Review Article

Nitrate leaching and soil tillage practices: global *vs*. Brazilian research trends for 2001-2011 and 2012-2022[1]

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ABSTRACT

This review article analyzed studies on nitrate leaching in an agricultural context, specifically comparing nitrate leaching between conventional and no-tillage systems, and also investigated the trends in research regarding this topic across two decades (2001-2011 and 2012-2022), both globally and in Brazil. The number of global studies focused on nitrate leaching during both decades varied across the analyzed databases, whereas Brazilian researches were scarce. Notably, the research on nitrate leaching in the no-tillage system was scarce overall, both globally and particularly in Brazil. Nevertheless, the global interest in agriculture-associated nitrate leaching increased between 2001-2011 and 2012-2022, as evidenced by the increasing number of publications across all the databases. In addition, the number of global studies on nitrate leaching in the no-tillage system increased during the last two decades, although this interest has not been emulated in Brazil. Among the 22 analyzed articles, 13 supported the no-tillage system as a strategy to reduce nitrate leaching, when compared to conventional tillage; 6 showed no significant difference between both systems; and 3 detected a reduction in leaching in the conventional tillage.

KEYWORDS: Nitrogen loss, no-tillage, conventional tillage, conservation agriculture.

RESUMO

Lixiviação de nitrato e manejo do solo: tendências de pesquisa globais *vs*. brasileiras para 2001-2011 e 2012-2022

Esta revisão de literatura avaliou estudos sobre lixiviação de nitrato que foram realizados em contexto agrícola, especificamente comparando a lixiviação entre manejo convencional e plantio direto, bem como tendências de pesquisa sobre esse tema no Brasil e no mundo, ao longo de duas décadas (2001-2011 e 2012-2022). O número de estudos no mundo com foco na lixiviação de nitrato durante ambas as décadas variou entre os bancos de dados analisados, enquanto as pesquisas no Brasil foram escassas. Notavelmente, a pesquisa sobre lixiviação de nitrato em plantio direto foi escassa no mundo todo e, particularmente, no Brasil. No entanto, o interesse mundial na lixiviação de nitrato associado à agricultura aumentou entre 2001-2011 e 2012-2022, fato evidenciado pelo aumento no número de publicações em todas as bases de dados. Além disso, o número de estudos ao redor do mundo sobre lixiviação de nitrato em plantio direto aumentou nas duas últimas décadas, embora esse interesse não tenha se refletido no Brasil. Entre os 22 artigos analisados, 13 apoiam o uso do plantio direto como estratégia para reduzir a lixiviação de nitrato, em comparação com o plantio convencional; 6 não apontaram diferença significativa entre os sistemas; e 3 detectaram redução da lixiviação em plantio convencional.

PALAVRAS-CHAVE: Perda de nitrogênio, plantio direto, plantio convencional, agricultura conservacionista.

INTRODUCTION

Nitrogen (N) is a nutrient extremely important for plant growth and development, and its application in agricultural systems leads to increased crop yields (Hawkesford et al. 2012). The N supply in farmlands can be met using organic or mineral fertilization, but its use efficiency is generally low (Dourado-Neto et al. 2010). Surplus losses can occur in various ways, mainly via nitrate leaching (Wang & Li 2019).

Nitrate leaching not only drives various ecological issues (e.g., eutrophication of rivers and contamination of groundwater), but is also the causative agent of certain human diseases (e.g., gastric cancer and methemoglobinemia), and these health issues are often caused by the consumption of water with high nitrate concentrations (Bijay-Singh & Craswell 2021, Picetti et al. 2022). Although there are methods for treating nitrate-contaminated water, these generally require large amounts of energy and generate by-products that require specialized means of disposal (Richa et al. 2022).

Although several studies have classified the leached nitrate as the only one that reaches the

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groundwater (Cameron et al. 2013), in agriculture, nitrate can be considered leached once it seeps beyond the effective root system (Bortolotto et al. 2012, Rosolem et al. 2018).

Nitrate leaching beyond the root zone is directly related to reduced soil fertility, because of not only the resultant N loss, but also the associated cation co-leaching, that is, the leaching of cations such as Ca^{2+}, Mg^{2+} and K^{+} along with the nitrate anions (Brady & Weil 2013, Cameron et al. 2013). Thus, this process can drive a cascade of economic losses (Pinto et al. 2017).

In agricultural systems, N is primarily lost because of low nitrate uptake by crops from the soil solution. Nitrate leaches because of its high water solubility and low adsorption capacity for soil colloids; and soils with predominantly negative charges repel nitrate (Brady & Weil 2013).

The charge balance in variable-charge soils, such as weathered tropical soils, depends on their mineralogical composition, organic matter content and pH. For example, lower organic matter content and pH can increase the positive electrical charges on the surfaces of soil particles, thereby increasing the retainment of nitrate anions. Consequently, agricultural practices that raise the pH, such as liming, may temporarily promote negative charges on the surface of soil particles. This can, at least acutely, increase nitrate leaching (Crusciol et al. 2011, Pinheiro et al. 2020).

