Research Article

Received: 8 December 2023 Revised: 24 June 2024 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/jsfa.14014

Site-specific effects of fertilizer on hay and grain yields of oats: evidence from large-scale field experiments

Liping Mao,[a] Hongbo Zhang,[a] Zengnan Yang,[a] Yuan Li[a,b*] and Yuying Shen[a*]

Abstract

BACKGROUND: Oat (*Avena sativa* L.) is a valuable crop due to its strong adaptability to marginal environments, making it an important component of agricultural systems in regions where other cereals may not thrive. The application of chemical fertilizer can influence oat hay and grain yield significantly. However, large-scale meta-analytical studies of the size and variability of oat hay and grain yields in response to fertilizer addition are still lacking. Based on 83 studies worldwide, this meta-analysis quantifies the impact of the addition of fertilizer on oat hay and grain yields under varying environmental conditions (e.g., soil nutrient levels, texture, and climate).

RESULTS: The results confirmed that the fertilizer application increased oat hay yield by 48.9% and grain yield by 36.2%. This study demonstrated that balanced fertilization with nitrogen, phosphorus, and potassium generally enhances oat hay and grain yield despite large temporal and spatial variations. Boosted regression tree (BRT) models suggest that changes in hay and grain yield were primarily dominated by soil pH and nitrogen fertilizer. The response ratio (the natural logarithm of the mean values of hay yield or grain yield with and without fertilization, respectively) of hay yield declined linearly with soil pH. Elevation was the second most important factor affecting the change in response ratio of hay yield and the third most important factor affecting the change in response ratio of grain yield but climatic conditions were not the dominant factors affecting changes in oat hay or grain yield.

CONCLUSION: Overall, these results will benefit producers considering site-specific fertilization management of oat. They could increase yields and save investment in fertilizer, and help to facilitate the genetic breeding of oat varieties with high nutrient use efficiency.

Supporting information may be found in the online version of this article.

Keywords: altitude; boosted regression tree; environmental factor; meta-analysis; managerial factors; soil pH

INTRODUCTION

The challenge of global food security is intensifying in the face of rapidly expanding demand for food, feed, fiber, and fuel.[1] Cereal crops, being a fundamental food source for the majority of the world's population, play a crucial role in this context.[2] Among them, oat (*Avena sativa* L.) is notable for its adaptability and higher yield potential in marginal growing areas in comparison with other cereals such as wheat (*Triticum aestivum* L.), rye (*Secale cereale* L.), and barley (*Hordeum vulgare* L.), particularly in regions with poorer soil quality, shorter growing seasons, and cooler climates.[3]

Oat exhibits remarkable resilience in cool and humid conditions during summer, tolerating excessive rainfall and requiring fewer growing degree days throughout its growth stages.[4] Predominantly cultivated as a forage crop due to its high protein content and palatability, oat thrives in marginal environments, including cool, wet climates and low-fertility soils, where it serves primarily as animal feed.[5-7] A study conducted between 2002 and 2004 across several locations in Saskatchewan demonstrated high oat yield potential and relatively low variability.[8]

* *Correspondence to: Y Li or Y Shen, Natural Resources Institute Finland, Kuopio Finland, E-mail: yuan.li@luke.fi (Li); E-mail: yy.shen@lzu.edu.cn (Shen)*

a *State Key Laboratory of Herbage Improvement and Grassland Agro-ecosystems of Lanzhou University, Qingyang National Field Scientific Observation and Research Station of Grassland Agro-Ecosystems, College of Pastoral Agriculture Science and Technology, Lanzhou University, Lanzhou, China*

b *Grasslands and Sustainable Farming, Production Systems unit, Natural Resources Institute Finland, Kuopio, Finland*

There has been an increasing interest in oats for human consumption, which has been attributed to their dietary benefits, such as their rich fiber, protein, and nutrient content.[9] This increased interest is reflected in global oat production, which saw a yield of approximately 25.3 million tons in 2020, marking a 14.48% increase from 22.1 million tons in 2014.[10] It is therefore important to investigate oat production for both grain and forage in order to enhance agricultural sustainability and resilience in marginal growing areas with limited input use.

The application of macronutrients through chemical fertilizers can influence crop yield significantly, with effects varying based on soil nutrient status.[11,12] However, the overuse of fertilizers has led to substantial concerns regarding land degradation and water pollution.[13,14] Studies have investigated the impact of fertilizer application on oat hay and grain yield, but these have often been limited in scope, focusing on specific locations and short time frames, resulting in inconsistent findings. For instance, a study conducted in Manitoba from 2000 to 2002 revealed that nitrogen (N) fertilizer application at rates of 40–80 kg ha^{-1} substantially increased grain yield, whereas higher application rates (120 kg ha^{-1}) posed risks of lodging and reduced grain plumpness.[15] A study in the central highlands of Ethiopia found that oat hay yield increased linearly with fertilizer application up to 175% of the recommended rate, while the optimal economic return was achieved at 125% (51.3 kg N ha^{-1}) of the recommended rate.[14] Patle[16] reported that application of N to hay oats significantly enhanced growth and yields, with optimal plant height and leaf number observed at 100 kg N ha^{-1}. Midha *et al.*[17] noted an increase in oat dry matter yield from 5.28 to 8.92 t ha^{-1} with a N application rate of 120 kg ha^{-1}. A study in Mexico City also reported a 44.9% and 49.2% increase in total biomass and crop yield with 138 kg N ha^{-1}.[18] In terms of phosphorus (P) and potassium (K) fertilization, Mohr *et al.*[15] found that P application only increased grain yield in 2002 at Brookdale and Brandon, and a moderate increase in yield was observed with the application of 33 kg K_2O ha^{-1}. A study by May[19] indicated that P application consistently improved both grain yield and biomass over 3 years at various sites. Meanwhile, research in Inner Mongolia, China, showed that the maximum grain yield was obtained at a P application rate of 78 kg ha^{-1}.[20] The varying results from these studies highlight the need for more comprehensive research to determine the effects of fertilization on oat yields.[14,21,22] It is also important to optimize fertilization practices to ensure high nutrient use efficiency and minimize environmental impacts, especially in marginal growing areas where environmental constraints may limit yield benefits.[14,22]

In addition to fertilization, oat yield is intricately linked to various environmental factors, including soil fertility, precipitation, temperature during growth, and soil type.[12,14,19] For example, oats can thrive at higher altitudes in tropical regions.[23] They are known to yield better in clay soils than other cereals and are tolerant of a wide pH range, from 4.5 to 8.6, accommodating low-fertility soils.[23,24] Optimal temperatures for maximizing oat grain and hay yield range between 13 and 19 °C.[23] Fertilizer efficiency is strongly dependent on soil properties and climatic conditions.[25,26] Accurate and region-specific agronomic recommendations for oat fertilizer application therefore require a comprehensive understanding of these environmental variables, particularly initial soil nutrient content.

Meta-analytical approaches have been instrumental in evaluating the effects of treatment factors systematically across different geographic locations under diverse environmental and management conditions. However, there is a noticeable lack of large-scale meta-analyses that specifically address the variability and magnitude of oat hay and grain yields in response to fertilizer application. There is also scant information on how environmental factors, such as initial soil nutrient conditions, soil texture, and climate, interact with fertilizer application to influence oat yields. This large-scale meta-analysis therefore aims to (1) elucidate the direction and magnitude of changes in oat hay and grain yield following the application of various nutrients in different forms, and (2) evaluate the impact of environmental factors (climate, soil, etc.) on oat hay and grain yield in the context of fertilizer application.

