Supplementary Information for

The productive performance of intercropping

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Method S1 List of the 132 publications used in this meta-analysis

We used a dataset by Li et al. (2020) (1) which was generated by combining databases by Yu et al (2015) (2) and Li et al (2020) (1). Publications extracted by Yu et al. (2015) (2) are labelled as Refs 1-63 and publications extracted by Li et al. (2020) (1) are labelled as Ref 64-132.

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Method S2: Additive partitioning method to calculate complementarity effect and selection effect, and the mathematical relationships between the net effect ratio, the land equivalent ratio, and the selection effect.

Loreau and Hector (2001) (3) define the net effect (NE) as the sum of a complementarity effect (CE) and a selection effect (SE):

$$\mathrm{NE} = \mathrm{CE} + \mathrm{SE} = N \times \overline{\Delta RY} \times \overline{M} + N \times \mathrm{cov}(\Delta RY, M)$$

$$\mathrm{Y}_1 + \mathrm{Y}_2 - \overline{\mathrm{M}} = (\mathrm{RYT} - 1)\,\overline{\mathrm{M}} + \mathrm{SE}$$

Here $\overline{\Delta RY}$ is the average relative yield gain of the two species, $\overline{M}$ is the average yield of sole crops, and $\mathrm{cov}(\Delta RY, M)$ is the covariance between the relative yield gain in the intercrop and the sole crop. *N* is the number of species, which is in all cases of the dataset *N*=2.

Y_1 and Y_2 are the yields (per unit of total area of the intercrop) of species 1 and 2 in the intercrop, P_1 and P_2 are the proportions of species 1 and 2 in an intercrop, based on their densities or designed row space, and M_1 and M_2 are the yields of species 1 and 2 in the pure stands. $\overline{\mathrm{M}}$ is the weighted average monoculture yield calculated as $\overline{\mathrm{M}} = \mathrm{P}_1\mathrm{M}_1 + \mathrm{P}_2\mathrm{M}_2$. RYT is the relative yield total, which is identical in value to the LER.

To derive the relationship between the LER and the NER, we divide both sides by $\mathrm{p}_1\mathrm{M}_1 + \mathrm{p}_2\mathrm{M}_2$, obtaining:

$$\frac{\mathrm{Y}_1 + \mathrm{Y}_2}{\mathrm{P}_1\mathrm{M}_1 + \mathrm{P}_2\mathrm{M}_2} - 1 = \frac{(\mathrm{RYT} - 1)(\mathrm{P}_1\mathrm{M}_1 + \mathrm{P}_2\mathrm{M}_2)}{\mathrm{P}_1\mathrm{M}_1 + \mathrm{P}_2\mathrm{M}_2} + \frac{\mathrm{SE}}{\mathrm{P}_1\mathrm{M}_1 + \mathrm{P}_2\mathrm{M}_2}$$

which simplifies to:

$$\mathrm{NER} - 1 = \mathrm{LER} - 1 + \frac{\mathrm{SE}}{\overline{\mathrm{M}}}$$

Therefore:

