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Minimizing the ecological footprint of food: closing yield and efficiency gaps simultaneously?

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Agriculture as a source of food has a substantial spillover that affects the Earth's ecosystems. This results in an 'ecological footprint' of food: negative environmental impacts per capita. The footprint depends on the dietary choice of types and amounts of food, on the non-consumed part of product flows and its fate ('waste' or 'reused'), on transport and processing along the value chain, on the environmental impacts of production per unit area, and on the area needed per unit product. Yield gaps indicate inefficiency in this last aspect: resource-use efficiency gaps for water and nutrients indicate that environmental impacts per unit area are higher than desirable. Ecological intensification aimed at simultaneously closing these two gaps requires process-level understanding and system-level quantification of current efficiency of the use of land and other production factors at multiple scales (field, farm, landscape, regional and global economy). Contrary to common opinion, yield and efficiency gaps are partially independent in the empirical evidence. Synergy in gap closure is possible in many contexts where efforts are made but are not automatic. With Good Agricultural Practice (GAP), enforceable in world trade to control hidden subsidies, there is scope for incremental improvement towards food systems that are efficient at global, yet sustainable at local, scales.

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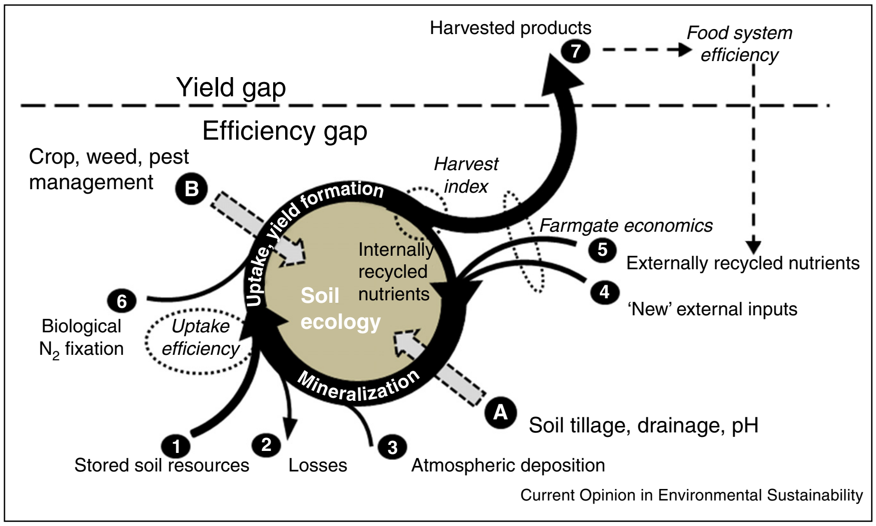
Introduction

Progress in seeing agriculture as the basis of complex value–chain interactions in 'food systems' [1] currently interacts with perspectives on agriculture as an important category of land use competing with other land functions [2], as a source of employment and livelihoods for a decreasing part of the rural population [3], as an important part of cultural heritage and identity[4], as modifier and storehouse of genetic resources [5•,6], as threat to environmental integrity and biodiversity at landscape scales [7], as source of greenhouse-gas emissions [8], and as a sector in the national and global economy [9]. Each of these interactions is a potential source of unsustainability [10•] and lack of sustainagility [5•]. From the consumer end of the chain, the concept of footprints [11] has become a useful integrative metric: the footprint of food depends on the dietary choice of types and amounts of food, on the non-consumed part of product flows (waste), on transport and processing along the value chain, on the environmental impacts of production per unit area and on the area needed per unit product. The latter two aspects are summarized in the related concepts of resource-use efficiency gap and yield gap and are the focus of this review.

Yield, defined as the harvested part of crop growth or animal production, is the result of complex processes of nutrient uptake, nutrient availability, soil ecological functioning, soil-and-crop management practices and input use, with the latter including crop residue, within farm nutrient cycling, inputs recycled from manure and waste within the regional economy, and new external nutrient inputs in the form of chemical fertilizer. The yield gap measures only the result of these interactions while resource-use efficiency gaps require a more detailed account of the underlying processes (Figure 1). Efficiency of the overall food system includes possible recycling of 'waste' back into the primary production process.

