

HOW MULTISPECIES INTERCROP ADVANTAGE RESPONDS TO WATER STRESS: A YIELD-COMPONENT ECOLOGICAL FRAMEWORK AND ITS EXPERIMENTAL APPLICATION

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SUPPLEMENTARY MATERIALS

Hypothetical examples of tradeoffs between RYT and ΔY

The way RYT and ΔY relate (because of overyield ecological components) can be relevant for land use change and ecosystem services at the landscape level. Consider for example the following case, where $RYT > 1$ and a $\Delta Y < 0$: a farmer monocrops two fruit tree species with identical crop price in the market. Sp.A is larger and produces more yield than sp.B. The farmer considers mixing the crops because B seems to benefit from A's shade and there is a biodiversity-premium price offered in the market for intercropped B. It turns out that A could potentially dominate B in the mixture, but this does not occur because B limits A's growth through moderate allelopathy.

The monocrop yields are $A = 100$; $B = 60$. The 50%: 50% substitutive intercrop yields are:

$A = 25$; $B = 50$. Then:

$$(RY_i - RYE_i) \text{ for sp. A} = \frac{25}{100} - \frac{1}{2} = -0.25 \quad (1)$$

$$(RY_i - RYE_i) \text{ for sp. B} = \frac{50}{60} - \frac{1}{2} = 0.33 \quad (2)$$

$$\Delta Y = (25 + 50) - \frac{100+60}{2} = -5 \quad (3)$$

$$RYT = \frac{25}{100} + \frac{50}{60} = 0.25 + 0.83 = 1.08 \quad (4)$$

The B monocrop yields less biomass than the A monocrop, but B has a positive ($RY_i - RYE_i$) value in the intercrop as expected by the farmer. The biodiversity premium over-compensates the income loss caused by A's negative ($RY_i - RYE_i$) value in the intercrop.

Simply eliminating sp.B's allelopathic capacities could produce the opposite scenario, where $RYT < 1$ and a $\Delta Y > 0$: Tree A becomes dominant in the mixture- yielding more than "expected", while B now yields less than "expected". The monocrop yields are still A = 100; B = 60. The 50% : 50% substitutive intercrop yields are now A = 70; B = 16. Then:

$$(RY_i - RYE_i) \text{ for sp. A} = \frac{70}{100} - \frac{1}{2} = 0.20 \quad (5)$$

$$(RY_i - RYE_i) \text{ for sp. B} = \frac{16}{60} - \frac{1}{2} = -0.23 \quad (6)$$

$$\Delta Y = (70 + 16) - \frac{100+60}{2} = 6 \quad (7)$$

$$RYT = \frac{70}{100} + \frac{16}{60} = 0.7 + 0.266 = 0.966 \quad (8)$$

The farmer might still be willing to shift to the intercrop if yield loss in species B is over-compensated by the biodiversity-friendly premium. This is the case if (premium B price/normal B price) * $RYT > 1.0$.

Suppose a community of farmers decides to shift all its cultivated land to the intercrop system. Under scenario 1, achieving the current overall community income would now require less land. Pressure on uncleared land, exerted by farmers pursuing a higher income through expanding crop production, would also be relatively smaller. Diversity-related ecosystem services would increase but biomass-related services (e.g., carbon sequestration) would decrease because ΔY is negative.

Under scenario 2 – and if (premium B price/normal B price) * $RYT > 1.0$ is satisfied - shifting to intercrop would increase carbon sequestration in cleared land because ΔY is positive. The land needed to be cleared to increase current income would be relatively less than in the monocrop but relatively more than in scenario 1. In each scenario, the consequences for ecosystem services of cropland expansion or reduction would ultimately depend on how ecosystem services provided by uncleared and cleared land relate to each other.

These two examples are extreme hypothetical scenarios; multicropping is a continuous adaptive optimization process developed historically through trial and error. We should expect many such systems to have achieved both $RYT > 1$ and $\Delta Y > 0$, but potential tradeoffs are possible. Tradeoffs like the ones mentioned here need to be further included in such discussion. Such tradeoffs become even more complex when we consider environmental heterogeneity across space and time.