$$\mathrm{NER} = \mathrm{LER} + \frac{\mathrm{SE}}{\overline{\mathrm{M}}}$$

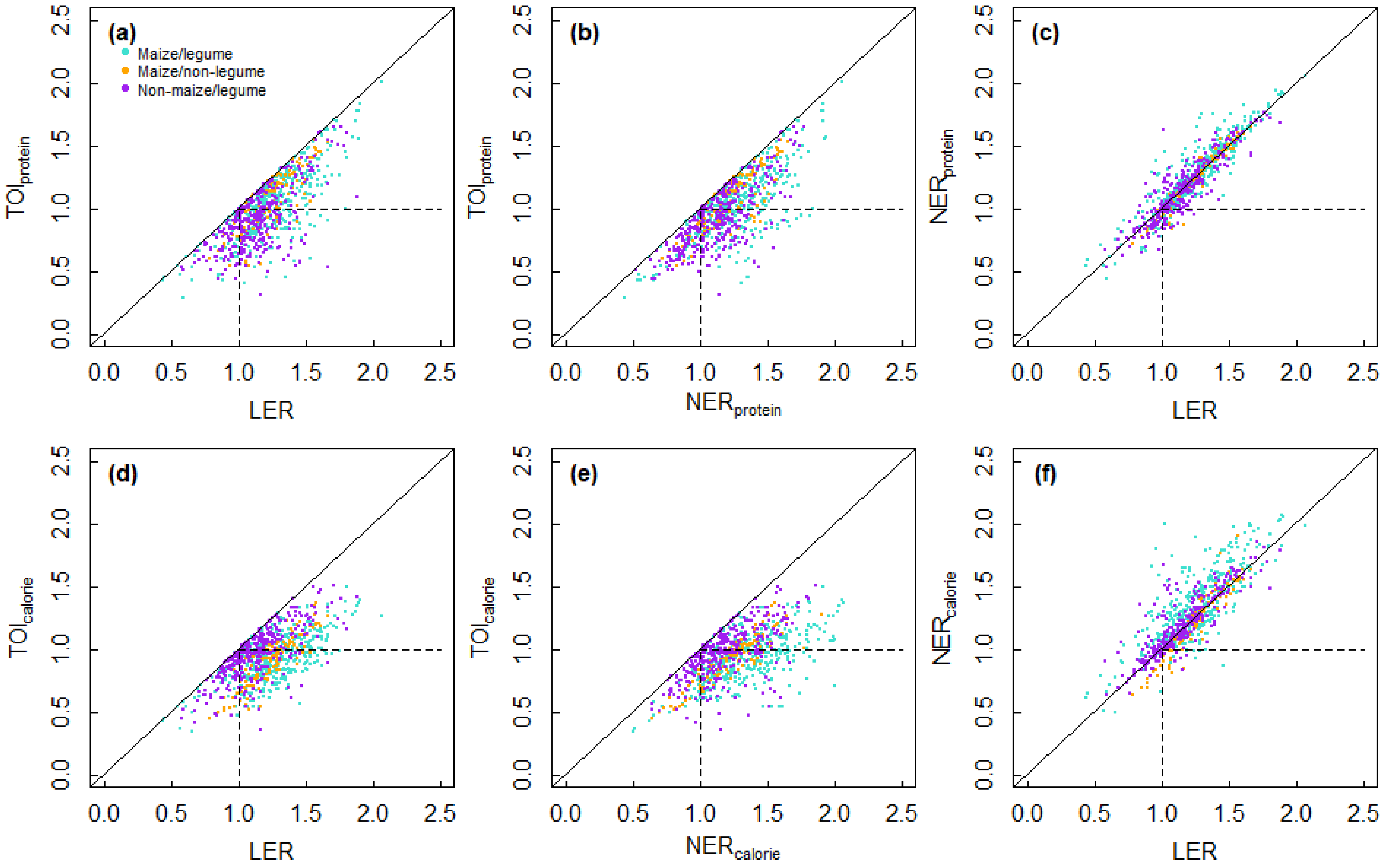


Fig. S1 Bivariate scatter plots illustrating relationships between different metrics. The LER (land equivalent ratio) based on grain yield

(LER_{grain}), NER and TOI based on grain calorie yield ($NER_{calorie}$, $TOI_{calorie}$) and protein yield ($NER_{protein}$, $TOI_{protein}$) in different species combinations in intercropping: maize/legume (turquoise), maize/non-legume (orange), non-maize/legume intercrops (purple). The diagonal lines represent the 1:1 lines, while the horizontal dashed lines represent $TOI_{calorie}$ = 1, and the vertical dashed lines represent $NER_{calorie}$=1 or LER_{grain} = 1.

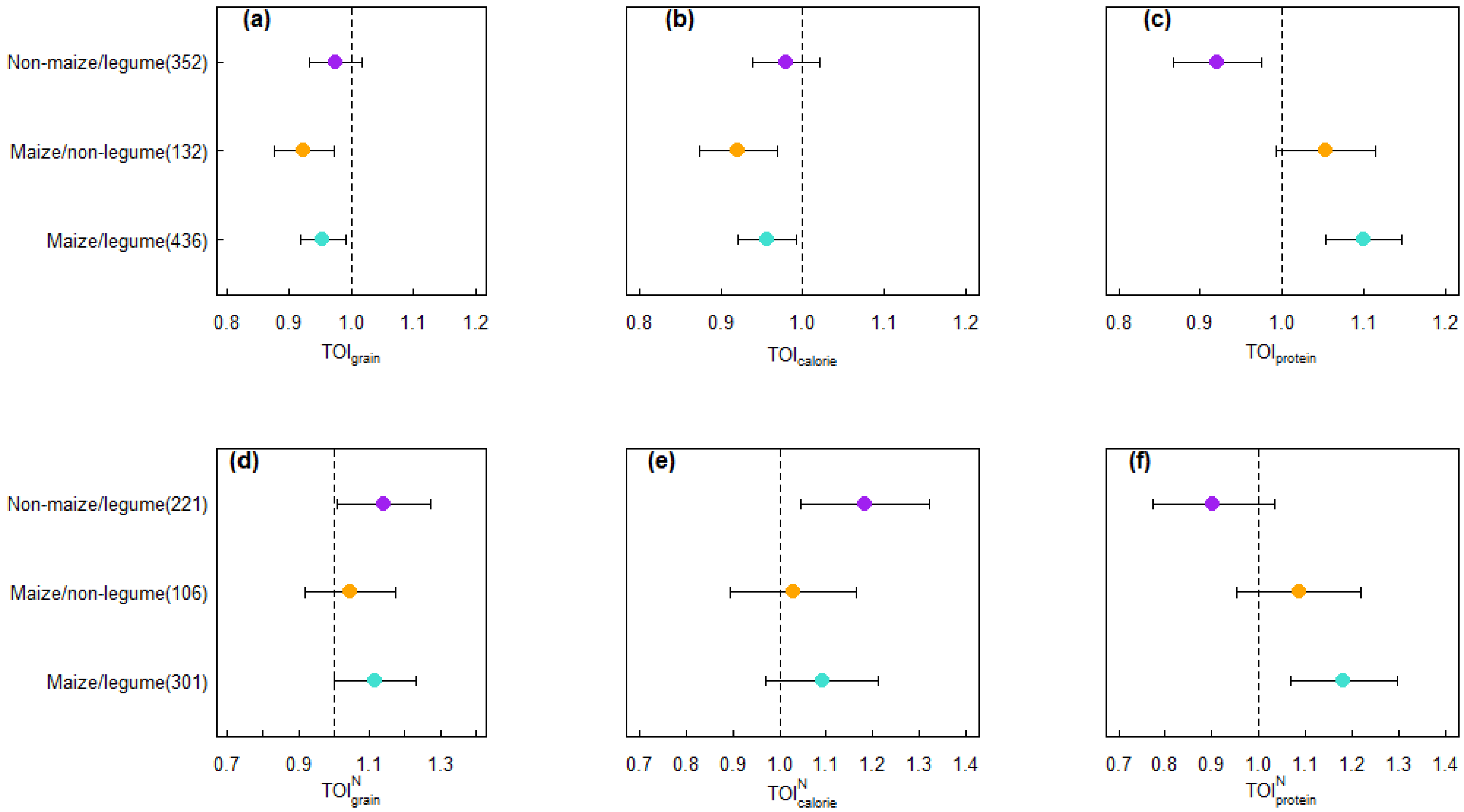
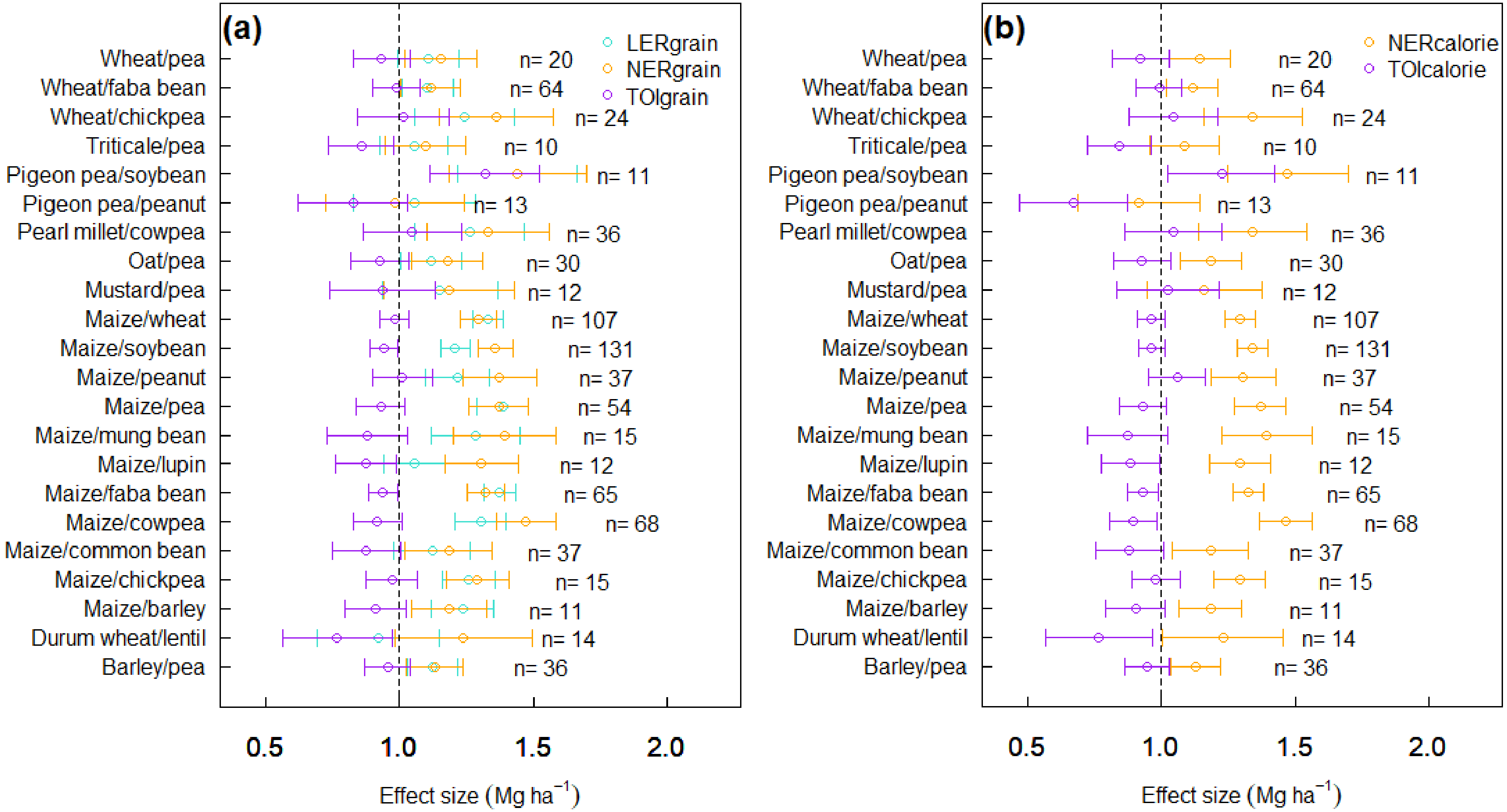