After defining yield and efficiency gap concepts and their relationships, this contribution to the debate reviews the scale dependency of yield and efficiency gaps and the consequences for internalizing externalities of farm-level decision making. A review of recent literature documents that both decreases and increases in efficiency gap occur in farming practice, as part of current efforts to close yield gaps. Finally, the opportunity is considered that articulation of Good Agricultural Practice (GAP) and its enforcement in global trade agreements, such as those in the

Figure 1



Food system efficiency perspective on soil **(A)** and crop **(B)** management as modifying factors of field-level interactions between soil (1), losses to atmosphere or water (2), nutrient inputs (3–6), and crop growth, leading to harvested products (7).

context of the World Trade Organization, can help in closing the two gaps simultaneously in the context of a debate on hidden subsidies implied by loss of natural capital.

Yield and efficiency gaps

Yield gaps, the difference in production per unit area between what is deemed to be feasible and what is achieved in terms of crop yield, indicate inefficient use of land [12•]. This can be formulated as: 'Yield gap = 1 − Achieved_yield/Potential_yield'. While Achieved_yield can be measured, Potential_yield is based on inferences drawn from models (especially ones that consider radiation and temperature of the actual location but assume that water and nutrient supply are non-limiting) or highest-observed local yield record [12•].

Resource-use efficiency is generically defined as the amount of targeted output achieved per unit input. If we see the production factor land as input — or as proxy for the way light, water and nutrients are accessible to crops — then the yield of harvestable products per unit area of land is a special case of resource-use efficiency. Different metrics are obtained for other types of resource-use efficiency if the same amount of harvested product is quantified relative to other types of inputs (e.g. fertilizer, agrochemicals, labour, total economic factor input). If negative consequences of production (non-targeted outputs), such as area of natural habitat converted or greenhouse-gas emissions, are used as denominator, a 'footprint' is calculated similarly.

Across various production systems the yield gap is not necessarily aligned with other efficiency gaps. A classical result of agricultural economics, challenged by some (see below), is that 'economic optimum' input levels do not achieve maximum yield and thus do not fully close the yield gap or, conversely, that fully closing yield gaps is not (micro)economically efficient and justifiable. There is a long tradition in publicly financed subsidies to inputs, such as fertilizer or irrigation where the micro-economic rationality does not match perceived macro-economic goals. There is a countervailing discussion on the relevance of taxing use of fertilizer and irrigation water where the microeconomic decisions tend to lead to low resource-use efficiency, loss of natural capital and increased environmental issues.

Yield gaps are most commonly discussed for one crop at a time but the Land Equivalent Ratio (LER), a common metric in mixed and multiple cropping systems [13], is similarly based on the sum of yields of various components relative to their potential value in reference systems. As it is quite possible for an LER to be above 1.0, however, the yield gap (interpreted as $1 - \Sigma_i(\text{Achieved\_yield}_i/\text{Potential\_yield}_i)$) can be negative for intercropping, which may appear to be a *contradictio in terminis*. It implies that the same amount of yield currently obtained in separate fields could have been achieved in intercropping with a smaller allocation of land.

For any steps towards closing yield gaps, there is a conceptually simple link to statements that land is being "spared" from agricultural use and may serve other functions. The value of these other functions can be high if land spared was left in a natural state and conversion was prevented. In the more common scenario where land was converted for agriculture and subsequently abandoned for other functions, restoration of other functions may involve additional cost [2,14]. Values of LER above 1, and hence negative yield gaps when we take monocultures as the point of reference, are possible whenever the combined resource capture exceeds what a monoculture could achieve [15,16]. With continuously increasing demand from a growing population with rising income and shifting diets, the urgency of closing yield gaps is widely acknowledged. However, the way this can best be done, through conventional or ecological intensification, in specialized monocultures or diversified mixed systems, remains debated [8,17–19]. If the environmental footprint of production increases more than proportionally in the effort to close the yield gap (thus increasing the efficiency gap), the environmental optimum solution may be found at yields below the maximum achievable, which could be a justification for accepting a certain yield gap. The efficiency gap, as well as the relationship between yield and efficiency gaps in monocultures and diversified cropping, depends on system and physical scale of consideration, underlining the futility of a search for universally applicable solutions [5•,20].

