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Crop Diversification and Fertilization Strategies in a Rainfed System with Drought Periods

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Abstract: Crop diversification and the reduction of nitrogen (N) inputs are key issues in the EU for more sustainable agriculture. An experiment was set up in a semiarid rainfed Mediterranean system. Our hypothesis was that these challenges could be addressed by introducing new crops and using pig slurries (PSs). The experimental factors were N fertilization at sowing (with or without PS) combined (according to a split-block design) with N fertilization as topdressing (the control, two N mineral rates, and two N rates from PS). Barley, rapeseed, and pea performances were evaluated in two different crop sequences: (i) barley–rapeseed or rapeseed–barley after a fallow season, and (ii) barley–pea or pea–barley after a fallow season followed by a non-fertilized barley crop. The results of the four-year study demonstrated that under a spring drought risk, barley performed better than peas in terms of relative crop yield maintenance. After fallow, N can be saved while maintaining the yields and total biomass of barley and rapeseed. In the second crop sequence, maximum pea and barley yields were associated with a minimum topdressing of 60 or 120 kg mineral N ha^{-1}, respectively. However, slurry fertilization at sowing also allowed the highest yields for barley. Rapeseed and peas can be introduced to reduce N fertilization inputs. However, the obtained yield plateau for pea and rapeseed (3 and 4 Mg ha^{-1}, respectively) and the effect of a yield spring drought on pea yields (50% reduction) might be a constraint for the success of EU policies on crop diversification.

Keywords: barley; fertilization; nitrogen; pea; rapeseed; slurry

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1. Introduction

The Farm to Fork Strategy in the European Union (EU) sets ambitious goals to transform the EU's food production system into a more sustainable one. This transformation includes a reduction in the use of fertilizers and nutrient losses while ensuring that the soil's fertility does not deteriorate [1]. To achieve these goals, the European Commission is working with member states to extend sustainable agricultural practices, especially in areas with intensive livestock farming, which is the case in some Spanish regions. The EU has also established [2] a common agricultural policy that addresses some requirements, such as crop diversification, to achieve the objectives of the Green Deal [3].

Rainfed Spanish agriculture represents 77% of the total cultivated area, mainly devoted to wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.), which is distributed over 4.6 million hectares with average yields of about 2.7 and 2.4 Mg ha^{-1}, respectively [4]. The traditional rotation was three years for barley and one year for wheat or fallow. In these areas, the amount of precipitation is the most important limiting factor for productivity [5–7] and is also associated with high annual variability [8]. Thus, N efficiency in winter cereals grown in such environments is usually lower than in temperate areas [9].

In semiarid areas with intensive livestock farming, different fertilization strategies have been proposed to increase the N efficiency, such as the biennial/triennial application of organics [10,11], different crop rotations [12], or intercropping systems [13–15].

It is well known that the rates of N fertilizers greatly affect crop production in terms of grain yield, biomass yield, profitability, and N uptake [16]. The use of organic fertilizers appears to also be a sound fertilization option [17]. Pig slurries are a matter of major concern in the EU and Spain due to the intensification of livestock farming. In fact, the number of pigs is close to 132.960 million in the EU and 33.803 million in Spain [18], which means approximately 399 million m^3 and 101 million m^3 of slurries, respectively. In Spain, average N concentrations are about 5 kg N m^{-3} [19]. This represents a significant source of N to be managed, apart from P and K, assuming a mean N/P/K ratio of 1:0.3:0.9 (over dry matter) [19]. However, as previously stated, the success of using N fertilizers in Mediterranean agriculture primarily depends on the soil moisture availability as per [20].

Leguminous crops and fallow periods are viable options to reach the objectives established by the EU strategy [21,22]. Fallow periods do not always increase water availability for the next season, but they do increase the mineral N content present in the soil profile that can be used for the following crop [23], providing an opportunity to save N fertilizer. Crop diversification has shown considerable potential to adapt to low soil moisture conditions, although the response effects are mediated by crop type [24,25]. Leguminous crops are of great importance in the sustainability of global agriculture because of their unique ability to fix atmospheric N and provide residual N to non-legume crops [26]. The inclusion of legumes in winter cereal rotations in Mediterranean areas can stabilize cereal yields and productivity in a climatic change context [27]. However, there has been a reduction in legume cultivation in the EU in recent decades [28].

The additional benefits of crop rotations include improvements in nutrient availability [29–32], enhancement of soil protection and its quality [33], reduction in pest and disease prevalence [34,35], and minimization of weed infestation [12]. However, although crop rotations are widely recommended for improving agroecosystems, few crops are suitable for semiarid conditions. This means that the right choice of break crops within a rotation period is highly relevant to maintaining yields. The introduction of legume crops like pea, clover, or soybean in a winter cereal rotation can significantly reduce N fertilizer requirements and increase crop yields [36–39]. The rotation of winter cereal (wheat) and legumes (pea) also increases the N-use efficiency of both crops [40]. The introduction of rapeseed in a winter cereal rotation increases grain yields [41], and the N balance in both crops can also be enhanced when pig slurry is used as a fertilizer [42]. Nevertheless, the benefits of introducing leguminous and cruciferous crops in a winter cereal rotation combined with fallow periods and the use of organic amendments are still unclear under semiarid Mediterranean conditions due to erratic rainfall.

In the context of a rainfed Mediterranean system with drought periods, the main objective of this research work was to evaluate different fertilization strategies using mineral fertilizers or pig slurries (PS) in three crops included in two different crop sequences: winter barley (before/after) rapeseed, or pea, and fallow seasons. We hypothesize that the crop sequence, crop characteristics, and type of fertilizer used (following a fallow period) will influence the grain/seed yield, biomass production, and N uptake in all crops, as well as the oil content in rapeseed and N content in peas. Additionally, our results will help to reduce N inputs in this system while allowing for crop diversification.

