energy use on the farm, as well as fuel combustion emissions, were represented by unit processes from the Ecoinvent v3.4 cut-off system model database (Wernet et al., 2016). Impact categories and characterization factors were adopted from the TRACI 2.1 impact assessment method (USEPA, 2012) because this impact assessment method was developed specifically for U.S. conditions. Life cycle impact assessment was calculated using the open LCA platform (ver. 1.10.2; Ciroth et al., 2020).

ARCHETYPE DEVELOPMENT

Primary experimental data, obtained from the TG field trials during 2018, were used to calculate fuel usage and the agrochemical volume associated with each field and implement with and without TG on a hectare basis. Herbicide TG-on field trials were conducted using water in lieu of agrochemicals, given that each field received repeat applications (from both on and off treatments); this was done to provide efficiency differences without adding additional error associated with field elevation, pass number, field shape, field irregularity, crop, and slope differences. We therefore established operating parameters for distinct field operations, e.g., the application of an agrochemical or fertilizer, using a specified implement, with or without the use of TG across a range of fields to serve as building blocks in archetype construction.

Each archetype was comprised of a series of operations required during a full year of forage production. Archetype operations (species, harvesting, fertilizer, and herbicide applications) were intended to represent a typical year of grassland management for ruminant animal production in the region. The management regimes outlined in consultation with agricultural researchers and regional forage production specialists were delineated into four archetypes intended to capture the intra-regional variation in forage production (Huneycutt et al., 1988). The archetypes encompassed two forages and two fertilizer sources: bermudagrass (BG) [*Cynodon dactylon* (L.)] and tall fescue (TF) (*Festuca arundinacea* Schreb.) using commercial fertilizer (F) and poultry litter (L). The production parameters assigned to each production archetype are described in table 1.

Operating data from the TG field trials were supplemented with experimental data from Huneycutt et al. (1988) to generate yield response curves under each management archetype. Fields trials conducted by Huneycutt et al. (1988) were conducted nearby with the same forage species, climate conditions, soil types, and management practices and were therefore representative of the conditions under which the

Table 1. Management for four forage production archetypes: bermudagrass with poultry litter (BG-L), tall fescue with poultry litter (TF-L), bermudagrass with synthetic fertilizer (BG-F), and tall fescue with synthetic fertilizer (TF-F) (adopted from Huneycutt et al., 1988).

	Production Archetypes			
	BG-L	TF-L	BG-F	TF-F
Fertilizer	Poultry litter	Poultry litter	Synthetic[a]	Synthetic[a]
Application rate (kg N ha^{-1})	168	168	84	84
Frequency (applications per year)	1.0	1.0	4.0	2.0
Total (rate × frequency, kg N ha^{-1})	168	168	336	168
Herbicide	Grazon P+D	Grazon P+D	Grazon P+D	Grazon P+D
Application rate (L ha^{-1})	3.5	3.5	3.5	3.5
Frequency (applications per year)	1.0	1.0	1.0	1.0
Total (rate × frequency, L ha^{-1})	3.5	3.5	3.5	3.5

[a] Synthetic fertilizers applied were ammonium nitrate, monoammonium phosphate, and potassium chloride.

TG trials were conducted for this study. Furthermore, yield trials reported by Huneycutt et al. (1988) were conducted over four years at varying fertilizer application rates for both warm and cool-season forage species. As such, yield was determined using a polynomial regression relating N application rates to observed yield published by Huneycutt et al. (1988), resulting in the approximate annual dry matter production of BG and TF in response to inorganic fertilizer and poultry litter (fig. 1). The yield response curves were used to determine annual forage production in areas of zero, single, or double coverage resulting from fertilizer applications with TG on and off as determined via geospatial analyses (Kharel et al., 2020a). More specifically, the fertilizer application rate was assumed to be zero, average, or twice the average for gap, normal, and overlap coverage, respectively. Total production estimates for gap, single, and double coverage areas in each field were then summed to estimate the cumulative production across all fields. Production gains calculated from the yield curves and the absolute gap/overlap fertilizer application rate assumptions with TG on ranged from 2.7% to 6.5% over the baseline (TG off), depending on the combination of species and nutrient source.

