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Nitrogen recycling across a spectrum of fertilization strategies: an assessment in olive groves

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ABSTRACT

Under the Zero pollution action, there is a strong emphasis on promoting management practices that enhance nitrogen (N) cycling to decrease reliance on inorganic N fertilizers and mitigate potential environmental impacts. Olive (*Olea europaea* L.) groves constitute the dominant landscape of many areas of Southern Mediterranean as Andalusia (Spain). Different farming models coexist in the olive sector, but they had not been studied in the context of N cycle. By integrating field and model data, we analyzed N flows, N balance, levels of N cycling closure, and N footprints in olive groves employing various cultivation models. Farms were categorized on: Org (organic external fertilization, high level of biomass recycling, temporary spontaneous cover crops), Tra (organic external fertilization, low recycling, bare soil), Int (inorganic external fertilization, low recycling, bare soil) and IPr (inorganic or organic external fertilization, low recycling, temporary spontaneous cover crops). Tree N demand, averaging 55 kg ha^{-1} y^{-1}, correlated with fruit production and canopy area, making them suitable proxies for calculating N demand without exhaustive sampling. The N balance was positive for all farming models, with the Org model showing a more neutral balance (+7.4 kg N ha^{-1} y^{-1}) and the IPr olive farms showing surpluses (+40.2 kg ha^{-1} y^{-1}). In Org farms, annual N inputs were the lowest and rely on natural entries like N fixation, while Cycling Index was significantly higher than those of other groups (between 1.45 and 1.81 times). This was attributed to N recirculation mechanisms such as cover crops, shredding tree pruning, and returning harvested N through composted olive mill pomace. Soil erosion, often overlooked, emerged as a major N outflow, especially in Org farms with the highest soil N content, resulting in the highest N losses per liter of oil. Per liter of olive oil, Trad, Ipr, and Int farms use between 1.9 and 2.2 times more anthropogenic N inputs than Org farms. Overall, our results highlight significant potential to enhance internal N cycling, increase self-sufficiency, and extend the lifespan of N in olive farming by implementing scalable management practices that promote nature-based processes.

1. Introduction

In natural terrestrial ecosystems nitrogen (N) circulates among the soil mineral pool, organisms and the organic matter in fairly closed cycles (Tivy, 1987). N inputs and outputs are often much smaller than internal flows in natural conditions and are considered to be counterbalanced. In contrast, agroecosystems are managed to boost N uptake by crops, most of which is exported outside the farm boundaries through harvest and only returned to agroecosystems in a small proportion (Frossard et al., 2009). In addition to harvest, disturbances provoked by soil management usually intensify natural outflow pathways of N such as leaching, runoff, soil erosion and gaseous losses (Magdoff et al., 1997). In most of the current intensive agriculture systems increasing amounts of N fertilisers are applied to overcome these losses. Globally, from 1950 to 2000 the use of N fertilizer increased 20-fold, whereas the portion of these recovered by crops fell sharply (Bouwman et al., 2009). Since the N fertilization strategy of intensive agriculture often aims to obtain large yields instead of curb N losses and increase soil fertility, the N surplus is released to neighboring ecosystems or to the atmosphere causing water pollution and greenhouse gas emissions (Sutton et al., 2013).

The EU's "Farm to Fork" strategy has established ambitious

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environmental objectives, aiming to reduce nutrient losses by at least half by 2030 without compromising soil fertility. Achieving this goal entails a targeted reduction in fertilizer usage by at least 20% by 2030 (European Comission, 2020), necessitating the promotion of management practices that foster a more closed-loop nutrient cycling system. To develop an effective fertilization protocol aligned with these objectives, it is imperative to accurately assess the annual nutrient requirements of crops and adopt crop-specific nature-based solutions tailored to local conditions.

Olive (*Olea europaea* L.) cultivation holds significant importance in various regions of the Mediterranean basin. In Andalusia (Spain), the largest global producer of olive fruits, olive cultivation account for 47% of the arable land (MAPA, 2020). This widespread cultivation has often led to accelerated erosion and soil degradation. Studies indicate that even with a moderate expansion of cover crops, olive groves in Andalusia experience average erosion rates above 20 t ha^{-1} y^{-1} (Gómez et al., 2014). While there's no official report on the doses and types of fertilizers used, there's growing concern regarding their excessive and inappropriate application (Gómez-Limón and Arriaza, 2011).

Until now, N fertilization recommendations have primarily relied on harvested N, disregarding other inputs and outputs (MAPA, 2010). However, any potential N loss poses a threat to the long-term productivity of olive groves, as well as the environmental health and the economic viability of farmers. Given that olive groves span approximately 1.7 million hectares in Andalusia, it becomes imperative to assess the dynamics of nutrient management comprehensively.

In response to soil degradation and nutrient pollution, European institutions are actively promoting regulations aimed at preserving soil fertility. For instance, the Spain's CAP 2023–2027 Strategic Plan encourages woody crops, such as olive cultivation, to maintain a living cover crop during the rainy season and utilize pruning residues as inert cover (MAPA, 2022). Additionally, the production of organic fertilizers from agro-industrial residues with potential environmental impact, such as the compost of olive mill pomace, has been boosted by technological development and increased investment. Over the past two decades, these practices have significantly proliferated within the olive sector (Junta de Andalucía, 2015; Junta de Andalucía, 2009; MAPA, 2020). Moreover, traditional practices like grazing and manure application persist in certain olive groves. Despite their well-known effects on nutrient dynamics (Lozano-García and Parras-Alcántara, 2013; Ordóñez-Fernández et al., 2015; Repullo-Ruibérriz de Torres et al., 2021), their impact on nutrient cycling at the farm level remains understudied.

Different mass balance approaches to monitor nutrient flows have been developed, tailored to specific research aims, scales, system boundaries, and the types of flows being accounted for. At the farm level, these approaches primarily serve as indicators of nutrient management effectiveness, while at the regional or national level, they function as agro-environmental indicators (Oenema et al., 2003). In Spain, the most recent regulation on sustainable nutrient management (Real Decreto 1051/2022, 2022) mandates the calculation of N requirements for fertilization based on the disparity between expected harvest output and specific inputs (such as soil mineralization, previous crop residues, organic amendments, and irrigation).

Studies on N balance in olive groves are limited, and the methods employed vary (Belguerri et al., 2016; Fernández-Escobar et al., 2012; MAPA, 2021). These studies often overlook significant nitrogen flows and fail to capture the diversity of management practices within this crop. We hypothesize that combination management strategies, such as the use of temporary cover crops, application of tree pruning, composted olive mill pomace and manure, and integration of livestock, could significantly impact the closure of N cycle. Furthermore, disregarded fluxes in other studies could significantly alter the overall understanding of N dynamics.

The objectives of this study are twofold: i) to evaluate, across seventeen commercial olive groves with contrasted nutrient management strategies, the magnitude and variability of primary N flows within olive groves, and ii) to examine the impact of different management practices on the closure level of N cycle, N footprints, and N outputs beyond harvested N.

2. Materials and methods

2.1. Experimental design and olive farm selection

Seventeen commercial olive groves located in the first (Jaen) and the third (Seville) provinces of Spain with the highest area planted with olive groves were selected for this study (Figure A1). These farms covered a wide diversity of farming models and managements in terms of i) tree density (from 70 to 333), ii) irrigation (rainfed to 5500 m^3 ha^{-1} y^{-1}), iii) fertilization strategy (inorganic, organic, inorganic plus organic, and no fertilization), and iv) management of crop residues and temporary spontaneous cover crop. The general characteristics of the selected farms are summarised in Table A1. The climate in both regions is Mediterranean (Csa, Köppen-Geiger classification), with long and very dry summers and rainfall concentrated in winter and early spring. Mean annual precipitation (MAP) ranges between 408 and 581 mm y^{-1}, with average values of 516 ± 56 mm y^{-1} and 482 ± 16 mm y^{-1} for the olive groves of Sevilla and Jaén, respectively. Mean annual temperature (MAT) are 15.6 ± 1.2 °C and 17.0 ± 0.2 °C for both areas, respectively (data from historical series 1991 – 2020).

Olive farms were classified into four groups. The main characteristics of each group of farms are summarized in Table 1, while detailed

Table 1
Summary of the main characteristics of the groups of olive farms. Data are means of the farms ± the standard deviation. Different lowercase letters in the same row indicate significant differences among groups ($p < 0.05$, Kruskal-Wallis and post-hoc Dunn's test).