The magnitude of nitrate leaching in agricultural soils is contingent upon several factors beyond the aforementioned ones, including natural soil fertility, anion exchange capacity, texture, microbial communities and hydraulic conductivity. Meteorological factors such as rainfall and air temperature also play significant roles in nitrate leaching, because of their importance in shaping soil microbiological processes (i.e., via nitrification) (Sahrawat 2008, Jabloun et al. 2015, Norton & Ouyang 2019, Grzyb et al. 2020). The use of nitrogenous fertilizers is also relevant. Specifically, the physiochemical properties and method of application of fertilizers (i.e., rate, timing, etc.) can affect leaching. Nitrate leaching is also influenced by location (e.g., temperate or tropical zone), plant characteristics (e.g., species, N use efficiency and growth stage) and the use of cover crops (Jadoski et al. 2010, Fioreze et al. 2012, Yang et al. 2017, Padilla et al. 2018, Rutting et al. 2018, Sanchez 2019, Spiess et al. 2020, Nouri et al. 2022).

In recent years, nitrate leaching in agricultural contexts has garnered attention from the scientific community because of the need to map the complex dynamics that underlies this phenomenon (Foster & Custodio 2019, Bijay-Singh & Craswell 2021, Tsadilas 2022). However, soil tillage practices, which directly influence various factors that affect nitrate leaching, remain understudied. This lack of research on tillage practices as drivers of nitrate leaching is apparent in countries such as Brazil, despite it being a key player in global agriculture and transitioning from conventional to no-tillage systems (Padilla et al. 2018, Rutting et al. 2018, FAO 2023). Thorough investigations into the relationship between tillage practices and nitrate leaching are needed, as the implications of such findings could greatly improve crop yield.

Therefore, this review article aimed to evaluate research trends concerning nitrate leaching in agriculture in conventional and no-tillage systems and compare these trends across two decades (2001-2011 and 2012-2022), both globally and in Brazil. By analyzing the selected studies, it also aimed to determine the soil tillage practices (conventional or no-tillage) that resulted in the least amount of nitrate leaching.

MATERIAL AND METHODS

Initially, to trace the trajectory of research on nitrate leaching across two distinct decades (2001-2011 and 2012-2022), a literature search was performed to extract global and Brazilian studies. Articles, reviews, conference papers, books and book chapters on nitrate leaching in agriculture were included, focusing on soil tillage, specifically conventional and no-tillage practices. The keywords "nitrate leaching" and "agriculture" or "nitrate leaching" and "agriculture" and "no-tillage" were used in the following databases: Google Scholar (2023), Scopus (2023) and Web of Science (2023). Publications from two decades, 2001-2011 and 2012-2022, were included to determine whether research on nitrate leaching driven by tillage practices has increased both globally and in Brazil.

Although the Google Scholar is less restrictive, it was used because it includes results from non-indexed journals, and these journals tend to publish regionally relevant studies. In the Google Scholar, to quantify studies related to Brazil, the term "Brazil" was used after the keywords, and, for studies focusing on

other countries (identified as "World"), the keywords were followed by the minus sign and the term "Brazil" (-"Brazil"). After the results were displayed, publications of "Any language" and "Any type" were considered, excluding patents and citations.

On the Scopus platform, "Article title, Abstract, Keywords" were selected in the "Search within" function, added the first keyword in "Search documents", and used the "Add search field - AND" function to add the other keywords. In "Add date range", the respective periods were chosen using the "Published from" and "To" functions. In "Added to Scopus", "Anytime" was chosen. All results were considered from tabs "Open access", "Year", "Author name", "Subject area", "Document type", "Source title", "Affiliation", "Funding sponsor", "Country/ territory", "Source type" and "Language". For the "Publication Stage" function, "Final" was chosen. To identify Brazilian researches, the number of publications listed under the "Country/Territory" tab was checked.

On the Web of Science database, for each keyword, the option "All fields" was selected. The "Add row - AND" function was used to add the other keywords. In the "Add date range" function, "Publication date" and "Custom" were chosen (2001-01-01 to 2011-12-31 and 2012-01-01 to 2022-12-31). All results were considered from the tabs "Quick filters", "Citation topics meso", "Citation topics micro", "Authors", "Publication years", "Document types", "Web of science categories", "Affiliations", "Publication titles", "Publishers", "Funding Agencies", "Open Access", "Sustainable Development Goals", "Editorial notices", "Editors", "Group authors", "Research areas", "Countries/ regions", "Languages", "Conferences titles", "Book series titles" and "Web of science index". After the global search, the same steps were repeated, with the addition of the "Add row" function and adding the keyword "Brazil" to find Brazilian studies.

To determine which soil tillage management strategy reduces nitrate leaching, publications were selected from the Web of Science, Scopus and Google Scholar. For the Google Scholar, the first three pages of publications were considered because of the large number of available results. Studies that directly addressed the research question were selected by screening the abstracts (mostly focusing on their aims and results) and excluded unrelated publications. Publications that used the terms "conventional tillage" and "no-tillage system", as defined by Possamai et al. (2022), were selected. Research articles using the terms "no-tillage", "reduced" or "minimum tillage" were also considered as publications discussing no-tillage systems. Similarly, research articles that did not explicitly mention "conventional tillage" but involved methods such as "plowing", "scarification" and "conventional ridge tillage" were classified as discussing conventional tillage. Finally, articles that compared leaching in conventional and no-tillage systems were selected to identify which tillage system caused reduced nitrate leaching, and summarized the findings.