Fig. S2 Transgressive overyielding across all species combinations. Estimated mean (and 95% confidence intervals) of TOI for grain yield (TOI_{grain}), for calorie yield ($TOI_{calorie}$), protein yield ($TOI_{protein}$) and N fertilizer TOI for grain yield (TOI^{N}_{grain}), calorie yield ($TOI^{N}_{calorie}$) and protein yield ($TOI^N_{protein}$). The TOIs with respect to N fertilizer (TOI^N_{grain}, $TOI^N_{calorie}$, $TOI^N_{protein}$) characterize the extent to which the partial factor productivity of N fertilizer on intercrop grain yield, calories and protein exceeds that of the sole crop species with the highest grain yield, calorie yield or protein yield, respectively.



(a)
LERgrain
NERgrain
TOIgrain
Wheat/pea
Wheat/faba bean
Wheat/chickpea
Triticale/pea
Pigeon pea/soybean
Pigeon pea/peanut
Pearl millet/cowpea
Oat/pea
Mustard/pea
Maize/wheat
Maize/soybean
Maize/peanut
Maize/pea
Maize/mung bean
Maize/lupin
Maize/faba bean
Maize/cowpea
Maize/common bean
Maize/chickpea
Maize/barley
Durum wheat/lentil
Barley/pea
n= 20
n= 64
n= 24
n= 10
n= 11
n= 13
n= 36
n= 30
n= 12
n= 107
n= 131
n= 37
n= 54
n= 15
n= 12
n= 65
n= 68
n= 37
n= 15
n= 11
n= 14
n= 36
0.5
1.0
1.5
2.0
Effect size (Mg ha^{-1})
(b)
NERcalorie
TOIcalorie
Wheat/pea
Wheat/faba bean
Wheat/chickpea
Triticale/pea
Pigeon pea/soybean
Pigeon pea/peanut
Pearl millet/cowpea
Oat/pea
Mustard/pea
Maize/wheat
Maize/soybean
Maize/peanut
Maize/pea
Maize/mung bean
Maize/lupin
Maize/faba bean
Maize/cowpea
Maize/common bean
Maize/chickpea
Maize/barley
Durum wheat/lentil
Barley/pea
n= 20
n= 64
n= 24
n= 10
n= 11
n= 13
n= 36
n= 30
n= 12
n= 107
n= 131
n= 37
n= 54
n= 15
n= 12
n= 65
n= 68
n= 37
n= 15
n= 11
n= 14
n= 36
0.5
1.0
1.5
2.0
Effect size (Mg ha^{-1})

