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Forage quality in cereal/legume intercropping: A meta-analysis

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ABSTRACT

Context: Meta-analyses have highlighted several advantages of cereal/legume intercropping for food compared to sole cropping, but none report on fodder quality and yield. In forage production, mixtures may more effectively balance fiber and crude protein concentrations of the forage in view of nutrient requirements of ruminants than sole crops. However, productivity, quality and the trade-off between these in cereal/legume intercropping of fodder species have not been systematically reviewed.
Objective: This paper reports on a meta-analysis of a database of global literature on intercropping of forage-producing cereal and legume crops to evaluate the effect of intercropping on dry matter (DM), crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), non-CP non-NDF yields and concentrations of intercrops as compared with the respective sole crops.
Methods: A literature search was carried in Web of Science searching in ‘all fields’ with as search terms: (intercrop* OR “mixed crop*” OR “crop mix* ” OR “mixed cultivation*” OR “polyculture*” OR “row crop*”) AND (forage OR fodder) AND (quality OR "nutri* content" OR "nutri* concentration" OR "nutri* value"). Out of the 759 papers further selection yielded a database based on 61 publications on cereal/legume intercropping reporting total biomass and at least one quality component for both sole crops and their intercrops.
Results: The net effects for DM (1.76 ± 0.38 Mg/ha), CP (0.20 ± 0.05 Mg/ha), NDF (1.01 ± 0.25 Mg/ha), ADF (0.63 ± 0.15 Mg/ha) and non-CP non-NDF (0.76 ± 0.22 Mg/ha) yields showed production of all increased upon intercropping. The difference in relative increase in total DM and the four components did not lead to any change in %CP, %NDF, %ADF and %non-CP non-NDF. The change in DM yield was due to enhanced cereal yield. Moreover, the cereal %CP in the intercrops was higher than expected and the cereal %NDF and %ADF in the intercrops was lower than expected, while the overall quality of the legume in the intercrops did not change.
Conclusion: Intercropping cereal and legume species will neither improve nor reduce the quality of produced feed, but it makes more effective use of the land through a higher production per unit area.
Significance: This study reports the combined forage quality and quantity in cereal/legume intercropping. The quantity/quality balance of forage production with cereal/legume intercrops is necessary to design intercropping for forage production. The results can be utilized to establish cereal/legume intercropping systems with different forage production aims.

1. Introduction

Intercropping is an ancient practice but seems to be under pressure in modern intensive agriculture (Zhang et al., 2010). However, intercropping may be a means to solve some of the major problems associated with modern agriculture, thereby contributing to the realization of productive, effective, and sustainable agriculture (Brooker et al., 2015; Martin-Guay et al., 2018; Li et al., 2021). Intercropping has been found to significantly increase yield (Bedoussac et al., 2015; Yu et al., 2016; Li et al., 2020b), resource use efficiency (Zhang and Li, 2003; Xu et al., 2020; Tang et al., 2021), and enhance a range of other agriculture ecosystem services, such as biological nitrogen fixation (Fujita et al., 1992; Rodriguez et al., 2020), control of pests (Zhang et al., 2019; Stomph et al., 2020) and weeds (Verret et al., 2017; Gu et al., 2021).

In addition to the advantages of intercropping mentioned above, cereal/legume mixtures may also more effectively balance fiber and crude protein concentration of the forage in view of the nutrient requirements of ruminants than sole crops. The addition of legumes may

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enhance the digestibility of crude fiber, and the resultant increase in digestibility is expected to improve feed intake and animal performance (Hassen et al., 2017). Further exploration of the feasibility of intercropping systems for forage production is therefore relevant. Several studies reported on intercropping systems that are not aiming to harvest grains but to produce forage, though a systematic quantitative review is missing (Ghanbari-bonjar, 2002; Sadeghpour et al., 2013; Baghdadi et al., 2016; Ashoori et al., 2021). Cereal/legume intercropping systems for forage production have been found advantageous over cereal sole crops in crude protein (CP) yield and concentration (Baghdadi et al., 2016; Zaeem et al., 2021). Compared with cultivating crops for human consumption, forage production is concerned with both total dry matter (DM) yield and its composition in terms of protein and fiber concentrations rather than with only grain yield, although the grain part significantly contributes to both the DM yield and its quality.

The concentrations of CP, neutral detergent fiber (NDF), and acid detergent fiber (ADF) are fundamental forage quality indicators for dairy producers (Linn and Martin, 1991). Crude protein is an important component in forages, especially in legumes. Inadequate CP intake can lead to reduced feed intake and lower digestibility in ruminants (Puhakka et al., 2016). Cellulose, hemicellulose, and lignin are three crucial constituents of forage fiber; NDF is composed of hemicellulose, cellulose and lignin, and ADF contains lignin and cellulose. NDF and ADF are essential parameters for assessing forage quality (Rohweder et al., 1978; Linn and Martin, 1991). The nutrients contained in forage, apart from CP and NDF, the so-called non-CP non-NDF fraction, are ether extract (crude fat), starch, sugar and organic acids, which provide the energy required for rumen digestion and metabolism of ruminants. In feed evaluation systems, it is commonly accepted that high fiber concentration represents low forage quality, however, ruminants require a certain amount of fiber for proper rumen functioning (Zebeli et al., 2011). Low-producing dairy cows require less energy intake, hence the NDF concentration of their diets could be relatively high, whereas high-producing dairy cows require a high energy intake and thus benefit from low NDF concentration and a high energy concentration in the diet (National Academies of Sciences and Medicine, 2021).