SCENARIO DEVELOPMENT

Due to data limitations (e.g., no yields collected in TG field trials) and the lack of published literature on this topic, yield response assumptions were made regarding the implications of overlaps and gaps in fertilizer and herbicide applications that introduced additional uncertainty. Thus, scenarios were devised to explore potential environmental impact reduction with increasing yield. The production archetype representing the baseline assumed TG off and no benefit or penalty attributed to areas that were missed or covered twice during both agrochemical applications (cumulative effects). Alternate production scenarios assumed TG on and various yield response scenarios. The zero-gain scenario (G0) shared the same underlying assumptions regarding yield response as the baseline scenario, where no benefit or penalty was applied to the yield response curves. Additional scenarios were evaluated using TG with overall yields increased by 5%, 10%, and 15% (defined as G5, G10, and G15, respectively). These hypothetical yield increases were based in part on estimates for fertilizer use as indicated above (2.7% to 6.5%) and on yield response to herbicides as observed on nearby fields but not in conjunction with fertilizer use. Hence, in these scenarios, yield served as a proxy for the various ways in which more uniform spatial coverage of herbicide and fertilizer (organic or inorganic) inputs could be beneficial.

ASSUMPTIONS AND LIMITATIONS

All field emissions were calculated by applying emission factors to the total quantity of fertilizer (organic and inorganic) or pesticide a.i. applied. As a result, responses to variations in application rate were unaffected by gaps and overlaps in coverage. Activities associated with harvesting were not included in this assessment because no field data were collected, which informed our choice of a functional unit of unharvested dry matter production.

The system boundary included upstream activities that were expected to be affected by the different operations associated with TG on versus TG off. Thus, for the comparative analysis, activities that are unaffected by TG (seeding and harvesting in particular) were excluded from the system. The background unit process for diesel emissions from the Ecoinvent database included the infrastructure of the tractor itself and ancillary equipment, even though these were not anticipated to be influenced by the different scenarios. Other inputs were included because the rate of application varied across scenarios.

All data for field operations in the baseline assessment were primary data collected during 2018 in the TG trials and were therefore high-quality data (Kharel et al., 2020a, 2020b). Although the temporal representativeness score was lower in this case and may have introduced some downward bias, if generally increasing yields through time prevail even in pasture systems, then any bias would be uniform across scenarios and would not likely affect the robustness of our comparative conclusions.

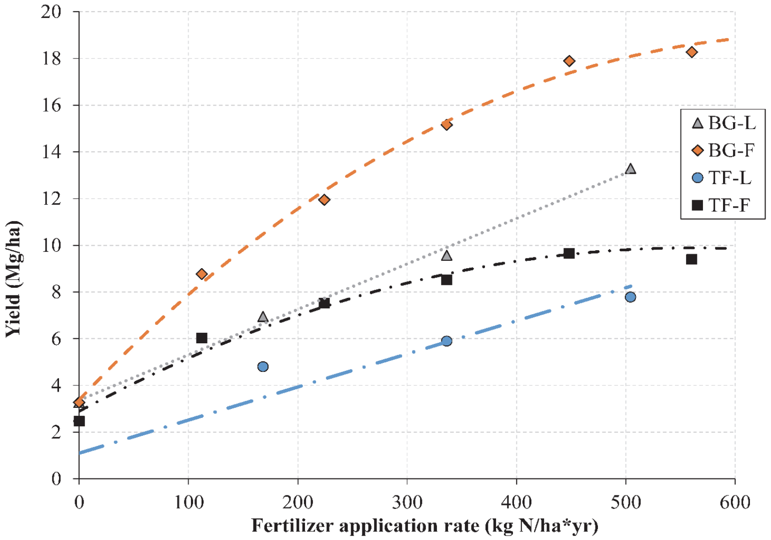


Figure 1. Yield response curves for bermudagrass (BG) and tall fescue (TF) with poultry litter (L) and synthetic fertilizer (F) applications. Data adapted from Huneycutt et al. (1988).

