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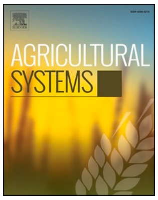

Circularity indicators and their relation with nutrient use efficiency in agriculture and food systems

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HIGHLIGHTS

- Nutrient cycling receives much attention but its contribution to nutrient use efficiency & system output remains elusive.
- Nutrient cycling indicators enable the calculation of equilibrium Output/Input ratio (*O/I*) from basic system properties.
- *O/I* responds more than proportionally to the fraction of flow retained per cycle.
- Analyses of three case studies show that nutrient cycling in farming and food systems is currently very limited.
- Proposed circularity indicators help prioritize between measures minimizing losses & promoting return of external waste.

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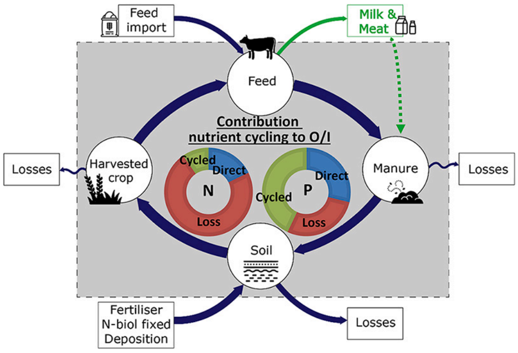
GRAPHICAL ABSTRACT



ABSTRACT

CONTEXT: Circular resource use in agriculture and food systems could play an important role when aiming for sufficient food output with limited environmental impact and resource depletion. Circularity, however, is not a goal in itself. With respect to nutrient use and emissions, agricultural system sustainability is currently commonly assessed by nutrient output/input ratio (*O/I*, nutrient use efficiency) or surplus per ha (*I*—*O*).
OBJECTIVE: Our aim is to assess how these sustainability indicators are related to nutrient cycling.
METHODS: Starting from basic circularity concepts, a set of equations (frame) is presented that relates nitrogen (N) and phosphorus (P) cycling to food product output, or to food use by human consumers. Circularity indicators express how many times a nutrient input cohort completes a full cycle (*CyCt*), or passes through the system's top trophic compartment (*UseCt*). Examples of such compartments are the crop (arable systems), the herd (livestock farms), and the human population (regional food systems). *UseCt* governs export in useful product. The frame allows to predict equilibrium *O/I* from system properties, and to attribute parts of *O/I* to direct (linear) and cycled flow. $CyCt_R$ quantifies how many cycles could be completed by nutrients in absence of product export. $CyCt_R$ allows to assess the efficacy of returning waste from exported products. Above indicators are compared against Finn cycling index and Figge circularity index, more commonly used in ecological and industrial research respectively. All indicators are calculated for systems of increasing complexity: (i) a UK wheat

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field, (ii) a Dutch dairy farm, and (iii) the Flanders regional food system. Their responses to changes in system properties are analysed for examples ii and iii.

RESULTS AND CONCLUSIONS: Nutrient flows in UK arable field and Flanders are almost linear. In UK arable field, *O/I* equals 0.74 (N) and 0.66 (P), with small contributions from cycled flow (9% for N, 5% for P). In Flanders, cycled flow constitutes only 2% of total N and P flows that reach the human consumer in Flanders. The dairy farm shows largest contributions of cycled flow: 35% (N) and 60% (P) of *O/I* comes from cycled flow, but *O/I* itself is only 0.28 (N) and 0.72 (P).

SIGNIFICANCE: The presented frame allows to assess the impacts of system changes on productivity, nutrient cycling, resource use and nutrient emissions. This is useful for ex-ante assessment of measures that reduce nutrient losses from the system or increase the retrieval of external waste flows.

1. Introduction

Circularity of resource flows has gained increasing attention during the last decade (Hamam et al., 2021). The European Commission (EC) has put circular economy high on the agenda as part of the European Green Deal, aiming to reach climate neutrality and reduce environmental pollution in 2050 (European Commission, 2019). To reach this aim in Europe, the use of circular materials should be doubled by 2030 (European Commission, 2020). Circular economy is often viewed as a framework for concretization of the sustainability concept (Carus and Dammer, 2018). Yet, various definitions are used (Kirchherr et al., 2017), and a common benchmark for successful implementation of the concept is lacking (and likely differs across sectors and resource flow types). Resource flows which are part of the agro-food system mainly consist of flows that cannot be refurbished or recycled in their original form (see butterfly diagram by MacArthur (2013)). Therefore, circular food systems research mainly focusses on improved recycling of nutrients via residual flows such as livestock manure, food waste, and ultimately recycling of human excreta (e.g. Van Zanten et al. (2019)).

The agro-food system is one of the major contributors to greenhouse gas emissions, biodiversity loss, and pollution of freshwater reservoirs (EEA, 2019). Moreover, artificial fertiliser nutrients are (partly) obtained from finite sources (phosphorus, P), or produced with the help of finite resources (energy in the case of nitrogen, N). A more circular agro-food system will likely reduce net resource use and emissions to the environment (de Boer and van Ittersum, 2018; Van Selm et al., 2022). The EC in its Farm to Fork strategy proposes that fertiliser use in agriculture can be reduced by 20% by minimizing nutrient losses and promoting recycling and re-use (European Commission, 2020).

Clear indicators are needed to monitor the contribution of circularity to environmental performance and resource use efficiency of agro-food systems. A wide variety of circularity indicators already exists (e.g. Garcia-Saravia Ortiz-de-Montellano and van der Meer, 2022; Saidani et al., 2019). They focus on different domains and economic sectors, scales and resource flow types. Cycling of nutrient flows specifically has received much attention in ecology. The Finn Cycling index (here *FinnCI*) was developed to express circularity of nutrient flows as a measure of complexity in ecosystems (Finn, 1980). Increased nutrient cycling is considered to contribute to higher ecosystem stability and better functioning (DeAngelis et al., 1989). Another example of a circularity indicator, the Figge circularity index (here *FiggeCI*), was first developed to express resource use efficiency in industry-consumer systems (Figge et al., 2018). The *FinnCI* (Rufino et al., 2009), and related indicators (e.g. recycling rate in Rufino et al. (2009) and Papangelou and Mathijs (2021)) were also applied to agro-food systems to assess nutrient recycling within a system. However, increased recycling in itself may not always be beneficial. Trade-offs can occur between environmental performance, productivity and recycling (e.g. Fernandez-Mena et al. (2020)). Similarly, Velasco-Muñoz et al. (2021) concluded that (a set of) indicators for circularity in agriculture should be able to combine multiple circular economy concepts: 1) efficient resource use; 2) recycling or re-use, and 3) regeneration of natural resources.