Table 1. The detailed description of fertilization treatment in this study

Fertilization description	Abbreviation
Balanced chemical fertilization of N, P, and K	CF
Unbalanced chemical fertilization of N, or P, or K	UCF
Manure and chemical fertilizers	CFM

MATERIALS AND METHODS

Literature retrieval

The primary sources for literature in this study were obtained from the China National Knowledge Infrastructure (CNKI) and the Web of Science Core Collection (WoS). The search strategy employed the following keywords: 'oat' OR '*Avena sativa*' AND 'fertilization' OR 'nitrogen fertilizer' OR 'phosphate fertilizer' OR 'potash fertilizer'. To ensure the relevance and quality of the literature and to minimize publication bias in this meta-analysis, the following inclusion criteria were applied:

(1) Studies had to report on the application rates of specific fertilizers (N, P, and/or K) and their effects on either hay yield or grain yield of oats, derived from field experiments with at least three replicates.
(2) The fertilization treatments in the studies had to include at least one of the nutrients N, P, and/or K. In cases where multiple fertilization levels were tested without a control group, the lowest level of fertilization was designated as the control.
(3) Consistency in other agronomic practices (e.g., crop variety, sowing rate, and irrigation) had to be maintained within each study to ensure comparability.
(4) When a single publication reported multiple levels of fertilizer treatment, each level was treated as an independent study and included in the dataset.[27]

Supporting Information, Fig. S1, illustrates the detailed process of literature selection. Fertilization strategies in this study were categorized into three groups to derive meaningful implications (Table 1). These included: balanced chemical fertilization (CF), entailing the application of full N, P, and K to avoid nutrient deficiencies that aligned with crop yield and nutrient requirements; unbalanced chemical fertilization (UCF), which involved applying only one or two of these nutrients; and a combined approach of manure and chemical fertilizers (CFM).[28,29]

Journal of the Science of Food and Agriculture published by John Wiley & Sons Ltd on behalf of Society of Chemical Industry.

Establishment of database

The hay and grain yield data published in the form of a graph were digitized by *GetData Graph Digitizer* (http://getdata-graph-digitizer.com/ version 2.26), and relevant data in the form of table or text were also extracted. Eventually, 325 observations of hay yield were obtained from 32 studies and 745 observations of grain yield from 51 studies. Figure 1 shows spatially distinct study sites. Other details of the selected studies are included in the supporting information.

Collected variables were further grouped to facilitate a meta-analysis subgroup in line with a previous study (Table 2).[30] More details have been given in the supporting information. However, the CFM subgroup of fertilization measures was excluded from the subgroup meta-analysis due to insufficient data (Supporting Information, Table S1).

Meta-analysis

The response ratio (ln*RR*) of hay or grain yield was calculated as the natural logarithm of the treatment (X_t) and control group (X_c):[31]

$$\ln RR = \ln\left(\frac{X_t}{X_c}\right) = \ln(Xt) - \ln(Xc) \qquad (1)$$

where, X_t and X_c are the mean values of hay yield or grain yield under treatment and control, respectively. A separate ln*RR* was calculated for each level of fertilizer application. The variance (v) of the ln*RR*, weighted response ratio (*RR*++), the weighting factor (*wij*), the standard error of *RR*++ (s(*RR*++)), and the 95% confidence interval (95% CI) were calculated; the relevant equations have been given in the supporting information. To facilitate the data interpretation, the percentage change between the treatment and the control was calculated as (exp (lnRR_{++}) − 1) × 100%.

Using the restricted maximum-likelihood estimator (REML) in the rma.unl model, the random-effect meta-analysis was performed in the 'metafor' package program in R (version 3.4.2),[32] and to mitigate the potential reduction in overall heterogeneity in effect sizes, the study ID was included, representing each unique geographic location, as a random effect. The mean response ratio (ln*RR*) and its 95% confidence interval (CI) were calculated with bias-correction, generated using bootstrapping (4999 iterations). A χ^2 test determined whether the heterogeneity among the ln*RR* of changes in hay yield or grain yield with sowing rate treatments (Q_{total}) exceeded the expected sampling error significantly. A randomization test determined the significance of between-group heterogeneity (Q_b).[33] χ^2 tests were also used to determine the statistical significance of the within-group heterogeneity (Q_w) (see Supporting Information, Tables S1–S5). Publication bias was determined by using Rosenthal's fail-safe number (Supporting Information, Table S1).[34]

Data analysis

The data analysis began by plotting the frequency distributions of various parameters: hay yield, grain yield, mean annual temperature (MAT), mean annual precipitation (MAP), elevation, initial soil organic carbon (SOC), initial soil pH, and the application rates of N, P, and K fertilizers. These distributions were visualized using Gaussian curve fittings.[35]

Subsequently, boosted regression tree (BRT) models, which integrate regression trees with a boosting algorithm,[36] were employed to ascertain the relative importance of environmental and agronomic factors on the ln*RR* of oat grain and hay yield. Boosted regression tree models are particularly adept at distinguishing independent influences of various factors, including site information (elevation, MAT, and MAP) and soil properties (soil texture, SOC, and soil pH), on the ln*RR* of grain and hay yield.

The study also used Pearson regression analysis to examine the correlations between the ln*RR* of oat grain or hay yield and various soil environmental and management conditions. Model comparisons were made using Akaike's information criterion (AIC).

The classification and regression trees (CART) methodology was used to elucidate the influences of different variables – fertilizer type, climate, initial soil properties, and agronomic factors – on the ln*RR* of oat yield.[37]

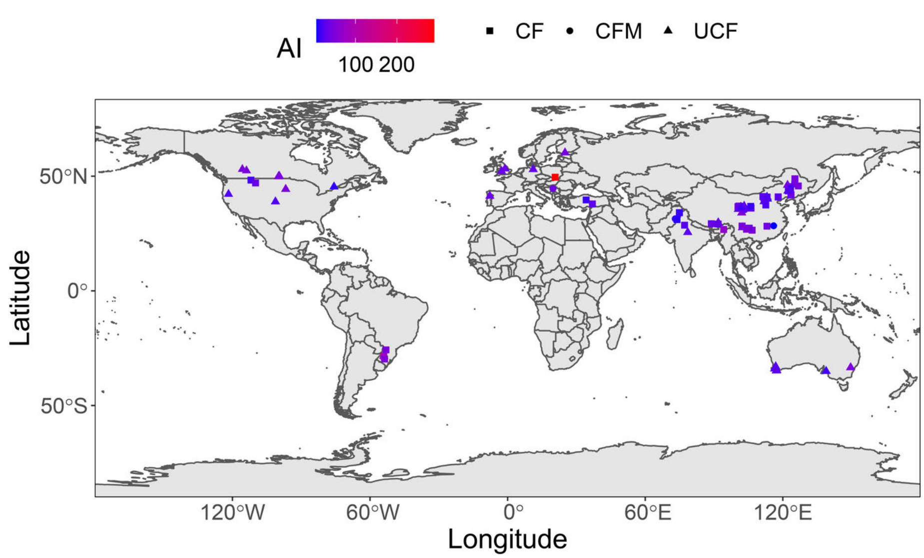

Figure 1. The geographical coverage of the studies used in the meta-analysis. Map showing the trial sites of the 83 studies included in the analysis. (To view the color version of the figure, readers are referred to the web version of this article.) Abbreviations: AI, arid index; CF, balanced chemical fertilization; UCF, unbalanced application of one or two types of chemical fertilizer; CFM, application of manure and chemical fertilizers. For a description of the abbreviations, refer to Table 1

Table 2. Data summary in each subgroup, which include elevation, mean annual temperature, MAT; mean annual precipitation, MAP; and initial soil organic carbon, SOC; and pH.