RESULTS AND DISCUSSION

LIFE CYCLE INVENTORY

The life cycle inventory results for individual sprayer and fertilizer operations with and without the use of TG are shown in table 2. The use of TG reduced absolute gaps on average by 7.6% and 10.1% and reduced overlaps by 32.5% and 4.2% during spraying and fertilizing operations, respectively. Similarly, Kharel et al. (2020a) reported that TG reduced overlaps during field operations by 6% of the total pasture field area, reduced gaps by up to 16%, and improved overall efficiency by up to 20%. However, tractor fuel consumption increased with TG in the present study during fertilization and herbicide applications relative to the effective coverage area. This observed increase in fuel use per hectare can be understood by comparing the increase in fuel use observed during field trials, considering that the effective area covered increased as more herbicide and fertilizer was applied. Alternately, as gaps decrease between all paths in the field during a given operation, more distance is needed, while decreasing overlaps reduce the distance driven by the tractor, and as shown in table 2, there was greater reduction in gaps with TG on. Therefore, despite improved operation efficiency gains, TG translated to greater fuel usage (L ha^{-1}), perhaps 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 (Kharel et al., 2020b). This result is counter to Bora et al. (2012), who observed 6.3% fuel savings when using TG and autosteer precision guidance equipment.

The use of TG resulted in higher annual forage production values for both forage species, regardless of nutrient source (table 3). As mentioned, production gains with TG on ranged from 2.7% to 6.5% over the baseline (TG off). For many of the impact categories, this geospatially estimated yield gain does not fully offset additional impacts associated with increased inputs. To explore the conditions under which TG-based pasture systems generate beneficial environmental results, we evaluated scenarios with additional hypothetical yield benefits, described below.

Although TG resulted in more effective coverage (fewer overlaps and gaps) during agrochemical applications, the environmental benefits from aggregate coverage efficiency gains were less than the emissions from the additional fuel required to operate TG for the G0 scenario, which had slightly larger impacts (fig. 2). The G5 scenario (5% yield increase) approximately offsets the increased fuel consumption impacts, and there are environmental benefits for the G10 and G15 scenarios. Previous work by Kharel et al. (2020b) found that overlaps increased with increased field irregularities (6% to 11% field area), shorter pass lengths, greater slope, and field roughness index when using TG. Therefore, further life cycle impact assessments should be conducted based on field attributes (shape, size, and slope) to identify the range of TG environmental efficiency gains.

LIFE CYCLE IMPACT ASSESSMENT

Life cycle impact assessment (LCIA) results are shown for each production archetype and scenario (per kg DM) in figure 3 and in percentage change from the baseline in table 4. Counter to expectations, forage production with TG on was associated with greater environmental impacts than with TG off when no yield benefit was applied, with one exception: ozone depletion potential declined by 0.45% in the BG with L archetype (BG-L - G0). When the TG yield benefit increased to 5% (G5), TG-on archetypes were more likely to show improved (i.e., lower) environmental impacts. Poultry litter archetypes had a reduction in six of the ten impact categories, while those with commercial fertilizer resulted in a reduction in all ten categories relative to corresponding archetypes with TG off. This discrepancy between nutrient sources stems from differences in N volatilization rates. The default volatilization factor for indirect soil N_2O emissions from organic N applied is twice that of synthetic N (IPCC, 2006). As a result, poultry litter archetypes require a greater yield benefit than their synthetic fertilizer counterparts for

Table 2. Combined field trial data for fertilizer and sprayer implements with TG on and off.

		Sprayer				Fertilizer			
Tractor Guidance	Total Field Area (ha)	Gap Area (ha)	Overlap Area (ha)	Diesel Fuel Use (L)	Herbicide Applied (L)	Gap Area (ha)	Overlap Area (ha)	Diesel Fuel Use (L)	Fertilizer Applied (kg N)
TG off	68.0	14.5	4.4	212.1	202.9	18.7	2.6	211.4	8,717
TG on	68.0	10.4	3.0	224.8	212.2	13.7	2.5	233.4	9,532
Difference	-	-7.6%	-32.5%	6.0%	4.6%	-10.1%	-4.2%	10.4%	9.3%

Table 3. Estimated total yield (kg DM^{-1}, from Huneycutt et al. 1988) with TG on and off for each forage species and nutrient source under 0%, 5%, 10%, and 15% yield benefit scenarios.