2. Materials and Methods

2.1. Study Site, Soil, and Climatic Conditions

This research work is a part of a long-term N fertilization experiment that started in 2002. The experimental field was located in Oliola (41° 52′30″ N, 1° 09′13″ E; 416 m a.s.l.), Lleida, Spain. The soil is described as Typic Xerofluvent [43], having a silty loam texture. It is calcareous and non-saline with an electrical conductivity (EC, 1:5; soil: distilled water) of 0–18 dS m^{-1}. The average soil pH (1:2.5; soil: distilled water) was 8.2. The organic carbon content diminished with soil depth and its average values were 9.5, 7.1, and 5.5 g C kg^{-1} for the 0.3 m, 0.6 m, and 0.9 m sampling depths, respectively. The soil water retention at −33 kPa was 0.223 m^3 m^{-3} (from undisturbed samples). The averages of available P (Olsen method) and potassium (ammonium acetate 1N, pH = 7) were 27 mg P kg^{-1} and 209 mg K kg^{-1}. At the start of the 2014–2015 and 2018–2019 cropping seasons, for the control (no N applied) and from 0 to 0.3 m depths, data on the mineral N average content were available. In September 2014, after a fallow year, the mineral N content was 142 kg N ha^{-1} [23]. In October 2018, after a fallow year plus a non-fertilized barley crop, the mineral N content was 41 kg N ha^{-1}. The climate in the area is classified as semiarid Mediterranean. Daily meteorological data are available from an automatic meteorological station next to the experimental field. The average annual precipitation between 2014 and 2020 was 455 mm, ranging from 348 mm in 2015 to 662 mm in 2018, with a high average reference crop evapotranspiration of 1079 mm yr^{-1}, obtained from the Penman–Monteith equation [44].

In the 2014–2015, 2015–2016, 2018–2019, and 2019–2020 cropping seasons, the amount of rainfall in September was 48.7 mm, 73.8 mm, 5.3 mm, and 11.6 mm, respectively. The amount of rainfall increased from October to June in each season: 251, 290, 359, and 590 mm, respectively. However, during the period from mid-March to April, which coincides with stem elongation in barley and the crop-flowering stage for the rest, the rainfall in 2014–2015 (40 mm) and 2018–2019 (45 mm) was much lower (drought period) than in the 2015–2016 (113 mm) and 2019–2020 (170 mm) cropping seasons (Figure 1).

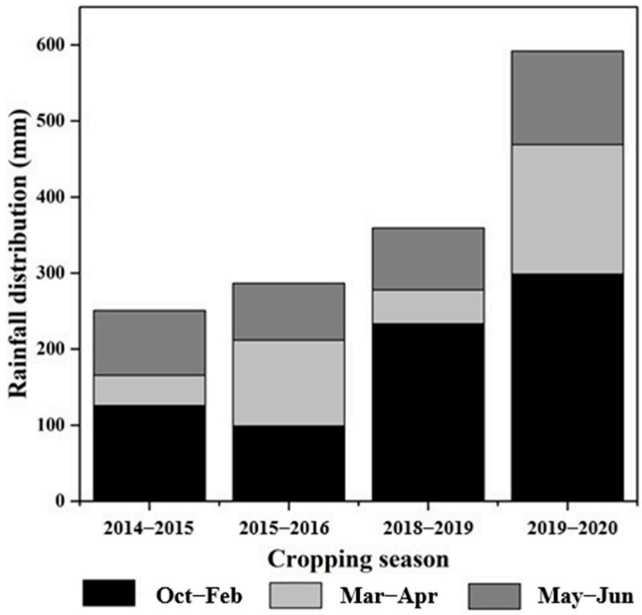

Figure 1. Rainfall distribution in three periods (from October to February, from March to April, from May to June) of four cropping seasons.

2.2. Experimental Design and Treatments

The experimental fertilization design was a split block. Three blocks (replicates) were established. The first factor was the N application (2 strategies), with or without pig slurry (SPS or S00, respectively) applied before sowing (September–October). They were randomized in each block as horizontal strips. The second factor was the nitrogen application (5 strategies) at topdressing (from February up to mid-March). They were randomized in each block as vertical strips, and the mineral fertilizer and PS were used as N sources (Table 1).

Table 1. Strategies of N application before sowing (factor 1) and at topdressing (factor 2) in the studied periods [1] of the experiment.

Strategy	Fertilizer	1st Period			2nd Period		
		Crop	2014–2015	2015–2016	Crop	2018–2019	2019–2020
		N applied before sowing (kg ha^{-1})					
S00	No N, control	Barley	0	0	Barley	0	0
		Rapeseed	0	0	Pea	0	0
SPS	Pig slurry	Barley	169	155	Barley	109	84
		Rapeseed	162	165	Pea	0	0
		N applied at topdressing (kg ha^{-1})					
T00	No N, control	Barley	0	0	Barley	0	0
		Rapeseed	0	0	Pea	0	0
TM1	Ammonium nitrate	Barley	60	60	Barley	60	60
		Rapeseed	60	60	Pea	60	60
TM2	Ammonium nitrate	Barley	120	120	Barley	120	120
		Rapeseed	120	120	Pea	120	120
TS1	Pig slurry	Barley	93	87	Barley	63	81
		Rapeseed	93	87	Pea	0	0
TS2	Pig slurry	Barley	190	177	Barley	125	162
		Rapeseed	190	177	Pea	0	0

[1] In each period, the two crops were also annually concurrent (in each cropping season). They were part of two rotations with the same crops but with an inverted crop sequence order.