	Nutrient management strategy			
	Org (n=4)	**Tra (n=2)**	**Int (n=3)**	**IPr (n=8)**
Tree density (number of trees ha^{-1})	147.3 ± 48.3	149.5 ± 122.3	197.7 ± 121.0	166.5 ± 82.0
Canopy area (m^2 ha^{-1})	2500.9 ± 1055.6	3029.5 ± 638.6	3422.6 ± 623.0	2958.3 ± 629.9
Irrigation (m^3 ha^{-1} y^{-1})	400.0 ± 461.9	0.0 ± 0.0	1433.3 ± 1401.2	1300.1 ± 1916.6
Slope (%)	18.9 ± 7.4a	5.3 ± 0.0ab	8.6 ± 5.3ab	6.1 ± 4.0b
External fertilization[a]	*Org fer*	*Org fer*	*Ino fer*	*Ino fer*
Crop residues reuse[b]	*Le* + *Pru* + *Pom**	*Pru*	*Pru*	*Pru*
Cover crop control[c]	(*Whole*) *Mow* + *Graz**	(*None*) *Till* + *Herb**	(*None*) *Till* + *Herb*	(*Band*) *Mow* + *Herb**
Fruit production (kg ha^{-1} y^{-1})	3565.0 ± 1514.2	4677.0 ± 456.8	5626.7 ± 1417.8	6394.8 ± 1775.1
Oil production (kg ha^{-1} y^{-1})	721.5 ± 302.1	968.1 ± 45.2	1125.3 ± 283.6	1270.8 ± 334.3
Soil organic matter content (%)	3.16 ± 1.00	1.79 ± 0.41	1.93 ± 0.85	2.06 ± 0.78
Soil Kjeldhal N content (%)	0.18 ± 0.05	0.09 ± 0.03	0.12 ± 0.03	0.12 ± 0.03

[a] *Org fer* and *Ino fer* stand for organic and inorganic fertilizers, respectively. These categories only account for the main sources of N, not the secondary sources (usually applied through irrigation or foliar application).

[b] *Le*, *Pom* and *Prun* are leaves from olive mill, olive mill pomace and light pruning, respectively.

[c] *Whole*, *Band* and *None* (within brackets) refer to spontaneous cover crops that cover the entire area of the farms, bands of 1–3 m in width, or no cover crop allowed to grow, respectively. *Mow*, *Graz*, *Herb* and *Till* stands for the management of the temporary spontaneous cover crop through mowing, grazing, herbicide application, or tillage, respectively.

[*] Management practice not include in one farm of the group.

descriptions of fertilizers used can be found in Table A2. Olive farms of group Org utilize a fertilization approach reliant on reused biomass generated on the farm (e.g. olive mill pomace) and/or organic fertilizers (e.g. off farm manure or compost). These farms implement spontaneous cover crops across the entire area of the farm, managed through mowing and/or grazing by livestock. Group Tra comprises olive groves without cover crops (i.e. bare soil) but whose fertilization relies on manure. Olive groves in group Int feature bare soil and utilize inorganic fertilizers. Finally, group IPr includes olive groves with cover crops in bands but with inorganic fertilization.

2.2. Methodological approach

A system approach was adopted to assess the N mass balance (Öborn et al., 2003), by using the flow analysis perspective of Finn (1982). Consistent with the assessment of nutrient stocks in natural ecosystems, the analysis focused on several system compartments: the top 30 cm of soil, the olive trees, the temporary spontaneous cover crop, and the livestock (Magdoff et al., 1997). Olive trees and the cover crop were treated as distinct stocks due to their varying management within the system, which influences different N flows and indicators. All N inputs, outputs and flows between the system components were recorded over a one-year time scale, measured in kg N per hectare and per year. For each stock, the difference between the N inflows and the outflows indicates the annual change in the N stock, reflecting net storage or depletion. Fig. 1 illustrates the conceptual model of the study.

2.3. Nitrogen inputs assessment

N inputs (N_{inp}) encompass all the yearly N inflows entering the olive grove, which include N entering through the soil ($N_{inp\text{-}soil}$), the cover crop ($N_{sym\ fix}$) and the livestock (N_{feed}). $N_{inp\text{-}soil}$ includes the N deposited with the annual rainfall (N_{atm}), the atmospheric N_2 entry due to the non-symbiotic free-living microorganisms ($N_{free\ fix}$), the N in the irrigation water (N_{irri}), and the N contained in fertilizers, either organic ($N_{org\ fer}$) or inorganic ($N_{ino\ fer}$). With respect to cover crop, only one external inflow is considered: the annual fixation of atmospheric N_2 by legumes of the cover crop ($N_{sym\ fix}$). Finally, the only external N input for livestock is that contained in imported feed (N_{feed}).

Additionally, inputs were classified in natural ($N_{inp\text{-}nat}$) and anthropogenic ($N_{inp\text{-}ant}$). $N_{inp\text{-}nat}$ include N_{atm}, $N_{freefix}$, and N_{symfix}, whereas $N_{inp\text{-}antr}$ is the sum of N_{irri}, $N_{org\ fer}$, $N_{ino\ fer}$ and N_{feed}.

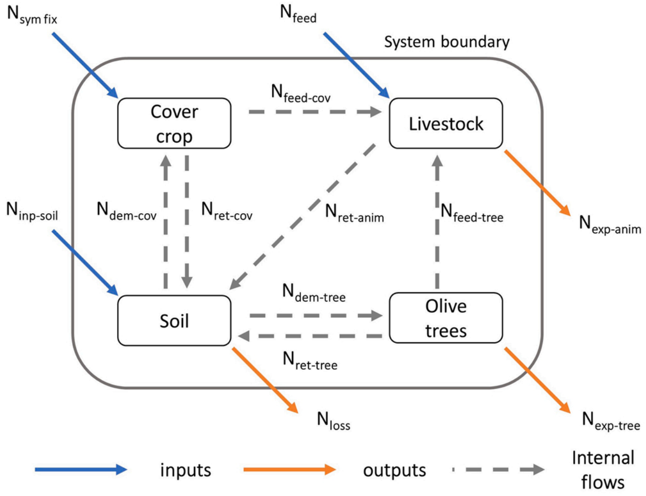

Fig. 1. Conceptual model adopted for assessing the N mass balance in the farms. Abbreviations are defined in detail in Section 2.

2.3.1. Natural nitrogen entries: rainfall and nitrogen fixation

N_{atm} was calculated by multiplying the annual average rainfall of the 2011–2021 period by the mineral N content in rainwater obtained in four rain gauges installed during the hydrological year 2021–2022 in four of the studied olive groves. Data of annual rainfall was obtained from the closest weather stations of the Agroclimatic Information Network of Andalusia (RIA). Rain water nitrate and ammonium concentrations were measured following Shinn (1941) and Koroleff (1966), respectively.

$N_{sym\ fix}$ was calculated following the approaches of García-Ruiz et al. (2010). First, the aboveground biomass of temporary spontaneous cover crops (TSCC) was measured as described in Section 2.4.1. Wild legumes were estimated to comprise 8% of the total weight of aboveground biomass in the TSCC communities. This value was the average of the contribution of legume to the total aboveground biomass in 34 sampling of semi-arid grassland of Spain (Corona et al., 1995). N content of the aerial biomass of the legume was assumed to be 3.3% dry weight, the mean content of vetch (*Vicia sativa*) (Sainju et al., 2005), which is a common wild legume in olive groves of Andalusia (Guzmán and Foraster, 2007). Legume root N content was assumed to be 33% of that of the aerial biomass (Wichern et al., 2008). Finally, it was assumed that 60% of N of legumes comes from atmospheric N_2 (Gathumbi et al., 2002).

$N_{free\ fix}$ was assumed to be 4 kg N ha^{-1} y^{-1} for no till olive groves (García-Ruiz et al., 2010) and the value was reduced according to the tillage intensity, since it has been shown that the higher is the soil perturbation the lower is the non-symbiotic N fixation (Zheng et al., 2020).

2.3.2. Anthropogenic nitrogen entries: fertilization, irrigation and livestock feed

The amount of each type of inorganic fertilizer and the amount (fresh weight) of compost, manure or other organic fertilizer applied were recorded in each of the olive groves. Several aliquots of each organic fertilizer were transported to the lab to analyse the water and, once dried and milled, N contents (CHNS elemental analyzer, Leco TruSpect Micro). N content of the chemical fertilizers was taken from the supplier information. The annual rate of N input by inorganic ($N_{ino\ fer}$) and organic ($N_{org\ fer}$) was calculated for each olive groves from the frequency, the doses of application and their N content.

N_{irri} was estimated from the irrigation doses and the mean values of nitrate and ammonium concentrations of the irrigated water (García-Ruiz et al., 2010).

The N supplied by livestock feed (N_{feed}) was obtained by multiplying the amount of feed provided by its N content.