			Yield Benefit			
Forage Species	Nutrient Source	Tractor Guidance	0%	5%	10%	15%
Bermudagrass	Poultry litter	TG off	415	415	415	415
		TG on	430	451	473	494
		Difference	3.4%	8.6%	13.7%	18.9%
	Synthetic fertilizer	TG off	866	866	866	866
		TG on	922	969	1015	1061
		Difference	6.5%	11.8%	17.1%	22.4%
Tall fescue	Poultry litter	TG off	275	275	275	275
		TG on	282	296	310	324
		Difference	2.7%	7.8%	13.0%	18.1%
	Synthetic fertilizer	TG off	412	412	412	412
		TG on	433	454	476	497
		Difference	4.9%	10.2%	15.4%	20.7%

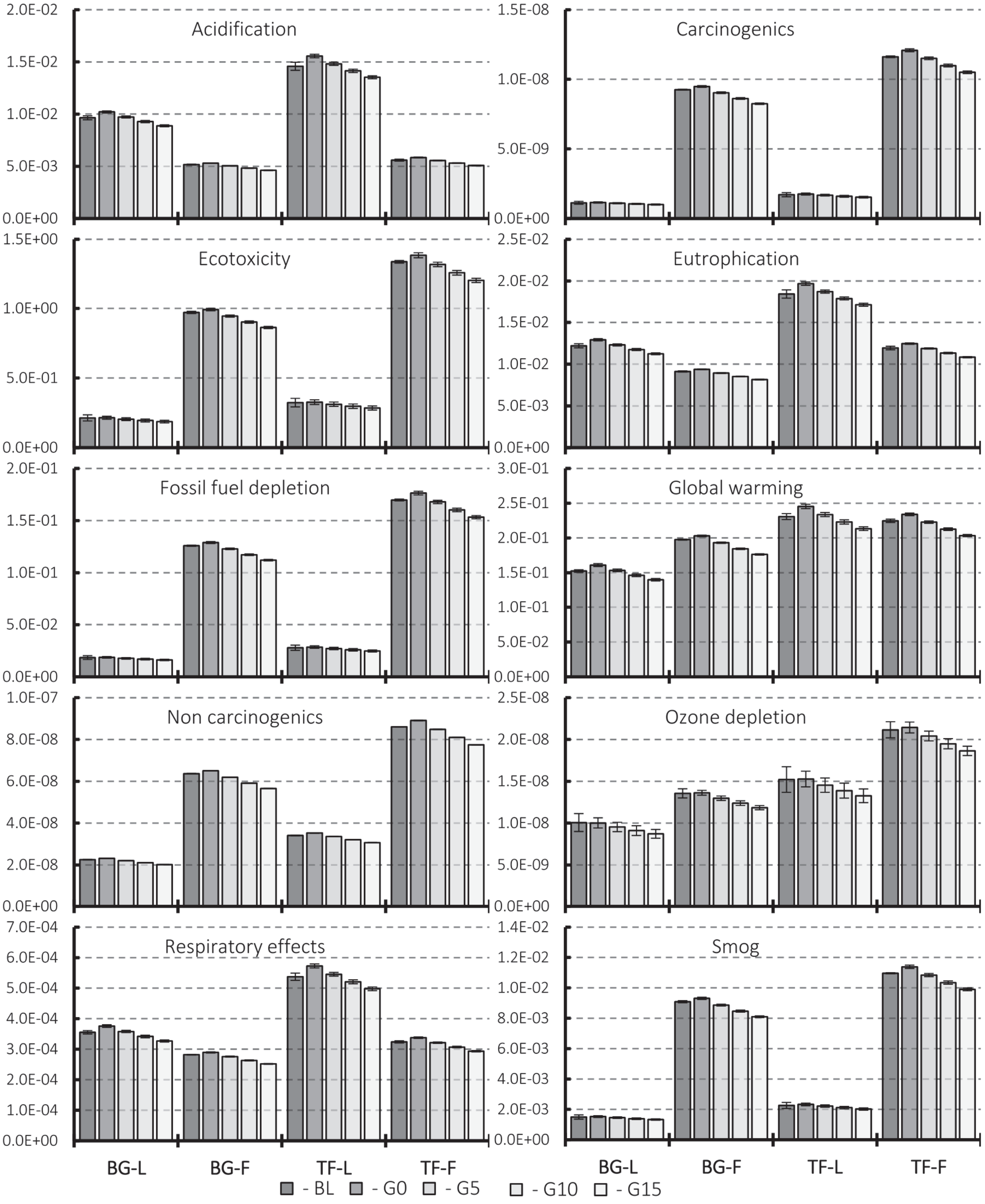
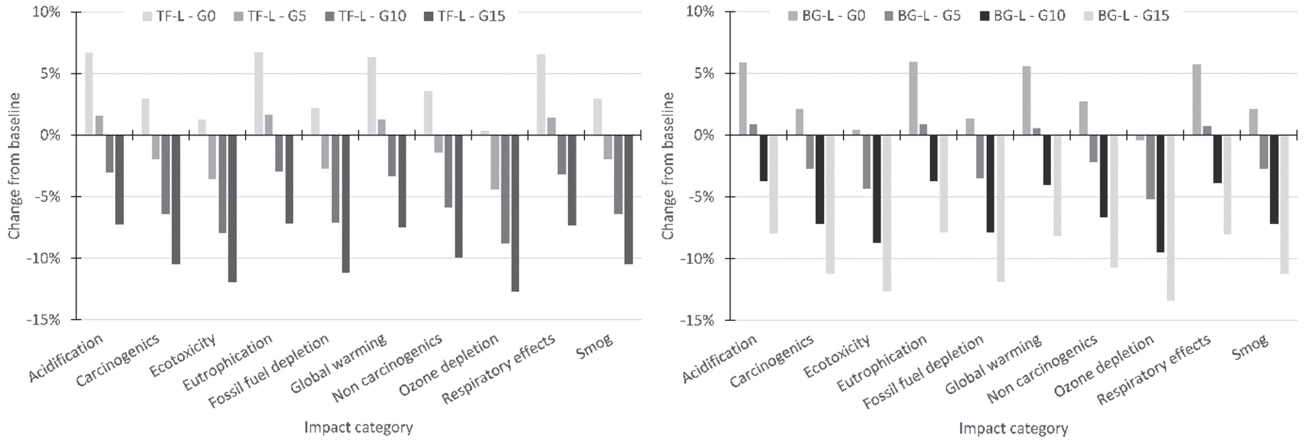