RESULTS AND DISCUSSION

The number of studies on nitrate leaching in the context of agriculture varied substantially across databases worldwide (4-16,800 publications) and for Brazil (0-4,520 publications) (Table 1). Specifically, a comparable number of publications were retrieved from the Scopus and Web of Science, whereas the Google Scholar returned considerably more results, indicative of its less restrictive nature. The Google Scholar likely included studies that were excluded from other databases because of perceived low quality or regional interest. Additionally, the Google Scholar often considers publications that are not directly related to keywords, but, for example, are included in the Reference section of other retrieved papers. Certain publications from the Scopus and Web of Science did not directly address our research question. Instead, they merely indirectly alluded to it or focused solely on the outcomes of a specific soil tillage approach.

When the keywords "nitrate leaching" and "agriculture" were used, the number of retrieved publications varied markedly; for example, 306 publications were retrieved from the Web of Science database, whereas 16,800 were retrieved from the Google Scholar. However, in general, very few studies focused on Brazil (Table 1).

Brazilian publications were found to be scarce across both decades (2001-2011 and 2012-2022), particularly for the Scopus (1 %) and Web of Science (2 %). In the more inclusive Google Scholar database, they constituted 17 % of the published works. In an academic context, uncertainties remain regarding the extent of nitrate leaching in Brazilian agriculture. This uncertainty can be attributed to the fact that, in general, few studies focusing on nitrate

Table 1. Number of scientific publications globally and for Brazil from different databases, regarding nitrate leaching in agriculture (keywords "nitrate leaching" and "agriculture") and no-tillage[1] systems (keywords "nitrate leaching" and "agriculture" and "no-tillage"), in the 2001-2011 and 2012-2022 decades.

Database	Keywords	Decade	World[2]	Brazil
Scopus	"Nitrate leaching" and "agriculture"	2001-2011	322	4
		2012-2022	576	7
	"Nitrate leaching" and "agriculture" and "no-tillage"	2001-2011	6	0
		2012-2022	16	0
Web of Science	"Nitrate leaching" and "agriculture"	2001-2011	306	8
		2012-2022	609	9
	"Nitrate leaching" and "agriculture" and "no-tillage"	2001-2011	4	0
		2012-2022	17	0
Google Scholar[3]	"Nitrate leaching" and "agriculture"	2001-2011	12,800	1,340
		2012-2022	16,800	4,520
	"Nitrate leaching" and "agriculture" and "no-tillage"	2001-2011	1,560	289
		2012-2022	3,300	1,190

[1] Including no-tillage systems, conservation agriculture and minimum and reduced tillage; [2] except Brazil; [3] approximate numbers.

leaching have been conducted in Brazil, with even fewer focusing on the rural Brazilian context. Most nitrate contamination studies in Brazil have only analyzed the groundwater supply of larger cities in which domestic sewage is the main source of nitrate (Stradioto et al. 2019, Hirata et al. 2020, CRH 2021).

Among the few Brazilian studies on nitrate leaching in rural areas, most only analyzed water contamination levels and assumed probable sources and transport processes without employing standardized methods to allow for comparisons across different contexts (e.g., Kaiser et al. 2010, Gomes & Barizon 2014). Overall, because of the limited Brazilian studies on leaching, the extent of nitrate leaching in rural Brazilian areas remains undetermined (CRH 2021). Considering the various implications of nitrate leaching, it is imperative to allocate greater attention to this subject, because Brazil has a wide range of edaphoclimatic conditions. For example, a study by Bortolotto et al. (2012) in the Bahia's Cerrado revealed significant nitrate leaching (1 m) in fertigated coffee plants cultivated in sandy soil with high nitrogen concentrations.

When the keyword "no-tillage" was also used, there was a decrease in the number of documents published globally across the databases; specifically, from four publications from the Web of Science to 3,300 from the Google Scholar (Table 1). This implies that research on nitrate leaching in no-tillage areas is limited, particularly in Brazil. In the most restrictive databases, there were no Brazil-specific publications during both analyzed decades, whereas, in the Google Scholar, the number of publications ranged from 289 (2001-2011) to 1,190 (2012-2022).

When comparing 2001-2011 to 2012-2022 (Figure 1A), global publications on nitrate leaching in agriculture increased by 79 and 99 % in the Scopus and Web of Science, respectively. However, the growth was relatively low for Brazil-specific publications, at 75 % in Scopus and 13 % in the Web of Science. According to the Google Scholar database, there has been a 31 % increase in global publications regarding nitrate leaching in agriculture and a 237 % increase in Brazilian publications.

The number of global publications on nitrate leaching in no-tillage agriculture grew markedly, when comparing results from 2001-2011 to 2012-2022 (Figure 1B). In total, 167 % more publications were retrieved from the Scopus, whereas 325 % more were retrieved from the Web of Science, and 112 % more were retrieved from the Google Scholar, between 2001-2011 and 2012-2022. Regrettably, there were no Brazilian publications on this topic in the Scopus or Web of Science. The Google Scholar reported a 312 % increase in publications on nitrate leaching in no-tillage. Despite the increase in publications, these findings underscore the scarcity of Brazilian research on nitrate leaching in no-tillage areas, when compared with global trends, despite the extensive adoption of no-tillage practices in Brazil. This scarcity is further highlighted by the fact that not all the Google Scholar manuscripts addressed this subject directly.