A control (T00) without N was included. At topdressing, ammonium nitrate was used as a mineral N fertilizer. The mineral N treatments were 60 and 120 kg N ha^{-1} (TM1 and TM2, respectively). Additionally, doses of phosphorus (P) and potassium (K) were applied at seeding at 96.5 kg P_2O_5 ha^{-1} and 107.2 kg K_2O ha^{-1}, also in T00. All minerals were applied by hand. The two treatments using pig slurries (TS1 and TS2) are described in Table 1. The nitrogen rates were calculated by assuming maximum barley grain yields of around 5 Mg ha^{-1} and considering the readily available mineral N applied. In pig slurries, it was assumed that we had an ammoniacal-N/total-N ratio of 0.69 [19]. In the second period of this study (2018–2020), the slurry rates were reduced in barley to better cover the crop's demand (taking advantage of the potential residual effect and the introduction of a leguminous crop). For peas, mineral N treatments (TM1 and TM2) were maintained as reference strategies in terms of the entire crop succession, but no slurries were applied. However, the TS1 treatment (Table 2) received the same P and K rates as the mineral N treatments to avoid P and K deficiencies. Pig slurries were obtained from a nearby farm next to the field site. The slurries were sampled from each tank before field application (with an inverted splash plate) and refrigerated for further analysis.

Table 2. Crop sequence and fallow seasons in two rotations from 2013 to 2020.

Cropping Season	13–14	14–15	15–16	16–17	17–18	18–19	19–20
Studied periods		1st period				2nd period	
Crop sequence in two rotations	Fallow	Barley Rapeseed	Rapeseed Barley	Fallow	Barley	Barley Pea	Pea Barley

After the 2013–2014 fallow season, barley (*Hordeum vulgare* L.)–rapeseed (*Brassica napus* subsp. *napus*) and rapeseed–barley crop sequences were introduced in 2014–2015 and 2015–2016 (the first period of this study, Figure 2a). The 2016–2017 season was left under fallow, and in the 2017–2018 period, a non-fertilized barley crop was established. In the 2018–2019 and 2019–2020 cropping seasons (the second period of this study, Figure 2b), barley–pea (*Pisum sativum* L.) and pea–barley crop sequences were established (Table 2). In the 2014–2015 and the 2018–2019 cropping seasons, the two crops were randomized against the first split-block factor (as a randomized strip). The size of the intersection plots (fertilization at sowing × fertilization at topdressing × crop) were 11 m × 12.5 m for the plots receiving slurries and 7 m × 12.5 m for the plots receiving only minerals.

Figure 2. General views of the field experiment: (**a**) the barley and rapeseed plots at their first stages by the end of winter, in the 2014–2015 cropping season (West view); (**b**) the barley (dark green) and pea (light green colored bands) plots at the spring of the 2019–2020 cropping season (North view).

Rapeseed was sown on the 18 September 2014 and 22 September 2015. Barley was sown on the 9 November 2014, 10 November 2015, 13 November 2018, and 4 November 2019. Peas were sown on the 13 November 2018 and 4 November 2019; the seeds were not inoculated. In all crops, the row distance was 0.19 m, and the sowing rates were 4 kg ha^{-1} for rapeseed, 190 kg ha^{-1} for barley, and 200 kg ha^{-1} for peas. In 2014–2015 and 2015–2016, barley and rapeseed were harvested on the 12 June 2015 and 20 June 2016, respectively. In 2018–2019 and 2019–2020, barley and peas were harvested on the 6 July 2019 and 17 June 2020, respectively.

In the first rotation period (Table 2), slurries were applied to rapeseed on the 10 September 2014, 10 February 2015, 21 September in 2015, and the 2 February in 2016; in barley, they were applied on the 23 October 2014, 10 February 2015, 20 October 2015 and 2 February 2016. In the second rotation cycle (Table 2), slurries were applied to barley on the 30 October 2018, 15 March 2019, 31 October 2019, and 10 February 2020. The slurry application on the 15 March 2019 was an exception because of an unusually rainy period in February. Topdressing in winter barley usually coincided with the tillering stage (21–24 of the Zadoks–Chang–Konzak decimal scale [45]). In rapeseed, it coincided with leaf development, with nine or more leaves unfolded, and in peas, with different numbers of stipules unfolded, before the presence of flower buds.

In the second period, based on the results from the first period and following the EU strategy of N reduction inputs, the slurry rates were reduced for barley (Table 1). At sowing (SPS), they were reduced by *c*. 40%. At topdressing, the average reduction was *c*. 20%, but the proportion (×2) between the rates in both treatments (TS1, TS2) was maintained.

2.3. Crop Sampling and Analysis

In the barley and rapeseed crops, a few days before mechanical harvest, four different rows in each plot (each 1.3 m in length) were manually harvested. Two rows were selected at the top and at the left-hand side positions, while two plots were selected at the bottom and at the right-hand side positions. The distance from the next plot was, in both cases, at least 2 m. Thus, 0.99 m^2 per plot was hand-harvested to establish the harvest index: the aboveground grain-seed biomass divided by the total biomass (grain seeds and straw). The edge rows were not sampled. The remaining harvesting of the plot was performed mechanically on a 1.5 m wide area along the length of the experimental plot. The grain-seed yield and grain moisture were directly obtained in the field. The Dickey–John® mini GAC™ (Princeton, KS, USA) portable grain moisture analyzer was used. A subsample per plot was taken for further analysis. Grain-seed yields were adjusted to dry content. The rest of the plant biomass in barley and rapeseed was obtained from the harvest index. The dry matter was obtained by drying at 60 °C. In peas, data from hand harvesting was always used.