Derivation of RMR formulas

(1) The first scenario, depicted in Fig. 2 with the number 1, is when the monocrop with water limitation fails but the multicrop does not. It is an ideal situation were drought tolerant species now become dominant and compensate for the losses of drought-intolerant species. In this case $RMR = (Mu_H/Mo_L) - (Mu_H/Mo_H)$. From Eq. (20) we have:

$$RMR = \frac{\Delta Y_L}{Mo_L} - \frac{\Delta Y_H}{Mo_H} \quad (9)$$

Which is equal to:

$$RMR = \frac{(Mu_L - Mo_L)}{Mo_L} - \frac{(Mu_H - Mo_H)}{Mo_H} \quad (10)$$

$$\text{RMR} = \left(\frac{\text{Mu}_L}{\text{Mo}_L} - \frac{\text{Mo}_L}{\text{Mo}_L} \right) - \left(\frac{\text{Mu}_H}{\text{Mo}_H} - \frac{\text{Mo}_H}{\text{Mo}_H} \right) \quad (11)$$

$$\text{RMR} = \left(\frac{\text{Mu}_L}{\text{Mo}_L} - 1 \right) - \left(\frac{\text{Mu}_H}{\text{Mo}_H} - 1 \right) \quad (12)$$

$$\text{RMR} = \frac{\text{Mu}_L}{\text{Mo}_L} - 1 - \frac{\text{Mu}_H}{\text{Mo}_H} + 1 \quad (13)$$

$$\text{RMR} = \frac{\text{Mu}_L}{\text{Mo}_L} - \frac{\text{Mu}_H}{\text{Mo}_H} \quad (14)$$

And since $\text{Mu}_H = \text{Mu}_L$ for this scenario:

$$\text{RMR} = \frac{\text{Mu}_H}{\text{Mo}_L} - \frac{\text{Mu}_H}{\text{Mo}_H} \quad (15)$$

(2) The second scenario, signaled by the number 2 in Fig. 2, is when $R\Delta Y_L > R\Delta Y_H$ and $\Delta Y_L = \Delta Y_H$. The monocrop and multicrop sets lose the same amount of yield, but the multicrop is more resistant in relative terms. $\text{RMR} = (\text{Mu}_L/\text{Mo}_L) - ((\text{Mu}_L - \text{Mo}_L)/\text{Mo}_H) - 1$. From Eq. (20) we have:

$$\text{RMR} = \frac{\Delta Y_L}{\text{Mo}_L} - \frac{\Delta Y_H}{\text{Mo}_H} \quad (16)$$

Which is equal to:

$$\text{RMR} = \frac{(\text{Mu}_L - \text{Mo}_L)}{\text{Mo}_L} - \frac{\Delta Y_H}{\text{Mo}_H} \quad (17)$$

$$\text{RMR} = \left(\frac{\text{Mu}_L}{\text{Mo}_L} - \frac{\text{Mo}_L}{\text{Mo}_L} \right) - \frac{\Delta Y_H}{\text{Mo}_H} \quad (18)$$

$$\text{RMR} = \left(\frac{\text{Mu}_L}{\text{Mo}_L} - 1 \right) - \frac{\Delta Y_H}{\text{Mo}_H} \quad (19)$$

And since $\Delta Y_H = (\text{Mu}_H - \text{Mo}_H) = \Delta Y_L = (\text{Mu}_L - \text{Mo}_L)$ in this scenario:

$$\text{RMR} = \frac{\text{Mu}_L}{\text{Mo}_L} - \frac{(\text{Mu}_L - \text{Mo}_L)}{\text{Mo}_H} - 1 \quad (20)$$

(3) $R\Delta Y_L = R\Delta Y_H$, this case appears with number 3 in Fig. 2. The monocrop and multicrop are equally resistant in relative terms: a simple scale reduction occurs, and the relation between monocrop and multicrop is not modified. Since, $\Delta Y_L/\text{Mo}_L = \Delta Y_H/\text{Mo}_H$, $\text{RMR} = 0$.

(4) $R\Delta Y_L = 0$ (number 4 inside Fig. 2). All multicrop overyield is lost. In this case, RMR is negative, and its value is $(\text{Mu}_H - \text{Mo}_H)/\text{Mo}_H$, since the first term on the right side of the RMR equation (Eq. (2)) is equal to 0.

$$\text{RMR} = 0 - \frac{(\text{Mu}_H - \text{Mo}_H)}{\text{Mo}_H} \quad (21)$$

(5) $R\Delta Y_L < 0$. The monocrop set now has a higher yield than the multicrop set because of reduced moisture. The first term on the right side of the RMR equation is less than zero, from which the second term is then subtracted, hence RMR will always be less than $(\text{Mu}_H - \text{Mo}_H)/\text{Mo}_H$. This case is depicted with number 5 inside Fig. 2.