So far, existing circularity indicators have failed to provide a direct link to nutrient use efficiency. This is because, by their nature, circularity indicators do not distinguish between (nutrients in) product output on the one hand, and losses on the other: it is only the total removal per cycle that determines how often a cohort of fresh nutrient input cycles through a system. As we aim to identify how cycling contributes to overall resource use efficiency, we need to modify current circularity concepts in a way that enables separation of the two removal flows, both generated from a unit input. To this end, here we propose a metric frame that consists of auxiliary system properties, new circularity indicators and their mutual relations. It needs to enable the quantification of direct and cycled flow contributions to product output. The approach is illustrated for selected examples of agricultural and food systems of increasing complexity and scale, where we investigate when and where high efficiency and circularity go hand in hand, and where they may be at conflict. In our analysis we introduce new circularity indicators that help explain how existing indicators (*FinnCI* and *FiggeCI*) are related to efficiency. As common indicators for nutrient use efficiency and emissions we use the ratio (*O/I*) and the difference (*I*—*O*), respectively, between input (*I*) and product output (*O*) flows of nutrients per unit time. As a measure of environmental impact, both nutrient use efficiency (*O/I*) and surplus (*I*—*O*) are meaningful only on the condition that the system is in steady state equilibrium. In agriculture it may take decades – after any major change – for systems to approach such state, and so observed efficiency and surplus have limited value as few systems meet the equilibrium condition. We believe that a chief benefit of our metric frame is that it enables the calculation of (future) equilibrium efficiency and surplus from basic system properties. This is not possible without addressing, explicitly or otherwise, the contribution of cycling to output. The aim of this paper is thus to assess how the two sustainability indicators are related to nutrient cycling.

2. Materials and methods

Section 2.1 presents how existing circularity concepts are modified by combining them with particular system properties, and what new indicators arise as a result. For a quick overview, a few key elements are briefly introduced in the current paragraph. Cycle Count (*CyCt*) is the average number of full cycles completed by a nutrient input cohort *I* before it has vanished as product exports and/or losses. *CyCt* is needed to express the *relative* contributions of direct and cycled flow to the *O/I* ratio. Similar to the existing *FinnCI* and *FiggeCI* (see SI section S1 for explanation calculation *FinnCI*, *FiggeCI*), however, *CyCt* alone is insufficient to quantify *O/I* itself. For this purpose we need Use Count (*UseCt*). This is the number of times an input cohort *I* passes, on average, through the top trophic compartment that generates the intended product output. *UseCt* is needed to assess the absolute values of *O/I* and its direct and cycled components. Moreover, *UseCt* can replace *O/I* to express overall nutrient use efficiency in systems without net product output (e.g. food systems that include humans as top trophic level; Table 1). These main indicators and their relations are illustrated for an example production system in Fig. 1a and b. Further indicators are introduced in Section 2.1.

In Section 2.2 we present three cases of agricultural production systems in order of increasing complexity. The systems have different scales (field, farm, region), different outputs, and different top trophic

Table 1

Examples of agro-ecosystems and food systems with their typical representations of input, *Use*, use compartment (top trophic level), and product output. (*I* and *O* in the main text denote flows of nutrients contained in input and product output mass flows respectively).

Example system	*Typical nutrient input form*	*Use*	Use compartment	Product
Crop-soil system	Fertiliser	Nutrient uptake in total crop biomass[1]	Crop	Food or feed products exported from field or farm, such as cereal grain or potatoes
Soil-crop-cattle (dairy farm)	Fertiliser; Feed roughage; Feed concentrates	Feed nutrient intake by dairy herd	Dairy herd	Milk and meat[2]
Regional food system (includes food industry and human consumer)	Fertiliser; Feed roughage; Feed concentrates; Food import	Nutrient intake by humans in food	Human consumer	Not applicable

[1] Not just offtake in farm product.

[2] Manure or roughage may be exported, but are lower grade outputs, not denoted as product output (O) in our terminology.

compartments (Table 1). The cases serve to illustrate the newly introduced indicators, their relations with *O/I*, and their relations with existing indicators *FinnCI* and *FiggeCI*. The contributions of direct, cycled and returned flow to *O/I* are also reported. Finally, the farm and regional cases are used to demonstrate impacts of system parameter changes – as could result from management interventions – on the various indicators.

2.1. Circularity indicators and their relation with efficiency

Consider a production system that consists of a sequence of n compartments linked into a single loop; we call this a circular system (for examples see Table 1). Upon introduction, a nutrient passes subsequently through all compartments before commencing a new cycle (Fig. 1a). From the local inflow into each compartment *i,* a fraction $f_{i,\mathrm{prod}}$ may leave the system as intended product (e.g. milk from a dairy farm), another fraction $f_{i,\mathrm{loss}}$ is lost to the environment (e.g. N leached to groundwater), and the remainder $f_{i,\mathrm{ret}}$ passes on to the next compartment (e.g. manure applied to the soil):

$$f_{i,\mathrm{prod}} + f_{i,\mathrm{loss}} + f_{i,\mathrm{ret}} = 1 \tag{1}$$

Thus, fraction a_i of the local nutrient flow is removed from the system via compartment *i:*

$$a_i = f_{i,\mathrm{prod}} + f_{i,\mathrm{loss}} \tag{2}$$

By the time a full cycle is completed, fraction *A* of the initial flow has been removed as exported product and/or losses (Fig. S2.1). This fraction removed per cycle is related to the individual removal fractions a_i per compartment according to:

$$(1-A) = \prod_{i=1}^{n}(1-a_i) = \prod_{i=1}^{n} f_{i,\mathrm{ret}} \tag{3}$$

Here, we assume steady state equilibrium: the amount of the nutrient held in each compartment is constant over time. The amount of nutrient removed per cycle or per unit time must then be replaced by fresh input *I*. Now, how many times will a single cohort of such input, upon introduction, pass through a full cycle before being dissipated? We refer to this number as the cycle count (*CyCt*). After completing one cycle, the remaining fraction (1-*A*) of the cohort goes into the next cycle. After two cycles, a fraction $(1\text{-}A)^2$ of the original input remains, and after m full cycles, a fraction $(1\text{-}A)^m$ remains. This series goes on ad infinitum and as it converges for $0 < A < 1$, summation of all these fractions yields the number of times that a cohort of original input *on average* completes the full cycle. This sum equals (1-*A*)/*A*:

$$CyCt \equiv \sum\nolimits_{m=1}^{\infty}(1-A)^m = (1-A)/A \tag{4}$$

Eq. 4 shows, for example, that for $A = 0.5$ a cohort *I* completes the cycle precisely once. In other words, half of the flow is removed per cycle, but cycling of the remainder causes that, on average, the entire cohort *I* completes the full cycle. The central component shared among *CyCt* and the aforementioned *FinnCI* and *FiggeCI* is (1-*A*), the fraction of input cohort *I* that is retained in the system after one cycle is completed. For circular systems, *FinnCI* reduces to (1-*A*). For more complex systems, however, calculation of *FinnCI* is more complex (SI section S1) and *FinnCI* does not express a cycle count. In contrast, *FiggeCI* and *CyCt* do both express, for circular systems, how many times a unit of fresh input *I* completes a full cycle before having vanished. The two differ in that *FiggeCI* adds 1 point to *CyCt* and so accounts for direct flow (i.e. flow that has not yet cycled). In addition, *FiggeCI* in its original form accounts for refurbishment, which can be ignored in agriculture and food systems. For more details on *FinnCI* and *FiggeCI* see SI section S1.