Variations in forage quality between cereal/legume intercropping systems can be related to differences in the mix of species and differences in growing environments. In cereal/legume intercropping systems, in most cases, the %CP of biomass from mixtures ranges between the %CP of biomass from the component sole crops (Stoltz and Nadeau, 2014; Baghdadi et al., 2016; Zaeem et al., 2021). Only in rare cases, the %CP of biomass from intercrops was higher than that of the sole legume crop or lower than that of the sole cereal crop. The higher %CP in mixtures is mainly because of the higher system level nitrogen uptake efficiency, as most of the nitrogen applied is taken up by the cereal crop and the legume crop keeps fixing nitrogen from the atmosphere (Steen Jensen, 1996; Ghanbari-bonjar, 2002; Rodriguez et al., 2020). There are some reports that compare the quality of intercrops based on the quality of only one component sole crop (Sadeghpour et al., 2013); e.g., it was reported that maize/soybean and maize/faba bean intercrops have higher forage quality than maize sole crop (Stoltz and Nadeau, 2014; Zaeem et al., 2021). Such a partial analysis is a typical problem in the literature when comparing the forage quality of intercrops and sole crops.

To our knowledge, meta-analyses have compared intercropping with sole cropping, primarily concentrating on grain yield (Yu et al., 2015), yield stability (Raseduzzaman and Jensen, 2017), resource use efficiency (Xu et al., 2020), weed control (Verret et al., 2017), grain protein yield (Li et al., 2023), etc. and all in essence related to food crops. To date, no quantitative synthesis is available on the combined effects of intercropping on both forage yield and quality. The reasons for the differences in forage quality between cereal/legume intercropping and their component sole crops and possible trade-off between total DM yield and forage quality remain therefore unexplored. Furthering our insight into the quantity/quality balance of forage production with cereal/legume intercrops is necessary to evaluate design options for intercropping for forage production, in search of a more sustainable agriculture.

Van der Werf et al. (2021) summarized several metrics that are considered reliable and relevant in estimating the effects of intercropping. Among those metrics, land equivalent ratio (LER) is typically described as the total of the relative yields of individual intercrops compared to corresponding sole crops (van der Werf et al., 2021), for which values typically are around 1.22 ± 0.02–1.30 ± 0.02 (Yu et al., 2015; Martin-Guay et al., 2018). But for forage, the LER makes less sense as the total biomass would be more relevant and the quality should be an integral element of the comparison. The index net effect (NE) refers to the difference between the actual yield and expected yield (Loreau and Hector, 2001). Li et al. (2020b) found an average NE of 1.5 ± 0.1 Mg ha^{-1} grain yield. The literature has hardly looked into quality of intercrops, the work by Li et al. (2023) is a first attempt but does not address the essential element of relevance to animal feed that energy, proteins and fibers all are needed in the final product in a ratio that depends on animal species and its stage in the life cycle. So, we will here assess both the NEs for total DM and each quality component (CP, NDF, ADF and non-CP non-NDF) and the relative changes in the latter (%CP, %NDF, %ADF and %non-CP non-NDF). To compare the %nutrient of mixtures and sole crops, the log of the net effect ratio will be used (Cardinale et al., 2007; van der Werf et al., 2021). The net effect ratio is the ratio between observed CP, NDF, ADF and non-CP non-NDF concentrations in the biomass from the intercrop and an expected concentration based on the same sowing ratio of biomass from the respective sole crops. The sowing ratio of intercrops is not necessarily always the same as its land share. The expectation is that there are positive NEs for DM, CP, ADF, NDF and non-CP non-NDF yields in intercrops. Based on the existing literature, we are unable to hypothesize changes in %CP, %NDF, %ADF and %non-CP non-NDF in intercropping, so how these fodder biomass components contribute to the expected positive NE remains a more open research question for this study. The overall aim of this study is to determine the effects of intercropping of gramineous crops and legumes on the combined forage quality and quantity and the key factors influencing these. To this aim a database was constructed of data from studies on gramineous/legume intercropping reporting total biomass and at least one quality component for both sole crops and their intercrops.

2. Materials and methods

2.1. Paper selection and data extraction procedures

A literature search was carried on 16 January 2023 using Web of Science (http://apps.webofknowledge.com/) searching all publications included between 1970 and the date of the search. The search string was: (intercrop* OR “mixed crop*” OR “crop mix*” OR “mixed cultivation*” OR “polyculture*” OR “row crop*”) AND (forage OR fodder) AND (quality OR "nutri* content" OR "nutri* concentration" OR "nutri* value") searching in ‘all fields’. This strategy resulted in 759 papers. In the second step, non-English articles, articles that did not report on field experiments, conference papers, and review articles were excluded. In the third screening step, publications were retained only if they met all three of the following selection criteria: (1) Mixtures combined a cereal or grass and a legume species. (2) The article reported either one or more of the percentages or amounts of CP, ADF or NDF. (3) The article reported dry matter yield and feed nutritive value of both intercrops and the respective sole crops. In the end, a total of 61 publications was retained during this selection process (Fig. A5), yielding 528 records from 84 experiments from across the globe (Fig. A6), where an experiment was considered a unique combination of site and year for both annual and perennial crops.

Within an experiment, treatments were unique combinations of species mixture, sowing density, fertilizer input, crop development stage at harvest, row spacing, and intercropping pattern. A single treatment yielded three records, one for each of the two sole crops and one for the mixture. Treatments that did not influence the effect of intercropping were included, while treatments that might have changed the effect of intercropping, such as rice bran bed planting, conservation tillage or no weed control, were excluded. Data for each treatment were extracted from tables or from images via GetData Graph Digitizer (http://getdata-graph-digitizer.com/), using unique identifiers for experiment and publication (Table A1). For each experiment, basic information about the experimental site was obtained, such as soil chemical properties and geographical region. For each treatment, information on DM yield (Mg/ha), CP yield (Mg/ha), ADF yield (Mg/ha), NDF yield (Mg/ha), and percentages CP, ADF, and NDF for both the intercrops and the sole crops were either directly obtained from the paper or calculated when data allowed deriving the value.

2.2. Response variables

In this analysis, the net effects (NE, Eq. 1) of yields of DM, CP, ADF, NDF and the calculated values of non-CP non-NDF were taken as response variables. The NE when calculated based on yield data can be interpreted as how many more tons of DM, CP, ADF, NDF or non-CP non-NDF can be produced per hectare from intercropping compared to what would be produced on the same area by the respective sole crops when sown in the same proportions as their land shares in the mixture. Dependent on availability of data on the component species in the mixture the NE can also be split into partial NEs of the component species (Eqs. 2 and 3).