		Numbers of studies		Numbers of observations	
Group	Sub-heading	Hay	Grain	Hay	Grain
Elevation	≤1200 m (a.s.l)	20	18	220	358
	>1200 m (a.s.l)	13	33	105	387
MAP	≤600 mm	22	39	221	431
	600–1000 mm	4	7	51	259
	≥1000 mm	7	5	53	55
MAT	≤8°C	18	37	182	495
	8–15°C	5	9	73	167
	≥15°C	10	6	70	83
Soil texture	Clayey	2	6	28	96
	Loamy	27	31	225	491
	Silty	2	10	4	101
	Sandy	3	6	38	57
SOC	≤10 g·kg^{-1}	12	22	81	323
	10–15 g·kg^{-1}	12	16	125	233
	15–20 g·kg^{-1}	3	3	23	36
	≥20 g·kg^{-1}	9	11	96	133
pH	≤7	13	15	135	283
	>7	20	36	190	442
Fertilization type	*CF*	20	28	203	350
	UCF	13	22	117	365
	CFM	1	4	5	30

To assess the impact of water, N inputs, and initial soil nutrient concentrations on the ln*RR* of hay and grain yield, a mixed-effects model was used. This analysis was conducted in the R package 'nlme', incorporating variables such as elevation, climate, initial SOC, application rates of N, P, and K, and sowing rate. Finally, all figures illustrating the RR_{++} were generated using GraphPad Prism version 8.4.2 (GraphPad Software, Inc., La Jolla, California, USA) and OriginPro 2018C (OriginLab Corporation, Northampton, MA, USA).

RESULTS

Dataset summary

Studies included in the present meta-analysis covered a wide range of climate and soil conditions (Fig. 2). Mean annual precipitation ranged from 162 to 2793 mm, with a median of 525 mm ($n = 1238$; Fig. 2(a)). Mean annual temperature ranged from −2.9 to 26.2 °C, with a median of 6.5 °C ($n = 1238$; Fig. 2(b)). The median elevation was 507 m ($n = 1238$; Fig. 2(c)), with a range of 10–4500 m. The median SOC was 11 g kg^{-1} ($n = 1214$; Fig. 2(d)), with a range of 0.7–39.4 g kg^{-1}. All observed soil pH values ranged from 4.5 to 8.7, with a median of 7.5 ($n = 1214$; Fig. 2(e)).

The N application rates ranged from 0 to 550 kg ha^{-1}, with a median of 80 kg ha^{-1} ($n = 1238$; Fig. 2(f)). The K application rates were between 0 and 450 kg ha^{-1}, with a median of 50 kg ha^{-1} ($n = 694$; Fig. 2(g)). The K addition rate ranged from 0 to 200 kg ha^{-1}, with a median of 48 kg ha^{-1} ($n = 696$; Fig. 2(h)).

Hay yields varied between 0.8 and 28.3 t ha^{-1}, with a median of 4.5 t ha^{-1} ($n = 400$; Fig. 2(i)). Grain yield ranged from 0.4 to 8.2 t ha^{-1}, with a median of 3.1 t ha^{-1} ($n = 893$; Fig. 2(j)).

Fertilizer addition enhanced hay yield

In general, fertilizer application enhanced the overall mean of lnRR_{++} of hay yield by 48.9% (95% CI: 0.30–0.50, Fig. 3). In comparison with CFM, balanced fertilizer addition significantly increased lnRR_{++} of hay yield by 88.3% (Fig. 3). Specifically, for balanced fertilization, the changes in elevation and soil initial pH had significant effects on the lnRR_{++} of hay yield (Fig. 4). The lnRR_{++} of elevations above 1200 m was significantly higher than that of elevations below 1200 m by 151.1%; the lnRR_{++} of pH > 7 was greater than that of elevations below 7 by 489.5% ($P < 0.05$), and fertilizer application did not increase hay yield in soils with pH < 7 ($P > 0.05$). Irrespective of climate condition (e.g., MAP, MAT) and soil condition (e.g., initial SOC and soil texture), the fertilizer addition enhanced hay yield significantly with the exception of that grown on clay soil. High MAP (>1000 mm), MAT (>15 °C), and low soil fertility (SOC < 10 g kg^{-1}) caused high variance, which is indicated by the larger confidence interval (Fig. 4).

For unbalanced fertilization, regardless of changes in climate condition (e.g., MAP, MAT), elevation, and initial soil pH, fertilizer application consistently increased the hay yield ($P < 0.001$, Fig. 4). Regardless of soil texture, fertilizer application also significantly increased the hay yield ($P < 0.001$), and applying fertilizer in silty soil resulted in higher hay yield than that in loamy soil ($P < 0.05$). Fertilizer application increased hay yield only when the initial SOC was greater than 20 g kg^{-1} ($P < 0.05$).

Fertilizer addition enhanced grain yield

In general, fertilizer application enhanced the overall mean lnRR_{++} of grain yield by 36.2% (0.24–0.38, Fig. 3). The addition of balanced fertilizer increased the lnRR_{++} of hay yield more than

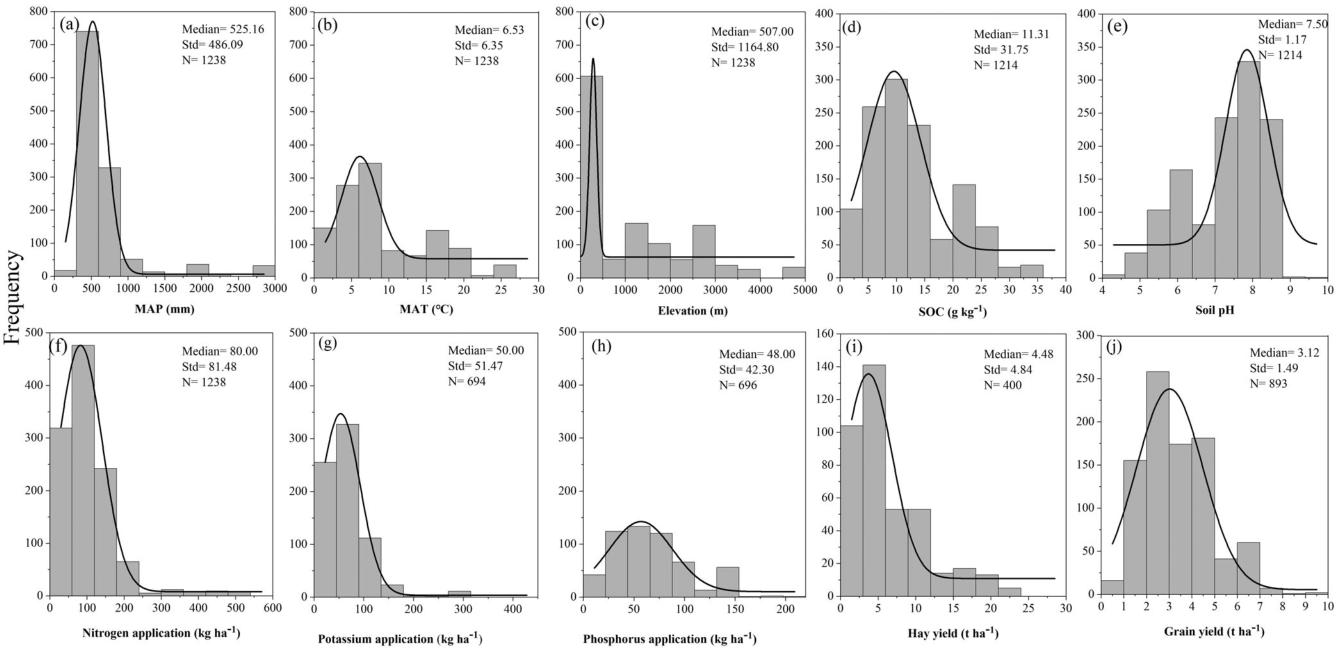

Figure 2. Frequency distributions of (a) MAT, (b) MAP, (c) elevation, (d) SOC, (e) soil pH, (f) nitrogen application, (g) phosphorus application, (h) potassium application, (i) hay yield and (j) grain yield. The fitted curve represents an estimated Gaussian distribution of frequency. The mean, standard error, and the number of observations for each variable are noted. Note the different scales among the graphs. Abbreviations: MAT, mean annual temperature; MAP, mean annual precipitation; SOC, initial soil organic carbon.