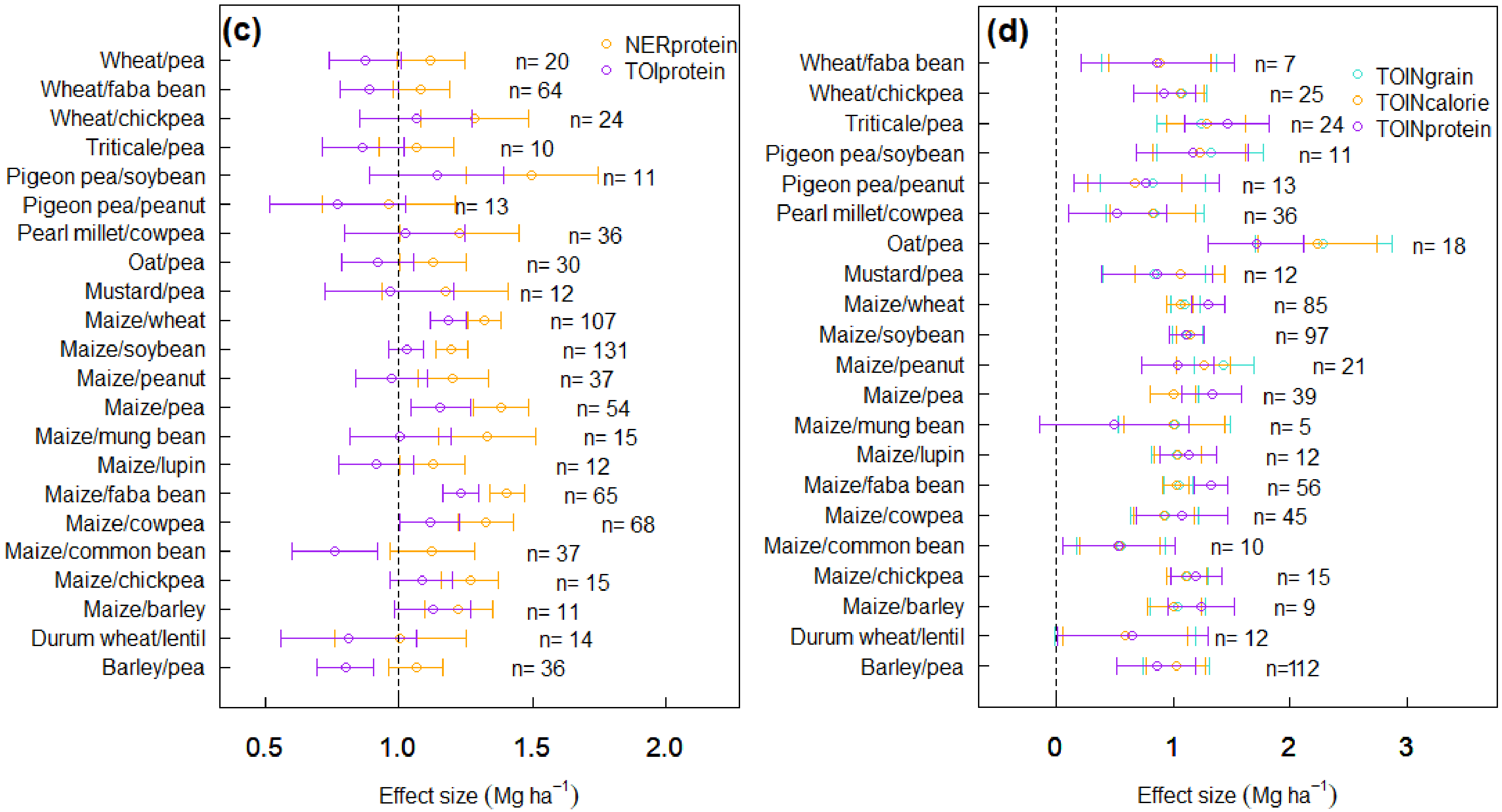


Fig. S3 Effect size of different metrics across species combinations. LER, NER, TOI based on grain yield (a), NER and TOI based on grain calorie yield (b), grain protein yield (c) and $TOI^{N}_{protein}$ of species combinations with ≥ 10 data records. Circles represent the means for a species combination, estimated with a mixed-effects model. The error bars represent 95% confidence intervals.

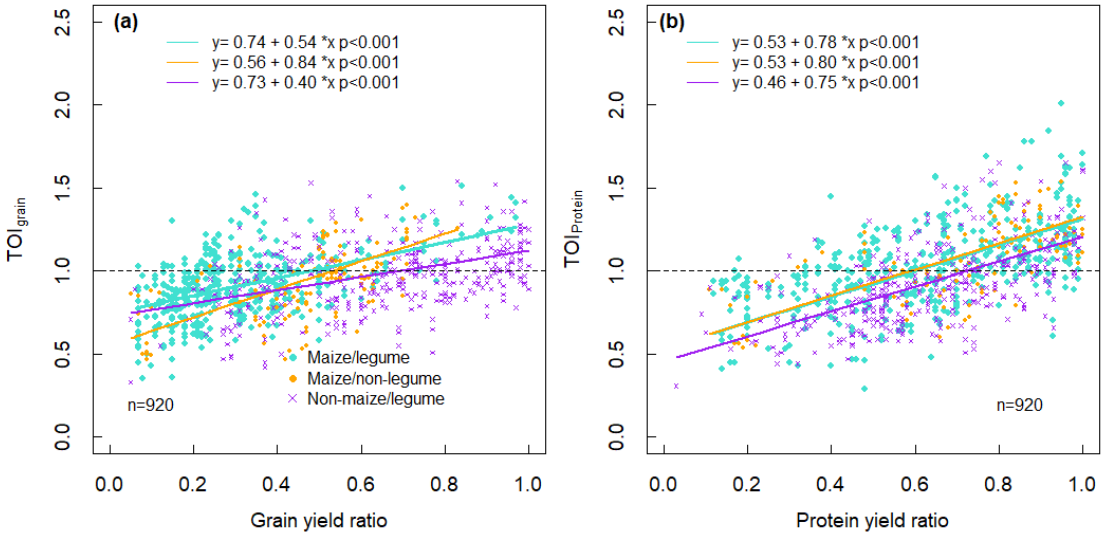


Fig. S4 Relationships between the transgressive overyielding index and yield ratio, both for grain yield (a) and protein yield (b). TOI increases significantly with yield ratio, both for grain yield and for protein yield.