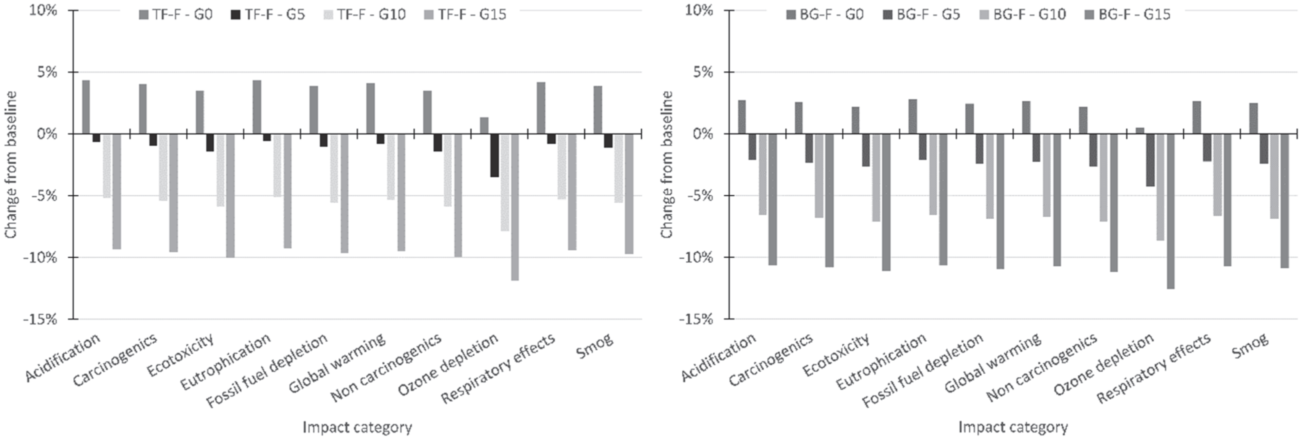
Figure 2. LCIA results for 1 kg of DM forage for each production archetype and scenario. Impact categories include acidification (kg SO_2 eq), carcinogenics (CTUh), ecotoxicity (CTUe), eutrophication (kg N eq), fossil fuel depletion (MJ surplus), global warming (kg CO_2 eq), non-carcinogenics (CTUh), ozone depletion (kg CFC-11 eq), respiratory effects (kg $PM_{2.5}$ eq), and smog (kg O_3 eq). BL = baseline scenario, G0 = yield gain zero [tractor guidance (TG) on], G5 = 5% yield gain (TG on), G10 = 10% yield gain (TG on), and G15 = 15% yield gain (TG on). Production archetypes with TG off (baseline; BL) and TG on (G0) share the same assumptions regarding yield response to overlaps and gaps in coverage, while G5 to G15 assume 5% to 15% yield increase from the baseline whole-field yield.