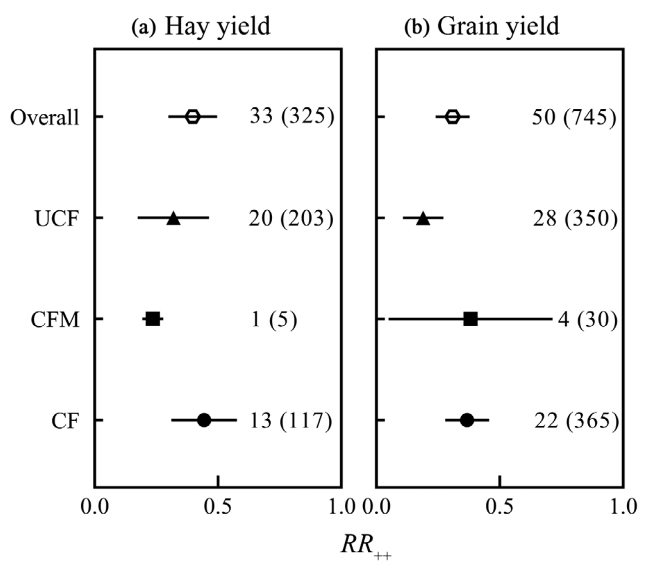

Figure 3. The weighted response ratio of (a) hay yield and (b) grain yield of oat between fertilizer treatment and its control. The response ratio indicates the natural logarithm of the mean values of hay yield or grain yield under treatment and control, respectively (see Eqn 1). Error bars represent the 95% confidence intervals. The number of studies and observations are noted adjacent to each bar. For a description of the abbreviations, refer to Table 1.

unbalanced fertilization by 94.0% (Fig. 3), while CFM increased the variance of lnRR_{++} as indicated by the large CI. Thus, the effects of CFM in this study should be interpreted with caution because of the low number of observations (relative to other subgroups) and the resulting large CIs. Although balanced fertilization generally led to increased grain yield across various elevations, climate conditions (such as MAP and MAT), and soil conditions (including SOC, pH, and soil texture), an exception was observed in clay soils (Fig. 5). The lnRR_{++} also varied in relation to moisture availability, displaying differing patterns from drought to optimum to excess moisture conditions; however, the elevation changes had no significant effect on the positive effect of fertilization on grain yield. The lnRR_{++} of grain yield to fertilizer was greater at sites that received less than 600 mm of MAP in comparison with those sites that received between 600 and 1000 mm of MAP ($P < 0.05$). The lnRR_{++} of grain yield at MAT below 8 °C was significantly lower than that at MAT above 8 °C. The lnRR_{++} of grain yield at SOC below 15 g kg^{-1} was higher than that at SOC above 15 g kg^{-1} ($P < 0.05$). The lnRR_{++} of grain yield was in the order of sandy > loamy > silty soil ($P < 0.05$), and the lnRR_{++} of grain yield of pH < 7 was significantly higher than that of pH > 7 (Fig. 5).

For unbalanced fertilization, irrespective of elevation, climate condition (e.g., MAP, MAT) and soil condition (e.g., SOC, pH, and soil texture), fertilizer application significantly increased grain yield (Fig. 5). While positive lnRR_{++} of grain yield responded to fertilizer addition varied with changes in elevation, climate condition and soil condition, and ertilizer application. Specifically, the lnRR_{++} of grain yield of MAP greater than 600 mm was significantly higher than that of MAP below 600 mm; the lnRR_{++} of grain yield at MAT greater than 8 °C was higher than that at MAT below 8 °C by 338.52% ($P < 0.05$). The lnRR_{++} of grain yield of elevation below 1200 m was significantly higher than that of elevation above 1200 m. The lnRR_{++} of grain yield of SOC above 20 g kg^{-1} was higher than that of SOC below 20 g kg^{-1} ($P < 0.05$). The lnRR_{++} of grain yield of clayey and silty soils was significantly higher than that of loamy and sandy soils. The lnRR_{++} of grain yield of pH < 7 was higher than that of pH > 7 by 568.4% ($P < 0.05$).

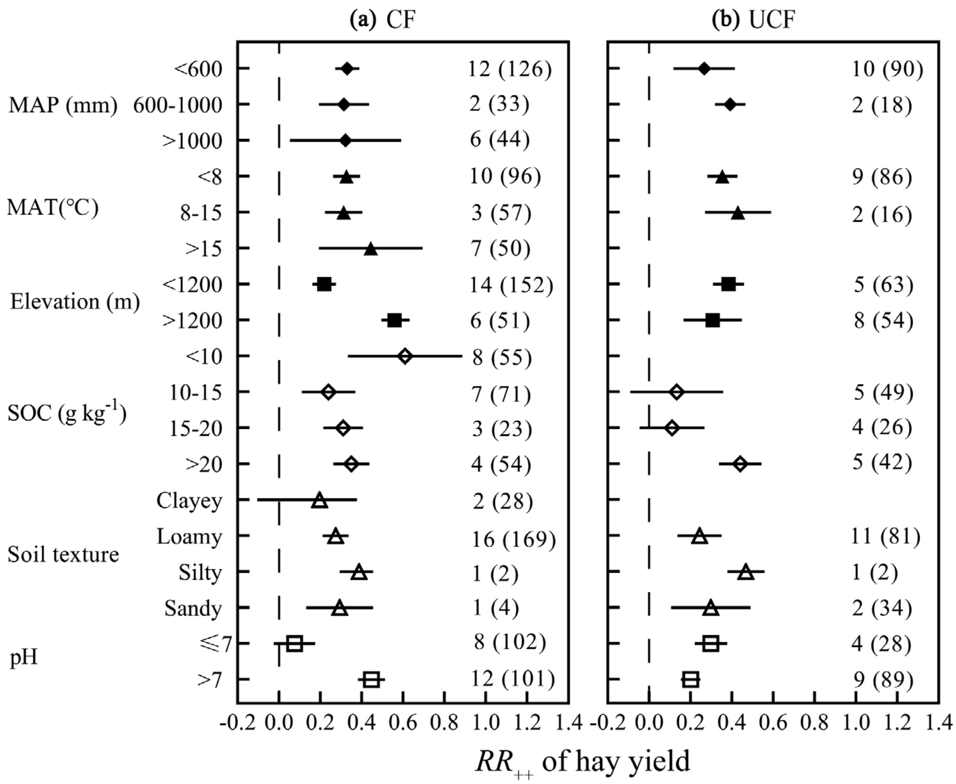

Figure 4. The weighted response ratio of oat hay yield between (a) CF fertilizer or (b) UCF fertilizer treatment and its control. Response ratio indicates the natural logarithm of the mean values of hay yield under treatment and control, respectively (Eqn 1). Error bars represent the 95% confidence intervals. The number of studies and observations are noted adjacent to each bar. For a description of the abbreviations, refer to Table 1.