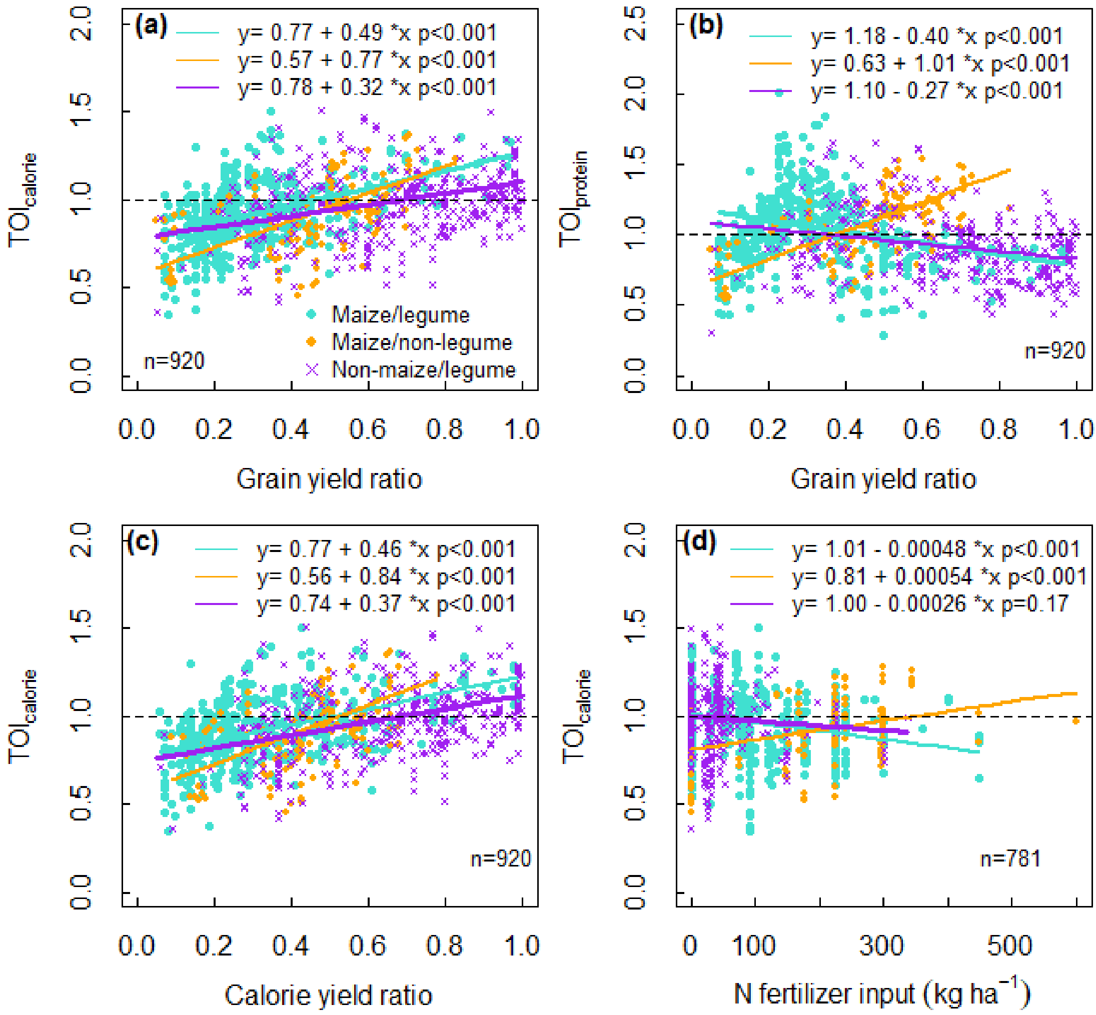


Fig. S5 Relationships between the transgressive overyielding index for calorie and protein yield and grain yield ratio, calorie yield ratio and N fertilizer input. Calorie TOI and the yield ratio of low yielding species to that of high yielding species (a), the relationship between the protein TOI and the grain yield ratio of low yielding species to that of high yielding species (b), the relationship between the calorie TOI and the calorie yield ratio of low yielding species to that of high yielding species (c) the relationship between the calorie TOI and N fertilizer input (d). TOI for grain yield increases with grain yield ratio while TOI for calorie yield increases with calorie yield ratio. TOI for protein yield increases with grain yield ratio in maize/non-legume intercrops but decreases with grain yield ratio in maize/legume and non-maize/legume intercrops. TOI for calorie yield increases with N fertilizer input in maize/non-legume intercrops but decreases with N fertilizer input in maize/legume intercrops.