2.4. Nitrogen internal flows assessment

2.4.1. Tree and cover crop demand for nitrogen

Annual demand of N of the olive trees ($N_{dem\text{-}tree}$) includes: the N annually taken by the olive fruits ($N_{dem\text{-}fruit}$), the N accumulated in vegetative tissue that will be pruned ($N_{dem\text{-}pru}$), the N uptake of leaves that will fall during harvest or naturally as litter ($N_{dem\text{-}leav}$), the N used for roots turnover ($N_{dem\text{-}root}$) and the N accumulated in the permanent structures of the trees ($N_{dem\text{-}per}$). It was assumed that the tree biomass is in steady state, except the permanent structures, so the pruned material, the leaves and the roots removed will be replace for an equivalent biomass. Therefore, the $N_{dem\text{-}tree}$ can be calculated following Eq. 1.

$$N_{dem-tree} \quad (kgN \quad ha^{-1} \quad y^{-1}) = \quad N_{dem-fruit} + N_{dem-pru} + N_{dem-leav} + N_{dem-root} + N_{dem-per} \tag{1}$$

To calculate $N_{dem\text{-}fruit}$, three bags of fifteen olives consisting of five olives from three randomly selected olive trees were taken from each olive grove during the harvest season (October till late January). They were dried in an oven for 4 days at 60 °C and analyzed for nitrogen in a

CHNS elemental analyzer (Leco TruSpect Micro) after milled. The $N_{dem-fruit}$ was calculated from the weight of harvested fruits, as stated by the farmers, and their water and N contents.

To calculate $N_{dem-pru}$, the tree pruning residues of between 3 and 6 olive trees per olive grove were weighted in the field, considering separately heavy and light pruning. A composite sample of light pruning (typically higher than 10 kg) of each tree was transported to the lab and water content (7 days at 50 ^{o}C in an oven) was measured and the proportion of leaves, twigs and branches recorded. Aliquots (> 100 gr) of leaves, twigs and branches from the light pruning were milled (blade mill < 1 mm) and analysed for N content. The amount of N in the light pruning residues was calculated from the contribution of leaves, twigs and branches to the total weight and their N contents. In parallel, aliquots of heavy pruning were transported to the laboratory, to determine the water content, and the N content after milled (blade mill < 1 mm). The amount of N uptake allocated to the heavy and light pruning was calculated by extrapolating the average production per tree to one hectare and multiplying by their respective N content and the pruning frequency, as stated by farmers.

Each year new leaves grow and take N ($N_{dem-leav}$) to replace those that have fallen as leaf litter and those unintentionally plucked during harvesting. To estimate these flows, a pararell field trial was performed. In four traditional and four intensive olive groves, three healthy and representative trees were selected and one (in 25–30 years old young trees) or two (> 50 years) open boxes (30 cm×30 cm x 12 cm) were installed under their canopies to collect the litter. Each three months, for twelve months (from March to March of the following year), the biomass deposited in the boxes, which consisted of olive leaves, flowers and very small aborted fruits, was collected and dried (50 °C during one week). An aliquot of each type of material and for each of the three-month periods was milled (blade mill < 1 mm) to determine the N content. For each box, the annual litter production per m^2 of canopy was calculated from the cumulative litter received along the year and the box area. The average value of annual litter production for the eight farms in this trial (779 g DM m^{-2} y^{-1}) and its average N content (9.69 g kg^{-1}) was applied to all the studied farms. The amount of N in the annual litter was calculated from the average litter production, its N content, and the tree canopy area. The canopy area of the olive trees was measured using recent (2021) aerial images. In addition, three samples of 4 kg of harvest as it is sent to the olive mill (i.e. freshly harvested olive fruits and residual felled leaves) were obtained in each of these eight farms. The fruits and the residual leaves on the harvest were separated and weighted in order to obtain the leaves-to-fruits fresh biomass ratio in harvest. This ratio, which averaged 8.8, was similar to the average of 9.4% obtained after a survey of many olive mills (AGAPA, 2015). The amount of N in the harvested leaves was calculated from the average leaves-to-fruits ratio, the water and N content of pruning leaves and the fruit production of each plot.

$N_{dem-per}$ was calculated in between 5 and 7 representative trees per olive grove. The height and the largest and smallest diameters of the trunk and primary branches were measured with a forestry caliper and flexible metallic metric tape. The estimation of the volume of the olive trees was carried out by comparing trunk and branches to a geometric figure corresponding to a truncated cone. To determine the wood density and the nitrogen content of the mentioned parts, cylindrical pieces of each of them were collected. The wood density was calculated based on the dry weight of the different cylindrical pieces over their fresh volume. In addition, root samples of olive trees just uprooted were collected in two farms to determine the root N content. Root samples with a diameter lower than 2 cm were dried, milled and N content was analysed. The aboveground dry biomass of the permanent structures was obtained by multiplying the biovolume of the trunk and main branches by the mean density of the wood. The biomass of the permanent roots was estimated applying a conservative root biomass to aerial biomass ratio of 0.21 to the biomass of the aboveground permanent structures, as found in the study of Almagro et al. (2010). Taking into account the dry biomass of permanent structures of olive trees, their nitrogen content and the tree density, the stock of total nitrogen (kg N ha^{-1}) was calculated. The stock of tree N was divided by the tree ages to calculate the mean annual rate of tree N accumulation in the permanent structures ($N_{dem-per}$).

To calculate the N demanded by the roots turnover ($N_{dem-root}$), the mentioned root biomass to aerial biomass ratio was applied to the vegetative aerial biomass annually renewed (pruning and leaves) in dry matter, and the estimation was multiplied by the N content of the roots analysed (Guzmán and González de Molina, 2017).

To calculate the N uptake of TSCC ($N_{dem-cov}$), the aboveground biomass of the TSCC was harvested from mid-March to the end of April, just a few days before being mowed or controlled by herbicides. Five 0.5 m × 0.5 m frames were randomly set in the area covered by TSCC in each of the olive groves, and the aboveground biomass was manually cut to ground level with grass shears and transported to the lab the same day (Gómez-Muñoz et al., 2014). The width of five strips was recorded in each of the olive groves where the TSCC occupied a band in the inter-row tree area. Samples were dried at 50°C for 4 days and weighed. The harvested aboveground dry biomass was considered as the aboveground net annual primary production for the period from May 2020 to mid-April 2021, coinciding with sampling period. It was assumed that 100% of the area was covered by TSCC in olive groves where the TSCC covered the entire soil. For olives groves where the TSCC occupied a band of a given width of the inter-tree row area, the number of inter-tree rows in 100 m and the average width of the bands were considered to calculate the area covered in one hectare. The annual aboveground net primary production (kg DM ha^{-1} y^{-1}) was calculated from the harvested biomass in the frames and the area of 1 hectare covered by the TSCC. An aliquot of between 20 and 100 g of the dried harvested biomass was powdered (< 1 mm) and N content was analysed. The N uptake by the root system of the TSCC was estimated by applying a root-to-aerial biomass ratio of 0.8 to the N uptake of the aboveground biomass (Guzmán and González de Molina, 2017).

2.4.2. *Tree and cover crop nitrogen consumed by livestock*

Livestock food intake was calculated from the metabolizable energy requirements of the herd and the metabolizable energy of the feeding material. Metabolizable energy requirements of horses and sheeps, which were the two livestock type in some of the Org olive farms, were taken from Martín-Bellido and Espejo-Diaz (1986). The metabolizable energy of cover crop was assumed to be that of Martín-Bellido and Espejo-Diaz (1986) for typical Mediterranean pasture, whereas the metabolizable energy of olive leaves was taken from Alkhtib et al. (2021). Livestock were assumed to meet their metabolic requirements in the following order: first, the external feed, then pruning leaves, and finally, the aerial biomass of cover crop, provided that they were supplied by the farmer. Therefore, $N_{feed-tree}$ was the N contained in the leaves of the pruning residues consumed by the livestock and $N_{feed-cov}$ was the N consumed by the animals through the biomass of the cover crop.

2.4.3. *Nitrogen returned to soil*

Soil receives internal flows of N from the olive trees ($N_{ret-tree}$), the cover crop ($N_{ret-cov}$) and the livestock ($N_{ret-anim}$). $N_{ret-tree}$ include the N naturally returning through litter ($N_{ret-litt}$) and roots turnover ($N_{ret-root}$), plus that contained in the fraction of fruits ($N_{ret-fruit}$) and harvested leaves ($N_{ret-leav}$) voluntarily returned by farmers from olive mill, as well as the pruning residues applied over the soil ($N_{ret-pru}$).

To estimate the $N_{ret-fruit}$, three samples of olive pomace were taken in each farm where it was applied to the soil, and they were transported to the lab. An aliquot of each sample was analysed for the water (7 days at 50 ^{o}C in an oven) and, after milled, for the N content. $N_{ret-fruit}$ was calculated based on the N content of olive pomace and the quantity and frequency of its application. Similarly, $N_{ret-leav}$ is the N applied to the soil through the leaves recovered by farmers from the olive mill, calculated from the recovered amount and its N content. Finally, $N_{ret\text{-}pru}$ was determined from the amount of light pruning applied to the soil, as reported by the farmer, and its N content.

On the other hand, $N_{ret\text{-}cov}$ corresponds to all the N contained in the biomass of cover crops that is applied in the soil. This includes the N from both aboveground and belowground biomass, excluding the fraction that is consumed by livestock.

Finally, the N return from livestock to soil ($N_{ret\text{-}anim}$) consist of the N excreted by the animals. The quantity of excreta and its N content were sourced from Ogejo et al. (2010) for sheep and from Lawrence et al. (2003) for horses.

