

Research Article

Nitrogen Uptake Efficiency and Total Soil Nitrogen Accumulation in Long-Term Beef Manure and Inorganic Fertilizer Application

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Livestock manure is a common soil amendment for crop-livestock production systems. However, the efficiency of crop nitrogen (N) uptake from the manure-amended soil may not equate with that from inorganic N sources. The objective of this paper was to determine the efficiency of N uptake, grain yield, and total soil nitrogen (TSN) accumulation in beef manure-amended soil compared to the inorganic N fertilizer-amended soil. Data (1990–2015) from a long-term continuous winter wheat (*Triticum aestivum* L.) fertility experiment at Stillwater in Oklahoma, USA, were used in this report. Three of the six “Magruder Plot” treatments used in this study were manure, NPK plus lime (NPKL), and a check (no nutrients applied). Pre-plant N, P, and K were applied annually at 67, 14.6, and 27.8 kg·ha⁻¹, respectively, while beef manure was applied every 4 years at 269 kg N·ha⁻¹. The results indicated that grain N uptake in the manure treatment (48.1 kg·ha⁻¹) was significantly ($p < 0.05$) lower than that in the NPKL treatment (60.2 kg·ha⁻¹). This represents 20.1% efficiency of inorganic N uptake than the manure N uptake. The average grain yield (1990–2015) from the manure and NPKL treatments was 2265.7 and 2510.5 kg·ha⁻¹, respectively, and was not significantly different. There was a trend of TSN increase over the study period for both manure and NPKL treatments. The average TSN from manure and NPKL treatments was 0.92 and 0.91 g·kg⁻¹ soil, respectively, and was not significantly different. While no significant difference between manure and NPKL grain yield was observed, there was a significantly lower uptake efficiency of manure N compared to inorganic N. Furthermore, the low uptake efficiency of the manure N could suggest a potential for environmental pollution. Appropriate timing and application rate of manure N sources could optimize crop use efficiency and limit potential threat to the environment.

1. Introduction

Nitrogen (N) is an important plant nutrient and commonly the most deficient in many intensive cereal monocropping systems. Additions from both synthetic and animal manures help supplement the native N pool from organic matter mineralization and/or rainfall supply [1, 2]. However, applications in excess of plant requirements from both sources have been blamed for aboveground environmental pollution [3, 4]. Environmental pollution from synthetic N sources has been extensively investigated, and attempts have been made to compare it with that coming from manure. By virtue of its popular use especially under large-scale crop production,

synthetic N sources are believed to cause the greatest threat to the environment. Inorganic sources are readily available and can be taken up by plants and/or lost within the soil system [5]. Manure N, on the contrary, has N mostly bound within organic fractions that require some kind of degradation so as to release available plant N [6, 7]. Accordingly, synthetic N could potentially cause more of an environmental threat relative to manure N. Some studies however note that animal manure N may comparatively lead to more environmental pollution depending on the source, rate, and timing of application [3, 8]. For instance, Chang and Entz [9] reported soil and groundwater contamination with increased leaching of NO₃-N in applied beef manure where

annual losses of nitrogen ranged from 93 to 341 kg N·ha⁻¹. Losses were higher under irrigated treatments and when application exceeded annual recommended rates of 60 Mg·ha⁻¹ wet weight. Therefore, the efficiency of plant N uptake and potential TSN accumulation strongly depend on the rate and frequency of application.

Total soil N is one of the indicators of soil fertility in an agricultural ecosystem [10]. Earlier studies indicate that TSN in the surface layers of most cultivated soils varies between 0.6 g·kg⁻¹ and 5 g·kg⁻¹ although it could reach up to 25 g·kg⁻¹ in peat [11]. Xu et al. [12] noted that this figure fluctuates depending on the land use and management system. Indisputably, agriculture takes a greater portion of the liability for the fluctuation. Several research reports present contrasting views on whether agriculture, particularly crop production, leads to a buildup or depletion of soil organic N [10, 12, 13]. Generally, it appears that continuous crop production without replenishing soil nutrients would certainly deplete soil resources [14]. On the contrary, intensive or high input production systems may lead to buildup of certain soil nutrients. Much as continuous crop production can cause significant loss in the quantity of soil organic matter and total N [15], certain crop production practices may lead to buildup of carbon and N within the soil system. For instance, Aula et al. [13] demonstrated from long-term trials that application of inorganic N fertilizer at rates above 90 kg·ha⁻¹ can increase and lead to buildup of TSN. The excess N in the soil system may pose an environmental threat if certain weather variables favor its loss. From an environmental perspective, total soil N, in addition to total soil phosphorus, is the cause of nonpoint source pollution for surface and groundwater [12]. This is true especially when inorganic N constitutes a higher proportion of the total soil N. Leaching and surface runoff through erosion of N applied in excess of plant needs are the main mechanisms for environmental pollution.