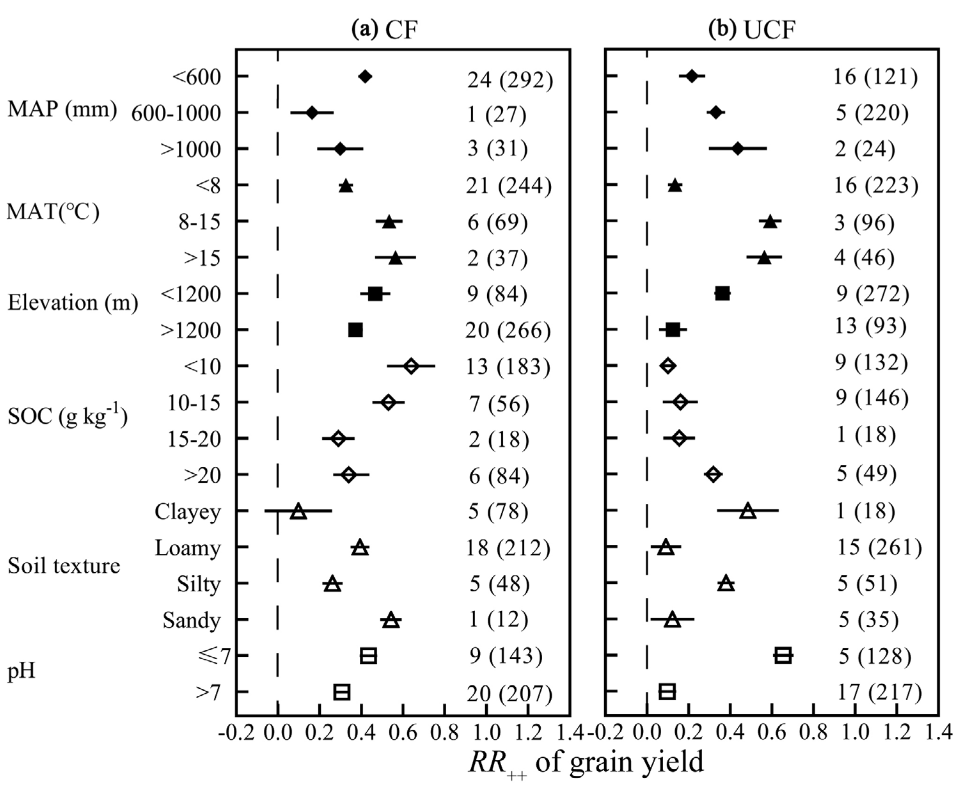

Figure 5. The weighted response ratio of grain yield of oat between (a) CF fertilizer or (b) UCF fertilizer treatment and its control. The response ratio indicates the natural logarithm of the mean values of grain yield under treatment and control, respectively (Eqn 1). Error bars represent the 95% confidence intervals. The number of studies and observations are noted adjacent to each bar. For a description of the abbreviations, refer to Table 1.

Journal of the Science of Food and Agriculture published by John Wiley & Sons Ltd on behalf of Society of Chemical Industry.

Environmental factors affecting hay and grain yield varied

The relative importance of environmental (e.g., elevation, MAT and MAP) and soil management factors (e.g., soil conditions, sowing rate, and fertilization), affecting hay and grain yield, differed (Table 3, Figs 6 and7). The response ratios of hay yield and grain yield were primarily dominated by soil pH (108.3%) and N fertilizer (178.0%), respectively (Fig. 6). In particularly, pooling data showed that the response ratio of hay yield declined linearly with soil pH, and the model explains more than 22% of the variation alone (Supporting Information, Fig. S2). Elevation played an important role in affecting the response ratio of hay (107.5%) and grain yield (141.5%) but fertilization type only slightly affected changes in hay and grain yield. Soil condition, initial SOC (93.7%), and soil texture (84.9%), also significantly impacted on response ratio of hay yield, and initial SOC (122.3%) significantly affected the response ratio of grain yield.

DISCUSSION

This meta-analysis represents a quantitative synthesis, evaluating the impact of the application of fertilizer on oat yields in the context of both fertilizer management and environmental factors. The response of oat yield to fertilizer applications is intricately linked with a complex interplay of region-specific factors, including MAT, MAP, soil properties, and soil pH. Notably, the meta-analysis highlights the positive effect of fertilizer application on both oat hay and grain yields.

Effect of fertilizer addition on hay and grain yield

The effect of CFM in enhancing oat hay yield compared with CF was not significant (Fig. 3). This could be attributed to the gradual release of nutrients from organic fertilizers, necessitating prolonged microbial activity for effective nutrient assimilation by crops, unlike the immediate availability of nutrients from mineral fertilizers.[18,38] A 21-year field experiment in a ley rotation context revealed a 20% lower yield with organic fertilizers than with mineral fertilizers.[39] For example, a three-year study in India found that a combination of manure and mineral fertilizer treatment yielded higher oat dry matter (10.38 t ha^{-1}) than mineral fertilizer treatment alone (8.72 t ha^{-1}), representing an increase of 19%.[21] However, research from Moystad, Norway, suggests that comparable yields between organic and mineral fertilizers are achievable with substantial nutrient surpluses.[40] This underscores the importance of considering application rates in future studies to provide comprehensive guidance for oat fertilizer management.

Nitrogen, a critical nutrient for cereal growth and yield components, plays a vital role in chlorophyll synthesis, enzyme formation, tiller development, and consequently, optimizing grain yield, despite oats' traditional tolerance for low-fertility soils.[25,41,42] Previous studies have consistently shown that N fertilizer application enhances cereal grain yields, with optimal rates between 80 and 115 kg ha^{-1}.[15,43,44] However, in our study, no statistically significant relationships were established between fertilizer application rates (e.g., N or P) and oat grain and hay yields (Supporting Information, Fig. S2), likely due to spatial and temporal variations in the data. This indicates the need for further research focused on quantifying the effects of specific fertilizer application rates.

Excess N fertilizer application can lead to decreased crop yields, reduced fertilizer use efficiency, and significant environmental pollution, such as increased nitrous oxide emissions and N leaching.[45-47] For example, in a study in Norway, an N application rate of 110 kg ha^{-1} resulted in an average N use efficiency of 74%, with higher rates leading to reduced efficiency and increased N surplus.[14,48] The long-term use of inorganic fertilizers also tends to decrease soil pH.[49] The recovery rates of P and K from applied fertilizers in cereal crops are relatively low, typically around 16% for P and 19% for K.[25] The results of this study indicate that the

Table 3. Mixed-effects model of the effects of elevation, mean annual temperature (MAT), mean annual precipitation (MAP), initial soil organic carbon (SOC), and application rate of nitrogen (N), phosphorus (P), potassium (K), and sowing rate (SR) on response ratio (*RR*) of hay and grain yield

Dependent variable	Model parameter	Value	Std error	df	*t*	*P*
RR of hay	Intercept	−0.40	0.78	145	−0.52	0.60
	Elevation	0.00006	0.0002		0.25	0.80
	MAP	−0.008	0.0019		−4.47	**0.0009**
	MAT	0.40	0.091		4.42	**0.001**
	SOC	0.10	0.013		8.02	**0.001**
	N	0.0001	0.0004		0.26	0.79
	P	−0.0001	0.0005		−0.27	0.78
	K	−0.0005	0.0007		−0.73	0.47
	SR	0.002	0.0008		2.50	**0.013**
RR of grain	Intercept	0.38	0.47	222	0.79	0.43
	Elevation	−0.00007	0.00003		−2.34	**0.02**
	MAP	−0.0002	0.0003		−0.88	0.38
	MAT	0.007	0.015		0.51	0.62
	pH	−0.02	0.048		−0.46	0.65
	SOC	0.004	0.004		1.04	0.30
	N	0.0006	0.0002		2.55	**0.01**
	P	0.0003	0.0003		1.06	0.29
	K	−0.0004	0.0003		−1.09	0.28
	SR	0.001	0.0005		1.99	**0.047**

Bold signifies $P < 0.05$.