2.2.1. How we use the term land share of crops in this paper

For experiments of mixed intercropping with a replacement design, the land share is the same as its sowing ratio, for experiments of mixed intercropping with an additive design the land share is the ratio between its sowing ratio and the sum of the sowing ratios of the two species. For experiments of strip intercropping and row intercropping, the land share of crops was calculated based on the row distance and the intra row distance of intercrop and its relative sole crop (Li et al., 2020a).

2.2.2. Calculations

$$NE = (Y1 + Y2) - (EY1 + EY2) \tag{1}$$

$$NE1 = Y1 - EY1 \tag{2}$$

$$NE2 = Y2 - EY2 \tag{3}$$

Where NE is the net effect, Y1 and Y2 represent the actual DM yields of Species 1 and Species 2 in the intercropping situation, whereas EY1 and EY2 represent the expected DM yields of the two species, which were calculated as the products of the yield of each sole crop and its land share (Li et al., 2020a). Similarly, the NEs of CP, ADF, NDF and non-CP non-NDF yields can be calculated independently. NE1 and NE2 represent the partial NE of the two intercropped species, NE equals to the sum of NE1 and NE2. Papers that did not report separately on the individual species were excluded from the analyses of the partial NEs, for the numbers of records included in the partial NE analyses see Table A1.

The advantage of intercropping over monocropping in terms of percentages of CP, ADF, NDF and non-CP non-NDF were measured by the log of the net effect ratio (Log-NER) (Cardinale et al., 2007; van der Werf et al., 2021). The net effect ratios (NERs) in this analysis are defined as the ratios between the concentration of CP, ADF, NDF and non-CP non-NDF in the intercrops and that in the sole crop. (Eq. 4 for an example on CP). When data allow, also partial NERs can be derived (Eqs. 5 and 6 for an example on CP).

$$NER_{CP\%} = \frac{\frac{CPY1+CPY2}{Y1+Y2}}{\frac{ECPY1+ECPY2}{EY1+EY2}} = \frac{NER_{cpy}}{NER_{dmy}} \tag{4}$$

$$NER1_{CP\%} = \frac{\frac{CPY1}{Y1}}{\frac{ECPY1}{EY1}} = \frac{NER1_{cpy}}{NER1_{dmy}} \tag{5}$$

$$NER2_{CP\%} = \frac{\frac{CPY2}{Y2}}{\frac{ECPY2}{EY2}} = \frac{NER2_{cpy}}{NER2_{dmy}} \tag{6}$$

Where NER is the net effect ratio, CPY1 and CPY2 are respectively the observed CP yield of Species 1 and Species 2 in the intercropping situation, ECPY1 and ECPY2 are the expected CP yields of the two species, which were calculated based on the CP yield of each sole crop and its land share. NER1 and NER2 represent the partial net effect ratio of the two intercropped species. The NE and NER are different in their methods of calculation. NE shows the actual yield difference between intercrops and the expected yield of the respective sole crops, while NER indicates the ratio between intercrop yield and the expected yield of the respective sole crops. Therefore, NER is not equal to the sum of NER1 and NER2. The NER calculated based on percentages CP, ADF, NDF and non-CP non-NDF can be considered the percent point change in percentages CP, ADF, NDF and non-CP non-NDF when crops are grown as intercrops compared with mixing forages of their sole crops at an equivalent ratio as their land shares in the intercrop. By equation transformation (cf. Eq. 4), the NER of %CP is equal to the NER of CP yield divided by the NER of DM yield. In other words, the indicated change in the percentage of a component indicates if its mass increased more (ratio>1) or less (ratio<1) than the total biomass. Quality components may thus combine a positive NE and a NER below 1. Comparable to %CP, the NERs of %ADF, %NDF and %non-CP non-NDF can be calculated independently. For a numerical example see Box 1.

2.3. Explanatory variables

In the analyses, in total four continuous explanatory variables were used. They are the land share of the cereal crop, and the rates of N and P application in intercrops. For mixed intercropping with a replacement design, the land share of the cereal crop equals to its relative density, for an additive design the land share of the cereal crop is the ratio between its relative density and the relative density total (Li et al., 2020a).

The term "relative density total" (RDT) refers to the sum of the relative densities (Eq. 7) of intercropped species in comparison to their respective sole crops (de Wit, 1960):

$$RDT = \frac{d1ic}{d1sc} + \frac{d2ic}{d2sc} = RD1 + RD2 \tag{7}$$

Where d1ic and d2ic respectively refer to the density of Species 1 and Species 2 in the intercrop, and d1sc and d2sc respectively refer to the density of Species 1 and Species 2 in sole crops. Replacement intercropping has a RDT of 1, whereas completely additive intercropping has a RDT of 2.

When N and P fertilization rates of the component crops in the intercrop differ from each other, then the N and P fertilization rates were calculated by the fertilization rate of each intercrop species and its land share as (Eq. 8 for an example on N fertilization):

$$N = N1 \times LS1 + N2 \times LS2 \tag{8}$$

Where N1 and N2 refer to the N fertilization rates of the crops in the intercrop and LS1 and LS2 refer to the expected yield proportion of two intercrops calculated based on their land shares.

Box 1
Example calculation of Log-NER for %CP in intercropping.