Neither of the three indicators (*FinnCI*, *FiggeCI*, *CyCt*) is directly related to nutrient use efficiency, because they do not distinguish nutrient removal in product output *O* from nutrient losses (Fig. 1b). To separate the two flows, we introduce *Use* as the nutrient flow through the ‘use compartment’, that is, through the system’s top trophic compartment (indexed *k*) which generates product output *O*. Coefficient $f_{k,\mathrm{prod}}$ then is the fraction of *Use* diverted into product output:

$$O = f_{k,\mathrm{prod}} * Use \tag{5}$$

The ‘use compartments’ in our three case studies (see below) are the crop, animal and human consumer, respectively. *Use* is composed of direct flow and the cycled flow cumulated from all previous inputs. Dividing this summed flow by input *I* gives:

$$UseCt \equiv Use/I \tag{6}$$

UseCt (Use Count) expresses how many times a unit of fresh nutrient input passes, on average, through the ‘use compartment’. Thus, *UseCt* enables to distinguish between nutrient removal in product output *O* and nutrient losses (Eqs. 5 and 6). It follows from Eqs. 5 and 6 that efficiency *O/I* is proportional to *UseCt:*

$$O/I = f_{k,\mathrm{prod}} * UseCt \tag{7}$$

UseCt is related to *CyCt* by*:*

$$UseCt = (1 + CyCt)*(1\text{–}A') \text{ for } A' \le A \tag{8}$$

where A' is the fraction of flow (both direct flow *I* and cycled flow *I*CyCt*) that is lost on the path from the point where *I* enters the system, to the ‘use compartment’. Eq. 8 expresses that *UseCt,* unlike *CyCt,* is sensitive to where *I* enters the cycle. Values of *UseCt* larger than 1 mean that nutrient flow through the ‘use compartment’ exceeds *I,* and imply that re-use of the nutrient by the top trophic compartment overcompensates for removals (losses and product output) from the system (see SI section S3 for more details on indicator value ranges). Combining eqs. 7 and 8 finally gives:

$$O/I = f_{k,\mathrm{prod}} * (1 + CyCt)*(1\text{–}A') \tag{9}$$

Parameters $f_{k,\mathrm{prod}}$ and A' thus provide the link between the cycling of nutrients – full cycles completed – on the one hand, and the system’s nutrient use efficiency (*O/I)* on the other (see also Fig. 1b). Eq. 9 shows that *O/I* consists of a part $f_{k,\mathrm{prod}}*(1\text{–}A')$ that is derived from direct flow, and a part $f_{k,\mathrm{prod}}*CyCt*(1\text{–}A')$ derived from cycled flow. Thus, the ratio between direct and cycled flow contributions to *O/I* is 1:*CyCt.* For food systems where the human consumer is included to constitute the top trophic level, $f_{k,\text{prod}} = 0$ and thus by our particular definition no output O is produced or exported. *UseCt* can then replace O/I to express system nutrient use efficiency.

In addition to direct and cycled components of O/I, a third term can be added to arrive at $(O/I)_R$. This $(O/I)_R$ is the value that O/I could attain if the entire nutrient flow now exported were returned to the system, and re-inserted at the point where it had left the system. Note that – while O still refers to main product output – export covers nutrient flows in main

Table 2
List of parameters, indicators and equations for the schematic hypothetical system illustrated in Fig. 1a. All variables are dimensionless unless indicated otherwise.

$f_{i,\text{loss}}$	Fraction of flow into compartment i that is lost to environment
$f_{i,\text{prod}}$	Fraction of flow into compartment i that leaves the system in the form of exported product
$f_{i,\text{ret}}$	Fraction of flow into compartment i that is retained and passed to the next compartment
Eq. 1	$f_{1,\text{prod}} + f_{1,\text{loss}} + f_{1,\text{ret}} = 1$; $f_{2,\text{loss}} + f_{2,\text{ret}} = 1$; $f_{3,\text{loss}} + f_{3,\text{ret}} = 1$
a_i	Fraction of flow into compartment i that is removed from the system (in products, losses, lower grade products)
Eq. 2	$a_1 = f_{1,\text{prod}} + f_{1,\text{loss}}$; $a_2 = f_{2,\text{loss}}$; $a_3 = f_{3,\text{loss}}$
$a_{i,L}$	Fraction of flow into compartment i that is lost to the environment
	$a_{1,L} = f_{1,\text{loss}}$; $a_{2,L} = f_{2,\text{loss}}$; $a_{3,L} = f_{3,\text{loss}}$
A	Fraction of nutrient flow removed from the system per full cycle
Eq. 3	$(1 - A) = (1 - a_1)*(1 - a_2)*(1 - a_3) = f_{1,\text{ret}} * f_{2,\text{ret}} * f_{3,\text{ret}}$
CyCt	Cycle Count; number of full cycles completed on average by a nutrient input cohort I before the entire cohort has vanished through all exports and losses
Eq. 4	$CyCt = (1 - A)/A$
O	Nutrient flow in product output (mass per time; or mass per time per area)
Use	Total (direct and cycled) nutrient flow into the top trophic compartment ('use compartment') (mass per time; or mass per time per area)
Eq. 5	$O = f_{1,\text{prod}} * Use$
I	Nutrient input (mass per time; or mass per time per area)
UseCt	Use Count; number of times that an input cohort I passes on average through the top trophic compartment ('use compartment')
Eq. 6	$UseCt = Use / (I_1 + I_3)$
O/I	Output / Input ratio
Eq. 7	$O/I = f_{1,\text{prod}} * UseCt$
A'	Fraction of flow that is lost per cycle between original entry point of I into the cycle, and arrival at the top trophic compartment ('use compartment')
Eq. 8	$UseCt = (1 + CyCt) * (1 - A')$ for $A' \leq A$
Eq. 9	$O/I = f_{1,\text{prod}} * (1 + CyCt) * (1 - A')$
A_L	Fraction of flow that would be lost per cycle if no products were exported
$CyCt_R$	Number of full cycles that would be completed on average by an input cohort I if no products were exported
Eq. 10	$CyCt_R = (1 - A_L)/A_L$
$(O/I)_R$	O/I value if all nutrient flow in exported product were returned and re-inserted at the point where it had left the system
Eq. 11	$(O/I)_R = f_{1,\text{prod}} * (1 + CyCt_R) * (1 - A') = f_{1,\text{prod}} * UseCt_R$
*UseCt**	Use count augmented to cover external use of the flow type that typically feeds the top trophic compartment
Use_{ext}	External use of the flow type that typically feeds the top trophic compartment (mass per time; or mass per time per area)
Eq. 12	$UseCt^* = UseCt + Use_{\text{ext}} / (I_1 + I_3)$
O^*/I	O/I augmented to cover output generated externally from lower grade exports
Eq. 13	$O^*/I = O/I + f_{1,\text{prod}} * Use_{\text{ext}} / (I_1 + I_3)$