certain impact categories. The G10 and G15 scenarios both showed improvements across all ten impact categories (table 4).

Figure 3 presents a comparison across multiple impact categories for each of the experimental tracts (error bars represent the range of results across replicated fields and illustrate that variability in gaps and overlap areas is relatively independent of field shape). Figure 3 presents results as an offset from baseline, illustrating that there must be yield gains with TG to achieve improved environmental impacts. When either poultry litter or inorganic fertilizers are used as the source of fertilizer on BG or TF, yield improvements must be in excess of 5% to compensate for increased potential for acidification, eutrophication, global warming, and respiratory effects due to the more effective coverage achieved with TG on.



Tall fescue with poultry litter (TF-L) **Bermudagrass with poultry litter (BG-L)**



Tall fescue with synthetic fertilizer (TF-F) **Bermudagrass with synthetic fertilizer (BG-F)**

Figure 3. Yield gain scenario comparison against baseline production without tractor guidance. Production archetypes include bermudagrass with poultry litter (BG-L), tall fescue with poultry litter (TF-L), bermudagrass with synthetic fertilizer (BG-F), and tall fescue with synthetic fertilizer (TF-F). Yield gain (G) scenarios at 0%, 5%, 10%, and 15% are labeled G0, G5, G10, and G15, respectively.

Table 4. Heat map showing percentage change in environmental impact associated with each yield scenario. For the conditions evaluated in this study, the breakeven point is between 5% and 10% yield improvement for enhanced environmental impacts from tractor guidance.

Scenario	Acidification	Carcinogenics	Ecotoxicity	Eutrophication	Fossil Fuel Depletion	Global Warming	Non-Carcinogenics	Ozone Depletion	Respiratory Effects	Smog
BG-L - G0	5.9	2.1	0.5	5.9	1.3	5.6	2.7	-0.5	5.7	2.1
BG-L - G5	0.8	-2.8	-4.3	0.9	-3.5	0.5	-2.2	-5.2	0.7	-2.8
BG-L - G10	-3.7	-7.2	-8.7	-3.7	-7.9	-4.0	-6.6	-9.5	-3.9	-7.2
BG-L - G15	-7.9	-11.2	-12.7	-7.9	-11.9	-8.2	-10.7	-13.4	-8.1	-11.2
BG-F - G0	2.7	2.5	2.2	2.8	2.4	2.6	2.2	0.5	2.7	2.5
BG-F - G5	-2.1	-2.3	-2.7	-2.1	-2.4	-2.2	-2.7	-4.3	-2.2	-2.4
BG-F - G10	-6.6	-6.8	-7.1	-6.6	-6.9	-6.7	-7.1	-8.6	-6.7	-6.9
BG-F - G15	-10.7	-10.8	-11.1	-10.6	-10.9	-10.7	-11.2	-12.6	-10.7	-10.9
TF-L - G0	6.7	2.9	1.3	6.7	2.2	6.3	3.5	0.3	6.5	2.9
TF-L - G5	1.6	-2.0	-3.6	1.6	-2.7	1.3	-1.4	-4.4	1.4	-2.0
TF-L - G10	-3.0	-6.4	-8.0	-3.0	-7.1	-3.3	-5.9	-8.8	-3.2	-6.4
TF-L - G15	-7.2	-10.5	-12.0	-7.2	-11.2	-7.5	-10.0	-12.7	-7.4	-10.5
TF-F - G0	4.3	4.0	3.5	4.4	3.9	4.1	3.5	1.4	4.2	3.9
TF-F - G5	-0.7	-0.9	-1.4	-0.6	-1.1	-0.8	-1.4	-3.5	-0.8	-1.1
TF-F - G10	-5.2	-5.4	-5.9	-5.1	-5.6	-5.3	-5.9	-7.9	-5.3	-5.6
TF-F - G15	-9.3	-9.6	-10.0	-9.2	-9.7	-9.4	-10.0	-11.9	-9.4	-9.7