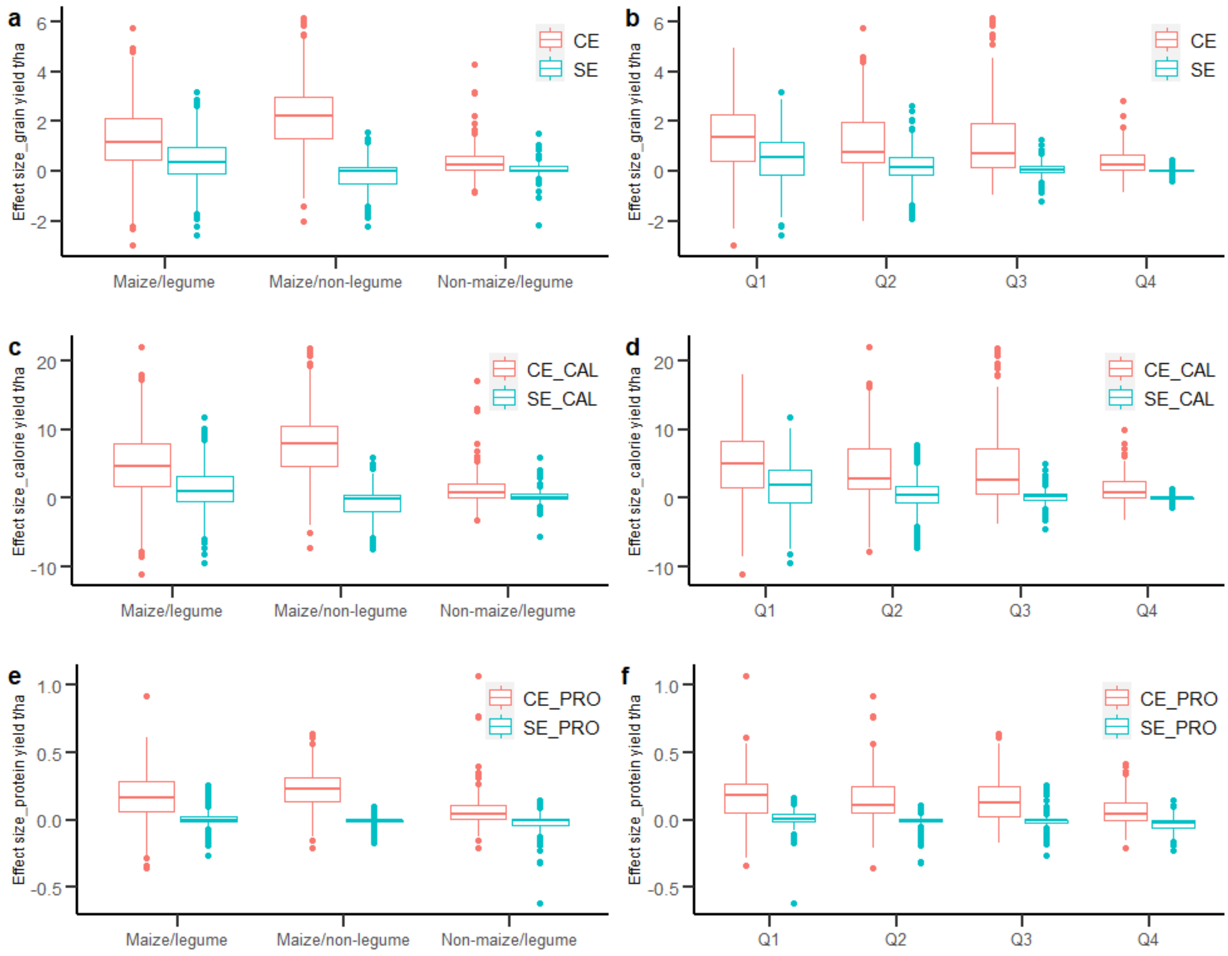


Fig. S6 Boxplots illustrating how the complementarity effect and selection effect of species mixtures vary between different species combinations and how they are related to yield ratio of the sole crops. The complementarity effect (CE) and selection effect (SE) for grain yield (CE, SE), calorie yield (CE_CAL, SE_CAL) and protein yield (CE_PRO, SE_PRO) of different species combinations: maize/legume, maize/non-legume, non-maize/legume intercrops (a, c, e), and of four subgroups according to the grain yield ratio of low yielding species to that of the high yielding species (Q1:0-0.25, Q2: 0.25-0.50, Q3: 0.50-0.75, Q4: 0.75-1.00) (b, d, f). The CEs were larger in maize/legume intercrops than in non-maize/legume intercrops. The SEs was also larger in maize/legume intercrops than in non-maize/legume intercrops, but the SEs were mostly around zero. The SEs tended toward zero and the CEs decreased but were mostly larger than zero as the yield of the low yielding species approached that of the higher yielding species.