Padilla et al. (2018) observed a similar outcome in their analysis of global trends in nitrate

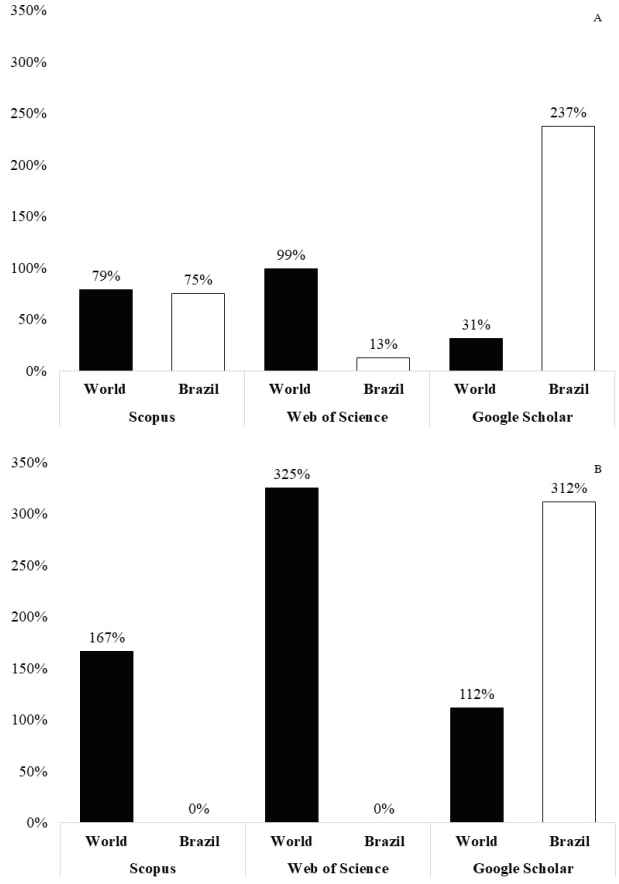

Figure 1. Percentage increase in the number of scientific publications on nitrate leaching in agriculture (A) and no-tillage (B) systems from different databases (Scopus, Web of Science and Google Scholar), globally (except Brazil) and in Brazil, between the 2001-2011 and 2012-2022 decades.

leaching from 1960 to 2017. They used broader search terms (nitrat* and leach*) in the Scopus database, which encompasses research across diverse fields. Most studies worldwide have been conducted in rural areas, focusing on corn, wheat and grasses, and were primarily published after 1990. The USA led the research output with 2,182 documents (21 %), followed by China (9 %), the United Kingdom (8 %) and Germany (6 %). Their findings revealed that Brazilian nitrate leaching research is limited, with only 175 publications.

To assess which soil tillage practices reduced nitrate leaching, 22 articles were analyzed. Among the publications considered in each database, the Scopus had only 5 % of exclusivity, whereas the Web of Science and Google Scholar had 24 and 30 %, respectively. After removing duplicates, a content analysis was conducted on 47 publications, of which only 22 specifically investigated the effect of conventional or no-tillage methods on reducing nitrate leaching (Table 2).

Thirteen articles, constituting the majority, demonstrated that no-tillage reduces nitrate leaching, whereas six found no differences between the two soil tillage practices. Only three studies concluded that conventional tillage was more advantageous in this regard (Table 2). Therefore, based solely on these conclusions, it appears that no-tillage practices reduce nitrate leaching. However, considering the limited number of analyzed articles and the fact that nine did not support the idea that no-tillage reduces nitrate leaching (Table 2), it is not possible to conclusively say that no-tillage is superior in this context.

Controversial results regarding agricultural nitrate loss were also observed in a literature review conducted by Wang & Li (2019). They noted that, even though tillage, especially when conducted before the wet season, has been shown to affect various soil-linked processes that impact leaching, its effects are contingent upon soil type, climate and initial soil nitrate content. The authors highlighted that under prolonged and continuous treatment, the nitrate content was higher under conventional tillage than under no-tillage. This was attributed to the possible reduction in net N mineralization owing to slower decomposition, increased N immobilization and differences in nitrification in no-tillage.

Nevertheless, a meta-analysis conducted by Daryanto et al. (2017), which included 43 studies published between 1985 and 2016, showed that no-tillage exhibited an increased leachate nitrate load, when compared to conventional tillage, although the nitrate concentrations were similar in both. The effect of no-tillage on the leached nitrate load was attributed to the changes in the soil water flow. This phenomenon occurs because of many factors, including the greater number of macropores in the no-tillage system, which alters the soil water flow. Dead roots and earthworms create macropores that form preferential water flow channels, resulting in increased capacity for water to infiltrate the soil and, therefore, increased nitrate leaching. However, the authors concluded that additional factors such as the use of cover crops or split N application enhance the soil retention of N and effectively reduce nitrate leaching.

Further research will be necessary to investigate the efficacy of different soil tillage

Table 2. Reference, study region, highlights of conclusions and impacts of tillage type on nitrate leaching from research articles focusing on soil tillage practices (conventional tillage[1] - CT and no-tillage[2] - NT) and nitrate leaching in agriculture from 2001-2011 to 2012-2022.