Suppose an intercrop with 0.5 land share of both the legume and the cereal components. Let the sole cereal crop DM yield be 6 Mg/ha, while its CP yield is 0.6 Mg/ha and so its %CP is 10%. Let the sole legume crop DM yield be 2 Mg/ha, while its CP yield is 0.6 Mg/ha and so its %CP is 30%. The expected yields are now determined as the sole crop yields times their respective land shares. The expected intercropped legume DM yield thus is 1 Mg/ha, while its expected CP yield is 0.3 Mg/ha. The expected cereal intercrop DM yield thus is 3 Mg/ha, while its expected CP yield is 0.3 Mg/ha. Let the real intercrop DM yield be 7 Mg/ha composed of 5 Mg/ha cereal and 2 Mg/ha legume, and the related CP yield be 1.25 Mg/ha with 0.5 Mg/ha from the cereal and 0.75 Mg/ha from the legume. Now the observed %CP and the expected %CP (E%CP) can be calculated as:

$$\%CP = \frac{CPY}{Y} = \frac{(0.5+0.75)\times 100}{(2+5)} = 18\% \text{ and}$$

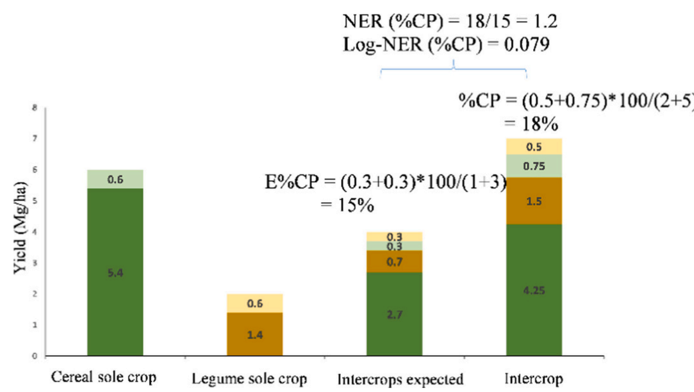
$$E\%CP = \frac{ECPY}{EY} = \frac{(0.3+0.3)\times 100}{(1+3)} = 15\%$$

Their net effect ratio (eq. 4) then equals

$$NER\ (\%CP) = \frac{\%CP}{\%ECP} = \frac{18\%}{15\%} = 1.2$$

And the log transformed net effect ratio equals

$$Log - NER\ (\%CP) = 0.079$$



A graphic display of how Log-NER (%CP) is calculated. The CP yields of cereal and legume crops are displayed as light green and light yellow bars respectively, while non-CP yields are displayed as dark green and dark yellow bars respectively.

In this example, the intercrop provides a 20% higher %CP than expected, resulting in a 3%-point increase in %CP. The NER of %CP is 1.2, while the Log of NER is 0.079.

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2.4. Statistical analysis

All analyses were carried out in R (R Core Team, 2022), using the R package nlme (Pinheiro et al., 2023). Relationships between the NEs for DM, CP, ADF, NDF, non-CP non-NDF yields, Log-NER of %CP, %ADF, % NDF, %non-CP non-NDF and explanatory variables, as well as the effect of interactions between N and P fertilization rate, land share of cereal crop and co-variables on those indices, were estimated using mixed effects models (Table 1). To explain the differences between studies, studies and experiments within studies were regarded as random effects. In total six models were fitted to the data. Records with missing values for a variable were removed from analyses requiring that variable.

3. Results

3.1. Descriptive analysis

3.1.1. Net effects

Net effects (NE) of cereal/legume intercropping on average attained a DM yield gain (NE= 1.76 ± 0.38 Mg/ha, (mean± s.e.m.) with 81% records> 0) compared with producing fodder sole crops at equivalent land shares. The intercrops also produced more crude protein (CP) (NE= 0.20 ± 0.05 Mg/ha, with 75% records>0), neutral detergent fiber (NDF) (NE= 1.01 ± 0.25 Mg/ha, with 53% records>0), acid detergent fiber (ADF) (NE= 0.63 ± 0.15 Mg/ha, with 57% records>0) and non-CP non-NDF (NE= 0.76 ± 0.22 Mg/ha, with 53% records>0) (Fig. 1, Model 1). However, the extent of the increase and the distribution changes were different among NEs. The partial NEs of legume crops for DM (−0.02 ± 0.32 Mg/ha), CP (−0.10 ± 0.14 Mg/ha), NDF (−0.18 ± 0.22 Mg/ha), ADF (-0.11 ± 0.17 Mg/ha) and non-CP non-NDF (-0.04 ± 0.12 Mg/ha) yields were all not different from zero. Conversely, the partial NE of cereal crops for DM (2.56 ± 0.83 Mg/ha) was higher than zero, while those for CP (0.21 ± 0.11 Mg/ha), NDF (0.89 ± 0.49 Mg/ha), ADF (0.53 ± 0.37 Mg/ha) and non-CP non-NDF (0.69 ± 0.44 Mg/ha) yields were all not different from zero (Fig. 2a, Model 1).

3.1.2. *Log net effect ratios*

The average Log-NER values for %CP (0.009 ± 0.008), %NDF (0.002 ± 0.007), ADF% (-0.005 ± 0.006) and %non-CP non-NDF (0.002 ± 0.005) were all not different from zero (Fig. 3, Model 1). But the change in %CP showed a much wider distribution than the change in %NDF and %ADF. The partial Log-NER values of legume crops for % non-CP non-NDF (0.017 ± 0.006) were higher than zero, while those for %CP (-0.019 ± 0.010), %NDF (0.002 ± 0.008) and %ADF (0.008 ± 0.009) were not different from zero. Conversely, the partial Log-NER values of cereal crops for %CP (0.035 ± 0.014) and %non-CP non-NDF (0.014 ± 0.004) were higher than zero, while those for %NDF (-0.015 ± 0.004) and %ADF (-0.018 ± 0.004) were lower than zero (Fig. 2b, Model 1).

3.2. *Effect of the land share of cereal crop*

The land share of the cereal crop had a significant, negative effect on NEs for DM yield ($P < 0.01$), NDF yield ($P < 0.01$), ADF yield ($P < 0.01$) and non-CP non-NDF yield ($P = 0.01$). The land share of the cereal crop had a significant positive effect on Log-NER for %CP ($P < 0.01$), while it had a significant, negative effect on Log-NER for %NDF ($P < 0.01$) (Fig. 4, Model 5). In other words, a 10% increase in the land share of the cereal crop led to a decrease in the NE of DM yield with 0.22 Mg/ha, in the NE of NDF yield with 0.13 Mg/ha, in the NE of ADF with 0.07 Mg/ha and in the NE of non-CP non-NDF yield with 0.09 Mg/ha. With the same increase of 0.1 in the land share of the cereal crop the Log-NER of %CP increased with 0.01, while the Log-NER of %NDF decreased with 0.03 in the intercropping situation (Fig. 4).