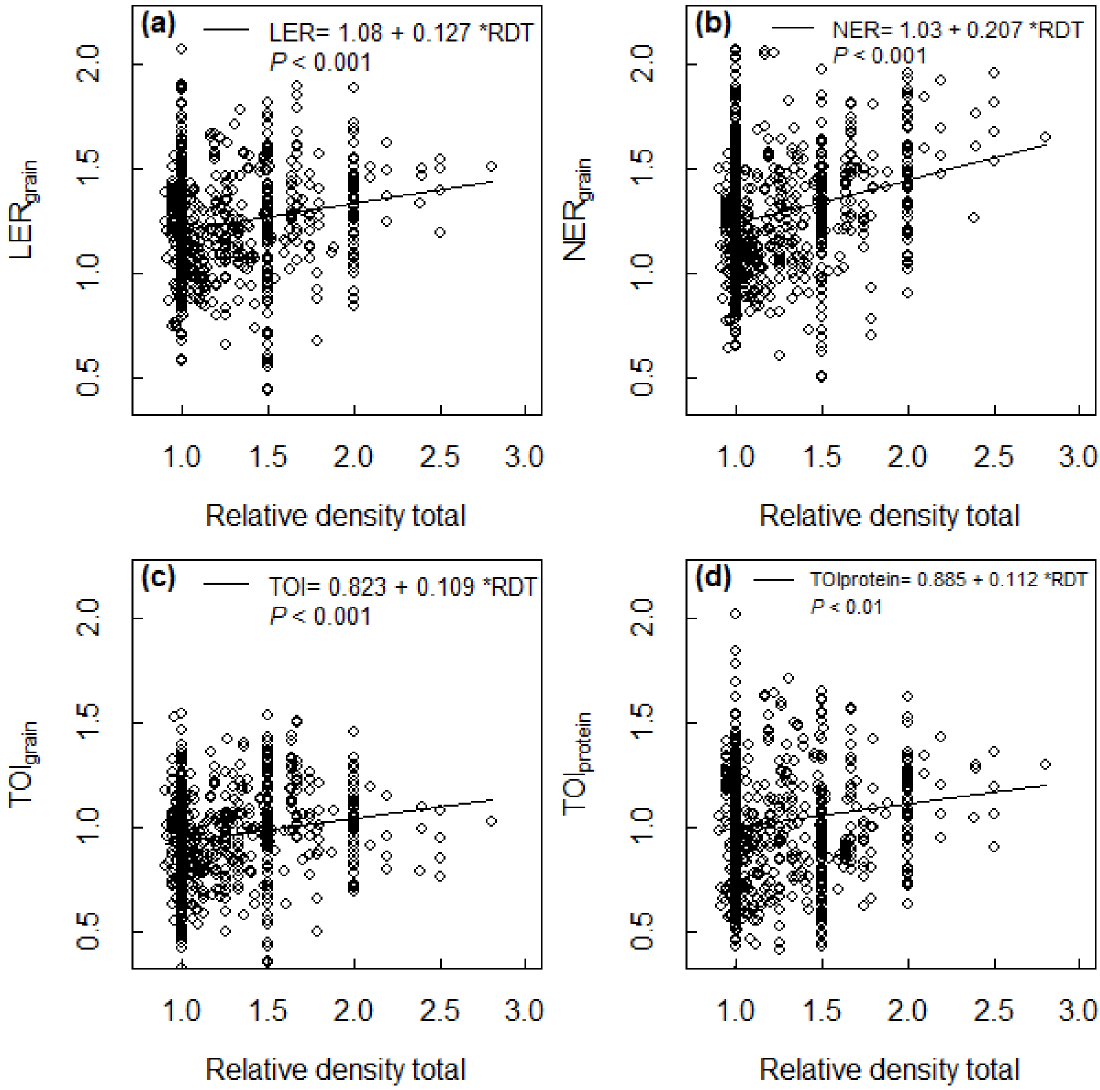


Fig. S7 Scatter plot of LER, NER and TOI for grain yield and TOI for protein yield against relative density total.

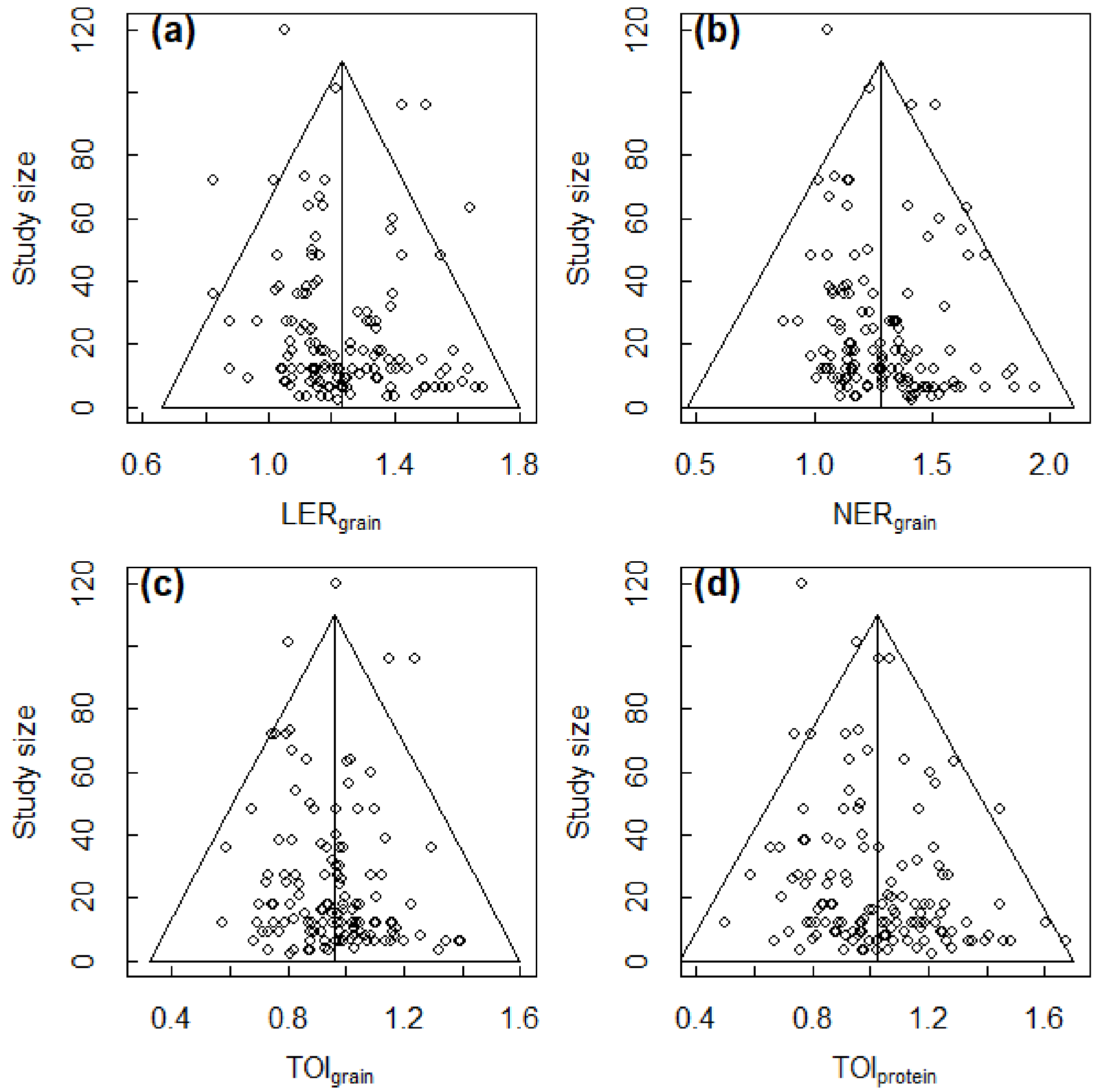


Fig. S8 Funnel plots. Funnel plots show study size (y-axis) against metric values (x-axis) (a) Land equivalent ratio (LER_{grain}), (b) net effect ratio (NER_{grain}) and (c) transgressive overyielding index for grain yield (TOI_{grain}) and for protein yield ($TOI_{protein}$). The vertical line in each panel represents the estimated grand mean of LER_{grain}, NER_{grain}, TOI_{grain} and $TOI_{protein}$, estimated with a mixed effects model.