The ratio of output to input at an accounting border changes with system scale, mostly due to the (ecological) internalization of external inputs: while nitrogen-use efficiency (NUE) in a crop field can be higher with inorganic rather than organic fertilizers, farm-level NUE is generally increased if there is no waste and all residues and by-products are recycled. Agricultural sector efficiency is increased if all manure and food processing waste is re-utilized [21]. While the yield gap was progressively closed for Dutch dairy farming, farm-gate NUE — here defined as N in products sold per unit external (N-fertilizer) input — decreased between 1950 and 1985 from 46% to 16% [22]. Specialization and loss of previous mixed-farming concepts, along with substituting biological N_2 fixation (not counted as input) by fertilizer (counted as input) as a step towards closing the yield gap, increased the efficiency gap as defined at this accounting scale. Subsequent concerted research effort raised farm-gate NUE to 72% in prototype (mixed) farms [23•], while reducing losses to the environment.

Consequences of an efficiency gap can be viewed in three ways: firstly, keeping the input level constant, efficiency gaps indicate that feasible outputs are not achieved; secondly, keeping the output level constant implies that more inputs are used than necessary, with generally negative environmental consequences; and thirdly, regarding both, it implies that total input use can be optimized along both input and output axes. Economic rationality may be best approximated in the third approach [24] but this needs to be based not only on the benefits associated with the outputs and the costs associated with the inputs but also with the costs and benefits of the non-utilized part of inputs. If nutrients added are not taken up by crops in the accounting period but are added to the nutrient capital that can be used in future, they may be added on the benefit side. If the nutrients not used are lost to ground- or surface water or emitted as greenhouse gas or air pollutant, they are part of the cost to society. Increasing efforts to have the bill for such costs sent to the farmer are meant to bring efficiency goals at a societal accounting scale closer to the on-farm decision-making processes. Once a standard of acceptable levels of pollution and emissions is set, society may also use positive economic instruments to reward farmers who have a cleaner production system than the norm. These policy instruments are aimed at reducing the various efficiency gaps by aligning micro-economic decisions based on farmgate prices more closely to choices optimal for society at large (internalizing economic externalities) [25,26]. Externalities are effects or consequences of decisions that are not taken into account at the decision level. Internalizing implies that such consequences become part of the decision-making process.

Internalizing externalities, ecologically and economically, across scales

Yield metrics generally scale with area (length dimension 2) and the yield gap calculated over a larger area is the area-weighted yield gap for all fields under consideration (retaining dimensionality of 2) [27]. For the different aspects that in combination lead to efficiency gaps, the scaling rules and thus the dimensionality of the resulting metric differ. By implication, the ratio of yield and efficiency gap will depend on scale unless the net effect on a certain type of efficiency gap would exactly conform to area-based scaling. If yield is evaluated in economic terms as yield × unit price, it is likely that the value per unit product is not independent of the scale of application: there may be bulk price benefits and there may be opposite effects where relative scarcity increases price. If the analysis shifts from gross to net benefits, it incorporates production factors with a variety of scaling rules and dimensionality (Table 1) as well as environmental externalities with dimension below or above 2. For example, losses to the atmosphere and to groundwater (deep percolation) may scale by area but losses to the environment that are based on lateral flows to surface water have more complex scaling rules and are potentially subject to edge effects, interception and recycling, depending on field and filter dimensions [28].

Situations where the net dimension for cost terms is above 2 are associated with a ‘small is beautiful’ paradigm as costs increase more quickly with scale than benefits. In contrast, in situations with values below 2, costs decrease relative to benefits with increase of scale. When heterogeneity in uniformly managed fields is explicitly considered, as in precision agriculture, the ‘safe operating space’ between input levels sufficient to close yield gaps

Table 1

Tentative scaling rules for components of efficiency gaps (production factors and environmental externalities) (*D* = 2 implies length to the power 2 which equals area as basis for extrapolating between system scales)