2.5. Nitrogen outputs

N_{out} are all the N flows that exits the olive groves and include the N exported from the trees ($N_{exp\text{-}tree}$), from the livestock production ($N_{exp\text{-}anim}$) and the losses from the soil (N_{loss}). $N_{exp\text{-}tree}$ includes the N of the fruits harvested and whose olive pomace is not recovered ($N_{exp\text{-}fruit}$), the N embeded in the leaves unintentionally harvested that are not recovered from the mill ($N_{exp\text{-}leav}$) and the N contained in the pruning that is burned in the field or sold as firewood ($N_{exp\text{-}pru}$). The N leaving the farm as animal products (milk or meat) was included in $N_{exp\text{-}anim}$. Finally, N_{loss} include the ammonia N volatilization (N_{vol}), the N loss by denitrification (N_{den}), the organic N loss by soil erosion (N_{ero}), and the nitrate lost by leaching (N_{leach}).

2.5.1. N outputs from the tree and animal products

Substracting $N_{ret\text{-}fruit}$ from $N_{dem\text{-}fruit}$, the N exported as fruit production ($N_{exp\text{-}fruit}$) was calculated. Thus, the $N_{exp\text{-}fruit}$ represent the 100% of the $N_{dem\text{-}fruit}$ in most farms, where olive pomace is not recovered. Similarly, is frequent that all the leaves unintentionally harvested are left on the olive mill as $N_{exp\text{-}leav}$, but when part of them are recovered ($N_{ret\text{-}leav}$), this fraction have to be substracted.

$N_{exp\text{-}pru}$ is all the $N_{dem\text{-}pru}$ that is exported as firewood or burned in the field. Heavy pruning is always exported as firewood, whereas the light pruning is rarely burned or exported.

Finally, the N embedded in animal products such as milk or meat ($N_{exp\text{-}anim}$) was assumed to be the difference between the N ingested and the N excreted.

2.5.2. Nitrogen gaseous losses and leaching

N_{vol} depended on inorganic and organic inputs. The ammonia volatilization from fertilizers was calculated from the annual N entry ($N_{org\ fer}$ and $N_{ino\ fer}$) and the specific emission factors (i.e, amount of N-NH_3 volatilized per unit of N applied) (Dore et al., 2019), which depends on the type of fertilizer applied. N volatilization from the olive leaves which fell down below tree canopy after senescence, tree pruning which is shredded and applied on top of the soil and composted olive mill pomace was assumed to be negligible because of the high or very high C-to-N ratio of these biomass (typically higher than 30). N volatilization from the TSCC residues were estimated according to de Ruijter and Huijsmans (2019) based on the net primary production of the TSCC.

N_{den} was calculated from the annual N entry due to $N_{org\ fer}$ and $N_{ino\ fer}$ and specific N_2O emission factors (i.e., amount of N-N_2O lost per unit of N applied) from IPCC 2019 (2019). The N_2O-to-N_2 ratios of Vinther (2005), which is based on the soil clay content, was applied to calculate the annual $N_2 + N_2O$ emissions.

N_{leach} was calculated from the daily water balance in the soil and the N potentially leachable. The daily water balance was calculated from the mean daily rainfall and evapotranspiration and the soil properties (soil texture and water holding capacity) following Thornthwaite and Mather (1957). Weather data were obtained from the closest weather stations to the farms of the Agroclimatic Information Network of Andalusia (RIA). The proportion of percolation and runoff was estimated from Saxton and Rawls (2006) and USDA (1986). The N potentially leachable was calculated as the difference between the N inputs and the sum of N_{vol}, N_{den}, plus the N mineralized during a year, assuming that 2% of total soil N in the top 30 cm is mineralized annually. The water lost through percolation and the N potentially leachable were applied to the equations of Di and Cameron (2002) to estimate the annual rate of N lost by leaching.

2.5.3. Nitrogen leaving the farm due to soil erosion

The USLE equation (Wischmeier and Smith, 1978) based on geographic information systems (GIS) was used to estimate the potential soil losses by erosion, due to its wide support on literature. The detailed procedure was explained in Torrús-Castillo et al. (2023). Nitrogen lost by soil erosion N_{ero} was estimated from the annual potential loss of soil by erosion (Mg ha^{-1} y^{-1}) and the percentage of total soil N (TN), assuming an enrichment TN-to-eroded soil ratio of 1, as the enrichment SOC-to-eroded soil ratio found by López-Vicente et al. (2021) in olive groves with similar characteristics of our farms.

2.6. Ecological indicators

For each component, the N mass balance was calculated as the difference between N inflows and outflows. Since cover crop is ultimately consumed by livestock or incorporated to the soil, the change in this stock was zero in all cases. Also, the change in the stock of N of livestock was considered zero because farmers keep the herd stable over the years. The change in N stock of trees is equivalent to $N_{dem\text{-}per}$. Therefore, the change in the N stock was only calculated for the soil. According to the model of Fig. 1, the change in the stock of soil N was calculated as Eq. 2:

$$\Delta N_{soil}\ \left(kgN\ \ ha^{-1}\ \ y^{-1}\right) = N_{inp-soil} + N_{ret-tree} + N_{ret-\mathrm{cov}} + N_{ret-anim} - N_{dem-tree} - N_{dem-\mathrm{cov}} - N_{loss} \tag{2}$$

Total System Throughflow (TST), Total System Throughflow Cycled (TSTc), the Cycling Index (CI), the ratio of output to recycling (N_{out}/TSTc) and the turnover time (N_{soil}/N_{out}) were calculated following Finn (1982). TST is the sum of all component throughflows and TSTc represent the portion of TST that is cycling, that is, that pass more than once for the same compartment. CI indicates the proportion of TST that is cycling.

In addition, the values of $N_{inp\text{-}ant}$ and N_{loss} were normalized to 1 liter of olive oil to calculate the N footprints based on Leip and Uwizeye (2019) review as stated in Eq. 3 and Eq. 4:

$$Foot_{inp} = N_{inp-ant}/oil(l) \tag{3}$$

$$Foot_{out} = N_{loss}/oil(l) \tag{4}$$

2.7. Sensitivity analysis

Nutrient mass balances involve numerous uncertainties, particularly concerning system mass balances (Öborn et al., 2003; Oenema et al., 2003). Certain flows may exhibit a high level of uncertainty but contribute minimally to the balance, while other flows of greater magnitude may have lower uncertainty levels. A sensitivity analysis based on scenario modelling was conducted. Scenario A assumed a 50% increase in symbiotic N fixation. In this scenario, legumes contribute 12% of the cover crop biomass instead of the initial 8%, a target that farmers could reach by adapting cover management. Given the uncertainty of the N being applied through organic fertilizers (material density, heterogeneity), the scenario B was simulated, in which a 50% decrease of N inputs from organic fertilizers was assumed. A third simulation, scenario C, assumed an 50% increase of N leaching, based on the larger values of leaching found in empirical studies. Finally, in scenario D a 50% decrease in N loss due to potential erosion was assumed, given that no other studies on olive groves considered this output.

2.8. *Statistical analysis*

Statistical analyses were performed using R (version 4.3.0; R Foundation for Statistical Computing, Vienna, Austria). Given the unbalance between groups and the distribution of data, the difference between groups were tested by non-parametric test Kruskal-Wallis ($p < 0.05$) and post-hoc Dunn's test.

3. Results

3.1. *Tree and cover crop demand for nitrogen*

The N content of the different parts of the trees and the cover crop is reflected in Table A3. Variability in the $N_{dem\text{-}tree}$ across all farms was moderate, with a coefficient of variation (CV) of 28% (Table A4). Values ranged from as low as 21.6 kg N ha^{-1} y^{-1} (JT-Org) to as high as 77.0 kg N ha^{-1} y^{-1} (CC-IPr), averaging 55.0 kg N ha^{-1} y^{-1}. $N_{dem\text{-}leav}$ annually accounted for the highest N demand in the tree (47.9% of $N_{dem\text{-}tree}$), with an average of 25.4 kg N ha^{-1} y^{-1} showing relatively low variability between farms (22% CV). In fact, only the N uptake by litter, the most important part of $N_{dem\text{-}leav}$, accounted for 41.0% of the total tree N demand. Average $N_{dem\text{-}fruit}$ and $N_{dem\text{-}pru}$ were 13.9 and 10.2 kg N ha^{-1} y^{-1}, representing 25.1 and 17.1% of the $N_{dem\text{-}tree}$, respectively. Variability in N uptake was greater in these organs, with up to 41.7% CV and 65.8% CV for $N_{dem\text{-}fruit}$ and $N_{dem\text{-}pru}$, respectively. Lastly, the $N_{dem\text{-}per}$ and $N_{dem\text{-}root}$ were relatively low, averaging 0.9 kg N ha^{-1} y^{-1} (or 1.6% of the $N_{dem\text{-}tree}$) and 4.7 kg N ha^{-1} y^{-1} (or 8.5% of the $N_{dem\text{-}tree}$), respectively.