Some research reports that continuous application of N fertilizer can increase the likelihood of TSN accumulation with time [16]. However, N from fertilizers in excess of plant requirements is not the only factor in the equation. Biological processes such as symbiotic and nonsymbiotic N₂ fixation in addition to atmospheric N in rainfall contribute a substantial amount of TSN [17, 18]. These biological or natural processes, which significantly influence soil N availability and subsequently crop yield, are independent of N fertilizer application rates and largely controlled by the environment [19]. In addition to atmospheric N₂ fixation, microorganisms contribute to the availability of mineral N under favorable soil temperature, moisture, and aeration. Free-living decomposer microbes convert organic matter into nutrients for plants and other microorganisms, while rhizosphere organisms are symbiotically associated with plant roots and free-living N fixers [20]. These microorganisms are capable of extracting N from organic matter and other soil substances and subsequently releasing available plant N to the soil pool. Knops and Tilman [15] studied N and carbon dynamics in an abandoned field and reported that the rate of N accumulation depended on atmospheric deposition and symbiotic fixation by legumes. Jurgensen

[21] reported that N fixation by autotrophic microorganisms can reach 70 kg·ha⁻¹·yr⁻¹. Therefore, N from the soil pool is subject to either plant uptake or various loss pathways. If N supply from fertilizer, symbiotic or nonsymbiotic fixation, and/or straw mineralization exceeds plant requirements, significant quantities can be either lost or immobilized. Immobilization, which is a biological process, is in turn dictated by environmental conditions. This is the reason for TSN accumulation under continuous fertilizer N application.

2. Materials and Methods

The Magruder Plots located at Stillwater in Oklahoma, USA, is a long-term continuous winter wheat (*Triticum aestivum* L.) fertility experiment situated on a Kirkland silt loam (fine, mixed, thermic Udertic Paleustolls). The experiment was started by Alexander C. Magruder and included a manure treatment that was started in 1892, while inorganic fertilizer treatments were initiated in 1929 [22]. The six treatments included in this long-term experiment are manure, P, NP, NPK, NPK plus lime (NPKL), and an unfertilized check plot, where no nutrients have been applied. However, only three treatments (manure, NPKL, and check) were used for this report. Plot sizes are 30 m by 5 m. Inorganic chemical fertilizer treatments were applied every year prior to planting. Nitrogen was applied as urea (46-0-0) at a rate of 67 kg N·ha⁻¹, P was applied at 14.6 kg P·ha⁻¹, and K was applied at 27.8 kg K·ha⁻¹, while beef manure was applied every 4 years at 269 kg N·ha⁻¹ (Table 1). Therefore, similar quantities of N (269 kg) were provided both in the manure-treated and inorganic N-treated plots during a four-year period in which manure was applied once. Lime was applied when soil pH dropped below 5.5.

It is important to note that, at the time of establishment of this long-term experiment, modern statistics did not exist. Consequently, replications were not included in the experimental design. However, a long-term study of this nature can be used as a basis for understanding the effect of manure application and general agronomic management including yield potentials as well as losses of crop nutrient elements. For this work, only data from 1990 to 2015 were used due to availability of data on total soil N. Wheat grain was harvested with a Massey Ferguson 8XP combine and yield data recorded for each year reported in this study. Wheat subsamples were taken and oven-dried at 105°C for 24 hours. These samples were then ground to pass a 1 mm mesh size. Total elemental grain N for each sample, expressed as a percent, was determined using dry combustion analysis (LECO TruSpec) [23]. Each year, post-harvest soil samples were also taken, oven-dried, and ground for TSN analysis. Grain N uptake was determined by multiplying yield times grain N content and expressed in kg·ha⁻¹ (Table 2). Analysis of variance was performed using the GLM procedure in SAS 9.4 [24], and means were separated using Tukey's HSD. Due to lack of replications, the study period (years) was used to estimate experimental error during analysis of variance. Comparisons were made between average grain yield, N uptake, and TSN for the

TABLE 1: Treatment structure, composition, and description for Magruder Plots located at Stillwater in Oklahoma, USA.