Production factor and externalities	Agrobiodiversity benefits[a]	Dimension (*D*) of field-level metrics[b]			Lateral flows involved in *D* deviating from 2[c]
		$D > 2$	$D = 2$	$D < 2$	
Production factors, included in farmgate economics					
Land	**1**		+++		
Labour	**1**		++	+	$^+$Economies of scale
Energy: equipment cost	**1**		++	+	$^+$Economies of scale
Energy: running cost	**1**		++	+	$^+$Economies of scale
Water supply by irrigation	**1**	+	++		Delivery losses
Water: avoiding excess by drainage[d]	**2**	(+)	++	(+)	Edge effects
Nutrients: external input costs	**2**	+	++		Heterogeneity [29]
Nutrients: recycling costs[d]	**1**	+	++		Transport increase
Weed control: external inputs	**2**		++	+	$^+$Economies of scale
Pest control: external inputs	**3**	+	++		Biotic flows
Pollination: external inputs	**3**	+	++		Biotic flows
Knowledge (generically applicable)			–		Scale-free
Site-specific information fine-tuning soil and crop management	**2**	(+)	++	(+)	$^+$Economies of scale, observation intensity
Environmental externalities influencing 'footprint' metrics					
Soil loss and downstream sedimentation	**2**	+	++		Filter effects [30,31]
Water pollution with excess nutrients	**2**	+	++		Filter effects [32]
Greenhouse-gas emissions	**2**	(+)	++	(+)	Mixed effects
Pollution due to pest control	**3**	+	++		Filter effects

[a] Agrobiodiversity effects are tentatively classified as 1 = absence or weak relationship; 2 = medium; 3 = strong dependence.

[b] *D* is the fractal dimension that can be used to estimate parameter value *Y* at any scale *x*, on the basis of its value *Y*(1) at length scale 1, via $Y(x) = Y(1) \times (\text{Length}(x)/\text{Length}(1))^D$; the likelihood that *D* is below, at or above 2 is indicated as (+) = possible but rare, + = possible in specific circumstances, ++ = most likely, +++ = can be taken for granted.

[c] Deviations from *D* = 2 can often be linked at process level to a prominence of lateral flows.

[d] Factors indicated here are specifically responsive to a shift to other system scales, from field to farm and landscape.

and those where N losses become unacceptable (with higher efficiency gap) may decrease and become negative [32]. As indicated in Table 1 as well, a number of the production factors and environmental externalities are influenced by the agrobiodiversity that is maintained at plot, farm and landscape scale. In fact the level of agrobiodiversity may not only influence the efficiency gap (and economic profitability) at a given scale but also the scaling rules.

Beyond physical field scale, the nesting of fields in farms in landscapes in a regional economy provides opportunities for efficiency gaps to be reduced by internal recycling. If what otherwise would be considered a waste can be used to substitute for new external inputs at a certain scale, efficiency gaps narrow, even if field-level losses may increase. Every system scale has its own expression of efficiency, defined as targeted output per unit input, as non-target outputs become recycled. Many authors have noted the scale dependence of water-use efficiency from crop to catchment scale, once reuse options are included [33,34,35$^{\bullet}$].

A further elaboration of the key processes operating at field scale, embedded in wider food systems, can clarify that yield gaps scale by different rules than efficiency gaps (Figure 1). The various losses to the environment depend on the same set of factors but are influenced by non-area-based scaling and opportunities for scale-dependent recycling [36]. Total factor productivity [37], assessed at farm gate, reflects this more complex scaling but the input and output prices may not yet internalize externalities important to society at large [38].

A point of caution, however, is relevant here. This framing ignores a substantial part of farmers' reality in decision making [10$^{\bullet}$,39]. Viewing a farmer as an entrepreneur operating with 'micro-economic' rationality, is ignoring 'pico-economic' and 'meso-economic' aspects [40] of rural decision making that have emotional, societal and environmental contexts. The rediscovery of the peasant as a theoretically meaningful concept strategic to future world food security, followed the agrarian crisis that grew out of five decades of state-induced modernisation that promoted system homogenization (e.g. monocultures) and focus on a single function (e.g. productivity) [41]. Empirical studies of how farmers frame their own situation may not straightforwardly reflect the peasant–entrepreneur typology of current discourse but they are highly compatible with multifunctionality concepts [42$^{\bullet}$].