Based on the above results, an average of 49.5% of the annual $N_{dem\text{-}tree}$ is naturally recycled through litter and rhizodeposition, while 1.6% is stored in the permanent structures of the trees over the long term. Consequently, the remaining 48.9% of the N is potentially recoverable by farmers to some extent, depending on technical possibilities and willingness to process light pruning and olive mill by-products.

The proportion of $N_{dem\text{-}fruit}$ and $N_{dem\text{-}leav}$ over the $N_{dem\text{-}tree}$ was consistently similar among groups, ranging from 21.5% to 28% for $N_{dem\text{-}fruit}$, and 44.3 to 53.5% for $N_{dem\text{-}leav}$, respectively. The $N_{dem\text{-}fruit}$-to-$N_{dem\text{-}leav}$ ratio varied very little in groups Org, Tra and Int (from 0.44 to 0.47), while it was the highest for group IPr (0.67). Variability in the proportion of $N_{dem\text{-}tree}$ represented by $N_{dem\text{-}fruit}$ between farms was moderate (26% CV), and small in the case of $N_{dem\text{-}leav}$ (15% CV). Therefore, $N_{dem\text{-}tree}$ was analyzed using a linear model, with fruit production and canopy area as predictors (Fig. 2).

The average annual N uptake by plant biomass of the farms is shown in Table 2. $N_{dem\text{-}tree}$ in olive groves was lowest in Org farms, moderate in group Tra, and highest in groups Int and IPr. Differences between groups in the N demand of trees were not uniformly reflected across all tree organs; variations were smaller for $N_{dem\text{-}leav}$ and more pronounced for $N_{dem\text{-}fruit}$ and $N_{dem\text{-}pru}$. Specifically, in Org farms, N allocated to $N_{dem\text{-}fruit}$ and $N_{dem\text{-}pru}$ were 47% and 56% less than those of Int or IPr farms, whereas it was only 27% less for $N_{dem\text{-}leav}$.

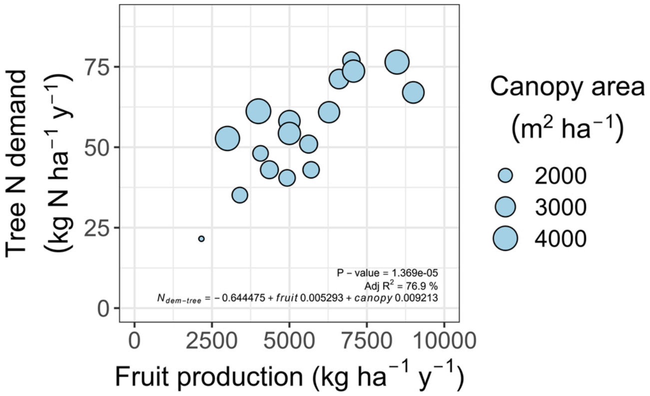

Fig. 2. Relationship between N uptake by olive trees (whole tree), harvest and canopy area. The linear model parameters, p-value and R^2 are displayed within the figure. $N_{dem\text{-}tree}$ represent the N uptake (kg ha^{-1} y^{-1}) by trees, while *fruit* is the quantity of harvested fruits (kg ha^{-1} y^{-1}), and *canopy* is tree canopy area (m^2 ha^{-1}).

Table 2
Annual N internal flows (kg N ha^{-1} y^{-1}) between soil and the other compartments for each of the groups. Data are the mean ± the standard deviation. Different lowercase letters in the same row indicate significant differences among farm types ($p < 0.05$, Kruskal-Wallis and post-hoc Dunn's test).

	Nutrient management strategies			
	Org (n=4)	**Tra (n=2)**	**Int (n=3)**	**IPr (n=8)**
$N_{dem\text{-}tree}$	38.1 ± 13.2	48.7 ± 8.0	64.4 ± 5.9	61.5 ± 14.1
$N_{dem\text{-}cov}$	53.9 ± 25.1	-	-	28.2 ± 28.9
$N_{dem\text{-}tree}$ + $N_{dem\text{-}cov}$	92.0 ± 25.15a	48.7 ± 8.0b	64.4 ± 5.9ab	89.7 ± 31.4ab
$N_{ret\text{-}tree}$	33.7 ± 10.7	33.1 ± 7.9	45.2 ± 8.2	36.6 ± 10.3
$N_{ret\text{-}cov}$	50.8 ± 22.7	-	-	30.3 ± 30.5
$N_{ret\text{-}anim}$	7.1 ± 9.5	-	-	0.3 ± 0.9
$N_{ret\text{-}tree}$ + $N_{ret\text{-}cov}$ + $N_{ret\text{-}anim}$	91.6 ± 28.2a	33.1 ± 7.9b	45.2 ± 8.2b	67.2 ± 29.4ab

At the farm level, the presence of cover crops significantly increased the demand for N. $N_{dem\text{-}cov}$ represented on average 145% of $N_{dem\text{-}tree}$ in Org group and 45% in IPr group. N taken up by the plant components ($N_{dem\text{-}tree}$+$N_{dem\text{-}cov}$) was the highest for groups Org and IPr, intermediate for olive groves of the group Int, and lowest for those of the group Tra.

3.2. *N inflows to the system*

Table 3 shows all the inflows, outflows and the balance of all the groups. The main N inflow was fertilization, either organic or inorganic. On average for all of the studied olive groves, N_{org}+N_{ino} accounted for an average of 66% of N inflows or 49.8 kg N ha^{-1} y^{-1}. However, variability was very high, with values ranging from as low as zero for some of the organically certified olive groves in the Org group (SP-Org and JT-

Table 3
Nitrogen inflows, outflows and balance (kg N ha^{-1} y^{-1}). Data are the mean ± the standard deviation. Different lowercase letters in the same row indicate significant differences among farm types ($p < 0.05$, Kruskal-Wallis and post-hoc Dunn's test).

		Nutrient management strategies			
		Org (n=4)	**Tra (n=2)**	**Int (n=3)**	**IPr (n=8)**
N_{inp}	N_{atm}	7.7 ± 1.4	7.1 ± 0.0	7.2 ± 0.2	7.5 ± 0.9
	N_{irri}	0.8 ± 0.9	-	2.9 ± 2.8	2.6 ± 3.7
	$N_{sym\ fix}$	7.1 ± 2.4a	-	-	2.4 ± 2.17b
	$N_{free\ fix}$	4.0 ± 0.0ab	1.5 ± 0.7c	2.7 ± 0.6bc	4.0 ± 0.0a
	$N_{org\ fer}$	19.2 ± 30.0ab	60.7 ± 7.6a	-	1.1 ± 2.9b
	$N_{ino\ fer}$	0.2 ± 0.2b	0.9 ± 0.7ab	59.4 ± 32.4ab	65.3 ± 38.9a
	N_{feed}	0.1 ± 0.1	-	-	-
	N_{inp}	38.3 ± 28.0	70.2 ± 9.0	72.2 ± 32.8	83.0 ± 37.6
N_{out}	$N_{exp\text{-}fruit}$	2.2 ± 3.7b	11.3 ± 0.0ab	13.7 ± 3.8ab	17.4 ± 6.5a
	$N_{exp\text{-}pru}$	0.2 ± 0.2	0.5 ± 0.1	0.8 ± 0.5	2.5 ± 7.8
	$N_{exp\text{-}leav}$	1.1 ± 1.32b	3.3 ± 0.3ab	4.0 ± 1.0ab	3.9 ± 1.4a
	$N_{exp\text{-}anim}$	3.8 ± 3.9	-	-	0.1 ± 0.4
	N_{vol}	3.9 ± 2.6	3.1 ± 0.5	6.8 ± 4.1	7.9 ± 4.2
	N_{den}	3.5 ± 1.2	3.7 ± 0.7	3.9 ± 1.5	4.6 ± 1.5
	N_{ero}	17.5 ± 8.9	18.9 ± 3.8	10.9 ± 10.0	6.2 ± 10.2
	N_{leach}	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.3 ± 0.5
	N_{out}	31.6 ± 8.1	40.8 ± 2.5	40.0 ± 15.5	42.5 ± 10.2
ΔN_{soil}		+7.4 ± 31.0	+29.5 ± 11.4	+32.2 ± 17.8	+40.2 ± 41.5

Org) to as high as 120.0 kg N ha^{-1} y^{-1} for the olive grove PA-IPr (Table A5). On average, the lowest N input by fertilization was found in olive groves of the group Org (19.4 kg N ha^{-1} y^{-1}), while figures were very similar for the other groups (59.4 kg N ha^{-1} y^{-1} to 66.4 kg N ha^{-1} y^{-1}).

The average N_{atm} across the olive groves was 7.45 kg N ha^{-1} y^{-1} with very little variability (12% CV). $N_{sym\ fix}$ was, on average, the highest for Org group, the lowest for Tra and Int groups, and intermediate for the IPr group. The annual entry of $N_{inp\text{-}nat}$ accounted for an average of 67% and 22.5% of the total N_{inp} in olive groves of the Org and IPr groups, respectively, whereas values were below 15.1% in the Tra and Int groups.