Treatment	Composition	Description	Input sources	Form and quantity applied
1	Manure	Cattle manure applied every 4 years	Cattle manure	Cattle manure 269 kg N·ha ⁻¹
2	—	Check, no nutrient applied	—	—
3	P	P applied each year	TSP	P ₂ O ₅ (0-34-0)
4	NP	N and P applied each year	Urea, TSP	N, P ₂ O ₅ (67-34-0)
5	NPK	N, P, and K applied each year	Urea, TSP, KCl	N, P ₂ O ₅ , K ₂ O (67-34-34)
6	NPKL	N, P, and K applied each year + lime applied when soil pH < 5.5	Urea, TSP, KCl + Aglime	N, P ₂ O ₅ , K ₂ O + lime (67-34-34)

TABLE 2: Wheat grain yield (kg·ha⁻¹), grain N content (%), N uptake (kg·ha⁻¹), and total soil N (g·kg⁻¹ soil) of Magruder Plots (1990–2015) located at Stillwater in Oklahoma, USA.

Year	Grain yield (kg·ha ⁻¹)			Grain N (%)			N uptake (kg·ha ⁻¹)			Total soil N (g·kg ⁻¹ soil)		
	Manure	Check	NPKL	Manure	Check	NPKL	Manure	Check	NPKL	Manure	NPKL	Check
1990	2325.1	1451.5	2184.0	2.04	2.00	2.28	47.4	29.0	49.8	0.70	0.76	0.59
1991	1753.9	1115.5	2963.5	2.33	2.04	2.44	40.8	22.8	72.2	0.70	0.76	0.59
1992	1429.2	903.2	1973.7	2.17	1.96	2.35	31.0	17.7	46.4	0.74	0.77	0.60
1993	2499.5	1259.6	2754.3	2.22	1.91	2.26	55.5	24.1	62.2	0.74	0.77	0.60
1994	1510.1	628.4	1865.4	2.23	2.34	2.39	33.6	14.7	44.7	0.95	0.99	0.62
1996	1669.2	967.7	1884.3	2.28	2.18	2.28	38.1	21.1	43.0	1.07	0.93	0.69
1997	3454.1	1397.8	4186.6	2.28	2.18	2.28	78.8	30.5	95.5	1.17	1.07	0.69
1998	2071.8	974.4	2591.9	2.31	2.03	2.43	47.9	19.8	63.0	—	—	—
1999	2744.6	1767.5	2527.9	2.31	2.50	2.32	63.3	44.2	58.7	—	—	—
2000	2473.4	1511.6	2377.7	2.25	1.80	2.12	55.7	27.3	50.3	—	—	—
2001	2563.0	795.1	2663.8	2.32	2.24	2.30	59.5	17.8	61.1	0.59	0.68	0.52
2002	2369.4	1212.0	2790.4	1.96	1.85	2.52	46.4	22.4	70.3	0.68	0.68	0.49
2005	2956.8	1209.6	2956.8	2.43	1.96	3.02	72.0	23.7	89.2	—	—	—
2006	2225.1	1414.8	3112.7	2.14	2.02	2.65	47.6	28.5	82.4	1.09	0.98	0.74
2008	3473.6	1823.5	3281.4	1.74	1.91	2.21	60.5	34.9	72.5	—	—	—
2009	166.7	330.0	357.5	2.12	1.92	2.08	3.5	6.3	7.4	1.05	0.95	0.79
2010	2313.4	1244.4	2669.3	2.51	2.60	2.81	58.1	32.3	75.1	1.05	0.95	0.79
2011	1286.8	431.9	1675.5	2.25	2.17	2.83	29.0	9.4	47.4	0.84	0.76	0.72
2012	2655.7	1022.8	3007.9	1.94	1.79	1.96	51.6	18.3	58.9	0.81	0.77	0.53
2013	2860.0	1029.5	3571.7	1.58	1.69	1.60	45.1	17.4	57.3	0.96	1.01	0.63
2014	2243.5	1161.6	2365.9	1.69	1.78	1.85	38.0	20.6	43.8	1.46	1.65	1.23
2015	3117.4	1816.1	4048.2	1.77	1.73	1.80	55.2	31.3	72.9	1.04	1.04	0.81

NPKL = nitrogen, phosphorus, potassium, and lime; check = no fertilizer applied; manure = beef manure applied every four years.

manure-treated plots and the inorganic N-treated plots. Correlation analysis was performed to determine the degree of linear relationship between TSN content in the manure and NPKL treatments (Table 3).