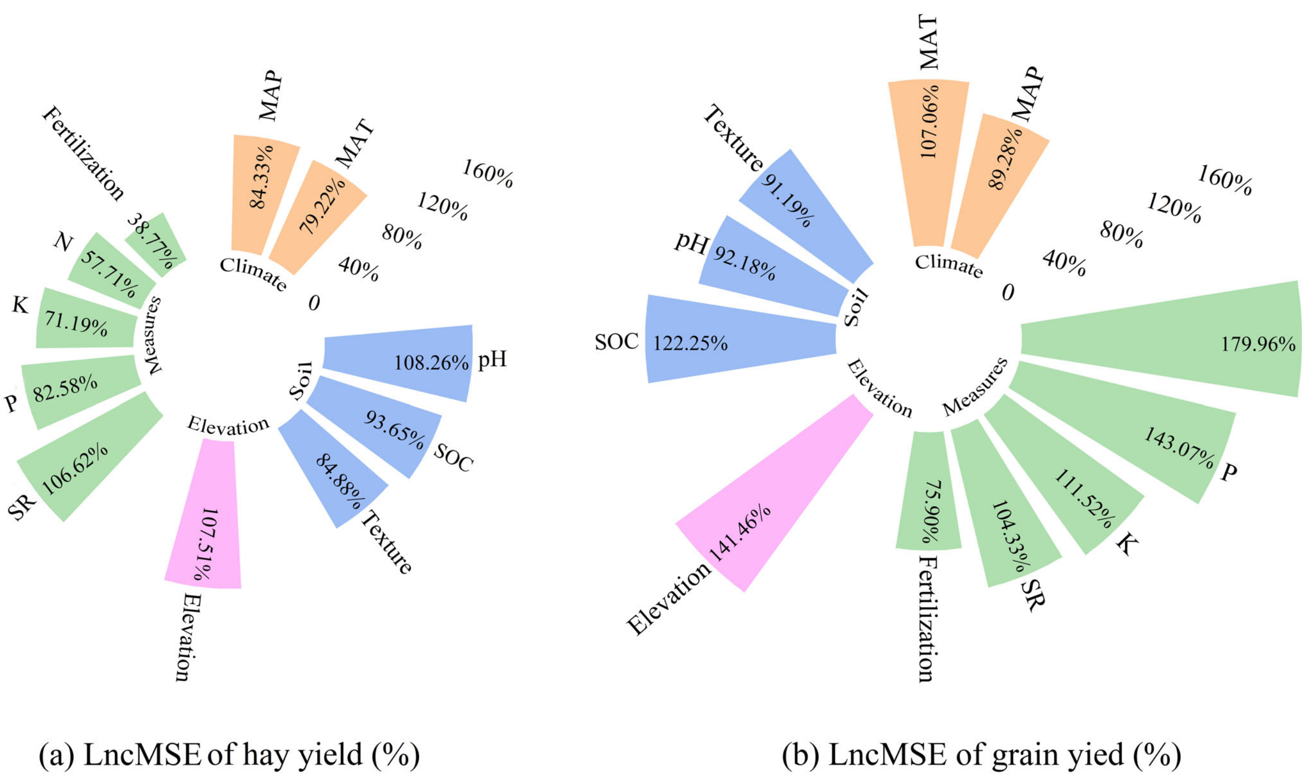

Figure 6. The relative importance of independent variables for the response ratio (*RR*) of (a) hay yield (BD), and (b) grain yield. Higher IncMSE% means more important in affecting *RR*. Random forest analysis was used. Variables include mean annual precipitation (MAP), mean annual temperature (MAT), initial soil organic carbon (SOC), initial soil pH, soil texture, fertilization type, sowing rate (SR), and application rate of nitrogen (N), phosphorus (P), potassium (K).

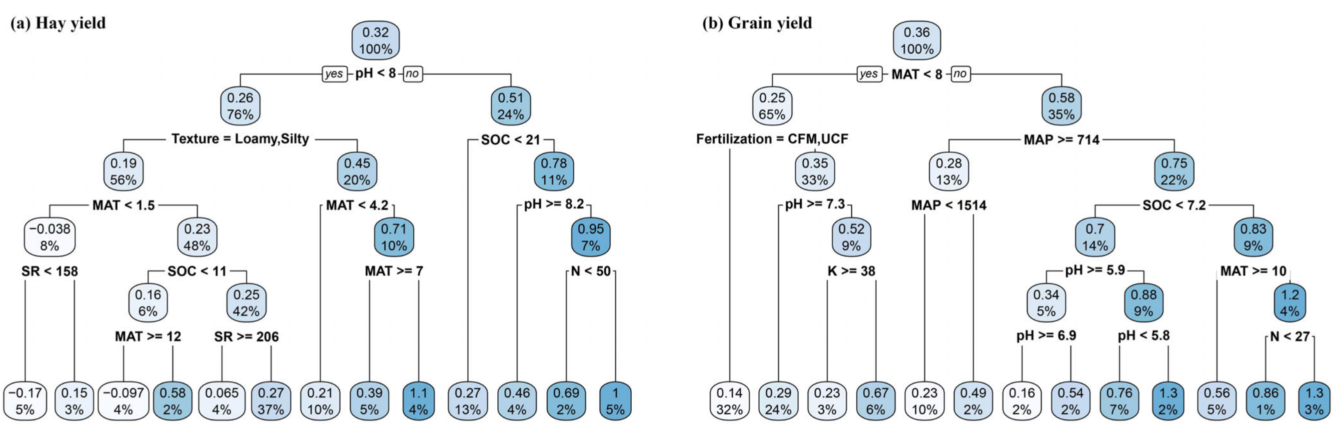

Figure 7. Classification and regression trees illustrated the influence of fertilizer type, climate (MAP, mean annual precipitation; pH, initial soil; SOC, initial soil organic carbon), application rate of nitrogen and potassium, and sowing rate on the response ratio of oat (a) hay yield and (b) grain yield. The numbers and the shading in the boxes represent the mean values at each decision point; the percentages indicate the percentages of all values considered at each decision point.

fertilizer application rate impacts hay and grain yields consistently, with P having a greater effect than K (Fig. 6). High sowing rates generally aim to increase hay yield, with P application enhancing cereal root density.[50] In contrast, N application can increase the risk of lodging.[51] The optimal N application rate therefore varies between hay and grain yields, as the balance between maximizing yield and minimizing negative effects such as lodging and environmental impact differs for these two outputs.

Our analysis also revealed that balanced fertilizer application resulted in greater grain yield improvements than unbalanced fertilization (Fig. 3). Supporting this, studies in Lithuania have shown higher oat yield and fertilizer use efficiency with balanced rather than unbalanced fertilization.[52,53] In line with hay yield results, no significant difference was found between organic and mineral fertilizer applications for grain yield. A study in Roque, Mexico, corroborated this finding, showing comparable oat grain yields between earthworm complex and mineral fertilizer use.[54]

Factors affecting hay and grain yield in response to fertilizer addition

The factors influencing hay and grain yield in response to fertilizer addition differ significantly. Our analysis revealed that soil pH predominantly impacts the response ratio of hay yield, whereas N application is the key determinant for grain yield changes (Fig. 6). This insight is crucial for guiding genetic processes and site-specific fertilization strategies in oat cultivation.

Soil pH is a critical factor affecting crop growth, influencing a myriad of chemical and biological soil reactions.[55] Although oats can tolerate a wide pH range (4.5–8.6),[23,24] the findings of this study suggest that balanced fertilization does not significantly enhance hay yield in acidic soils (Fig. 4). This could be due to acidic conditions reducing P availability and exacerbating toxicity from elements such as aluminum, thereby affecting the utilization of applied fertilizers.[55,56] In fact, the study observed a linear decline in the response ratio of hay yield with decreasing soil pH (Supporting Information, Fig. S2), indicating a critical soil pH threshold for optimal oat growth.

Elevation emerged as the second most influential factor affecting hay yield and the third most influential factor affecting grain yield. High elevations, often characterized by extreme conditions like severe cold, intense UV radiation, and poor soil quality,[57] pose unique challenges for oat cultivation. A study in Qinghai Province, China, demonstrated the adverse effects of high altitude on oat growth and yield,[58] suggesting that balanced fertilization can significantly improve hay yield at elevations above 1200 m. However, unbalanced fertilization may be ineffective in these conditions due to the lack of certain chemical elements (Fig. 5).

Despite oats' adaptability to marginal environments, low initial SOC contents (<10 g kg^{-1}) can hinder early growth.[40,42] Fertilizer addition, especially balanced fertilization, was found to increase grain yield significantly (Fig. 5), although the impact on hay yield was more variable (Fig. 4). Unbalanced fertilization tends to result in poorer soil conditions, and its effectiveness varied with SOC contents, showing no enhancement in hay yield in soils with medium SOC content (10–20 g kg^{-1}). Surprisingly, sandy soils, typically considered less fertile, exhibited the highest $\ln RR_{++}$ for grain yield, possibly due to their dramatic response to fertilization or the limited number of studies available for each soil type.