3.3. *N outflows from the system*

The N exported through harvest ($N_{exp\text{-}fruit}$+$N_{exp\text{-}leav}$) together with N_{ero} constituted the major outflows, accounting for averages of 38.7 and 28.2% of the N_{out} across the studied olive groves, respectively. However, there was significant variability for both between groups and among olive groves within groups. Mean $N_{exp\text{-}fruit}$+$N_{exp\text{-}leav}$ ranged from less than 2.6 kg N ha^{-1} y^{-1} in three farms of Org group, where the N in the harvest was returned to the soil as olive mill pomace and leaves, to 32.5 kg N ha^{-1} y^{-1} in a highly productive farm of group IPr (Table A6). Values of $N_{exp\text{-}fruit}$+$N_{exp\text{-}leav}$ were the lowest for group Org (3.3 kg N ha^{-1} y^{-1}, on average) and similar for the other groups of farms (between 14.6 kg N ha^{-1} y^{-1} and 21.3 kg N ha^{-1} y^{-1}).

On the other hand, N_{ero} ranged from 0.4 kg N ha^{-1} y^{-1} (CC-IPr) to 32.4 kg N ha^{-1} y^{-1} (AL-Org). Values of N_{ero} were the lowest for group IPr and highest for the olive groves of groups Tra, characterized by high levels of soil erosion, and also for farms of group Org, which have very N-rich soils.

On average, the sum of potentially pollutant N outputs, referred to as N_{loss}, accounted for 56% of the total N_{out} (or 21.6 kg N ha^{-1} y^{-1}) across the studied olive groves. There were not significant differences between the group with the lowest value (IPr group, 18.9 kg N ha^{-1} y^{-1}) and that with the highest (Tra group, 25.7 kg N ha^{-1} y^{-1}). However, the processes that contributed the most to these outflows varied among the different groups of farms. N_{ero} contributed the most for Org, Tra, and Int groups whereas N_{vol} did so in the IPr group, which has the highest annual N inputs by fertilization. N_{leach} was negligible ($<$ 1.4 kg N ha^{-1} y^{-1}) in all the olive farms.

3.4. *Soil nitrogen balance, internal recirculation and ecological indicators*

The annual soil N balance for the whole set of studied farms ranged from -25.7 kg ha^{-1} y^{-1} (the soil is losing nitrogen) to +94.4 kg N ha^{-1} y^{-1} (the soil is gaining nitrogen). Mean values were positive for all the groups, although no significant differences were found between groups due to the high variability within groups.

A visual comparison of the average inputs, outputs and internal flows between compartments in each group is presented in Figure A2. Regarding internal flows (Table 2, Table A7), Org and Tra groups had the smallest values of $N_{ret\text{-}tree}$, whereas the Int group had the highest value. However, in Org group, $N_{ret\text{-}tree}$ represented 89% of the $N_{dem\text{-}tree}$, whereas in the other groups, this percentage ranged from 60% to 70%. Additionally, Org farms showed higher values of $N_{ret\text{-}cov}$ and $N_{ret\text{-}anim}$, compared to IPr farms.

Org and IPr olive farms had the highest total N throughflow (TST), with nearly identical results, whereas smaller values were found in Tra and Int farms, which lacked cover crop (Table 4). A similar trend was found for TSTc, which is the amount of N recirculating annually. The highest values were found for Org farms, while the lowest were found in Tra olive groves. However, the mean TSTc for Org was 47% higher than that of the IPro olive farms.

The indicators CI and out:rec ratio are different measures of the relative amount of N recirculating within the system (Finn, 1982). These indicators showed that Org and Tra olive farms had the greatest and the lowest relative recycling, respectively, with the values of the remaining groups falling closer to those of Tra group. On the other hand, turnover time determine the number of years that would take the soil N stock to empty given the N_{out} and no N_{inp}, that is, the relative size of soil N stock. According to our findings, Org farms show the highest turnover time, followed by Int.

N anthropogenic input footprint refers to the off-farm N entering the olive farms due to farmer management per liter of olive oil, whereas N output footprint denotes the N leaving the farm through erosion, leaching and gaseous losses per liter of olive oil. The olive groves of Org group had the lowest N input footprint and the highest N output footprint (Table 4). Consequently, farms of this group invest the least amount of N per liter of olive oil but show the highest potential pollution-related N per liter of oil. In contrast, Tra group showed the highest footprint for N inputs due to significant applications of manure, not compensated by an increase in fruit production. Meanwhile, IPr group achieved the lowest footprint for N outputs owing to minimal release of pollutant outputs and the highest oil productions.

Table 4
Nitrogen cycling indicators and footprints for the different groups of olive farms. Values are the mean ± standard deviation. Different lowercase letters in the same row indicate significant differences ($p < 0.05$, Kruskal-Wallis and post-hoc Dunn's test).

	Nutrient management strategies			
	Org (n=4)	**Tra (n=2)**	**Int (n=3)**	**IPr (n=8)**
TST (kg N ha^{-1} y^{-1})	239.7 ± 47.0	152.0 ± 24.9	181.8 ± 45.3	245.0 ± 58.1
TSTc (kg N ha^{-1} y^{-1})	141.6 ± 59.0a	48.7 ± 11.7b	70.6 ± 8.1ab	95.9 ± 50.2ab
CI (proportion)	0.58 ± 0.14	0.32 ± 0.02	0.40 ± 0.07	0.38 ± 0.12
N_{out}/TSTc ratio (unitless)	0.25 ± 0.11a	0.87 ± 0.26b	0.57 ± 0.2ab	0.50 ± 0.14ab
N_{soil}/N_{out} (y)	167.4 ± 44.52	87.1 ± 29.13	108.5 ± 41.82	99.9 ± 32.59
Inp N foot	0,028 ± 0,040	0,064 ± 0,006	0,055 ± 0,021	0,055 ± 0,027
Out N foot	0,041 ± 0,027	0,027 ± 0,004	0,019 ± 0,011	0,016 ± 0,009

3.5. *Sensitivity analysis*

If the share of legume biomass were 16% instead of 8% of the cover crop, it would lead to an increase in the N balance of the farms of Org and IPr groups by 0.1 and 5.3 kg N ha^{-1} y^{-1} (Fig. 3). Simulating a 50% reduction in the N input by organic fertilizers due to overestimation of density, dry matter content or N content would result in a reduction of 0.1–33.0 kg N ha^{-1} y^{-1}. This reduction translates to a decrease of 50–150% of the N balance for farms supplied with manure or compost. Considering that leaching was a minor output, increasing this output by 50% would result in reductions in the N balance of at most 2.3 kg N ha^{-1} y^{-1}. However, a 50% reduction in soil erosion would lead to an increase in the N balance in almost all farms, ranging from 0.4 to 16.2 kg ha^{-1} y^{-1}.

4. Discussion

4.1. *Olive farms demand for nitrogen*

The quantification of total nitrogen demand in the crops is often overlooked, yet it plays a crucial role in determining their suitability for a specific environment and constitutes the foundation for sustainable nutrient management in agriculture. According to our findings, the N demand of olive tree is in line to that of others woody crops. Trees from the studied farms, which include medium and high productivity olive groves, exhibited average N demand of 55.0 kg N ha^{-1} y^{-1}, closely aligned with the N uptake of grapes (38–59 kg N ha^{-1} y^{-1}) and apple trees

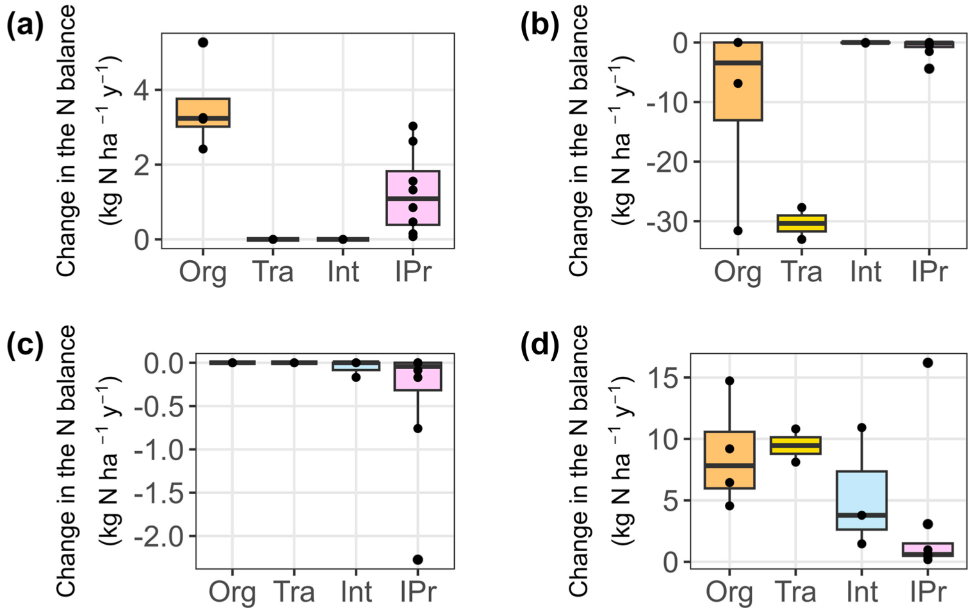

Fig. 3. Changes in the N balance of farms resulting from (a) a 50% increase in the proportion of legumes, (b) a 50% reduction in N input from organic fertilizers, (c) an 50% increase in N leaching, and (d) a 50% decrease in soil erosion.