3. Results and Discussion

The results indicate that wheat grain yield was higher in the NPKL plot but not significantly different from that in the manure plot. Over the period reported in this study, the average grain yields recorded were 2510 and 2265 kg·ha⁻¹ in NPKL and manure treatments, respectively (Table 3).

As was expected, grain yields from both treatments were significantly higher than those obtained in the control plot recorded at 1165 kg·ha⁻¹. Lentz and Lehrs [25] made similar observations where the contribution of manure to sugarbeet yield was either equal to or more than that of mineral N fertilizer depending on the application rate and timing. According to Eghball and Power [26], the observation that manure can produce grain yields equal to or greater than

those of synthetic fertilizer application is true when the application rate is based on the correct N or P requirement. The manure application rate used in this study was based on the N requirement that was purposely matched with the N rate from the inorganic source (NPKL). Abdulmaliq et al. [27] recommended curing livestock manure for up to 6 weeks in order to obtain corresponding yield levels or even more than those of chemical fertilizer N application. This work shows that the manure soil amendment can sustainably support an intensive cereal-based cropping system when compared to inorganic sources. If the impact of manure and mineral N on crop yield is identical, it is possible to imagine that any environmental concerns associated with mineral N application could equally be experienced through manure soil amendment. Accordingly, the potential for environmental contamination needs to be assessed alongside increasing biomass or grain yield as the usefulness of manure application in crop production is considered. Therefore, the quality can be assessed by determining efficiency of N uptake and TSN accumulation over time.

TABLE 3: Analysis of variance for wheat grain yield, grain N uptake, and TSN including summary of relationships between these variables in manure, check, and NPKL treatments (1990–2015) of Magruder Plots located at Stillwater in Oklahoma, USA.

Treatment	Grain yield (kg·ha ⁻¹)		Grain N uptake (kg·ha ⁻¹)		TSN (g·kg ⁻¹ soil)	
<i>Treatment means</i>						
Manure (n = 22)	2265.7 ^A		48.11 ^B		0.920 ^A	
Check (n = 22)	1165.6 ^B		22.82 ^C		0.684 ^B	
NPKL (n = 22)	2510.5 ^A		60.19 ^A		0.913 ^A	
<i>Correlation coefficient</i>						
	<i>P > F</i>	<i>R</i>	<i>P > F</i>	<i>R</i>	<i>P > F</i>	<i>R</i>
Manure vs NPKL	<0.0001	0.89	<0.0001	0.84	<0.0001	0.93
Manure vs check	<0.0001	0.79	<0.0001	0.73	<0.0001	0.87
NPKL vs check	<0.001	0.67	<0.01	0.58	<0.0001	0.92

NPKL = nitrogen, phosphorus, potassium, and lime-treated plot; check = no fertilizer applied; manure = beef manure applied every four years; TSN = total soil nitrogen; treatment means within the same column with the same letter superscript are not significantly different (Tukey's HSD test).

There was a significant difference in grain N uptake among treatments. Grain N uptake varied from 3.5 to 78 kg·ha⁻¹ in the manure treatment and 7.4 to 95 kg·ha⁻¹ in the NPKL treatment (Table 2). The average grain N uptake of 60.2 kg·ha⁻¹ in the NPKL treatment was significantly higher ($p < 0.05$) than that of 48.1 kg·ha⁻¹ in the manure treatment. Grain N uptake in both the NPKL and manure treatments was significantly higher ($p < 0.05$) than that in the control treatment recorded at 22.8 kg·ha⁻¹ (Table 3). The pattern of change in average grain N uptake over the study period for the two inputs was similar, as illustrated in Figure 1.