The N content of grain seeds and the rest of the plant biomass was determined by the Kjeldahl digestion method [46], but the Near InfraRed (NIR) spectroscopy technique was used for the N content in barley grain seeds [47] using the NIR InfraAlyzer 2000 apparatus from Bran + Luebbe (Norderstedt, Germany). The total N uptake for each crop was calculated as the sum of the product of each biomass fraction multiplied by its N content. In rapeseed, ten grams of dry rapeseed from each treatment were analyzed for oil content by pulsed NMR spectrometry (Bruker Minispec NMS110; Bruker, Karlsruhe, Germany). To calibrate the NMR, rapeseed oil was used to calibrate the curves. The NMR analyzer results were reported as percentages on a moisture-free basis.

2.4. Statistical Analysis

The data were statistically analyzed by using the statistical package SAS (v9.4) [48]. The SAS system's MIXED procedure [49] was used for all analyses of crop yield, biomass, and N uptake for each crop, as well as for oilseed content in rapeseed. The Akaike information criterion (AIC) [50] was chosen to compare the relative goodness-of-fit among non-nested candidate models. The performance of the AIC was better when the N at sowing, N at topdressing, and year, and the interaction effects were considered fixed, and block and block triple-interaction were considered random. We tested for homogeneity of variances and normality of distributions. Only biomass was not normally distributed and was subjected to a log10 transformation and retested for normality. Multiple comparisons of the least squares mean of the main effects and interactions were made with the LSMEANS option. We selected a value of 5% (i.e., $p < 0.05$) as the minimum criterion for significance.

3. Results

Crop yields for barley were the highest in 2015–2016 (Figure 3a), with a maximum average value of 5.2 Mg ha^{-1}. Pig slurry applied at sowing enhanced yields from 3.9 Mg ha^{-1} to 4.6 Mg ha^{-1}, represented an 18% increase. No significant differences were associated with Ntop; however, the yield response to Ntop varied according to the season as the interaction cropping season (year) ×Ntop was significant (Table A1). The barley total biomass tended to decrease in the order of 2015–2016, 2014–2015, 2019–2020, and 2018–2019. The highest value was achieved in 2015–2016 with the TS2 treatment (11.7 Mg ha^{-1}). The lowest value was obtained in the 2018–2019 season with the S00 treatment (5.3 Mg ha^{-1}). Pig slurry fertilization at sowing increased the biomass, but the biomass response to Ntop depended on the year (Figure 3b, Table A1). Barley N uptake was significantly higher in the first two seasons (2014–2015, 155 kg N ha^{-1}; 2015–2016, 160 kg N ha^{-1}) than in the rest (2018–2019, 86 kg N ha^{-1}; 2019–2020, 94 kg N ha^{-1}). Thus, responses to the Nsow or Ntop treatments on N uptake depended on the season (Figure 3c, Table A1). For instance, with the SPS treatment, N uptake was reduced by more than half between 2015–2016 (196 kg N ha^{-1}) and 2018–2019 (98 kg N ha^{-1}).

Rapeseed yields differed neither between the years nor fertilization treatments (Figure 4a, Table A2). Seed yields ranged from 2.6 to 3.1 Mg ha^{-1}. Total rapeseed biomass and N uptake increased in the 2015–2016 cropping season (Figure 4b,c) by 76% and 41%, respectively. The N uptake also increased with Nsow, and with mineral treatments at topdressing (Figure 4c, Table A2). With the SPS treatment, the N uptake was 141 kg N ha^{-1} in 2014–2015 and 200 kg N ha^{-1} in 2015–2016. The oilseed content diminished with fertilization at topdressing from 45% up to 42%, except for the lowest slurry rate (Figure 4d, Table A2); an interaction between the year and Nsow was recorded (Table A2).