3.3. *Effect of N and P fertilizer input*

The NEs for DM, CP, NDF, ADF, and non-CP non-NDF yields, and Log-NERs for %CP, %NDF, %ADF, and %non-CP non-NDF did not respond to either N or P fertilizer input (Fig. A1 and Fig. A2).

4. Discussion

The findings of this meta-analysis demonstrate that cereal/legume intercropping leads to a positive net effect (NE) for both dry matter (DM) and all analyzed quality components of forages including crude protein (CP), neutral detergent fiber (NDF), acid detergent fiber (ADF), and non-CP non-NDF. The increase in overall DM yield was due to the increase in cereal DM yield as the legume contribution to DM in intercrops did not differ from its expected DM yield (Fig. 2a). Moreover, the %CP of the cereal in the intercrops was higher than expected, while the %NDF and %ADF of the cereal in the intercrop were lower than expected (Fig. 2b). The overall quality of the legume in the intercrop did not change. This suggests that the quality of the cereal crop improved as did its productivity compared to its sole crop. As cereals have a lower forage quality than legumes, this resulted in no change in overall quality (Fig. 3). The NEs and Log-NERs were independent of N and P fertilizer input (Fig. A1 and Fig. A2).

4.1. *Net effects*

We had expected positive NEs for DM, CP, ADF, NDF and non-CP non-NDF yields in intercrops. The findings of this study did indeed show a positive NE for DM yield of 1.76 ± 0.38 Mg/ha. Similarly, Li et al. (2020b) found a positive net effect for grain yield of 1.5 ± 0.1 Mg/ha. Our results also indicate that the extents of the increase in NEs and the distribution of effect sizes varied between variables. The NE for CP yield showed limited NE and a more narrow distribution compared with other analyzed NEs. Li et al. (2023) reported in their supplementary material (Fig. A3) a positive net effect ratio (NER) for CP grain yield. Our study further found that NER of %CP was not different from one, which was not reported by Li et al. (2023). In addition, our study is the first to show positive net effects for NDF yield and ADF yield. In other words, compared to combined forage from sole crops mixed according to the land share of the component species in the intercrop, the increased DM yield of intercrops mainly consisted of NDF yield, ADF yield and non-CP non-NDF yield with only a small portion of CP yield. This is due to the fact that this increased DM yield of the intercrop is associated with an increase in the yield of the high fiber and low protein crops in the mixtures.

4.2. *Competitiveness in cereal/legume intercropping*

The results of the partial NEs of the cereal and the legume components shows that positive NE values are due to the biomass production gains made by the cereal crops in cereal/legume intercropping. This production gain was, for all analyzed constituent properties larger than the loss through the reduced legume productivity. This finding concurs with that of Yu et al. (2016) for grain production, who found that in cereal/legume intercropping, cereal crops on average gained more than legume crops which they related to the cereals being more competitive. This means that in cereal/legume intercropping a higher proportion of cereal biomass is usually obtained at harvest than expected based on relative land shares.

This study found no significant change in fodder quality of cereal/legume intercrops compared to fodder from sole crops mixed at the same relative land shares as used in the intercrop. The result of the partial Log net effect ratios (Log-NER) of the cereal and legume components indicated that the %CP of the cereal in the intercrops was higher than expected, while the %NDF and %ADF of the cereal in the intercrop was lower than expected. This implies a quality improvement in the cereal plants when growing in a cereal/legume mixture rather than in a stand with only cereals. Consequently, the overall quality of the legume in the intercrop did not change. The particular changes in CP proportion and fiber proportion of forage has been suggested to be a side effect of changes in plant height and leaf area for light competition (Lemaire and Belanger, 2019). In cereal/legume intercropping, the cereal crop typically is the taller crop therefore in a dominant position in light competition. This advantage in light competition may result in plant height reduction and leaf area increase of the cereal plants in the intercrop compared to cereal plants growing in a sole crop. The lower plant height

Table 1
Mixed-effects models used during data analyses. The indices i, j and k stand for publication ID, experiment ID and treatment ID, respectively. In all six models, a_i is a random publication effect. b_{ij} is a random experiment effect nested within the i^{th} publication. a_i and b_{ij} are assumed normally distributed with constant variances. ε_{ijk} is a residual random error assumed normally distributed with constant variance. The variance terms a_i, b_{ij} and ε_{ijk} are all assumed independent. In all mixed effect models, the NE represents the net effects of dry matter, CP, NDF, ADF, or non-CP non-NDF yields, and the Log-NER represents the log of the net effect ratios of %CP, %NDF, %ADF, or %non-CP non-NDF. LS1 represents the land share of the cereal crop.

Model	Equations
1	$\mathrm{NE/Log-NER_{ijk}} = \beta_0 + a_i + b_{ij} + \epsilon_{ijk}$
2	$\mathrm{NE/Log-NER_{ijk}} = \beta_0 + \beta_1^* N_{ijk} + a_i + b_{ij} + \epsilon_{ijk}$
3	$\mathrm{NE/Log-NER_{ijk}} = \beta_0 + \beta_1^* P_{ijk} + a_i + b_{ij} + \epsilon_{ijk}$
4	$\mathrm{NE/Log-NER_{ijk}} = \beta_0 + \beta_1^* LS1_{ijk} + a_i + b_{ij} + \epsilon_{ijk}$
5	$\mathrm{NE/Log-NER_{ijk}} = \beta_0 + \beta_1^* LS1_{ijk} + \beta_2^* N_{ijk} + \beta_3^* LS1_{ijk}^* N_{ijk} + a_i + b_{ij} + \epsilon_{ijk}$
6	$\mathrm{NE/Log-NER_{ijk}} = \beta_0 + \beta_1^* LS1_{ijk} + \beta_2^* P_{ijk} + \beta_3^* LS1_{ijk}^* P_{ijk} + a_i + b_{ij} + \epsilon_{ijk}$