Reference	Region	Highlight of conclusions	Nitrate leaching
Bakhsh et al. (2002)	USA	Nitrate losses from chisel plow were lower than those from NT	NT > CT
Mkhabela et al. (2008)	Canada	In most cases, nitrate was higher under CT than NT at all soil depths	NT < CT
Hooker et al. (2008)	Ireland	CT without cover crop had lower nitrate concentrations in the first season and was not different from NT in the second season	No difference
Kaiser et al. (2010)	Brazil	NT and CT had no significant differences in the nitrate concentration of the soil solution	No difference
Follador et al. (2011)	Europe	Fertilizer/manure application during the cold and wet seasons (CT) led to an increase of N leaching	NT < CT
Amon-Armah et al. (2013)	Canada	Tillage did not have a significant effect on crop yield and nitrate leaching	No difference
Bécel et al. (2015)	France	The total amount of nitrate leaching was lowest in the cropping system using no herbicide and NT	NT < CT
Huang et al. (2015)	China	CT with straw minimized nitrate leaching	NT > CT
Meisinger et al. (2015)	USA	NT can increase nitrate leaching during seasons with excessive rainfall	NT > CT
Yagioka et al. (2015)	Japan	Nitrate leaching was lower in NT than in CT	NT < CT
Jokela & Nair (2016)	USA	Soil and water quality benefits associated with NT, especially nitrate leaching, were not consistently seen in this study	No difference
Celik et al. (2017)	Turkey	NT could significantly reduce nitrate leaching	NT < CT
Pisani et al. (2017)	USA	Nitrate leaching was not different between NT and CT with winter cover crops	No difference
Laine et al. (2018)	Finland	NT has the potential to decrease nitrate leaching	NT < CT
Jabro et al. (2019)	USA	CT and NT had no significant difference in nitrate leaching, probably because of the high spatial variability	No difference
Zhang et al. (2020)	China	NT treatments had significantly lower nitrate leaching than CT	NT < CT
Colombani et al. (2020)	Italy	NT with compost and mineral fertilization can diminish nitrate leaching when compared to CT	NT < CT
Spiess et al. (2020)	Switzerland	NT showed lower leaching rates than CT	NT < CT
Hess et al. (2020)	USA	Rainfall intensification increases nitrate leaching from CT but not NT	NT < CT
Dai et al. (2021)	China	NT reduced nitrate leaching	NT < CT
Yuan et al. (2022)	China	NT with 100 % straw reduced nitrate leaching when compared to CT	NT < CT
O'Brien et al. (2022)	USA	NT with rye as a cover crop reduced the nitrate concentration and, consequently, the leaching loss	NT < CT

[1] Plowing, scarification and conventional ridge tillage were classified as conventional tillage (CT); [2] no-tillage systems, conservation agriculture and minimum or reduced tillage were classified as no-tillage (NT).

practices in reducing nitrate leaching worldwide, while considering various edaphoclimatic conditions and tillage types. Such studies are particularly important in the context of Brazil, where only one publication on this issue was found (Table 2), despite the increasing adoption of no-tillage practices (Fuentes-Llanillo et al. 2021). The Brazilian study by Kaiser et al. (2010), focused on nitrate leaching in a tobacco cropland in the Rio Grande do Sul state, compared nitrate concentrations in soil solutions collected within and below the root zone under three management practices (i.e., no-tillage, minimum tillage and conventional tillage), and found no significant differences in nitrate concentrations among these practices, and this was likely because of the high coefficient of variation.

As edaphoclimatic conditions in Brazil differ significantly from those highlighted in most studies that demonstrate reduced leaching under no-tillage, additional research is crucial to understand the nitrate dynamics in tropical and subtropical environments.

CONCLUSIONS

1. In both the analyzed decades (2001-2011 and 2012-2022), the number of studies on nitrate leaching in global agriculture varied markedly across different

databases, and studies conducted with a focus on Brazil were limited;
2. There was limited research on nitrate leaching in no-tillage, both globally and in Brazil, with the latter having no publications available in the most restrictive databases (i.e., Scopus and Web of Science);
3. Global interest in nitrate leaching in agriculture increased across both decades (2001-2011 and 2012-2022), as evidenced by the percentage increase in publications for all databases. The increase in Brazil-specific publications was more noticeable in the Google Scholar than in more restrictive databases;
4. Global publications on nitrate leaching in no-tillage experienced even a greater growth between the two analyzed decades. However, this global interest was not mirrored in Brazil, as there was no increase in publications in the most restrictive databases;
5. Of the 22 analyzed articles, 13 supported that no-tillage reduces nitrate leaching, when compared to conventional tillage, whereas six found no difference between the systems, and three indicated that conventional tillage resulted in less nitrate leaching. Given that only a limited number of papers were available and nine of them did not support the hypothesis that no-tillage practices reduce nitrate leaching, further research in different agricultural settings will be necessary to establish a definitive conclusion.

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REFERENCES

AMON-ARMAH, F.; YIRIDOE, E. K.; AHMAD, N. H. M.; HEBB, D.; JAMIESON, R.; BURTON, D.; MADANI, A. Effect of nutrient management planning on crop yield, nitrate leaching and sediment loading in Thomas Brook watershed. *Environmental Management*, v. 52, n. 5, p. 1177-1191, 2013.