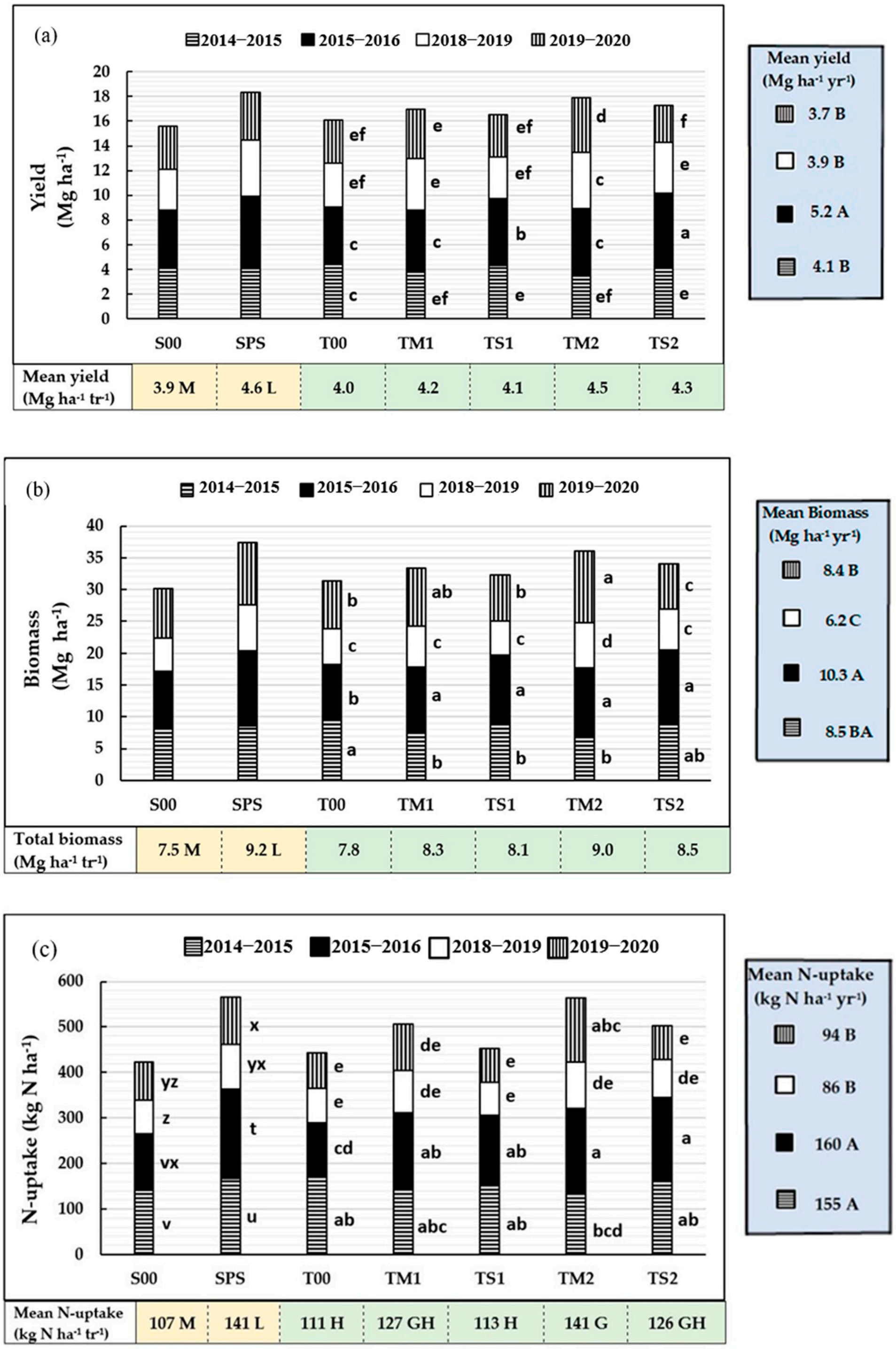

Figure 3. Accumulated barley grain yields (**a**), total biomass (**b**) and total N uptake (**c**) from four different cropping seasons (or years, yr^{-1}) and according to the different fertilization treatments (tr^{-1}) defined in Table 1. Mean values for years, treatments, and interactions with different letters are significantly different according to the LSD test ($p < 0.05$): (i) "A" or "B" for years, (ii) "L" or "M" for S00 and SPS sowing fertilization treatments, (iii) from "t, u, v, x, y and z" for the interactions year × sowing fertilization treatments, (iv) from "a" to "f" for year × tillering fertilization treatments (T00, TM1, TS1, TM2, and TS2), and (v) "G" and "H" for fertilization as topdressing (T00, TM1, TS1, TM2, and TS2).