(55 kg N ha^{-1} y^{-1}) (Tagliavini and Scandellari, 2013).

The total N demand of these woody crops contrasts sharply with the N requirements of annual herbaceous crops, such as the 200–250 kg N ha^{-1} y^{-1} demanded by wheat or barley (Delogu et al., 1998). This outcome was anticipated due to two main factors: i) only a relatively small proportion of the land is covered by the tree canopy in traditional and intensive olive groves (López-Vicente et al., 2021), and ii) most of the biomass produced by olive trees has a low N content (< 1% N). The olive tree modest N requirements, combined with its resilience to drought, explain why olive cultivation have been extensively cultivated in regions characterized by organic-poor soils, prevalent in many Mediterranean and hilly areas.

Our findings indicate that fruit production and tree canopy area serve as reliable predictors of tree N demand. These data are readily accessible, as fruit production is accurately quantified upon commercialization, and canopy area can be determined using recent satellite images and GIS techniques. By utilizing the equation provided in Fig. 2 for calculating the N demanded by the olive tree, the process can be streamlined, eliminating the need for exhaustive sampling and calculations. Nevertheless, this approach should be considered as complementary, as leaf analysis remains the most effective tool for assessing the short-to-medium termn nutritional status of the trees.

The differences between groups in $N_{dem\text{-}leav}$ were smaller than differences in $N_{dem\text{-}fruit}$ or $N_{dem\text{-}pru}$. In healthy trees, leaf renewal mainly depends on canopy volume, while fruit and pruning production are influenced by additional factors such as fertilization or irrigation. Consequently, the reduced biomass production and N uptake in Org farms could be partially attributed to the lower tree density and irrigation doses, which were approximately 20 and 70% lower, respectively, compared to Int or IPr olive farms. However, the extent to which this lower production of the Org farms is linked to the implementation of management practices aligned with organic production remains unknown.

Often, the most important outflow in N balances is the N removed with the harvest, as the harvest is intended for consumption by society (i.e. not recovered) and typically represents the largest output. However, in olive oil sector most of the N content in the fruit can be recovered at the olive oil processing stage through olive pomace. Therefore, the measurement of $N_{dem\text{-}fruit}$ provides insight into the amount of potentially recyclable N on a regional scale. The magnitude of this flow varies widely in the literature. For instance, Fernández-Escobar et al. (2012) found a N demand of fruits of 9.4–11.5 kg N ha^{-1} y^{-1} in a 50-year-old traditional olive grove and 14.5–18.9 kg N ha^{-1} y^{-1} in a 12-years-old intensive olive grove, both grown on southern Spain. These relatively modest values, similar to those found in our study, might be offset by natural inputs and soil mineralization. This implies that deficient nutrient supply could be buffered across years, potentially leading to fertilization having a limited impact on overall yield. However, larger values have been reported when either the N content of fruits or fruit yield was higher. For instance, according to (MAPA, 2018), olive groves in Spain extract an average of 30.6 kg N ha^{-1} y^{-1} with harvest, based on the assumptions that fruits contain 19.2 g N kg^{-1} and that the overall fruit yield is 2500 kg ha^{-1} y^{-1}. Results were even higher in the empirical study of El-Fouly (2014), who found a N harvest of 73.7 kg ha^{-1} y^{-1} in an Egyptian farm with a tree density of 278 trees ha^{-1} and a fruit exceeding 20,000 kg ha^{-1} y^{-1}. The N content in fruits in the last two examples was more than three times higher than the 2.4 g N kg^{-1} found by Fernández-Escobar et al. (2012) or the 5.3 g N kg^{-1} found in our work. These differences illustrate the importance of accurately measuring N content in fruits to determine real extractions. In Andalusia, which produces annually about 5.9 M tons of olives for oil production, the utilization of treated olive pomace as organic amendment would mean the recovery of 20,650 tons of N, assuming a N content of 5 g kg^{-1} in fruits and a recovery efficiency of 70%.

At farm level, the presence of cover crop significantly increases the demand for N. The annual N uptake by the cover crops could play an important role in reducing N and other nutrients prone to loss through soil erosion, runoff and leaching, thereby promoting soil nitrogen conservation (Marañón-Jiménez et al., 2022). Indeed, the soil total N content in the Org farms is between 50% and 100% higher than in those groups with bare soil throughout the year through intensive tillage or those where cover crops partially cover the farm. The ability of the herbaceous cover crop to capture highly mobile nutrients in its biomass and release them gradually at rates more aligned with the needs of olive trees contributes to a more efficient nutrient cycling. For instance, Tassinari et al. (2021) found in a field experiment that 11% of the N derived from cover crop decomposition under the canopy of peach trees was taken by the trees. It is quite likely that most of the N absorbed by the cover crop originates from mineralization of native soil organic matter, as the inter-row area covered by the cover crop is typically not fertilized. However, the extent to which cover crops can reduce the availability of nutrients and water for trees and affect to yield is still debated (Marañón-Jiménez et al., 2022; Zuazo et al., 2020). Therefore, caution should be taken regarding the distribution of cover crops and the development of vegetation cover in nutrient limiting contexts.

4.2. Nitrogen balance and internal N recycling

The N balance was near neutral or positive in the studied olive groves, which represent the main olive farming models of southern Spain. The average surplus of 27 kg N ha^{-1} y^{-1} found in our work was 1.5 times higher than the estimated value reported in the national N balance of 2016 for olive groves of Andalusia and Spain (MAPA, 2018). However, national N balances for Spain (MAPA, 2021; MAPA, 2018) underestimate the N balance of olive groves for two reasons: firstly, because the assumed N content in olive fruits is too high compared to empirical values reported for this crop in Spain and Portugal (Fernández-Escobar et al., 2012; Rodrigues et al., 2012); and secondly, because the amount of pruning assumed to be burned does not align with the current management trends.

Previous empirical studies on soil N balance in olive orchards have shown values within the range of our findings. For instance, Fernández-Escobar et al. (2012) found in two olive groves of Andalusia (Spain) that soil N balance averaged −32 kg N ha^{-1} y^{-1} in unfertilized plots and +35 kg N ha^{-1} y^{-1} in plots receiving 80–200 kg N ha^{-1} y^{-1}. Similarly, in an olive grove of Catalonia (Spain), a soil N balance of −40 kg N ha^{-1} y^{-1} was recorded in an unfertilized plot and a value of −20 kg N ha^{-1} y^{-1} in a plot fertilized with +55 kg N ha^{-1} y^{-1} (Belguerri et al., 2016). In both studies, the N contained in pruned material was considered an output, and the magnitude of this flow was more than three times higher than the N uptake of pruning residues found in our study. Considering that the N from pruning returns to the soil instead of being exported, the results of these balances would range from -10–0 kg N ha^{-1} y^{-1} in unfertilized plots and from +35 to +70 kg N ha^{-1} y^{-} in fertilized plots.

Our results of N balances were not validated with empirical measurements of soil N content for two main reasons. Firstly, there is significant heterogeneity in the N soil stock within the farm due to the unequal distribution of inputs and soil characteristics. Secondly, conducting such comparisons would require long-term sampling to detect significant changes accurately. For instance, if the current N balance of +40 kg N ha^{-1} y^{-1} of IPr farms were sustained over 10 years, the soil N content (assuming $\rho_{0\text{–}30} = 1.37$ Mg m^{-3}, S = 1 ha^{1}, z = 0–30 cm) would only increase from 0.12% to 0.13%. This increase would be close to the methodological limits for detecting significant changes.

For N surplus to be stored in the soil as stabilized organic N, proportional amounts of C must enter the system to meet the stoichiometry of soil organic matter. Therefore, farms with higher C inputs are more likely to retain the N surplus through immobilization and stabilization processes. Indeed, laboratory experiments conducted by Gómez-Muñoz et al. (2016), García-Ruiz and Baggs, (2007), and Gómez-Muñoz et al. (2011) have shown that the decomposition of olive tree pruning, olive leaves and olive mill pomace immobilize N. This is clearly the case on Org plots, where external N is always incorporated through organic amendments (i.e. linked to C), and additional C inputs are ensured through the incorporation of pruning residues, cover crop, olive leaves and olive mill pomace. This might partially explain why Org farms, with the lowest external N inputs and N balances had the highest content of soil N. This finding is also consistent with Martinez-Feria et al. (2018), who found that a rye cover crop decreased N losses by enhancing the soil's capacity to act as a net sink of N. Similarly, in IPr farms, significant amounts of C are incorporated through pruning residues and cover crops, which could capture part of the mineral N excess derived from mineral fertilization. On the contrary, the N excess of Int and Tra farms, whether derived from manure or from inorganic fertilization, is more likely to contribute to the mineral N stock prone to be lost due to the lack of C inputs.