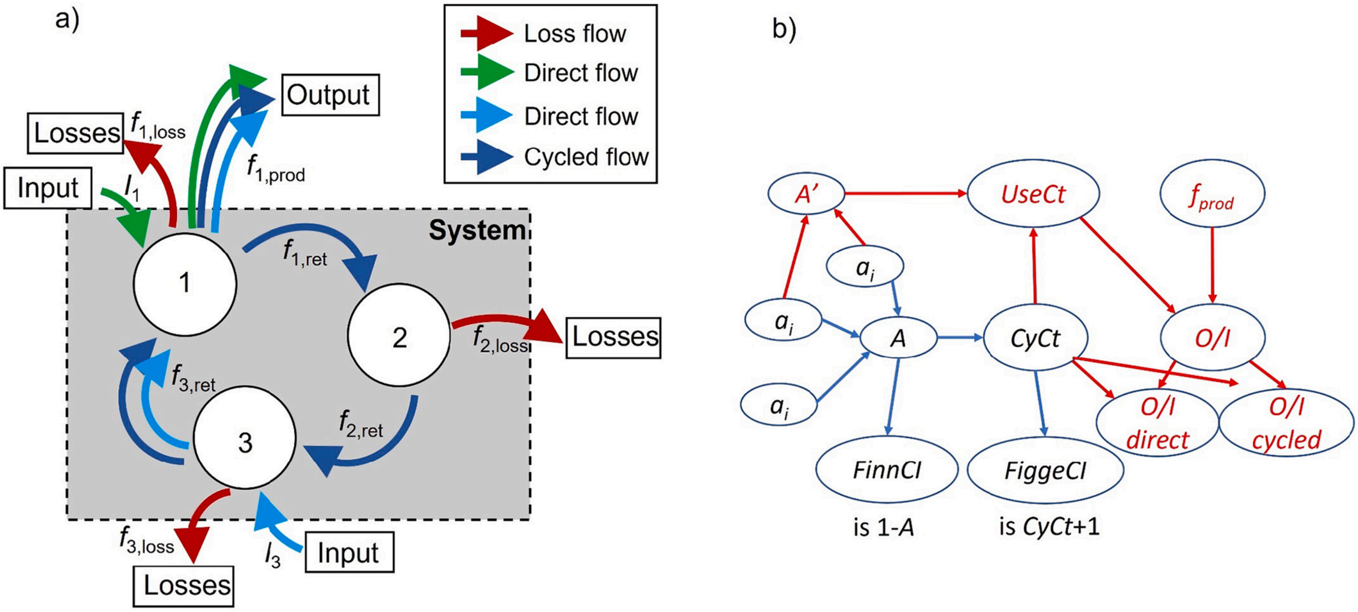

Fig. 1. (a) Example of a cyclic production system with two inputs (I_1, I_3), each with their distinct entry point. Light blue and green arrows represent direct flows from entry point to Compartment 1 which is the top trophic (or 'use') compartment, where product output is generated (e.g. milk by a dairy herd). Direct flows continuing from Compartment 1 to entry points of I_1 and I_3, respectively, are not shown. Dark blue arrows represent cycled flows derived from both I_1 and I_3. Red arrows represent loss flows. (b) Relational diagram showing existing (black) and newly introduced (red) concepts. Note that there can be multiple a_i, all of which contribute to A, but fewer may contribute to A'. For systems with inputs at multiple entry points (compartments), A' is an average weighted by the size of input flows. Our equating of *FinnCI* to (1-A) is valid only for single loop systems (see also Results and Discussion sections). See Table 2 for meaning of symbols and equations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

product as well as by-products, be they of *Use* grade or lower grade. Losses, however, are not part of export. Obviously, complete return of all exported nutrients is hypothetical and not practically possible. To calculate $(O/I)_R$ we need the number of cycles $CyCt_R$ that an input I could complete in absence of exports, that is, if it were subject to in-system losses only:

$$CyCt_R = (1–A_L)/A_L \tag{10}$$

where A_L is the fraction of flow that would be lost per cycle. The difference ($CyCt_R$ – $CyCt$) indicates whether cycling could be substantially increased by returning waste from exported products. Such return is worthwhile when that difference is large. If it is small and $CyCt$ is small, too, then one should better focus on reducing internal nutrient losses. (For natural ecosystems without product output, $CyCt_R$ is equal to $CyCt$). Substituting $CyCt_R$ for $CyCt$ in Eq. 9 gives.

$$(O/I)_R = f_{k,\text{prod}}*(1+CyCt_R)*(1–A') = f_{k,\text{prod}}*UseCt_R \tag{11}$$

where $UseCt_R$ is the number of times a unit input would pass through the 'use compartment' in absence of product output. (It can be argued that $(O/I)_R$ can be obtained more directly by applying the series development in Eq. 4 to O/I. The result, however, is slightly different; see SI section S4). Eq. 11 states that the contribution of 'cycled plus returned' flow to $(O/I)_R$ is proportional to $CyCt_R$. The contributions of direct, cycled and returned flow to O/I are graphically illustrated in Fig. 2 for a case presented later (Section 2.2; see also SI excel sheet "N-dairy-OI-example" and "P-dairy-OI-example".)