Climate conditions, surprisingly, were not the dominant factors affecting oat hay or grain yield (Fig. 6). The adaptability and resistance to rain of oats, coupled with their lower thermal degree day requirements, might explain this finding. However, fertilizer application notably enhanced grain yield in areas with MAT below 8 °C (Fig. 5), highlighting the critical role of temperature during specific growth stages in grain formation.[59,60]

This study offers significant insights but some limitations warrant caution in interpreting the results. The reliance on MAP and MAT as climate indicators may not fully capture seasonal climate variations critical to an understanding of nutrient responses. Furthermore, the study did not differentiate between the lengths of oat growing seasons, which could affect nutrient response curves. The varying responses of oat cultivars to fertilizer applications were not accounted for due to data limitations. Future research should aim to incorporate more detailed seasonal climate metrics, examine nutrient responses across different oat growing seasons, and include data on specific oat cultivars to refine fertilization strategies.

CONCLUSIONS

This comprehensive meta-analysis, encompassing 83 studies from around the world, has quantified the impact of fertilizer application on oat cultivation, demonstrating a substantial increase in oat hay yield by 48.9% and grain yield by 36.2%. In particular, it demonstrated the effectiveness of balanced fertilization involving N, P, and K in enhancing both hay and grain yields. However, fertilizer management should be tailored to account for factors such as soil pH and environmental constraints specific to marginal lands. In acidic soils, balanced fertilization strategies that include phosphorus may be necessary to mitigate nutrient availability issues. Conversely, in regions with higher soil organic carbon and clay content, careful management of nitrogen application rates is essential to avoid overfertilization and its associated negative impacts.

These insights suggest that site-specific fertilization management strategies can optimize oat yields, improve nutrient use efficiency, and enhance sustainability in diverse environmental conditions. Future research should focus on the effects of specific fertilizer rates on oat yield, fertilizer use efficiency, and nutrient leaching to support sustainable agricultural practices globally.

ACKNOWLEDGEMENTS

This work was supported by the China Agricultural Research System-34 (Grant number: CARS-34), Gansu Provincial Cold and Arid Agricultural Science and Technology Project (Grant number: GSLK-2022-2118), Key Technology Integration and Demonstration for Improving Quality and Efficiency of High-Quality Forage Grass in Arid Regions of Huan County (Grant number: 2022YFD1602102). The authors acknowledge the assistance of Narasinha J. Shurpali, Panu Korhonen, Sanna Kykkänen, and Perttu Virkajärvi for reviewing the paper and providing expert suggestions and comments, and thank all the researchers whose data were used in this meta-analysis.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

AUTHOR CONTRIBUTIONS

LP Mao, HB Zhang, and ZN Yang: designed the research, collected data, visualization, writing – review and editing. Y Li, and YY Shen: writing – review and editing, supervision, project administration, and funding acquisition.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could appear to influence the work reported in this paper.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

REFERENCES

1 Alexandratos N and Bruinsma J, *World Agriculture towards 2030/2050: The 2012 Revision, In, ESA Working Paper*. FAO, Rome, FAO (2012).
2 Tilman D, Balzer C, Hill J and Befort BL, Global food demand and the sustainable intensification of agriculture. *Proc Natl Acad Sci* **108**: 20260–20264 (2011).