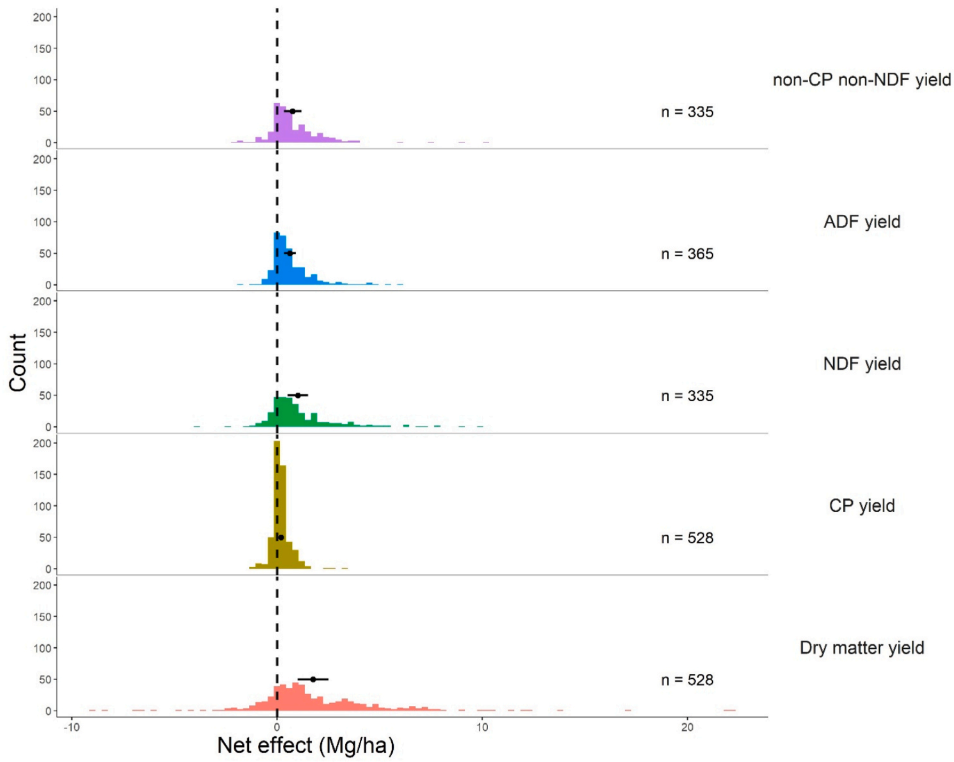

Fig. 1. The frequency diagrams of net effects of cereal/legume intercropping calculated for the non-CP non-NDF, ADF, NDF, CP and DM yields of intercrops. The dots represent the mean value. The horizontal bars reflect 95% confidence intervals. The dashed vertical line represents zero net effect.

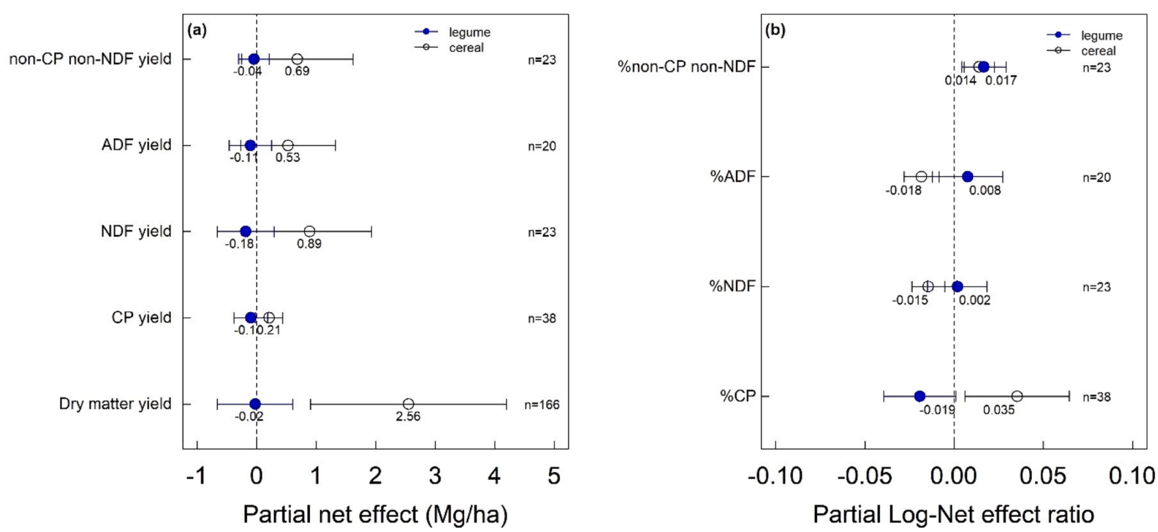

Fig. 2. The partial net effects (a) and partial log net effect ratios (Log-NER) (b) of species in cereal/legume intercropping. The numbers in the figure are the mean values. The horizontal bars reflect 95% confidence intervals. The dashed vertical lines represent zero partial net effect and zero partial log-NER. n = number of records.

reduces the structural part, while the higher leaf area increases the metabolic part of total above ground biomass (Lemaire and Belanger, 2019).

The higher share of the biomass of cereal plants in cereal/legume intercrop forage can explain why the quality of the cereal crop improved as did its productivity compared to its sowing proportion, while the overall quality of the mixture remained unchanged. As cereals have a lower forage quality than legumes, this resulted in no change in overall quality. But it’s worth noting that although the overall quality did not change, intercrop has a higher proportion of higher quality cereal than sole crops mixed at the same land share as its relative intercrop.