In all of the above, nutrient output O refers exclusively to the main product output from the top trophic compartment, the *raison d'être* of the system. Complicating matters, however, farms and food systems may export multiple flows, some of which may be of lower grade than the main product. A dairy farm exports milk and meat as main outputs, but may also export manure which is used elsewhere, and hence is not a loss. To account for such lower-grade exports we convert them – by passing them through the cycle, using the system's own partitioning coefficients (Eq. 1) – into the material flow type that could feed the system's top user, e.g. into feed for cattle in the dairy farm. Such presumed external use (Use_{ext}) is then included in the expanded indicator $UseCt^*$ according to:

$$UseCt^* \equiv UseCt + Use_{ext}/I \tag{12}$$

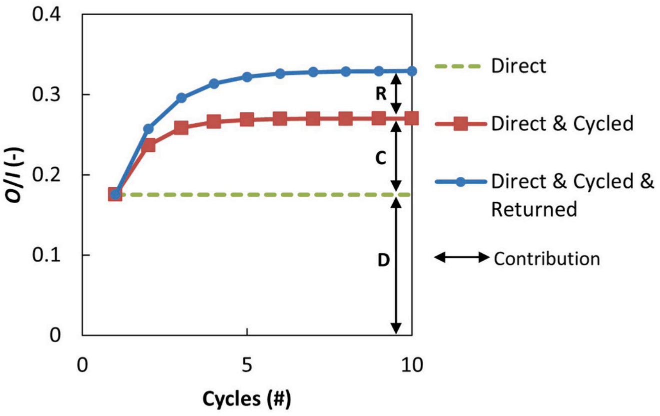

Fig. 2. O/I (Output/Input) ratio for N cycling at De Marke, a Dutch experimental dairy farm (see also Fig. 4), and its partitioning into contributions by direct flow (arrow D), and cycled flow (arrow C). The increment of O/I that could – hypothetically, see text – be attained by full retrieval and back-feeding of nutrients from external waste flow is indicated by arrow R. It constitutes no part of O/I, but of $(O/I)_R$. See explanation in text and in SI excel sheet "N-dairy-OI-example".

A corrected main product output O^* accounts for such by-product exports:

$$O^*/I \equiv O/I + f_{k,\text{prod}}*Use_{ext}/I \tag{13}$$

In special cases, the exported flow is of the same grade as the *Use* flow, i.e. meant for the same trophic level as the *Use* flow. Examples are the export of 'home-grown' roughage from a dairy farm; and the export of excess human food from systems that include the human consumer as top level (as in Flanders food system, see Section 2.2). In such cases no conversion such as described prior to Eq. 12 is needed, and Use_{ext} is equal to the exported by-product flow.

Eqs. 7, 9, 11 and 13 thus connect system circularity with nutrient use efficiency, O/I. Recognizing this connection is essential when circularity of agro-food systems is promoted to reduce emissions and resource use, whilst ensuring sufficient food output.

2.2. *Cases to illustrate circularity indicators and the contribution of cycling to nutrient use efficiency*

The first case is a crop-soil system, illustrated in Fig. 3a (N) and 3b (P). It represents a field plot from the long-term winter wheat experiment at Broadbalk, UK (Rothamsted Research, 2021). The treatment has run since 1986. Nutrient flows are based on the treatment where only grain is exported and straw is retained on the field. N deposition is ignored. Partitioning coefficients are derived from Rothamsted Research (2021) and represent averages over two seasons (1998–1999) and over all seven N rates applied in the experiment (ranging from 0 to 280 kg N ha^{-1}). Most likely, the short time lapse since the treatment started (12 years) implies that soil nutrient pools are not yet in steady state. Aggregated coefficients (A and A') are given in Table 3.

The second case is the experimental dairy farm De Marke in the Netherlands (Fig. 4a, b for N and P, respectively). This four-compartment representation of a dairy farm was first proposed by Schröder et al. (2003). Partitioning coefficients are based on Oenema (2013), and the intensities (N and P inputs per ha per year in feed and fertiliser) are based on Aarts (2000). Aggregated coefficients (A and A') are given in Table 4.

Nutrient use efficiency is known to increase for an agricultural system when losses are externalized, for example by using imported feed instead of home-grown forage. The other option – perhaps more truthful – is reducing internal losses, for example by improving manure storage, or improving feed conversion through choice of livestock breed or diet. To assess whether circularity indicators and O/I respond similarly or differently to such interventions, we investigated effects of changes in: i) feed nutrient import as fraction of total nutrient intake by the herd; ii) the efficiency by which the herd converts feed to milk and meat; and iii) the efficiency by which nutrients excreted by the herd are made available for crop uptake.

The third case illustrates a food system that includes, besides primary production, also food processing and the human consumer. The example refers to the Belgian region of Flanders as taken from Papangelou and Mathijs (2021). Following their approach, subsystems distinguished as separate compartments are called 'Agriculture', 'Food industry', and 'Waste management'. Nutrient flows in our example refer to the year 2014. Partitioning coefficients were derived from Papangelou and Mathijs (2021). Aggregated coefficients (A and A') are given in Table 5. For N and P we investigate how circularity indicators and O/I respond to the fraction of consumer waste flow cycled back to the 'Agriculture' and 'Food industry' compartments. Note, that this refers to waste cycling within the system, and not to the retrieval of external waste flows implied in Eqs. 10 and 11.

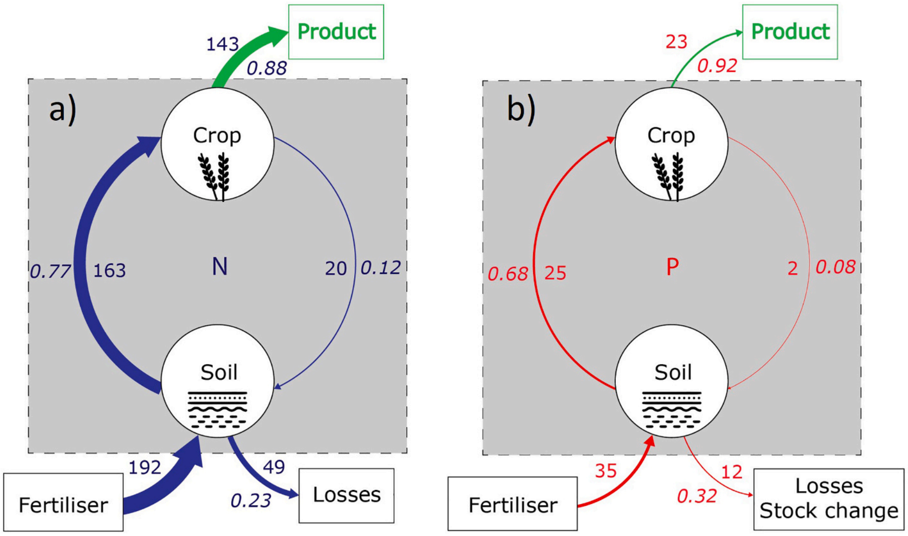

Fig. 3. Simplified representation of nutrient flows at Broadbalk (UK) for field plots in the continuous winter wheat experiment where straw is returned to the field. Values larger than 1 represent nitrogen (a) and phosphorus (b) flows in kg ha^{-1} year^{-1}. Values in italic (smaller than 1) represent partitioning coefficients with reference to total inflow into the corresponding compartment (Eq. 1), values for outgoing arrows adding up to 1. Data source: Rothamsted Research (2021).