3 Wang J, *Cultivation of Forage Crops for Grazing*. China Agricultural Press, Beijing (2018).
4 Mut Z, Akay H and Kose ODE, Grain yield, quality traits and grain yield stability of local oat cultivars. *J Soil Sci Plant Nutr* **18**:269–281 (2018).
5 Buerstmayr H, Krenn N, Stephan U, Grausgruber H and Zechner E, Agronomic performance and quality of oat (*Avena sativa* L.) genotypes of worldwide origin produced under central European growing conditions. *Field Crop Res* **101**:343–351 (2007).
6 Ren CZ, Ma BL, Burrows V, Zhou J, Hu YG, Guo L *et al*., Evaluation of early mature naked oat varieties as a summer-seeded crop in dryland northern climate regions. *Field Crop Res* **103**:248–254 (2007).
7 Murphy JP and Hoffman LA, *The Origin, History, and Production of Oat, in: Oat Science and Technology*, American Society of Agronomy, Crop Sciences Society of America and the Soil Science Society of America, Wisconsin, USA, pp. 1–28 (1992).
8 May WE, Klein LH, Lafond GP, McConnell JT and Phelps SM, The suitability of cool- and warm-season annual cereal species for winter grazing in Saskatchewan. *Can J Plant Sci* **87**:739–752 (2007).
9 Fitzsimmons R, Oh, what those oats can do. Quaker oats, the Food and Drug Administration, and the market value of scientific evidence 1984 to 2010. *Comprehensive Reviews in Food Science and Food Safety* **11**:56–99 (2013).
10 FAOSTAT, Production of Ats in World, in, Food and Agriculture Organization of the United Nations (2019).
11 Wang Z, Jiang H and Shen Y, Forage production and soil water balance in oat and common vetch sole crops and intercrops cultivated in the summer-autumn fallow season on the Chinese loess plateau. *Eur J Agron* **115**:126042 (2020).
12 Ramadhan MN, Assessment of the yield and yield attributing characters of oat (*Avena sativa* L.) grown under different tillage methods and NPK fertilizer rates in semi-arid conditions, all. *Life* **17**:2304338 (2024).
13 Galloway JN, Winiwarter W, Leip A, Leach AM, Bleeker A and Erisman JW, Nitrogen footprints: past, present and future. *Environ Res Lett* **9**:11 (2014).
14 Kebede G, Worku W, Jifar H and Feyissa F, Effects of fertilizer levels and varieties on fodder yield productivity, nutrient use efficiency, and profitability of oat (*Avena sativa* L.) in the central highlands of Ethiopia. *J Agric Food Res* **16**:101161 (2024).
15 Mohr RM, Grant CA, May WE and Stevenson FC, The influence of nitrogen, phosphorus and potash fertilizer application on oat yield and quality. *Can J Soil Sci* **87**:459–468 (2007).
16 Patle AN, Effect of soil enrichment in conjunction with bio organics and chemical fertilizers on yield and quality of fodder oat (*Avena Sativa* L.). *J Trop For* **28**:59–63 (2012).
17 Midha LK, Duhan BS and Arya S, Performance of promising entries of oat (*Avena sativa* L.) under different nitrogen levels (2015).
18 Beltrán-Paz O, Solleiro-Rebolledo E, Martínez-Jardines G and Chávez-Vergara B, Short-term response of oat crop yield and soil microbial activity promoted by inorganic fertilization suppression and organic fertilization addition in a periurban agroecosystem. *Appl Soil Ecol* **195**:105249 (2024).
19 May WE, Altering the competitiveness of tame oat (*Avena sativa* L.) versus wild oat (*Avena fatua* L.) with phosphorus and seeding rate. *Can J Plant Sci* **98**:582–590 (2017).
20 Wang L, Wang FW, Gao Q, Liu JH and Zhao BP, Effect of different sowing date and combined application of nitrogen and phosphorus fertilizers on oats yield. *J North Agric* **48**:6 (2020).
21 Koireng RJ, Shamurailatpam D, Devi TS, Singh SD, Senjam P, Yumnam S *et al*., Impact of mineral and organic fertilizer management on the performance of oat-chickpea cropping systems. *Sustainability* **14**: 15431 (2022).
22 McCabe CP and Burke JI, Impact of varying N fertiliser rate and timing on yield formation and grain filling in winter and spring-sown oats. *Eur J Agron* **139**:126550 (2022).
23 Sorrells ME and Simmons SR, *Influence of Environment on the Development and Adaptation of Oat, in: Oat Science and Technology*, American Society of Agronomy, Crop Sciences Society of America and the Soil Science Society of America, Wisconsin, USA, pp. 115–163 (1992).
24 Hoffman LA, World production and use of oats, in *World Production and Use of Oats*. Springer, Netherlands (1995).
25 Lollato RP, Figueiredo BM, Dhillon JS, Arnall DB and Raun WR, Wheat grain yield and grain-nitrogen relationships as affected by N, P, and K fertilization: a synthesis of long-term experiments. *Field Crop Res* **236**:42–57 (2019).
26 Li Z, Zhang Q, Wei W, Cui S, Tang W and Li Y, Determining effects of water and nitrogen inputs on wheat yield and water productivity and nitrogen use efficiency in China: a quantitative synthesis. *Agric Water Manag* **242**:106397 (2020).
27 García-Palacios P, Vandegehuchte ML, Shaw EA, Dam M, Post KH, Ramirez KS *et al*., Are there links between responses of soil microbes and ecosystem functioning to elevated CO_2, N deposition and warming? A global perspective. *Glob Chang Biol* **21**:1590–1600 (2015).
28 Zhang Q, Miao F, Wang Z, Shen Y and Wang G, Effects of long-term fertilization management practices on soil microbial biomass in China's cropland: a meta-analysis. *Agron J* **109**:1183–1195 (2017).
29 Miao F, Li Y, Cui S, Jagadamma S, Yang G and Zhang Q, Soil extracellular enzyme activities under long-term fertilization management in the croplands of China: a meta-analysis. *Nutr Cycl Agroecosyst* **114**: 125–138 (2019).
30 Zhang H, Liu C, Mao L, Li Y and Shen Y, Divergent response of hay and grain yield of oat: effects of environmental factors and sowing rate. *J Sci Food Agric* **103**:233–242 (2023).
31 Osenberg CW, Sarnelle O, Cooper SD and Holt RDJE, Resolving ecological questions through meta-analysis: goals, metrics, and models. *Ecology* **80**:1105–1117 (1999).
32 Viechtbauer W, Conducting meta-analyses in R with the metafor package. *J Stat Softw* **36**:1–48 (2010).
33 Adams DC, Gurevitch J and Rosenberg MS, Resampling tests for meta-analysis of ecological data. *Ecology* **78**:1277–1283 (1997).
34 Rosenthal R and Rosnow RL, *Essentials of Behavioral Research: Methods and Data Analysis*, 3rd edn. McGraw-Hill, New York (2008).
35 Luo Y, Hui D and Zhang D, Elevated CO_2 stimulates net accumulations of carbon and nitrogen in land ecosystems: a meta-analysis. *Ecology* **87**:53–63 (2006).
36 De'ath G, Boosted trees for ecological modeling and prediction. *Ecology* **88**:243–251 (2007).
37 Izenman AJ, Recursive Partitioning and tree-based methods, in *Modern Multivariate Statistical Techniques: Regression, Classification, and Manifold Learning*. Springer, New York, New York, NY, pp. 281–314 (2008).
38 Šimon T and Czakó A, Influence of long-term application of organic and inorganic fertilizers on soil properties. *Plant Soil Environ* **60**: 314–319 (2014).
39 Mader P, Fliessbach A, Dubois D, Gunst L, Fried P and Niggli U, Soil fertility and biodiversity in organic farming. *Science* **296**:1694–1697 (2002).
40 Riley H, Long-term fertilizer trials on loam soil at Moystad, south-eastern Norway: Crop yields, nutrient balances and soil chemical analyses from 1983 To 2003. *Acta Agric Scand Sect B-Soil Plant Sci* **57**:140–154 (2007).
41 Song X, Zhou G, Ma B-L, Wu W, Ahmad I, Zhu G *et al*., Nitrogen application improved photosynthetic productivity, chlorophyll fluorescence, yield and yield components of two oat genotypes under saline conditions. *Agronomy* **9**:115 (2019).
42 Vasileva V and Kostov O, Performance of oats (Avena sativa) in response to preceding alfalfa (Medicago sativa) on mineral fertilization versus organic manuring on Chernozem soil. *Indian J Agric Sci* **88**:416–419 (2018).
43 Hamill ML, The Effect of Cultivar, Seeding Date, Seeding Rate and Nitrogen Fertility on Oat (*Avena Sativa* L.) Yield and Milling Quality, M.Sc. thesis. University of Manitoba, Winnipeg (2002).
44 Coblentz WK, Jokela WE and Bertram MG, Cultivar, harvest date, and nitrogen fertilization affect production and quality of fall oat. *Agron J* **106**:2075–2086 (2014).
45 Goulding K, Jarvis S and Whitmore A, Optimizing nutrient management for farm systems. *Philos Trans Royal Soc B: Biol Sci* **363**:667–680 (2008).
46 Huang S, Lv W, Bloszies S, Shi Q, Pan X and Zeng Y, Effects of fertilizer management practices on yield-scaled ammonia emissions from croplands in China: a meta-analysis. *Field Crop Res* **192**:118–125 (2016).
47 Rütting T, Aronsson H and Delin S, Efficient use of nitrogen in agriculture. *Nutr Cycl Agroecosyst* **110**:1–5 (2018).
48 Øgaard AF, Nitrogen balance and nitrogen use efficiency in cereal production in Norway. *Acta Agric Scand, Sect B — Soil Plant Sci* **63**:146–155 (2014).

49 Williams A, Borjesson G and Hedlund K, The effects of 55 years of different inorganic fertiliser regimes on soil properties and microbial community composition. *Soil Biol Biochem* **67**:41–46 (2013).
50 Ibrikci H, Ulger A, Korkmaz K, Oktem A, Buyuk G, Ryan J *et al*., Genotypic responses of corn to phosphorus fertilizer rates in calcareous soils. *Commun Soil Sci Plant Anal* **40**:1418–1435 (2009).
51 Amanullah J and Stewart BA, Dry matter partitioning, growth analysis and water use efficiency response of oats (*Avena sativa* L.) to excessive nitrogen and phosphorus application. *J Agric Sci Technol* **15**: 489–497 (2013).
52 Jankauskas B and Otabbong E, Combined N, P, K fertilization and liming maximises crop productivity of acid loams in Lithuania. *Acta Agric Scand Sect B-Soil Plant Sci* **54**:60–66 (2004).
53 Liang G, Sun P and Waring B, Nitrogen agronomic efficiency under nitrogen fertilization does not change over time in the long term: evidence from 477 global studies. *Soil Till Res* **223**:105468 (2022).
54 Mendoza Elos M, Figueroa-Rivera MG, Cervantes-Ortiz F, García-Rodríguez JG, Salgado-Ramírez O and Rodríguez-Herrera SA, Fertilización química y orgánica en avena: rendimiento y calidad de la semilla. *Agron Mesoamericana* **31**:567–579 (2020).
55 Li Y, Cui S, Chang SX and Zhang Q, Liming effects on soil pH and crop yield depend on lime material type, application method and rate, and crop species: a global meta-analysis. *J Soil Sediment* **19**:1393–1406 (2019).
56 Holland JE, White PJ, Glendining MJ, Goulding KWT and McGrath SP, Yield responses of arable crops to liming – an evaluation of relationships between yields and soil pH from a long-term liming experiment. *Eur J Agron* **105**:176–188 (2019).
57 Körner C, The use of 'altitude' in ecological research. *Trends Ecol Evol* **22**:569–574 (2007).
58 Yu J, Li B, Song T, He J, Lian L, He W *et al*., Integrated physiological and transcriptomic analyses responses to altitude stress in oat (*Avena sativa* L.). *Front Genet* **12**:638683 (2021).
59 Baltenberger DC and Frey K, Genotypic variability in response of oat to delayed sowing 1. *Agron J* **79**:813–816 (1987).
60 Hjelkrem A-GR, Torp T, Brodal G, Aamot HU, Strand E, Nordskog B *et al*., DON content in oat grains in Norway related to weather conditions at different growth stages. *Eur J Plant Pathol* **148**: 577–594 (2017).