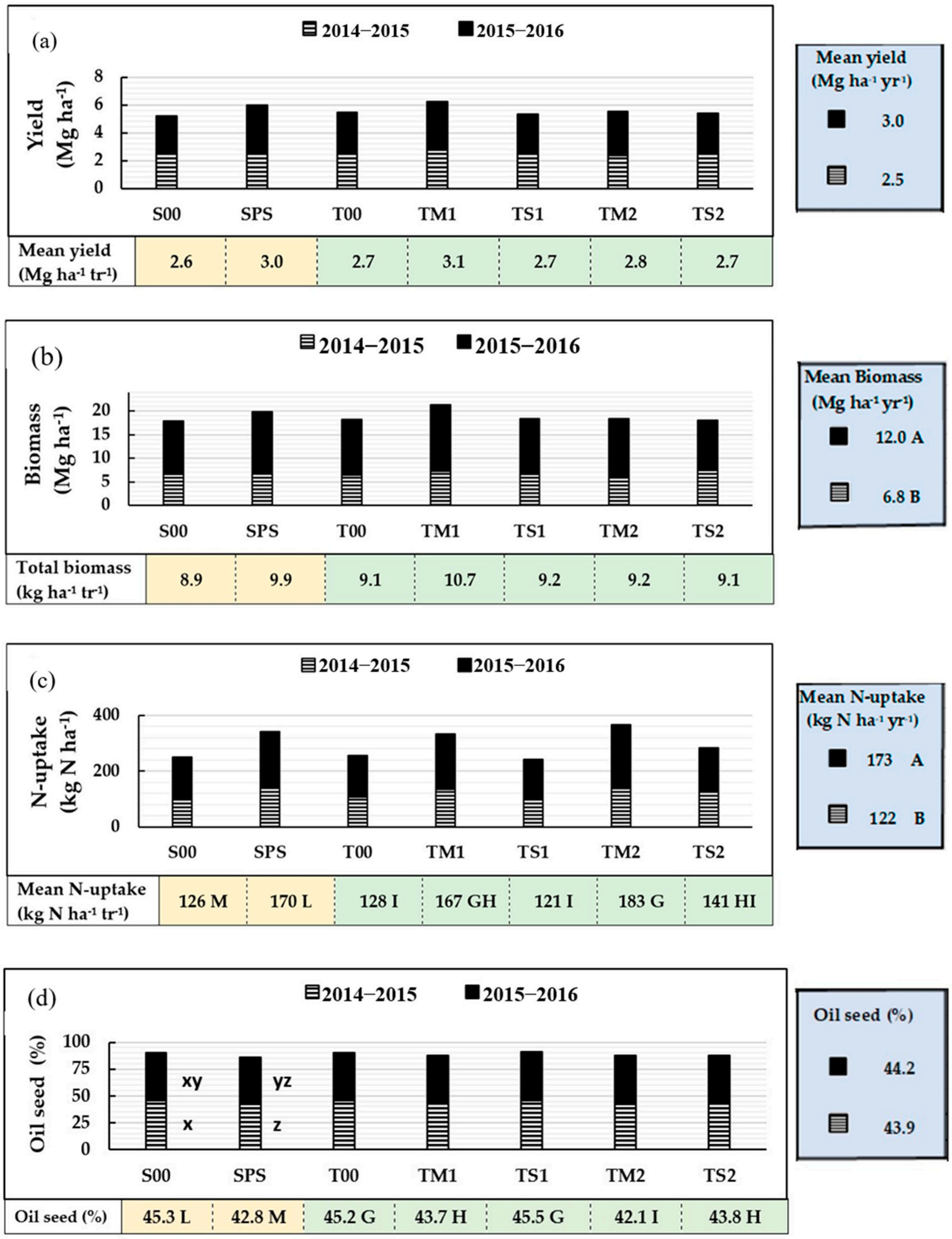

Figure 4. Accumulated rapeseed yields (**a**), total biomass (**b**), N uptake (**c**), and annual oilseed content (**d**) in two cropping seasons (or years, yr^{-1}) and according to fertilization treatments defined in Table 1. Mean values for years, treatments (tr^{-1}), and interactions with different letters are significantly different according to the LSD test ($p < 0.05$): (i) "A" or "B" for years, (ii) "L" or "M" for S00 and SPS sowing fertilization treatments, (iii) from "G" to "I" for fertilization as topdressing (T00, TM1, TS1, TM2, and TS2), and (iv) from "x" to "z" for the interactions year × sowing fertilization treatments.

The pea yield, total biomass, N uptake, and seed N uptake were higher in the 2019–2020 cropping season (Figure 5, Table A3). The pea yield increased by more than 90% in the 2019–2020 cropping season compared to the previous one. Yield was the only parameter that increased with residual N from former Nsow in previous crops (Figure 5a, Table A3). The pea yield, total, and seed N uptake (Figure 5a,c,d) increased with mineral fertilization as topdressing. Seed N uptake in treatment TM1 increased from 92.63 kg N ha^{-1} (2018–2019) to 160.14 kg N ha^{-1} (2019–2020). The pea biomass (Figure 5b) was not affected by the fertilization strategies.