4.3. Options to increase the land share of the cereal crop

This meta-analysis finds that NEs for DM, NDF, ADF and non-CP non-NDF yields decrease with the increase of the land share of the cereal in the intercrop. This finding can be explained by the lower competitiveness of legumes in cereal/legume intercropping compared to cereals (Yu et al., 2016). Our study found that positive NE values are mostly contributed by the cereal crops in cereal/legume intercropping. The NEs decrease with an increase in land share of the cereal in the intercrop, as the intraspecific competition between cereal plants within the system increases. Therefore, due to the low competitiveness of legumes in

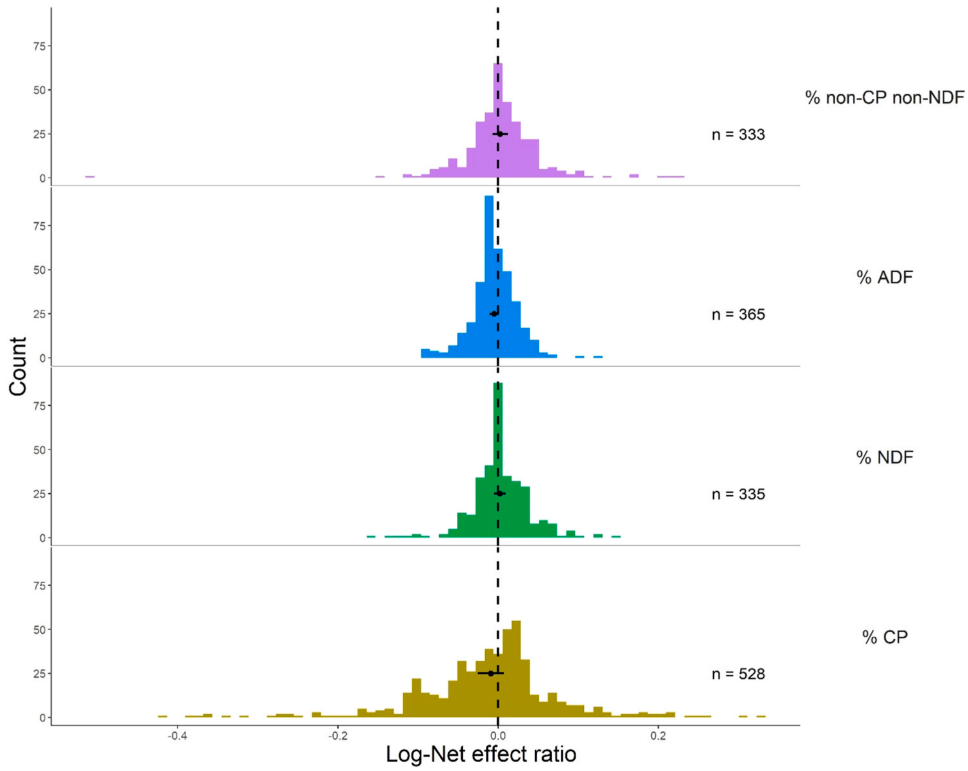

Fig. 3. The frequency diagrams of log net effect ratios (Log-NER) of cereal/legume intercropping calculated for the %non-CP non-NDF, %ADF, %NDF and %CP of intercrops. The dots represent the mean value. The horizontal bars reflect 95% confidence intervals. The dashed vertical line represents zero Log-NER.

cereal/legume intercropping, a higher relative density of the legume than the cereal in the mixture may be required to obtain a higher intercropping yield advantage (Lichtfouse et al., 2009).

Moreover, with the increase of land share of the cereal intercrop the Log-NER for %CP increases, while the Log-NER for %NDF decreases. When the land share of cereal intercrop is 0.6, the Log-NER value for % CP is equal to 0, which implies that the %CP of the intercrop does not change compared to the expected %CP based on the relative land shares of the cereal and the legume. When the land share of the cereal intercrop is 0.58, the Log-NER value for %NDF is equal to 0. In other words, with a land share of cereal intercrop of about 0.6, it is possible to achieve an intercrop of the same quality as expected but with a DM yield of 1.56Mg/ha more than expected.

4.4. Net effects of yield and net effect ratios of %nutrient in relation to N and P input

We found that the NEs and Log-NERs did not respond to either N or P fertilizer input. Similarly, Li et al. (2020a) found that the NE for grain yield of cereal/legume intercropping was independent of both N and P fertilizer input. The results of our study indicate that this finding also applies to the NE of DM yield and further demonstrate that net effect ratios for %CP, %NDF, %ADF and %non-CP non-NDF are also independent of both N and P input. There are meta-analysis studies stating that the use efficiency of applied N (Xu et al., 2020) and P (Tang et al., 2021) fertilizer were enhanced by cereal/legume intercropping. However, we found that in cereal/legume intercropping for forage production, the importance of N and P input in obtaining a higher net effect is small compared to other factors such as the land share of the cereal crop. This again highlights the importance of cereal crop land share in balancing quantity/quality of forage production in cereal/legume intercrops.

4.5. Tradeoff between quality and productivity

There is a tradeoff between productivity and forage quality effects of intercropping with a change in land share of the cereal intercrop (Fig. 4). As the land share of the cereal in the intercrop increases, less decrease in quality came with less positive NE of DM, NDF, ADF and non-CP non-NDF yields (Fig. 4). As illustrated in Fig. A3 and Fig. A4, when the land share of the cereal crop is lower than 0.6 the intercrop has higher %NDF and lower %CP than expected but a relatively high NE. When the cereal crop land share is higher than 0.6, the intercrop has lower %NDF and higher %CP than expected but a relatively low NE. When the cereal crop land share is equal to 0.6 the overall quality of the intercrop remains the same but its productivity is higher compared to the relative sole crops given their land shares.

Generalizing, as the land share of the cereal crop increases, the %CP of the intercrop will drop, while the %NDF and %ADF will increase, due to the low %CP and high %NDF of cereal crops compared to legume crops. However, we found that these changes are less than expected in an intercropping system, where "expected" means mixing cereal and legume sole crop fodder in the same proportions as in intercropping. At the same time, however, we found that as the land share of the cereal increased, the quality of the intercrop declined less than expected, but the NE was also less positive. In other words, increasing the land share of the cereal crop is a way to improve the NER for %nutrient in cereal/legume intercropping, but at the cost of lowering the NEs for yields, which is where the "trade-off between quality and productivity" comes in.