Limited literature exists on the environmental consequences of TG and precision-guided technologies. Balafoutis et al. (2017a) performed a life cycle assessment to identify the environmental effects of variable-rate applications in vineyard agroecosystems. Their results suggested a reduced carbon footprint and energy consumption for grape production when implementing precision techniques such as variable-rate technology, indicating that precision agriculture may reduce the effects of viticulture on GHG emissions. In addition, Shockley et al. (2015) modeled a commercial corn and soybean farm using TG during planting and fertilizer applications and observed cost savings of 2.4%, 2.2%, and 10.4% for seed, fertilizer, and fuel, respectively, which also translated to GHG emission mitigation.

Previous work by Ashworth et al. (2018) found that TG led to total farm-level carbon-equivalent emission reductions of 15.7, 3.5, and 9.6 kg ha^{-1} for cotton (*Gossypium hirsutum* L.), soybean [*Glycine max* (L.) Merr.], and cotton-soybean mixed operations, respectively. Those results highlight that emission reductions are crop, scale, and agro-input specific. Additionally, Kharel et al. (2020b) found that factors such as terrain attributes (increased slope, variable topography) and field shape and irregularity drive the extent of these efficiency gains relative to non-TG systems. Other likely important factors include operator experience level for the non-TG comparison; however, evaluations of driver experience have not been done to date. Therefore, the results of this study provide environmental gain estimates based on actual TG field scenarios under set conditions. Further work should be done to evaluate how fuel use assumptions and driver experience level affect environmental gains via sensitivity analyses.

Despite more targeted applications of inputs and irrigation during production leading to fewer nutrients in water systems, more sustainable production of food, and improved producer profitability for pasture systems, yield benefits are required for enhanced environmental performance when employing TG. Further work is needed to determine efficiency gains and the feasibility of adopting this technology by determining breakeven prices based on farming operation type, farm size, and capital investment requirements, as well as subsequent soil health and water quality impacts from reductions in agricultural inputs based on in-field data from crop farms and cattle ranches (Kharel et al., 2020b). In addition, future work is needed to refine these estimates to gain greater precision on input-use savings based on on-farm data. The number of turns a tractor makes in the turn row at the edge of the field, as well as the width and type of equipment, need further investigation to allow better evaluation of cost savings, as well as LCA-based environmental implications of precision TG technologies.

CONCLUSIONS

This study addresses a critical knowledge gap in the literature: how do precision agricultural tools, such as tractor guidance (TG), affect the efficiencies of field operations, i.e., fertilization (organic and inorganic) and herbicide application, and subsequent environmental impacts. Further, this study explores how a range of pasture production systems, for which TG has not been widely adopted, affects environmental gains. This study found that the use of TG reduced absolute gaps by 7.6% and 10.1% and reduced overlaps by 32.5% and 4.2% during spraying and fertilization, respectively. Therefore, TG resulted in less overlaps and gaps during field operations across pasture landscapes. Production gains with TG on ranged from 2.7% to 6.5% over the baseline (TG off); however, tractor fuel consumption increased when TG was employed due to the longer travel distances required for more uniform coverage of herbicides and fertilizer. Yield gains ($\geq$5%) are therefore crucial for the sustainability of pasture-based systems when employing TG.

Quantitative assessment of management benefits is required before identifying best management practices that may lead to having auto-guidance systems listed as an NRCS Environmental Quality Improvement Program (EQIP) practice. Future research focused on field-based measurements of actual yield impacts and N_2O and NO_X emissions from soil, as well as PO_4^- loads in runoff, due to overlaps and gaps (without guidance systems) remains a critical need for refinement of environmental impact assessments.

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