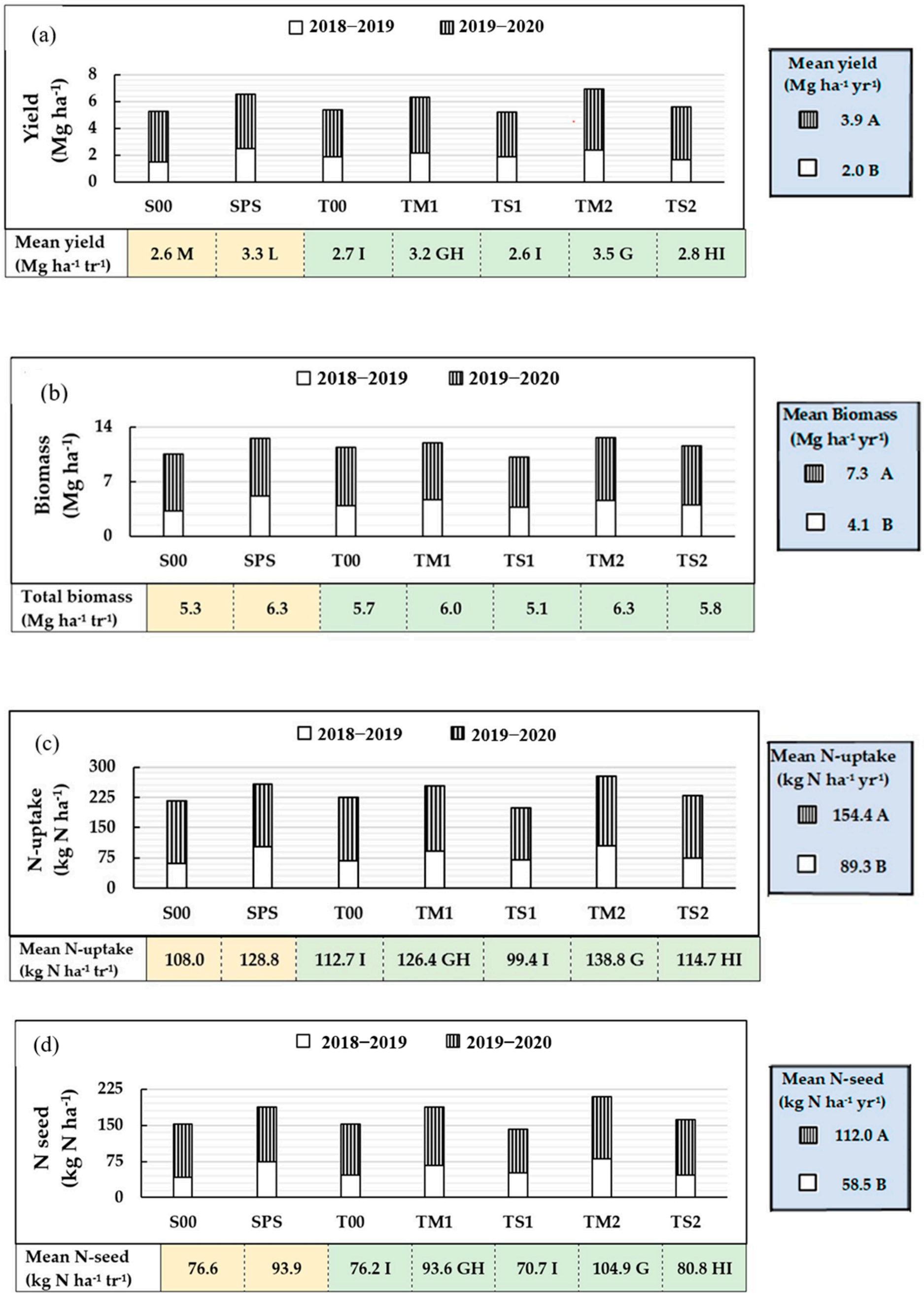

Figure 5. Accumulated seed pea yield (**a**), total biomass (**b**), total N uptake (**c**), and seed N (**d**) uptake in two cropping seasons (or years, yr^{-1}) and according to fertilization treatments defined in Table 1. Mean values for yields, treatments (tr^{-1}), and interactions with different letters are significantly different according to the LSD test ($p < 0.05$): (i) "A" or "B" for years, (ii) "L" or "M" for S00 and SPS sowing fertilization treatments, and (iii) from "G" to "I" for fertilization as topdressing (T00, TM1, TS1, TM2, and TS2).

4. Discussion

Under limited seasonal rainfall (251–290 mm for the 2014–2015 and 2015–2016 cropping seasons), the yield results show how barley took advantage of the 2015–2016 spring rainfall while rapeseed did not (Figures 1, 3a and 4a; Tables A1 and A2). Barley has a much greater water-use efficiency than rapeseed [51]. The rainfall in March–April also coincided in the experimental area with barley stem elongation and flowering. Drought periods during the cereal stem elongation development stage negatively affected the yields [52]. Thus, a higher rainfall in March–April of the 2015–2016 season further favored barley yields (Figure 3a).

In the 2014–2015 cropping season, the initial high amount of available N in the first layer (142 kg N ha^{-1}) is a common pattern in these systems after a fallow period [23]. This residual N reduced the N fertilization demand in barley and rapeseed, leading to maximum seasonal yields and total biomass (Figures 3a,b and 4a,b) without needing any additional N fertilization at topdressing (T00 treatment). Moreover, previous winter leaching was negligible in this first period of the experiment (2014–2016), as rainfall from October to February was approximately half of the volume equivalent to the water content at soil field capacity for this depth (Figure 1). Barley and rapeseed have important root exploratory abilities that enable them to reach water [53] and N in the lower layers. Furthermore, in the 2014–2015 season, Nsow diminished the oilseed content in rapeseed (Figure 4d) and increased N uptake by barley plants (Figure 3c). In fact, N fertilization decreases the oleic acid content in rapeseed [54]. In barley, the enhancement of N uptake according to N availability is also in agreement with [55]. Slurries can increase the N uptake when compared with mineral fertilizers [56] but this was not observed with our slurry rates at topdressing when compared with the minerals (Figure 3c).

In the 2015–2016 cropping season with a more humid spring (Figure 1), rapeseed did not need any additional N fertilization (Figure 4a), and none of the studied parameters were affected by the Nsow or Ntop treatments. Rapeseed absorbs relevant amounts of N at the early stages [57], allowing the crop to profit from residual N in the soil. In fact, Porter et al. [58] found no rapeseed yield response to N soil supplies that exceeded 100 kg N ha^{-1} at six of seven studied sites. Thus, rapeseed introduction is an interesting strategy to control the risk of nitrate leaching into underground water during the winter period and also to reduce the N inputs in the system. In barley, excessive N supply enhances the total biomass, and excessive vegetative growth may cause early water depletion, resulting in a lack of soil-available water during grain filling, leading to a yield reduction under Mediterranean conditions [59,60], as seen in the TM2 treatment (Figure 3a,b).

In the 2018–2019 cropping season, residual N at sowing was limited (41 kg N ha^{-1}). In the 2019–2020 cropping season, the autumn–winter rains (October–February) were higher than 250 mm, surpassing the value of water content at the soil's field capacity, which could have caused some nitrate leaching. Barley always needed pig slurry fertilization at sowing (c. 109 kg N ha^{-1}) or a mineral Ntop application of 120 kg N ha^{-1} for maximum yields (Figure 3a). Peas increased yields with the residual N from former pig slurries applied at sowing and also with the mineral application as Ntop (60 kg N ha^{-1}) in the cropping season, despite the expected atmospheric N fixation [61]. Nitrogen fertilization in peas is supported by some authors [62,63], related to the presence/absence of rhizobacteria. Inoculation with plant-growth-promoting rhizobacteria increases the growth rate of pea plants, but in their absence, N inputs cannot be reduced. It must be noted that pea yields were low in the 2018–2019 season (~2 Mg ha^{-1}, Figure 5a) and constrained by the spring drought period. The pea yield is negatively influenced by drought and high temperatures [64,65]. Barley performed better than peas and attained previous average yields despite the lower total biomass and derived a lower N uptake (Figure 3).

Nitrogen absorption in barley is important in the advanced cropping season [66]. Slurry use at topdressing is an accepted practice [10]. In this experiment, during periods of abundant spring rainfall (2015–2016, 2019–2020; Figure 2), the barley yields increased more when readily available mineral N topdressing was applied at a rate of 120 kg N ha^{-1}.

In the 2019–2020 cropping season, the previous pea crop (2018–2019) did not constrain the significance of the Ntop treatment in barley, despite it being reasonable to expect it [67]. Again, the previous low spring rainfall (2018–2019) might have limited the N fixed by peas, as drought reduces total N fixation even more severely than shoot mass [68].