This result could be utilized to establish cereal/legume intercropping systems by adjusting the land share of intercrops with different forage production aims; gaining in yield or in quality which both only possible at the expense of the other. So a certain level of yield or quality advantage may need to be sacrificed to obtain a desired balance between quality and yield advantages. However, due to the much wider distribution of Log-NER for %CP than that of Log-NER for %NDF and %ADF,

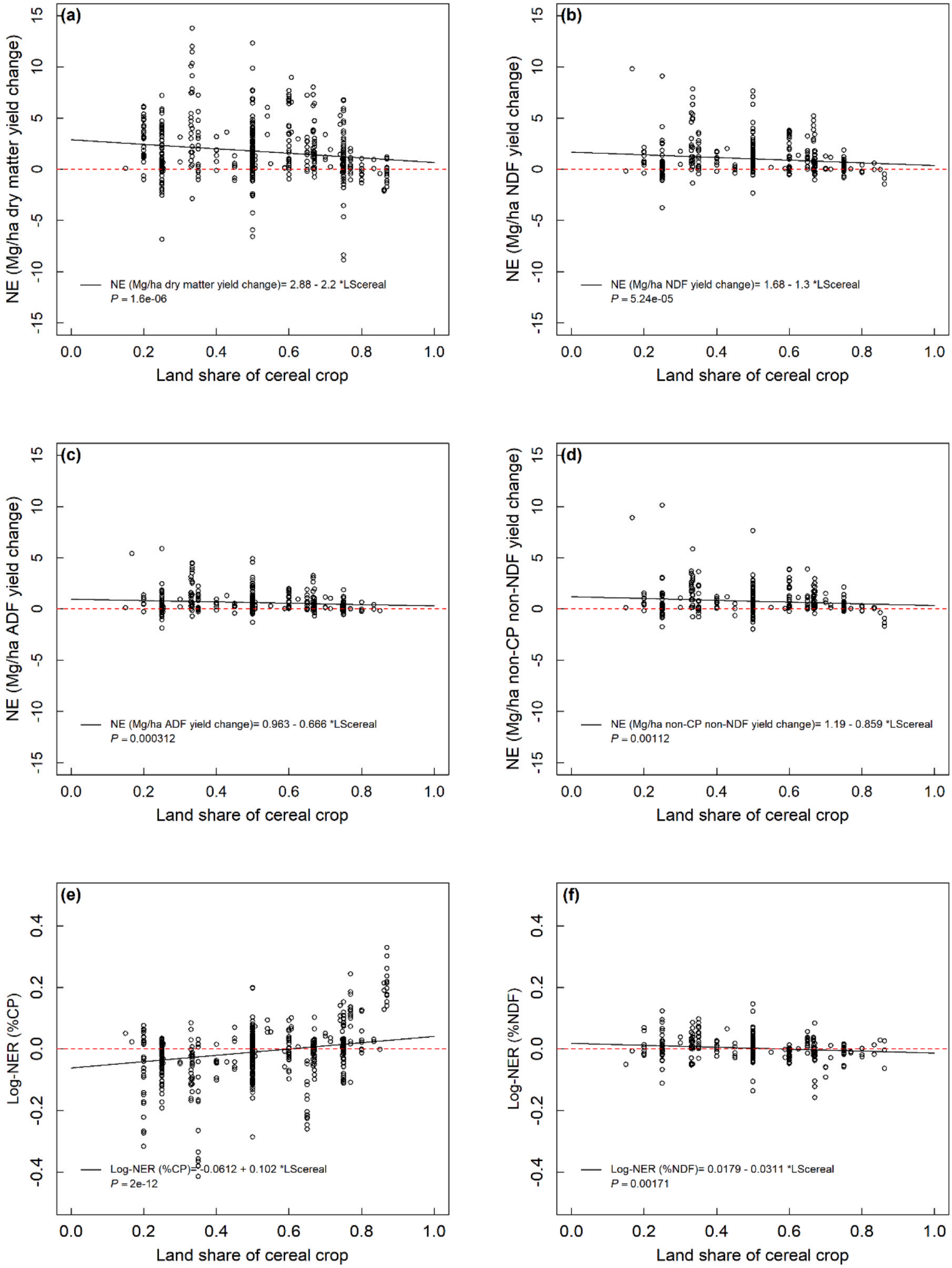

Fig. 4. Scatter plots and estimated regression lines showing the relationship between net effects for DM yield (a), NDF yield (b), ADF yield (c), non-CP non-NDF yield (d), Log-NER for %CP (e), Log-NER for %NDF (f) and the land share of cereal crop. The dashed horizontal red lines represent zero net effects and zero Log net effect ratios.

there is still room for improving our understanding of management practices and experimental designs to achieve the desired quality/ quantity balance of fodder intercrops.

5. Conclusion

In this meta-analysis, we quantitatively evaluated the productivity and quality of cereal/legume intercrops. We found that intercropping can increase the DM, CP, NDF, ADF and non-CP non-NDF yields of cereal/legume intercrops grown for fodder, without compromising the overall quality. The quality of the cereal crop improved as did its productivity compared to its land share. As cereals have a lower forage quality than legumes, this resulted in no change in overall quality. These results can be utilized to establish cereal/legume intercropping systems for different forage production aims. A further analysis of the best forage intercrop design should consider the land equivalent ratio on the basis of the animal production outcome of forage, for which the data will need to be combined with realistic models for digestibility and animal productivity estimates based on changes in forage composition in terms of fiber, energy and crude protein.

CRediT authorship contribution statement

Hao Liu: Conceptualizetion, Methodology, Data curation, Formal analysis, Visualization, Writing - original draft. **Paul C. Struik:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition. **Yingjun Zhang:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition. **Jingying Jing:** Conceptualization, Methodology, Data curation, Writing - review & editing, Supervision; Funding acquisition. **Tjeerd-Jan Stomph:** Conceptualization; Methodology; Writing - review & editing; Supervision.

Declaration of Competing Interest

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

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.fcr.2023.109174.

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