The high inconsistency in grain N uptake could be attributed to changes in the environmental variables especially rainfall and temperature over the study period. In some years, grain N uptake exceeded the amount of N in manure or inorganic fertilizer applied. For instance, in 1997, grain N uptake was 78 and 95 kg·ha⁻¹ in the manure and NPKL treatments, respectively (Table 2). These values were higher than 67 kg N·ha⁻¹ applied in the fertilizer. The same observation was made in 2005 where grain N uptake was 72 and 89 kg·ha⁻¹ in the manure and NPKL treatments, respectively. This phenomenon is not unusual and can be explained by the random abiotic and/or biological events that favor the availability of N from sources other than fertilizer. The additional grain N comes from rainfall, symbiotic and non-symbiotic fixation of atmospheric N₂, and mineralization of soil organic matter. In an analysis that included data from 213 site-years, Dhital and Raun [19] reported that maize grain yield and the optimum fertilizer N rate varied from year to year. This suggested that the influence of the environment was reflected in resultant N uptake from soil amendment sources. In the current study, no significant grain yield differences were observed between the manure and NPKL treatments. Likewise, grain N uptake was expected to follow the same trend. Nonetheless, this was not observed. Increased grain yield in the manure treatment that was statistically equivalent with grain yield in the NPKL treatment could be due to increased NH₄-N supply that is known to be more efficient [28]. Improved soil physical and/or biological properties in the manure treatment could also explain the matching yield levels with the NPKL treatment. Shirani et al. [29] attributed the increased biomass yield with manure amendments to

improved soil physical properties. Similarly, Haynes and Naidu [30] noted that crop grain yield increases due to manure were likely a result of increased water-holding capacity, porosity, infiltration capacity, and hydraulic conductivity. Therefore, it is possible to have an identical wheat grain yield under manure and inorganic N treatments despite the low N uptake efficiency in the manure treatment.

At a constant N application rate of 67 kg·ha⁻¹ for both manure and NPKL treatments, TSN content in these treatments recorded at 0.92 and 0.91 g·kg⁻¹ of soil, respectively, was not significantly different ($p > 0.05$). The small difference in average TSN content (0.01 g·kg⁻¹ of soil) between the manure and NPKL treatments demonstrates a comparable level of TSN content in these treatments (Table 3). However, significant differences were observed ($p < 0.05$) when compared to the check treatment (0.68 g·kg⁻¹ of soil). Much as no significant differences were observed in TSN content between manure and NPKL treatments, linear regression over the study period showed a difference in the slope components of the regression equations (Figure 2). The slope for NPKL ($r^2 = 0.20$) was not significant ($p > 0.05$), while that for manure ($r^2 = 0.24$) was significant ($p < 0.05$). The significance in the rate of accumulation of TSN under manure treatment is due to comparatively low uptake efficiency of the manure N. Although there is a difference in significance of the slope components, a similar trend of TSN with time for the two inputs was observed (Figure 2). Additionally, the correlation coefficient ($r = 0.93$) showed a positive linear relationship and suggests comparable levels of TSN content in the manure- and NPKL-treated plots (Table 3). Similar observations were made in a long-term study by Aula et al. [13] where an average increase in TSN of 0.64 g·kg⁻¹ was noted at three locations comparing two sets of samples (1993 and 2014) for treatments where high inorganic N was applied. Evidence that recovery of the applied N fertilizer was far below the quantity applied was present. In 2009, for instance, only 3.5 and 7.4 kg N·ha⁻¹ were recovered in the grain in manure and NPKL treatments, respectively. This in part is a result of unfavorable environmental conditions for optimum plant uptake and that could also have been a result of a near total crop failure circumstance. Substantial quantities of the

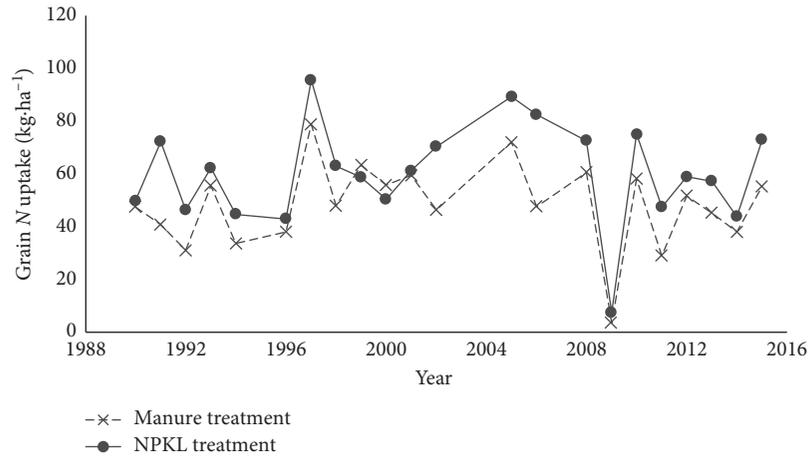


FIGURE 1: Changes in grain N uptake in manure and NPKL treatments, 1990–2015.