BAKHSH, A.; KANWAR, R. S.; BAILEY, T. B.; CAMBARDELLA, C. A.; KARLEN, D. L.; COLVIN, T. S. Cropping system effects on NO_3-N loss with subsurface drainage water. *Transactions of the ASAE*, v. 45, n. 6, p. 1789-1797, 2002.

BÉCEL, C.; MUNIER-JOLAIN, N. M.; NICOLARDOT, B. Assessing nitrate leaching in cropping systems based on integrated weed management using the STICS soil-crop model. *European Journal of Agronomy*, v. 62, n. 1, p. 46-54, 2015.

BIJAY-SINGH; CRASWELL, E. Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem. *SN Applied Sciences*, v. 3, e518, 2021.

BORTOLOTTO, R. P.; BRUNO, I. P.; REICHARDT, K.; TIMM, L. C.; AMADO, T. J. C.; FERREIRA, A. O. Nitrogen fertilizer (^{15}N) leaching in a central pivot fertigated coffee crop. *Revista Ceres*, v. 59, n. 4, p. 466-475, 2012.

BRADY, N. C.; WEIL, R. R. *Elements of the nature and properties of soils*. 3. ed. Porto Alegre: Bookman, 2013.

CAMERON, K.; DI, H.; MOIR, J. Nitrogen losses from the soil/plant system: a review. *Annals of Applied Biology*, v. 162, n. 2, p. 145-173, 2013.

CELIK, I.; GÜNAL, H.; ACAR, M.; GÖK, M.; BEREKET BARUT, Z.; PAMIRALAN, H. Long-term tillage and residue management effect on soil compaction and nitrate leaching in a Typic Haploxerert soil. *International Journal of Plant Production*, v. 11, n. 1, p. 131-150, 2017.

COLOMBANI, N.; MASTROCICCO, M.; VINCENZI, F.; CASTALDELLI, G. Modeling soil nitrate accumulation and leaching in conventional and conservation agriculture cropping systems. *Water*, v. 12, e1571, 2020.

CONSELHO ESTADUAL DE RECURSOS HÍDRICOS (CRH). Câmara Técnica de Águas Subterrâneas. *Nitrato nas águas subterrâneas*: desafios frente ao panorama atual. São Paulo: Sima, 2021.

CRUSCIOL, C. A. C.; GARCIA, R. A.; CASTRO, G. S. A.; ROSOLEM, C. A. Nitrate role in basic cation leaching under no-till. *Revista Brasileira de Ciência do Solo*, v. 35, n. 6, p. 1975-1984, 2011.

DAI, Z.; HU, J.; FAN, J.; FU, W.; WANG, H.; HAO, M. No-tillage with mulching improves maize yield in dryland farming through regulating soil temperature, water and nitrate-N. *Agriculture, Ecosystems and Environment*, v. 309, e107288, 2021.

DARYANTO, S.; WANG, L.; JACINTHE, P. A. Impacts of no-tillage management on nitrate loss from corn, soybean and wheat cultivation: a meta-analysis. *Scientific Reports*, v. 7, e12117, 2017.

DOURADO-NETO, D.; POWLSON, D.; ABU BAKAR, R.; BACCHI, O. O. S.; BASANTA, M. V.; THI CONG, P.; KEERTHISINGHE, G.; ISMAILI, M.; RAHMAN, S. M.; REICHARDT, K.; SAFWAT, M. S. A.; SANGAKKARA, R.; TIMM, L. C.; WANG, J. Y.; ZAGAL, E.; VAN

KESSEL, C. Multiseason recoveries of organic and inorganic nitrogen-15 in tropical cropping systems. *Soil Science Society of America Journal*, v. 74, n. 1, p. 139-152, 2010.

FIOREZE, C.; CERETTA, C. A.; GIACOMINI, S. J.; TRENTIN, G.; LORENSINI, F. N release in different textures soils with or without organic fertilizers. *Ciência Rural*, v. 42, n. 7, p. 1187-1192, 2012.

FOLLADOR, M.; LEIP, A.; ORLANDINI, L. Assessing the impact of cross compliance measures on nitrogen fluxes from European farmlands with DNDC-EUROPE. *Environmental Pollution*, v. 159, n. 11, p. 3233-3242, 2011.

FOOD AND AGRICULTURE ORGANIZATION (FAO). *Crops and livestock products*. 2023. Available at: https://www.fao.org/faostat/en/#data/QCL. Access on: Oct. 30, 2023.

FOSTER, S.; CUSTODIO, E. Groundwater resources and intensive agriculture in Europe: can regulatory agencies cope with the threat to sustainability? *Water Resources Management*, v. 33, n. 6, p. 2139-2151, 2019.

FUENTES-LLANILLO, R.; TELLES, T. S.; SOARES-JUNIOR, D.; MELO, T. R.; FRIEDRICH, T.; KASSAM, A. Expansion of no-tillage practice in conservation agriculture in Brazil. *Soil and Tillage Research*, v. 208, e104877, 2021.

GOMES, M. A. F.; BARIZON, R. R. M. *Panorama da contaminação ambiental por agrotóxicos e nitrato de origem agrícola no Brasil*: cenário 1992/2011. Jaguariúna: Embrapa Meio Ambiente, 2014.

GOOGLE SCHOLAR. *Database*. 2023. Available at: https://scholar.google.com. Access on: May 25, 2023.

