SUPPLEMENTARY MATERIAL

To understand how genetics (G), environment (E) and management (M) influence resource use efficiency, and how multiple resource limitations interact, it is necessary to consider the mathematical form of the crop identity scheme. In Quadrant A, the resource use efficiency (X_iUE, where X_i is the resource of interest) is given by:

$$X_iUE = Y/X_I \quad (5)$$

To increase sustainability we must increase yield (Y) without increasing (or ideally reducing) X_i. To understand how this can be achieved, we work backwards through the identity. In Quadrant D, Y can be represented (Reid, 2002) as:

$$Y = B_{max}\beta B_* HI \quad (6)$$

Where B_{max} is the maximum potential biomass production for a specific cultivar grown in a specific location without limitation from biotic or abiotic stress; β is a factor (0-1) representing the extent of biotic constraint to yield (weeds, pest, diseases, sowing density), B_* is a factor (0-1) representing the extent of abiotic constraint to yield. HI is harvest index, the proportion of biomass that is partitioned to yield. If we firstly consider a situation without biotic stress (β = 1) then the path to increased sustainability is by increasing B_{max} and/or B_* and/or HI. B_* can be calculated for a given resource using the polynomial function (Reid, 2002):

$$B_* = (1+\gamma)\left(X_U/X_{opt}\right)^{\gamma} - \left(X_U/X_{opt}\right)^{(1+\gamma)} \quad (7)$$

Where X_U is resource uptake from the soil and X_{opt} is the amount of resource the crop requires to achieve its maximum yield; γ is a coefficient defining the shape of the response. Equation 6 defines the shape of the response of Y to X_U and B_{max} sets the upper asymptote for the relationship shown in Quadrant D. This shows the first way of increasing sustainable intensification through breeding to improve potential biomass production (B_{max}) and the response to limited X_U (γ). Next we move into Quadrant C and consider X_U. This is a function of the amount of resource available (X_A), the efficiency with which the crop can extract that resource (ε_R) and the maximum amount of that resource that the crop could extract given all limitations (X_{Umax}).

$$X_U = \min(X_A \varepsilon_R, X_{Umax}) \tag{8}$$

The parameter ε_R represents the next place where we might make improvements in sustainability, through breeding and management to increase the ability of crop roots to capture X_A. Finally we move into Quadrant B where the amount of resource available to the crop is a function of the amount that is input (X_I), the amount that will be supplied by the soil throughout the season (X_S), a soil efficiency factor (ε_S) and the capacity of the soil to retain applied resource (X_{Amax}):

$$X_A = \min[(X_I + X_S)\varepsilon_S, X_{Amax}] \tag{9}$$

The parameter ε_S represents the third place where we may improve sustainability, through management to reduce the amount of X_i that is lost through processes such as evaporation, drainage, volatilisation and leaching. In most cases there will be some water or nitrogen in the soil when the crop is planted and some more will mineralise or precipitate during the season, so X_S will be positive giving non-zero intercepts for the lines in Quadrants A and B. The X_{Umax} and X_{Amax} are also important parameters to consider in the improvement of resource use efficiency as the input of resource in excess of these maximums will inevitably lead to losses from the system and a decrease in sustainability. Overall, we can see that the relationship between Y and X_i in Quadrant A becomes an emergent property of the system in response to the efficiencies represented in the other three quadrants.

A spreadsheet is provided (SupplementaryFile_1.xlsx) that illustrates the calculation of the nutrient identity elements for the maize example, described in the main paper. It can be used and modified to generate other identity diagrams and to derive 'walk around' analyses for other cropping systems to analyse their proximity to an ideosystem. Also attached is the script (KPB.ipynb) and data (Maize.data, Cocksfoot.data and Maize.data) for constructing the quadrants.