In line with this, only a combination of a slightly positive N balance with a significant C input can ensure that the N surplus will be stabilized in the soil. In other words, only by mimicking natural ecosystems by recycling the N in biomass cycle can the soil fertility be ensured.

Applying the shredded light pruning is a common practice and, together with the natural biomass recirculation of trees, it ensures that above 60% of the $N_{\text{dem-tree}}$ is returned to soil. In Int and Tra farms, the application of pruning residues was the only intentional practice to boost N internal cycles. In addition to shredded light pruning, IPr farms improved the internal cycles by incorporating the TSCC to the soil, as evidenced by the greater results on TST and TSTc. However, the nutrient strategy of all these groups (Int, Tra and IPr) is to offset the N outputs mainly with external fertilization (either organic or inorganic) and maximize fruit production. This implies that even with the highest TST and TSTc, the CI of group IPr was smaller than that of Int group due to its greater inputs and outputs. In contrast, the strategy of Org farms is based on i) reducing the harvested N by recycling olive mnill pomace and leaves, ii) substituting external fertilization by biological N fixation, and iii) reinforcing internal nutrient loops by incorporating livestock in some cases. This is reflected in the higher values of $N_{\text{ret-cov}}$ and $N_{\text{ret-anim}}$, as well as the high levels of recycling of $N_{\text{dem-tree}}$ (up to 97% in SP-Org). Consequently, this group had the highest TSTc and CI, despite its levels of $N_{\text{ret-tree}}$ being lower than in other cases.

These management practices in olive farming, which enhance nitrogen recirculation, are also scalable and economically viable. The economic cost of shredding light pruning instead of burning tree pruning is estimated at 71–83 EUR ha^{-1} in machinable olive groves (Penco-Valenzuela, 2020), but it could be reduced through shared equipment among farmers, either by renting or collective purchase. Temporary spontaneous cover crops are typically managed through cutting, tillage, or herbicide application from mid-March to late April, primarily to prevent potential water competition with the olive trees. The economic cost of this control is comparable to alternative bare soil management methods like intensive tillage/herbicide. Applying olive mill pomace compost is straightforward, but it demands costly facilitation for the composting phase, which only large companies or cooperatives can afford. Finally, integrating livestock into olive groves can be achieved by either allowing an external herd to graze during certain periods or by integrating livestock into the farm business. However, incorporating livestock into the farm implies a whole new farming model, yet economic diversification might represent a promising opportunity for some regions.

4.3. Environmental implications of nutrient fertilization strategies

Nutrient management in agricultural systems has three environmental consequences: i) reliance on fossil fuels or finite minerals, ii) the emission of potential pollutants, and iii) alterations in soil fertility.

With a mean annual production of olive fruits exceeding the Andalusian average (Junta de Andalucía, 2020), Org farms only covered 30.3% of total N inputs with external fertilizers, resulting in half the external N input per liter of olive oil produced compared to other groups of olive farms. Therefore, these olive farms are already well aligned with the goal of reducing anthropogenic N inputs set by the Zero Pollution EU action.

To compensate the lack of external fertilization, Org farms enhance symbiotic fixation by maintaining a highly developed vegetation cover. In our study, the contribution of legumes of the spontaneous cover crops to the increase of the annual N entry was limited (maximum 10.5 kg N ha^{-1} y^{-1}), but decisive (on average, 27.0% of the total inputs) for these farms. None of the studied commercial farms seeded the inter-row with legumes, mainly due to the relatively high cost of the seeds, the lack of regular rainfall in autumn, and the primary purpose of implementing a cover crop, which is to reduce soil erosion and runoff, for which gramineous species are preferred (Ordóñez-Fernández et al., 2018). Previous works have found significant increases in the soil nitrate concentration of olive groves where residues of cover crops of legumes were applied to the soil (Ordóñez-Fernández et al., 2018). In IPr farms, the contribution of symbiotic fixation was smaller both in absolute and relative terms, given the limited extension of the TSCC.

On the other hand, IPr group showed the lowest value of N losses and the lowest ratio of N losses per liter of oil. Although these farms had the highest release of gaseous losses, the erosion was minimized due to their low slopes and the use of cover crops. In contrast, Org olive farms lost between 1.5 and 2.5 times more nitrogen per liter of olive oil produced than the other farms, mainly due to N lost through soil erosion. Indeed, the highest annual N outputs other than harvested N were due to soil erosion. Soil erosion is recognized as an important nutrient output in conceptual studies (Meisinger, and Randall, 1991; Oenema et al., 2003). However, to our knowledge, there are very few studies that have included soil erosion in assessing farm-gate N balance. Even assuming a significant level of uncertainty in our calculations, the relevance of this output cannot be overlooked. Indeed, the model sensitivity assessment indicates that a change in this outflow accounts for a significant change in the magnitude and direction of the N balances. N lost by soil erosion for Org was the highest because the mean slope of these farms and the soil N content were higher than the others. This suggests that in olive farms where N retention mechanisms are implemented resulting in an increase in the soil stocks of N, as was the case for Org olive farms, there is a critical risk of exacerbating N loss due to soil erosion. The results of our study indicate that: i) N losses due to soil erosion should be included in N balance, and ii) the implementation of management practices to limit soil erosion will contribute to closing the N cycle, decreasing fertilizer application and reducing impacts of soil erosion on other ecosystems.

N leaving the farm due to ammonia volatilization in the olive groves of our study tended to be similar or slightly higher than that reported in other studies on olive groves. Fernández-Escobar et al. (2012) estimated values of about 3.6 kg N ha^{-1} y^{-1}, which is aligned with the N outputs for Org, Trad and Int farms. However, this figure was nearly half of what was calculated for IPr farms, which had the highest annual input of chemical N fertilizer.

The release of reactive N to water bodies, particularly as nitrate, is one of the main concerns of agriculture (Sutton et al., 2013). In olive grove, reported leaching N losses exhibit considerable variation among studies, including ours. When modelled from water balance and potentially leachable N, negligible or null levels of leaching were found, as in the study of Belguerri et al. (2016) or our own study. However, Fernández-Escobar et al. (2012) measured leaching losses of up to 117.4 kg N ha^{-1} y^{-1} in an olive grove fertilized with 204 kg N ha^{-1} y^{-1}, while recording only 14.1 kg N ha^{-1} y^{-1} in another fertilized olive orchard and less than 3 kg N ha^{-1} y^{-1} in unfertilized plots. This discrepancy highlights the possibility that, in certain cases, the water balance method is not sensitive enough to detect leaching losses, and therefore significant fractions of the N surplus can be lost as leached N.

5. Conclusions

Our findings represent significant advancements in current N fertilization strategies in olive farming. A substantial proportion of the N demanded annually by the tree is allocated to olive leaves and tree pruning, ultimately ending into the soil and facilitating N recirculating within the farm. Therefore, it is advisable not to replace these N fluxes when planning N fertilization. Moreover, our findings suggest that olive fruit production, along with canopy area, can serve as proxies for estimating the N demand of the tree, thereby potentially contributing to improve N fertilization protocols.

While the closure level of N cycling in olive farming is relatively high due to the majority of N taken up by the trees (olive leaves and tree pruning) ending up in the soil, there remains considerable room for improvement through better integration of carbon and nitrogen cycling. Implementing temporary spontaneous cover crops, which help reduce nitrogen stocks prone to loss by converting soil mineral nitrogen into organic forms, and applying olive mill pomace, the primary byproduct of olive oil extraction that retains harvested nitrogen, are scalable strategies with multiple benefits. These practices enhance nutrient recirculation and promote additional ecosystem services such as carbon sequestration. Furthermore, promoting these practices can reduce fertilization inputs and associated costs without compromising soil fertility or fruit production.

Organic olive farms, which exhibited the lowest positive balances, demonstrated a significantly lower off-farm nitrogen input-to-olive oil ratio and a 54% longer turnover time for nitrogen compared to other farms, indicating higher levels of self-sufficiency and a longer lifespan for nitrogen within the farm.

Changes in eroded N had pronounced effects on the nitrogen balance, underscoring the importance of including this flux when assessing nitrogen balances, particularly in situations where balances are tighter, as is often the case for organic olive farms.

Finally, the system flow analysis approach adopted in this study is also suitable for assessing contribution of management practices to the internal recirculation of P and K in olive groves.

CRediT authorship contribution statement

Pablo Domouso: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Roberto García-Ruiz:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Julio Calero:** Supervision, Methodology. **Gustavo Ruiz-Cátedra:** Methodology.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.109096.

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