Table S1 Explanation of abbreviations and mathematical terms

Abbreviation	Name	Formula	Definition/explanation
M	Density	$\frac{n}{m^2}$	Density of n plants per square meter
N	Plot number	N	Number of contiguous and equally sized plots for monocrop-multicrop comparisons
RY_i	Relative yield (RY_i)	$RY_i = \frac{Y_{i \text{ multicrop}}}{Y_{i \text{ monocrop}}}$	The yield a crop produces in multicrop in comparison with the average yield in monocrop for equally sized plots
$Y_{i \text{ monocrop}}$	Yield of crop i in monocrop	$M \times$ weight of the average individual plant of species i in the monocrop	The yield of a monocrop in a defined density plot
$Y_{i \text{ multicrop}}$	Yield of crop i in multicrop	$(M/N) \times$ weight of the average individual plant of species i in the monocrop.	The average yield of a multicrop in a plot of a defined density which is the same as the monocrop density in the same plot
RYE_i	Relative expected yield	$RY_i = RYE_i = \frac{1}{N}$	The relative yield to be expected if intra and interspecific net interactions are equal
RYT	Relative yield total	$RYT = \sum RY_i$	The sum of the relative yields of crop i
Mu	Multicrop	$\sum RY_i$ in multicrop	The sum of the yields of each individual species in a multicrop
Mo	Monocrop	$(\sum RY_i \text{ in monocrop}) / N$	Average yield of species i in monocrop
ΔY	Overyield	$\Delta Y = \text{Mu} - \text{Mo}$	The difference in absolute yield between multicrop and monocrop (can be negative)
TIC	Trait-independent complementarity	$\text{TIC} = N \times \text{Mo} \times \frac{\sum RY_i - RYE_i}{N}$ $\text{TIC} = \text{Mo} \times (\text{RYT} - 1)$	Quantifies the extent to which species observed yields in mixture deviate from a zero-sum game, but in a way that is independent of species traits
TDC	Trait-dependent complementarity	$\text{TDC} = N \times \text{Cov}\left(M_i, RY_i - \left(\frac{Y_i}{\text{RYT}}\right)\right)$	Quantifies the extent to which species observed yields in mixture deviate from a zero-sum game in a way that depends on species traits
DOM	Dominance	$\text{DOM} = N \times \text{Cov}\left(M_i, \left(\frac{RY_i}{\text{RYT}}\right) - RYE_i\right)$	Indicates niche similarity. Large positive values mean that species with high monocultural yields dominate the mixture at the expense of species with low monocultural yields; negative values indicate that it is the latter that dominate at the expense of the former
SEL	Selection effect	$\text{SEL} = \text{TDC} + \text{DOM}$	The “selection effect”, quantifies all overyield that is due to species traits

RMR	Relative multicrop resistance	$\text{RMR} = \frac{\Delta Y_L}{M_{O_L}} - \frac{\Delta Y_H}{M_{O_H}}$	Quantifies the amount in which a multicrop overyields the corresponding average monocrop yield sum
ΔY_L	Overyield in low moisture conditions	$\Delta Y_L = M_{u_L} - M_{o_L}$	The difference in absolute yield between multicrop and monocrop in low moisture conditions
ΔY_H	Overyield in high moisture conditions	$\Delta Y_H = M_{u_H} - M_{o_H}$	The difference in absolute yield between multicrop and monocrop in high moisture conditions
ΔY	Relative multicrop overyield	$\Delta Y = \frac{M_u - M_o}{M_o}$	The difference in absolute yield between multicrop and monocrop
ΔRYT	Delta relative yield total	$\Delta RYT = (RYT_L - 1) - (RYT_H - 1)$	Quantifies the change in yield (which reflects trait-independent complementarity) when a multicrop transitions to a low moisture condition, with respect to monocrop yield
$\Delta RDOM$	Delta relative dominance	$\Delta RDOM = \left(\frac{DOM_L}{M_{O_L}}\right) - \left(\frac{DOM_H}{M_{O_H}}\right)$	Quantifies the change in the dominance effect when a multicrop transitions to a low moisture condition, with respect to monocrop yield
$\Delta RTDC$	Delta relative trait-dependent complementarity	$\Delta RTDC = \left(\frac{TDC_L}{M_{O_L}}\right) - \left(\frac{TDC_H}{M_{O_H}}\right)$	Quantifies the change in the trait-dependent complementarity effect when a multicrop transitions to a low moisture condition, with respect to monocrop yield
$\Delta RSEL$	Delta relative trait-dependent selection effect	$\Delta RSEL = \Delta RDOM + \Delta RTDC$	Quantifies the change in the selection effect (all overyield that is attributable to species traits) when a multicrop transitions to a low moisture condition, with respect to monocrop yield