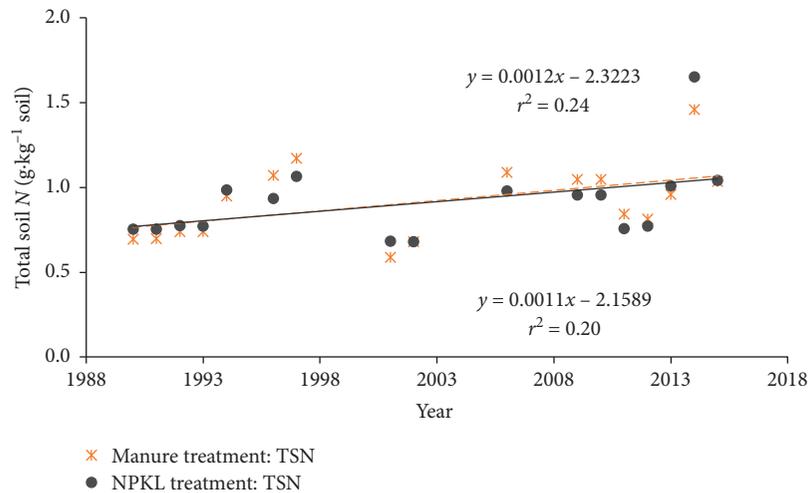


FIGURE 2: Total soil N accumulation in manure and NPKL treatments, 1990–2015.

applied N could be lost or immobilized within the soil system. If changes in the soil environment favor N immobilization, formation of soil organic N reduces crop uptake but favors TSN accumulation. Sarr et al. [18] reported a loss of N fertilizer between 55 and 60% and soil immobilization between 36 and 40% in a tracer N study. In the same study, N fixation from the inoculated plants increased N recovery by 81%. This implies that atmospheric fixation may counter the effect of seasonal dynamics which dictates the availability of N for plant uptake and further explains the cause for the TSN accumulation despite low grain N recovery.

4. Conclusion

From 1990 to 2015, N uptake was 20% greater in the NPKL treatment than manure treatment, while grain yield from the two sources (manure and NPKL) was not significantly different. Manure N uptake was notably lower compared to the uptake from inorganic N sources as it is, in most cases, not readily available for immediate crop uptake. This observation is similar to that by Ma et al. [31] who reported a

significantly lower manure N uptake efficiency compared to inorganic N uptake efficiency even when grain yield levels were comparable for the two input sources. It is also important to note that the observation made in this study indicates a strong influence of the environment on the uptake of N from both manure and inorganic sources evidenced by high variation in this parameter. A positive trend of TSN accumulation in soil over time was similar for organic and inorganic sources. Animal manure can produce similar yield levels to inorganic N fertilizer despite the low N uptake efficiency. The fact that identical quantities of N were supplied from the two input sources, low N uptake from the manure N source could suggest a potential for environmental pollution. Appropriate timing and application rate of manure N sources could optimize crop use efficiency and limit potential threat to the environment.

Data Availability

The dataset used for this study was obtained from a long-term winter wheat fertility experiment “Magruder Plots”

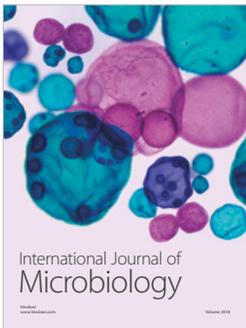
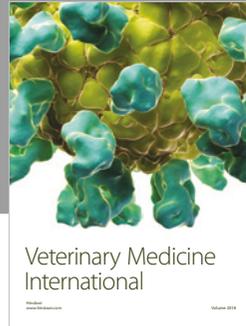
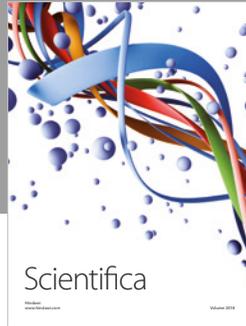
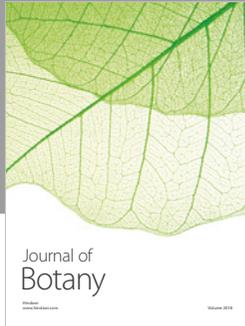
located at Stillwater and are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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