Table S1 Contingency table for number of data records of intercrops including maize, non-maize, legume and non-legume species. Analyses were made for the subgroups of maize/legume, maize/non-legume, and non-maize/legume. The sub-group non-maize/non-legume had too few records to allow accurate estimation of effect sizes.

	Maize	Non maize
Legume	436	352
Non legume	132	14

Table S2 Overview of species combinations in the data set

Groups of species combinations	Records of groups	Species combination
Maize/legume	436	Maize (*Zea mays*)/adzuki bean (*Vigna angularis*)
		Maize (*Zea mays*)/common bean (*Phaseolus vulgaris*)
		Maize (*Zea mays*)/chickpea (*Cicer arietinum*)
		Maize (*Zea mays*)/cowpea (*Vigna unguiculata*)
		Maize (*Zea mays*)/faba bean (*Vicia faba*)
		Maize (*Zea mays*)/white lupin (*Lupinus albus*)
		Maize (*Zea mays*)/mung bean (*Vigna radiata*)
		Maize (*Zea mays*)/pea (*Pisum sativum*)
		Maize (*Zea mays*)/peanut (*Arachis hypogaea*)
		Maize (*Zea mays*)/soybean (*Glycine max*)
Maize/small grain	120	Maize (*Zea mays*)/wheat (*Triticum aestivum*)
		Millet (*Setaria italica*)/maize (*Zea mays*)
		Maize (*Zea mays*)/barley (*Hordeum vulgare*)
Maize/others	12	Maize (*Zea mays*)/turnip (*Brassica campestris*)
		Maize (*Zea mays*)/oilseed rape (*Brassica napus*)
Small grain/legume	284	Pearl millet (*Pennisetum glaucum*)/cowpea (*Vigna unguiculata*)
		Pearl millet (*Pennisetum glaucum*)/peanut (*Arachis hypogaea*)
		Oat (*Avena sativa*)/faba bean (*Vicia faba*)
		Oat (*Avena sativa*)/pea (*Pisum sativum*)
		Rice (*Oryza sativa*)/mung bean (*Vigna radiata*)
		Rice (*Oryza* sativa)/peanut (*Arachis hypogaea*)
		Sorghum (*Sorghum bicolor*)/cowpea (*Vigna unguiculata*)
		Sorghum (*Sorghum bicolor*)/pigeon pea (*Cajanus cajan*)
		Triticale (× *Triticosecale* Wittmack)/pea (*Pisum sativum*)
		Wheat (*Triticum aestivum*)/chickpea (*Cicer arietinum*)

		Wheat (*Triticum aestivum*)/faba bean (*Vicia faba*)
		Durum wheat (*Triticum turgidum*)/lentil (*Lens culinaris*)
		Wheat (*Triticum aestivum*)/pea (*Pisum sativum*)
		Wheat (*Triticum aestivum*)/soybean (*Glycine max*)
		Barley (*Hordeum vulgare*)/faba bean (*Vicia faba*)
		Barley (*Hordeum vulgare*)/lentil (*Lens culinaris*)
		Barley (*Hordeum vulgare*)/narrow-leafed lupin (*Lupinus angustifolius*)
		Barley (*Hordeum vulgare*)/pea (*Pisum sativum*)
		Durum wheat (*Triticum turgidum*)/pea (*Pisum sativum*)
Legume/legume	25	Pea (*Pisum sativum*)/faba bean (*Vicia faba*)
		Pigeon pea (*Cajanus cajan*)/peanut (*Arachis hypogaea*)
		Pigeon pea (*Cajanus cajan*)/soybean (*Glycine max*)
Legume/others	43	Mustard (*Sinapsis alba*)/chickpea (*Cicer arietinum*)
		Mustard (*Sinapsis alba*)/lentil (*Lens culinaris*)
		Mustard (*Sinapsis alba*)/pea (*Pisum sativum*)
		Sesame (*Sesamum indicum*)/mung bean (*Vigna radiata*)
		Sesame (*Sesamum indicum*)/blackgram (*Vigna mungo*)
		Sesame (*Sesamum indicum*)/peanut (*Arachis hypogaea*)
		Oilseed rape (*Brassica napus*)/faba bean (*Vicia faba*)
		Oilseed rape (*Brassica napus*)/pea (*Pisum sativum*)
Small grain/small grain	3	Wheat (*Triticum aestivum*)/barley (*Hordeum vulgare*)
Small grain/others	7	Wheat (*Triticum aestivum*)/oilseed rape (*Brassica napus*)
		Barley (*Hordeum vulgare*)/flax (*Linum usitatissimum*)
		Barley (*Hordeum vulgare*)/oilseed rape (*Brassica napus*)
Others/others	4	Sesame (*Sesamum indicum*)/sunflower (*Helianthus annuus*)

Table S3 Number of data records with substitutive design and additive designs.

Intercropping design	Number of records
Substitutive design	542
Additive design	392

Table S4 Number of data records representing strip intercropping, alternate-row intercropping and mixed intercropping.

Intercropping pattern	Number of records
Strip intercropping	590
Alternate-row intercropping	161
Mixed intercropping	183

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