GRZYB, A.; WOLNA-MARUWKA, A.; NIEWIADOMSKA, A. Environmental factors affecting the mineralization of crop residues. *Agronomy*, v. 10, n. 12, e1951, 2020.

HAWKESFORD, M.; HORST, W.; KICHEY, T.; LAMBERS, H.; SCHJOERRING, J.; MØLLER, I. S.; WHITE, P. Functions of macronutrients. *In*: MARSCHNER, P. (ed.). *Marschner's mineral nutrition of higher plants*. London: Academic Press, 2012. p. 135-189.

HESS, L. J. T.; HINCKLEY, E. S.; ROBERTSON, G. P.; MATSON, P. A. Rainfall intensification increases nitrate leaching from tilled but not no-till cropping systems in the U. S. midwest. *Agriculture, Ecosystems and Environment*, v. 290, e106747, 2020.

HIRATA, R.; CAGNON, F.; BERNICE, A.; MALDANER, C. H.; GALVÃO, P.; MARQUES, C.; TERADA, R.; VARNIER, C.; RYAN, M. C.; BERTOLO, R. Nitrate contamination in Brazilian urban aquifers: a tenacious problem. *Water*, v. 12, n. 10, e2709, 2020.

HOOKER, K. V.; COXON, C. E.; HACKETT, R.; KIRWAN, L. E.; O'KEEFFE, E.; RICHARDS, K. G. Evaluation of cover crop and reduced cultivation for reducing nitrate leaching in Ireland. *Journal of Environmental Quality*, v. 37, n. 1, p. 138-145, 2008.

HUANG, M.; LIANG, T.; WANG, L.; ZHOU, C. No-tillage and fertilization management on crop yields and nitrate leaching in north China plain. *Ecology and Evolution*, v. 5, n. 6, p. 1143-1155, 2015.

JABLOUN, M.; SCHELDE, K.; TAO, F.; OLESEN, J. E. Effect of temperature and precipitation on nitrate leaching from organic cereal cropping systems in Denmark. *European Journal of Agronomy*, v. 62, n. 1, p. 55-64, 2015.

JABRO, J. D.; IVERSEN, W. M.; STEVENS, W. B.; SAINJU, U. M.; ALLEN, B. L. Tillage effects on drainage fluxes and nitrate leaching through unsaturated zone under irrigated corn-soybean rotation. *Applied Engineering in Agriculture*, v. 35, n. 3, p. 293-300, 2019.

JADOSKI, S. O.; SAITO, L. R.; PRADO, C.; LOPES, E. C.; SALES, L. L. S. R. Características da lixiviação de nitrato em áreas de agricultura intensiva. *Pesquisa Aplicada e Agrotecnologia*, v. 3, n. 1, p. 193-200, 2010.

JOKELA, D.; NAIR, A. Effects of reduced tillage and fertilizer application method on plant growth, yield, and soil health in organic bell pepper production. *Soil & Tillage Research*, v. 163, n. 1, p. 243-254, 2016.

KAISER, D. R.; REINERT, D. J.; REICHERT, J. M.; STRECK, C. A.; PELLEGRINI, A. Nitrate and ammonium in soil solution in tobacco management systems. *Revista Brasileira de Ciência do Solo*, v. 34, n. 2, p. 379-387, 2010.

LAINE, M.; RÜTTING, T.; ALAKUKKU, L.; PALOJÄRVI, A.; STRÖMMER, R. Process rates of nitrogen cycle in uppermost topsoil after harvesting in no-tilled and ploughed agricultural clay soil. *Nutrient Cycling in Agroecosystems*, v. 110, n. 1, p. 39-49, 2018.

MEISINGER, J. J.; PALMER, R. E.; TIMLIN, D. J. Effects of tillage practices on drainage and nitrate leaching from winter wheat in the northern Atlantic coastal-plain USA. *Soil & Tillage Research*, v. 151, n. 1, p. 18-27, 2015.

MKHABELA, M. S.; MADANI, A.; GORDON, R.; BURTON, D.; CUDMORE, D.; ELMI, A.; HART, W. Gaseous and leaching nitrogen losses from no-tillage and conventional tillage systems following surface application of cattle manure. *Soil & Tillage Research*, v. 98, n. 2, p. 187-199, 2008.

NORTON, J.; OUYANG, Y. Controls and adaptive management of nitrification in agricultural soils. *Frontiers in Microbiology*, v. 10, e1931, 2019.

NOURI, A.; LUKAS, S.; SINGH, S.; SINGH, S.; MACHADO, S. When do cover crops reduce nitrate leaching?: a global meta-analysis. *Global Change Biology*, v. 28, n. 15, p. 4736-4749, 2022.

O'BRIEN, P. L.; EMMETT, B. D.; MALONE, R. W.; NUNES, M. R.; KOVAR, J. L.; KASPAR, T. C.; MOORMAN, T. B.; JAYNES, D. B.; PARKIN, T. B. Nitrate losses and nitrous oxide emissions under contrasting tillage and cover crop management. *Journal of Environmental Quality*, v. 51, n. 4, p. 683-695, 2022.

PADILLA, F. M.; GALLARDO, M.; MANZANO-AGUGLIARO, F. Global trends in nitrate leaching research in the 1960-2017 period. *Science of the Total Environment*, v. 643, n. 1, p. 400-413, 2018.