The view that Resource-Use Efficiency Gap decreases while closing Yield Gap

De Wit [43], in his seminal paper on resource-use efficiency, claimed that, 'Trajectories over time of nitrogen use and yield show that the fertilizer is used as efficiently at the high end of the yield range, as at the low end', and, 'no production resource is used less efficiently and most production resources are used more efficiently with increasing yield level due to further optimizing of growing conditions'. There is indeed selected evidence supporting the view that efficiency gaps can close (or at least not widen) while yield gaps are closed. Such data generally derive from experiments where multiple yield constraining factors were simultaneously addressed and where part of the management directly influenced the likelihood of losses. For example, deepening of groundwater tables to allow mechanization can also increase nutrient buffering in the root zone, thus allowing increases in yield alongside increased nutrient-use efficiency [44]. Purely from a crop growth and yield perspective, however, the deepening of groundwater tables is a compromise that allows mechanization to be less harmful to the soil but it necessitates larger root systems that increase actual yield in this modified environment but, through additional carbon costs, also reduce potentially achievable yield (defined for a hypothetical situation without water and nutrient stress but with the belowground resource allocation typical for the locality) [45]. The level of implicit selection on shifts in shoot:root allocation and the responsiveness of this ratio to local conditions is debated in the literature; there are only a few examples of explicit selection for such traits [44].

Yield and efficiency gaps show different spatial patterns when analysed globally [46]. Field studies in Western Australia that have included a range of environments (sites and seasons), cultivars and levels of management (sowing times, fertilizer treatments, seed rates) have been interpreted as showing that the main effect of variation in E(nvironment) (including inter-annual rainfall variability) accounted for about 80% of the variability in grain yield, variation in M(anagement) accounted for about 6%, and variation in G(enotype) for about 3%. The GxExM interactions were generally unimportant within this specific context [47]. Analysis of a global N-input database (fertilizer, manure, fixation, deposition, and residues) that enables evaluation of trends in nitrogen use and recovery by country and by crop from the 1960s through 2007 showed that, despite growth in yields and increased N fertilization, differences in efficiency of N use between Organization for Economic Co-operation and Development countries (OECD; http://www.oecd.org) and other countries have persisted over nearly 50 years and exhibit no sign of convergence [48]: 'The high-yield, high-nitrogen input systems characteristic of rich countries have released large amounts of reactive N to the environment but have operated with greater efficiency, recovering a greater portion of added N in crops. Aggregate yields in OECD countries are 70% greater than in non-OECD countries on N input rates just 54% greater. Variation in recovery efficiency between countries suggests that there is scope for improvements through enhanced N delivery and capture in the world's low-yielding croplands and that increasing efficiency of N use is an important component of meeting food demand in the future.' A recent study of N-use efficiency in grain production in Australia (rainfed wheat systems), China (irrigated wheat–maize double-cropping systems) and Zimbabwe (rainfed maize systems) [49•] compared surveyed crop yields against simulated grain yields at farmer-specified levels of nitrogen (N) input. Many Australian commercial wheat farmers were found both close to existing production frontiers and used near-optimal N input, with infrequent and low losses of N from their systems. In contrast, the analysis showed that many Chinese farmers can reduce N input without sacrificing production through more efficient use of their fertilizer input. They can achieve both production increases and reduced losses to the environment. Zimbabwean farmers have the opportunity for significant production increases by both improving their technical efficiency and increasing their level of input, however, doing so will require improved management expertise and greater access to institutional support for addressing the higher risks.

De Wit's conclusion [43] still holds that, 'Therefore strategic research that is to serve both agriculture and its environment should not be so much directed towards the search for marginal returns of variable resources, as towards the search for the minimum of each production resource that is needed to allow maximum utilization of all other resources'. Spatial variability within what is managed as if it were uniform explains part of the difference between the results of experiments, typically in places selected for homogeneity, and the reality of farms and landscapes [31].

The Resource-Use Efficiency Gap commonly increases while closing the Yield Gap

Turning now to the opposite view that the correlation between the efficiency gap and the yield gap tends to be negative, there is a considerable amount of empirical evidence, but no necessity or causation. A recent meta-analysis of N_2O emissions by non-leguminous annual crops revealed that yield-scaled N_2O emissions were smallest (8.4 g N_2O-N kg^{-1} N uptake) at application rates of approximately 180–190 kg N ha^{-1} and increased sharply after that (26.8 g N_2O-N kg^{-1} N uptake at 301 kg N ha^{-1}) [50•]. The authors conclude that agricultural management practices to reduce N_2O emissions per unit product should focus on optimizing fertilizer-N use efficiency under median rates of N input, rather than on minimizing N application rates.