Table 3
System parameters (A, A', $f_{k,\mathrm{prod}}$), nutrient surplus, flow contributions to nutrient use efficiency *O/I*, and circularity indicators for N and P in the crop – soil system (continuous wheat plots with straw returned at Broadbalk, UK). See Table 1 for definitions of output and input and Table 2 for acronyms.

	N	P
A	0.91	0.95
1-*A*	0.09	0.05
A′	0.23	0.32
$f_{k,\mathrm{prod}}$	0.88	0.92
Surplus (kg ha^{-1} year^{-1})	49	12
O/I	0.74	0.66
O/I part from direct flow	0.67	0.62
O/I part from cycled flow	0.07	0.04
CyCt	0.10	0.06
$CyCt_R$	3.33	2.08
$CyCt_R$ - *CyCt*	3.22	2.03
UseCt	0.85	0.71
FinnCI	0.09	0.05
FiggeCI	1.10	1.06

3. Results

3.1. Circularity in the wheat field case (crop – Soil system)

Fig. 3 shows the nutrient flows for the crop-soil system at Broadbalk, UK. Nutrient input is via fertiliser, part of which is taken up by the crop (Table 1); the remainder part is lost (or stored in soil if no steady state was reached). *Use* is defined as the uptake of a nutrient (N or P) in the total aboveground crop biomass (kg ha^{-1} year^{-1}) and includes uptake from soil nutrient supply.

A relatively large part of nutrient import leaves the crop-soil system per cycle, with *A* values of 0.91 (=1–0.12*0.77) for N, and 0.95 (=1–0.08*0.68) for P (Eq. 3, Fig. 3). Most of this removal is in the form of harvested grain, the sole product output, and this flow represents a large fraction of crop nutrient uptake with $f_{k,prod}$ values of 0.88 (N) and 0.92 (P). Crop residues are incorporated into the soil, from where part of the nutrients are lost and others become part of the soil nutrient supply. Total system surplus is 49 kg N and 12 kg P per ha. As a result of large nutrient export in grain, *CyCt* is low with values of 0.10 (N) and 0.06 (P), while total *O/I* is relatively high at 0.74 (N) and 0.66 (P). Low *CyCt* results in small contributions of cycling to *O/I* as compared to the direct flow contribution, this holds for both for N and P (Table 3). In short, the system is largely linear and fertiliser-driven. Furthermore, the relatively high $CyCt_R$ value of 3.33 for N signifies that a unit of fertiliser N imported could be used (as crop N uptake) 3.33 times over, if all N exported in grain could be returned to the field. This implies that internal losses are relatively small, consistent with high *O/I*. *FinnCI* is low (0.09 for N and 0.05 for P), again indicating low cycling intensity. Overall, indicator values are lower for P than for N (See Discussion).

3.2. Circularity in the dairy farm case (soil – Crop – Cattle system)

Fig. 4 shows the flows of N and P in dairy farm De Marke in Hengelo, the Netherlands. *Use* is here defined as nutrient intake by the dairy herd (kg ha^{-1} year^{-1}). It consists of N and P in feed imports (largely concentrates) and on-farm cultivated feed crops.

The fractions ($f_{k,prod}$) of feed nutrient intake by the herd that are exported in milk and meat are 25% (N) and 30% (P) (Fig. 4; Table 4). Large N losses occur from manure, both from storage and land application (NH_3), and from soil (N_2O and NO_3). Phosphorus is less prone to loss than N which results in higher *O/I* (Table 4). Corresponding surplus values at farm gate balance are 174 (N) and 5 (P) kg ha^{-1} year^{-1}. The fraction of N flow removed per cycle (*A*) is 0.65 (=1–0.75*0.80*0.65*0.90); for P this fraction *A* is 0.40 (=1–0.70*1.00*0.95*0.90). For P, 85% of flow to the soil comes from cattle manure, for N this is only 50% (Fig. 2). This corresponds to relatively high *CyCt* (1.49 vs 0.54, Table 4), and contribution of cycled flow to *O/I* for P as compared to N. For P, cycled flow contributes more to *O/I* than direct flow (0.43 vs 0.29). This is reversed in the case of N, though both flow contributions are small here at 0.18 and 0.10, respectively, due to high N losses (Table 4).

Values of circularity indicators are between 1.7 and 6.8 times higher for P than for N (Table 4), resulting in *O/I* being 2.6 times higher for P than for N. As compared to the crop-soil system, the dairy farm shows higher values for all circularity indicators (except $CyCt_R$ which does not refer to circularity of the system itself), but much lower *O/I* and higher N losses. This illustrates that caution is required when circularity is compared between different systems (e.g. dairy vs arable farms), and that circularity by itself is no clue to efficiency.

The effects of changes in system parameters (Section 2.2) on circularity indicators for the Dutch dairy farm are shown in Fig. 5. Feed nutrient import as fraction of total nutrient import does not affect *CyCt*, $CyCt_R$, *FinnCI* and *FiggeCI* (Fig. 5a,c) because these indicators relate to the number of full cycles completed, which is insensitive to the entry point of nutrients into the cycle. In contrast, *UseCt* and *O/I* increase with increasing feed nutrient import (Fig. 5a,c) because this flow arrives directly at the *Use* compartment, so none of it is lost before ingestion and conversion to product output (milk and meat). Note, that losses associated with imported feed production are external to our system.

Second, the effects of the efficiency by which nutrients in feed are transferred to dairy products ($f_{k,prod}$) is shown in Fig. 5b,e. At higher $f_{k,prod}$, a smaller flow fraction remains within the system as manure cycled to soil and crop. While this increases the *O/I* ratio, it reduces all circularity indicators. In this case, less cycling means lower losses. Further, $CyCt_R$ remains unaffected by $f_{k,prod}$ (Fig. 5b,e). As long as there is no loss from the herd compartment itself, it makes no difference whether excreted nutrients pass directly from herd to soil, or make a detour via the consumer. Remember that full recovery and return of external consumer waste (urine and faeces) back to the dairy farm is presumed in the definition of $CyCt_R$ – highly hypothetical of course.