PICETTI, R.; DEENEY, M.; PASTORINO, S.; MILLER, M. R.; SHAH, A.; LEON, D. A.; DANGOUR, A. D.; GREEN, R. Nitrate and nitrite contamination in drinking water and cancer risk: a systematic review with meta-analysis. *Environmental Research*, v. 210, e112988, 2022.

PINHEIRO, R. B.; CANTARUTTI, R. B.; VILLANI, E. M. A.; CAVALCANTE, V. S.; FONTES, M. P. F. Nitrate mobility in variable-charge tropical soils. *Communications in Soil Science and Plant Analysis*, v. 51, n. 16, p. 2163-2173, 2020.

PINTO, V. M.; BRUNO, I. P.; VAN LIER, Q. J.; DOURADO-NETO, D.; REICHARDT, K. Excessive use of nitrogen causes monetary loss for coffee growers in the Cerrado. *Coffee Science*, v. 12, n. 2, p. 176-186, 2017.

PISANI, O.; STRICKLAND, T. C.; HUBBARD, R. K.; BOSCH, D. D.; COFFIN, A. W.; ENDALE, D. M.; POTTER, T. L. Soil nitrogen dynamics and leaching under conservation tillage in the Atlantic coastal plain, Georgia, United States. *Journal of Soil & Water Conservation*, v. 72, n. 5, p. 519-529, 2017.

POSSAMAI, E. J.; CONCEIÇÃO, P. C.; AMADORI, C.; BARTZ, M. L. C.; RALISCH, R.; VICENSI, M.; MARX, E. F. Adoption of the no-tillage system in Paraná state: a (re)view. *Revista Brasileira de Ciência do Solo*, v. 46, e0210104, 2022.

RICHA, A.; TOUIL, S.; FIZIR, M. Recent advances in the source identification and remediation techniques of nitrate contaminated groundwater: a review. *Journal of Environmental Management*, v. 316, e115265, 2022.

ROSOLEM, C. A.; CASTOLDI, G.; PIVETTA, L. A.; OCHSNER, T. E. Nitrate leaching in soybean rotations without nitrogen fertilizer. *Plant & Soil*, v. 423, n. 1, p. 27-40, 2018.

RUTTING, T.; ARONSSON, H.; DELIN, S. Efficient use of nitrogen in agriculture. *Nutrient Cycling in Agroecosystems*, v. 110, n. 1, p. 1-5, 2018.

SAHRAWAT, K. L. Factors affecting nitrification in soils. *Communications in Soil Science and Plant Analysis*, v. 39, n. 9-10, p. 1436-1446, 2008.

SANCHEZ, P. A. *Properties and management of soils in the tropics*. 2. ed. Cambridge: Cambridge University Press, 2019.

SCOPUS. *Database*. 2023. Available at: https://www.scopus.com/search/form.uri?display=basic#basic. Access on: May 25, 2023.

SPIESS, E.; HUMPHRYS, C.; RICHNER, W.; SCHNEIDER, M. K.; PIEPHO, H.; CHERVET, A.; PRASUHN, V. Does no-tillage decrease nitrate leaching compared to ploughing under a long-term crop rotation in Switzerland? *Soil and Tillage Research*, v. 199, e104590, 2020.

STRADIOTO, M. R.; TERAMOTO, E. H.; CHANG, H. K. Nitrates in groundwater of the state of São Paulo. *Revista do Instituto Geológico*, v. 40, n. 3, p. 1-12, 2019.

TSADILAS, C. *Nitrate handbook*: environmental, agricultural, and health effects. Boca Raton: CRC Press, 2022.

WANG, Z.-H.; LI, S.-X. Nitrate N loss by leaching and surface runoff in agricultural land: a global issue (a review). *Advances in Agronomy*, v. 156, n. 1, p. 159-217, 2019.

WEB OF SCIENCE. *Database*. 2023. Available at: https://www.webofscience.com/wos/woscc/basic-search. Access on: May 25, 2023.

YAGIOKA, A.; KOMATSUZAKI, M.; KANEKO, N.; UENO, H. Effect of no-tillage with weed cover mulching *versus* conventional tillage on global warming potential and nitrate leaching. *Agriculture, Ecosystems & Environment*, v. 200, n. 1, p. 42-53, 2015.

YANG, X.; LU, Y.; DING, Y.; YIN, X.; RAZA, S.; TONG, Y. Optimising nitrogen fertilisation: a key to improving nitrogen-use efficiency and minimising nitrate leaching losses in an intensive wheat/maize rotation (2008-2014). *Field Crops Research*, v. 206, n. 1, p. 1-10, 2017.

YUAN, L.; LIU, Y.; HE, H.; ZHU, T.; CHEN, X.; ZHANG, X.; LIANG, C.; XIE, H.; ZHANG, J.; MÜLLER, C.; ZHAO, X.; YAN, X.; LU, C. Effects of long-term no-tillage and maize straw mulching on gross nitrogen transformations in Mollisols of northeast China. *Geoderma*, v. 428, e116194, 2022.

ZHANG, Y.; XIE, D.; NI, J.; ZENG, X. Conservation tillage practices reduce nitrogen losses in the sloping upland of the Three Gorges reservoir area: no-till is better than mulch-till. *Agriculture, Ecosystems & Environment*, v. 300, n. 1, p. 3-7, 2020.