Rapeseed and peas might be introduced in the traditional rotation in semiarid rainfed areas for N input reduction, although water availability limits potential yields. The obtained average yield plateau (3 and 4 Mg ha^{-1} for rapeseed and peas, respectively) might constrain their expansion and, consequently, the success of the EU agricultural policy in these agricultural systems. Drought periods are predicted to be more frequent in the Mediterranean region within a climate change scenario [69,70], which might be aggravated by soil degradation [71]. Barley seems to be the most suitable crop in such water-stress conditions (vs. rapeseed or peas), mainly if a spring drought appears. If crop diversification should be successfully enhanced by agricultural policies, such constraints should be considered.

5. Conclusions

After a fallow period, the residual plus the annual mineralized N (142 kg N ha^{-1}, 0—0.3 m, in our experiment) allows a reduction in N fertilization that can even be omitted in barley and rapeseed crops for maximum yields. In rapeseed, the absence of additional fertilization also improves the oilseed content.

After a fallow period followed by a non-fertilized barley crop, pea and barley yields increased with mineral fertilization as the topdressing (>60 or 120 kg N ha^{-1}, respectively). Barley also increased its yields with slurry N fertilization at sowing. Peas are more affected than barley by a spring drought in terms of the relative yield reduction.

The inclusion of rapeseed and peas in the winter barley rotation associated with a fallow period reduces the N fertilization requirements in this system while favoring crop diversification.

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Appendix A

Table A1. Test of fixed effects in barley for grain yield (kg ha^{-1}), total biomass (kg ha^{-1}; log10 transformation), and total N uptake (kg ha^{-1}) according to cropping season (or year) and fertilization N treatments at sowing (Nsow) and at topdressing (Ntop). The MIXED procedure of SAS type III test [1] was used.

		Yield		Total Biomass		Total N Uptake	
Source	**df**	**Den df**	***p***	**Den df**	***p***	**Den df**	***p***
Year	3	5.99	0.0039	6	0.0047	6	0.0004
Nsow	1	9.35	0.0078	10.5	0.0043	15.5	<0.0001
Ntop	4	8.04	0.6164	8	0.4789	17.7	0.0174
Year × sow	3	7.33	0.0941	6.87	0.1982	28.1	<0.0001
Year × Ntop	12	24.1	0.0049	47.8	<0.0001	28.8	0.0006
Nsow × Ntop	4	9.26	0.3841	9.09	0.4657	15.5	0.1721
Year × Nsow × Ntop	12	23.3	0.2057	47.8	0.1219	28.1	0.0965

[1] For each variable, the results are shown in detail: block as the random effect and fertilization treatment at sowing or at topdressing, and year and fertilization treatments–time interactions as fixed effects; df, degrees of freedom for the factor; Den df, the denominator degrees of freedom.

Table A2. Test of fixed effects in rapeseed for seed yield (kg ha^{-1}), total biomass (kg ha^{-1}; log10 transformation), total N uptake (kg ha^{-1}), and oilseed content (%) according to cropping season (or year) and fertilization treatments at sowing (Nsow) and at topdressing (Ntop). The MIXED procedure of SAS type III test [1] was used.

		Yield		Total Biomass		Total N Uptake		Oilseed Content	
Source	**df**	**Den df**	***p***	**Den df**	***p***	**Den df**	***p***	**Den df**	***p***
Year	1	3.24	0.0990	3.39	0.0024	21.6	<0.0001	3.97	0.4379
Nsow	1	3.1	0.0709	4	0.2625	18.4	0.0003	1.97	0.0373
Ntop	4	14.1	0.1552	8.87	0.5596	18.4	0.0038	13.2	<0.0001
Year × Nsow	1	3.1	0.1013	4	0.5690	21.6	0.3234	3.97	0.0396
Year × Ntop	4	14.1	0.4063	23.9	0.4011	21.6	0.1307	14	0.4261
Nsow × Ntop	4	19.6	0.6208	23.9	0.6038	18.4	0.7800	13.2	0.0554
Year × Nsow × Ntop	4	19.6	0.5502	23.9	0.7512	21.6	0.3758	14	0.6926

[1] For each variable, the results are shown in detail: block as the random effect and fertilization treatment at sowing or at topdressing, and year and fertilization treatments–time interactions as fixed effects; df, degrees of freedom for the factor; Den df, the denominator degrees of freedom.

Table A3. Test of fixed effects in peas for seed yield (kg ha^{-1}), total biomass (kg ha^{-1}; log10 transformation), total N uptake (kg ha^{-1}), and seed N uptake (kg ha^{-1}) according to cropping season (or year) and fertilization treatments at sowing (Nsow) and at topdressing (Ntop). The MIXED procedure of SAS type III test [1] was used.

		Yield		Total Biomass		Total N Uptake		Seed N Uptake	
Source	**df**	**Den df**	***p***	**Den df**	***p***	**Den df**	***p***	**Den df**	***p***
Year	1	1.79	0.0234	7.78	0.0006	3.66	0.0051	1.99	0.0172
Nsow	1	3.3	0.0292	7.97	0.0517	4.78	0.1036	4.64	0.0619
Ntop	4	15.9	0.0053	16.7	0.2797	17	0.0216	17.2	0.0019
Year × Nsow	1	2.88	0.1098	7.78	0.0665	4.38	0.0949	3.87	0.0895
Year × Ntop	4	18	0.1800	15.6	0.8932	14.4	0.4751	14.7	0.2471
Nsow × Ntop	4	15.9	0.1004	16.7	0.5449	17	0.3923	17.2	0.2000
Year × Nsow × Ntop	4	18	0.2822	15.6	0.6827	14.4	0.1514	14.7	0.1549

[1] For each variable, the results are shown in detail: block as the random effect and fertilization treatment at sowing or at topdressing, and year and fertilization treatments–time interactions as fixed effects; df, degrees of freedom for the factor; Den df, the denominator degrees of freedom.

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