Finally, Figs. 5c,f show that increasing the efficiency by which manure N or P are transferred to soil N or P, respectively, increases all circularity indicators. Higher efficiency here means lower ammonia losses for N. (For P, however, losses in manure to soil transfer are unlikely, so the graph can be seen as a theoretical exercise). Obviously, also *O/I* and $CyCt_R$ increase when losses from the system are reduced. All responses are supra-proportional due to positive feedback between system nutrient retention (1-*A*) and cycle count (see also Fig. S2.1; and Eq. 4). This is most visible in $CyCt_R$ for P (Fig. 5f): a unit of original P import could complete over six cycles if – again hypothetically – all external consumer P waste could be returned to the farm.

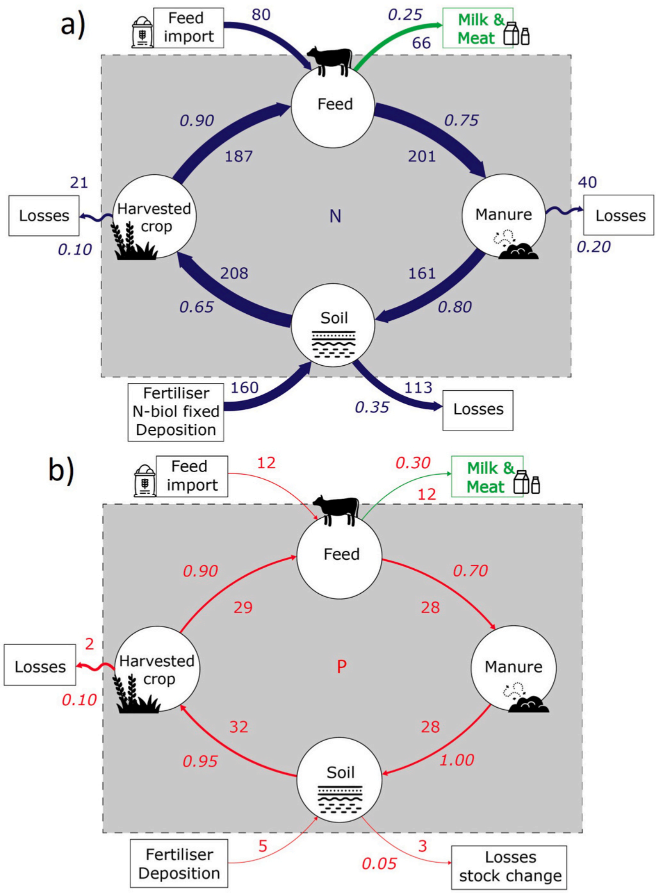

Fig. 4. Simplified representation of nutrient flows at De Marke experimental dairy farm in Hengelo, the Netherlands (soil – crop – cattle system). Values larger than 1 represent nitrogen (a) and phosphorus (b) flows in kg ha^{-1} year^{-1}. Values in italic (equal to or smaller than 1) represent partitioning coefficients with reference to total inflow into the corresponding compartment (Eq. 1), values for outgoing arrows adding up to 1. Data sources: Oenema (2013) and Aarts (2000).

Table 4
System parameters (A, A', $f_{k,prod}$), nutrient surplus, flow contributions to nutrient use efficiency *O/I*, and circularity indicators for N and P for the soil – crop – cattle system (dairy farm De Marke at Hengelo, the Netherlands). See Table 1 for definitions of output and input and Table 2 for acronyms.

	N	P
A	0.65	0.40
1-*A*	0.35	0.60
A' (see *)	0.28	0.04
$f_{k,prod}$	0.25	0.30
Surplus (kg ha^{-1} year^{-1})	174	5
O/I	0.28	0.72
O/I part from direct flow	0.18	0.29
O/I part from cycled flow	0.10	0.43
CyCt	0.54	1.49
$CyCt_R$	0.87	5.96
$CyCt_R$ - *CyCt*	0.33	4.47
UseCt	1.11	2.39
FinnCI	0.35	0.60
FiggeCI	1.54	2.49

* A' is the weighted average over feed and fertiliser imports, as these enter the system in different compartments.

3.3. *Circularity at regional scale (agro-food system)*

As shown in Fig. 6, Flanders is highly export oriented with more N in export of food or feed than in domestic food consumption. N losses are largest from the livestock sector, while P losses are largest from the food industry. *Use* is defined as the nutrient intake by the system's top trophic level, which in this case is the human consumer (see also Table 1). The *Use* flow is represented by the flow from the 'Agriculture & Food Industry' to the 'Consumption' compartment (Fig. 6). A prerequisite for the calculation of *CyCt* is that the system can be regarded as circular (see Section 2.1). Therefore selected compartments distinguished by Papangelou and Mathijs (2021) in the full scheme (Fig. 6a,c) were aggregated to demonstrate that the system can be viewed as a single cycle (Fig. 6b,d). *FinnCI* values differ substantially between full and aggregated schemes (cf. the corresponding lines in Table 5). This underlines that *FinnCI* in the first place is a complexity indicator: its value depends strongly on the number of compartments distinguished; none of the other indicators is affected by the aggregation (data not shown).

Table 5
System parameters (A, A', $f_{k,prod}$), nutrient surplus, flow contributions to nutrient use efficiency *O/I*, and circularity indicators for N and P for the Flanders regional food system documented by Papangelou and Mathijs (2021). See Table 1 for definitions of output and input, and Table 2 for acronyms. Acronyms that include an asterix include use by external consumers. Direct and cycled parts of *O/I* are not given because *O/I* equals zero. For direct and cycled parts of *UseCt*, see text.

	N	P
A	0.98	0.98
1-*A*	0.02	0.02
A'	0.86	0.86
$f_{k,prod}$	0	0
Surplus (kt year^{-1})	170	27
O/I	0.00	0.00
O/I*	0.00	0.00
CyCt	0.02	0.02
$CyCt_R$	0.05	0.09
$CyCt_R$ - *CyCt*	0.03	0.07
UseCt	0.14	0.14
*UseCt**	0.31	0.32
FinnCI-full scheme	0.24	0.26
FinnCI-aggregated	0.02	0.02
FiggeCI	1.02	1.02