The segregation of livestock and crop production, while reducing farmgate yield gaps, has dramatically increased the resource-use efficiency gap in a country such as The

Netherlands [51], while nutrient mining in areas exporting large volumes of animal feed continues. Simulation models suggest that closing yield gaps by 50% for crops and 25% for livestock by 2050 would decrease agricultural and land-use change emissions by 8% overall and by 12% per calorie produced [52]. The options for efficiency increase if crop-livestock systems remain or return to integration, thereby avoiding current depletion in areas mined and excess elsewhere, will need to be further assessed but are likely to be considerable [53].

The 'Pandora's box' effect that increased technical efficiency and profitability can increase rather than decrease conversion of tropical forests has been widely discussed [54,55], as it contradicts simple versions of the Borlaug agricultural intensification hypothesis (intensification spares land and saves forest). However, a recent critical review of the literature on the relationship between agricultural technological progress and deforestation showed that [56•] firstly, the empirical evidence on a positive link between regional technological progress and deforestation is mixed; secondly, at a global level, most analysts expect broad-based technological progress to be land-saving, however, composition landscape and regional configuration effects are important as low-yield, land-abundant regions are likely to experience further land reclamation.

Good Agricultural Practice as minimum acceptable yield plus efficiency gap

Global commodity trade has generally responded to market-based opportunities to increase cost efficiency of food production systems by supporting low-cost producers but it has had mixed effects on globally aggregated yield and efficiency gaps. Producers in countries with relatively strict environmental regulations, however, have an opportunity to reduce imports from countries where norms are low or not effectively maintained, through the rules of the World Trade Organization. An argument can be made that production that did not follow Good Agricultural Practice (GAP) and that in fact mined or polluted soil and water or unnecessarily converted natural habitat, is domestically subsidized in the exporting country and can be taxed accordingly at an international border. Can one GAP help to reconcile two existing gaps?

The difference between best and worst mode of production of a single commodity, evaluated from a given perspective, has been termed the 'management swing potential' [57]. This management swing potential indicates the scope, within existing production systems, to close the efficiency gap. Certification schemes tend to focus on the best production systems but the GAP rules can be used to make the worst production systems less attractive, at least in international trade.

We thus have three gaps that interact: the yield gap, various other efficiency gaps, and the GAP. The GAP rule makes it important to quantify yield and efficiency gaps under GAP conditions, as nationally defined. To the best of our knowledge, such a study has not yet been carried out. With a higher target of Best Management Practices [58], acknowledging that there is considerable site-related and climate-related variability in best-practice articulation [59••], intermediate intensities of land use, not fully closing the yield gap, appear to be environmentally superior.

Conclusions and priorities for further research

We conclude that yield and resource-use efficiency gaps at the production level are important components of the broader efficiency and footprint issues of the food systems at large. Where important policy framing has been built on the expectation that closing yield gaps is the priority and that closing efficiency gaps will follow as a consequence [42•], the evidence is mixed. An expectation of intrinsic independence of the two gaps is a safer starting point for the specific efforts needed to close the two gaps simultaneously, to the degree possible. While the ecological footprint of food requires understanding of a much broader set of actors and decisions [9], the key issues within the agricultural production part of the chain still need attention.

Ecological intensification entails the environmentally friendly replacement of anthropogenic inputs and/or enhancement of crop productivity by including regulating and supporting ecosystem services' management in agricultural practices [60]. Compared with conventional farming systems, diversified farming systems support buffering and resource-use efficiency through substantially greater biodiversity, soil quality, carbon sequestration, and water-holding capacity in surface soils, energy-use efficiency, and resistance and resilience to climate change [61]. If the role of multifunctional landscapes towards attainment of broader sustainable development goals is assessed, alternatives, involving trees, to crop monocultures have multiple benefits [62].

Process-based models, maximizing use of empirical data, of soil processes, uptake efficiency and yield formation that can support the cross-scale analysis of yield and efficiency gaps are still of fundamental importance as there is no time and budget to carry out directly empirical studies at all relevant nested scales [63]. Models for agroforestry and other mixed cropping systems exist in considerable diversity: from process-based models at tree–soil–crop interaction level [64] to models at higher aggregation levels [65,66] that use empirical nutrient-use efficiencies in their wider consequences [67].

Global comparative studies across the full range of land-use intensities show that in each context local changes are possible towards ecological intensification and reducing environmental footprints [68•]. Beyond generalizations about intrinsic linkages between yield and efficiency gaps, the devil is in the detail of local context, as well as in the pitfalls of local efficiency enhancement that reduces efficiencies measured at potentially more relevant higher system scales.

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