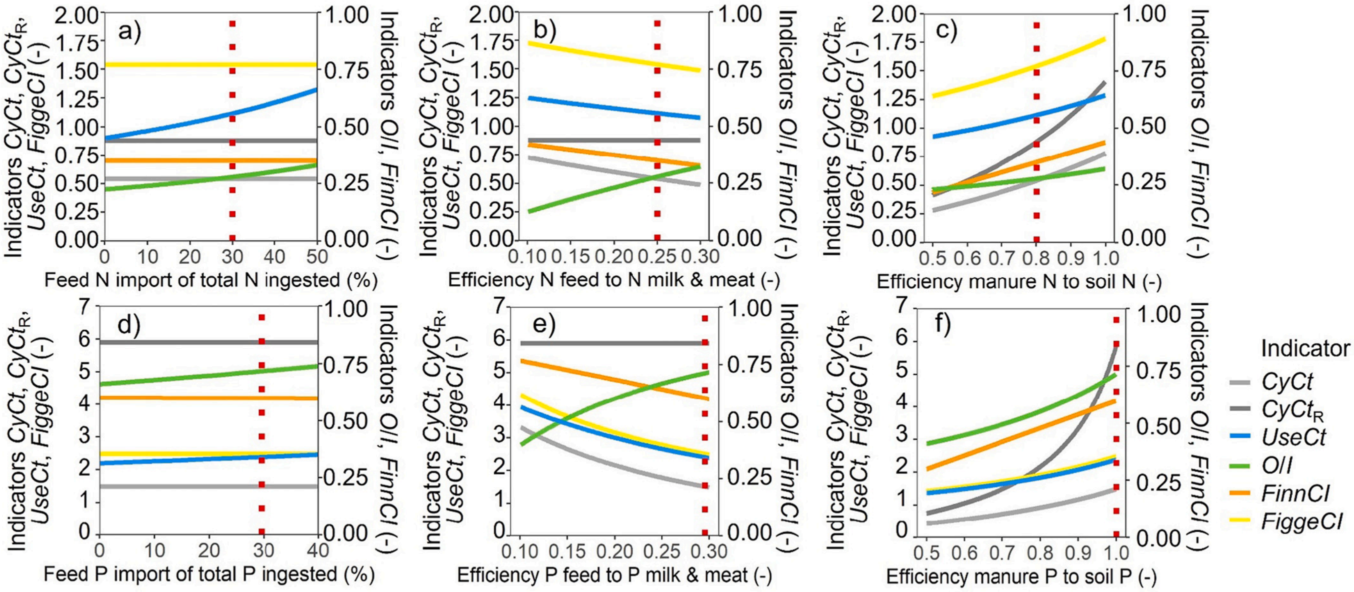

Fig. 5. Circularity indicator and *O/I* values for N (top row) and P (bottom row) in the dairy farm case, as function of: (subfig. a,d) feed nutrient import as fraction of herd nutrient ingested; (subfig. b,e) efficiency of feed nutrient conversion to nutrient output in milk and meat; and (subfig. c,f) efficiency of manure nutrient conversion to soil nutrients. Dashed red lines represent original values for De Marke in Hengelo, the Netherlands, as given by Oenema (2013) and used in Fig. 4 and Table 4. For each graph, parameters not varied were maintained at their original value as given in Fig. 4. (For colours, the reader is referred to the web version of this article.)

Because we defined output *O* as the nutrient flow in products exported *from* the top trophic compartment (here the human consumer), *O/I* is zero (nutrient accumulation in human body mass gain is ignored, moreover it is not exported). The same holds for products *from* the external consumer, hence *O*/I* is zero, too. Nutrient (N, P) exports in human food products and lower grade flows (e.g. manure) are accounted for in *UseCt** which expresses the sum of internal and (potential) external consumption by humans, relative to original nutrient input.

While internal consumption is 14% (N) and 14% (P) of nutrient import to Flanders (cf. *UseCt*, Table 5), *UseCt** is roughly two times these values. This reflects that consumption elsewhere (*UseCt** minus *UseCt*) is somewhat larger than 'home consumption'. Still, only about 30% of original N and P imports (in feed and fertilisers) reaches the human consumer in Flanders or elsewhere, its complement being wasted (or stored, e.g. in soil).

The agro-food system of Flanders is highly linear: cycling is virtually absent. Among the three systems investigated, the Flanders' food system showed lowest values for all circularity indicators, except *FinnCI*. Due to large export and loss terms, *A* is high (0.98 for both N and P, Table 5) resulting in very low *CyCt* and *FiggeCI* values (Table 5; note that *FiggeCI* is always 1 point higher than *CyCt*, see Section 2.1). Several of the circularity indicators values are slightly higher for P than for N, but absolute differences are small. In contrast to the earlier cases (Tables 3,4), contributions of cycling to *O/I* cannot be stated here because *O/I* itself is zero. It can be seen, however, that cycled flow (cf. *CyCt*, Table 5) contributes only about 2% ($=0.02/(1+0.02)$) to the N and P nutrient flow to consumers (*UseCt* and *UseCt**), its complement (98%) being direct flow.

The small *CyCt*$_R$ values of 0.05 (N) and 0.09 (P) signify that even if all nutrient export flows (human food products; animal feed and manure) were fully returned, hardly any cycling would occur: only 5% (N) and 9% (P) of original nutrient inputs would complete the full cycle. The Flanders food system is very 'leaky' due to both high losses from the 'Agriculture & Industry' subsystem (134 kt N year^{-1} and 22 kt P year^{-1}) and – less important – due to disposal of most internal consumer waste (Fig. 6b,d.).

Currently, 13% (N) and 18% (P) of the nutrient flow to the internal waste bin (Fig. 6b,d) cycles back to the 'Agriculture & Food Industry' subsystem. Full recycling of consumer waste nutrients only slightly increases most cycling indicators except for *CyCt*$_R$ (Fig. 7a,b). Nevertheless, even this indicator – which presumes cycle counts are governed only by losses, not exports – does not reach a value of 1 (Fig. 7a,b, end point of black curve) when internal food waste and human excreta are fully recycled. In other words, a unit of original nutrient import would not even be used once, on average, under full recycling of consumer waste bin nutrients *and* full return of waste from external consumers. Again, this underlines high losses from within the system. For N, losses are largely from the livestock sector (Fig. 4a), which was also observed in our dairy farm case. For P they are mainly from the food industry subsystem (Fig. 4c). These leaks are the main reason why all circularity indicators remain low.

4. Discussion

4.1. Significance of cycle counters

Among the circularity indicators evaluated here, *UseCt, UseCt*, CyCt*$_R$ are newly introduced (*CyCt* was already a component of *FiggeCI*, Fig. 1b). They express how many times an input cohort passes through the top trophic compartment (*UseCt*), or passes through any top trophic user including external users (*UseCt**), or how many times such cohort would complete the full cycle if it were subject to internal losses only (i.e. no exports) (*CyCt*$_R$). What do we gain by the new indicators? We consider three possible applications. First, their main added value lies in linking the concept of cycling to nutrient use efficiency (Eqs. 7, 9, 11 and 13). For systems not yet in steady state equilibrium, the future equilibrium *O/I* can now be easily obtained from basic system properties, that is, from the partitioning coefficients in Eq. 1 (see also SI excel sheet "N-dairy-OI-example", "P-dairy-OI-example"). The new indicators can thus also help to predict how *O/I* will respond to changes in system

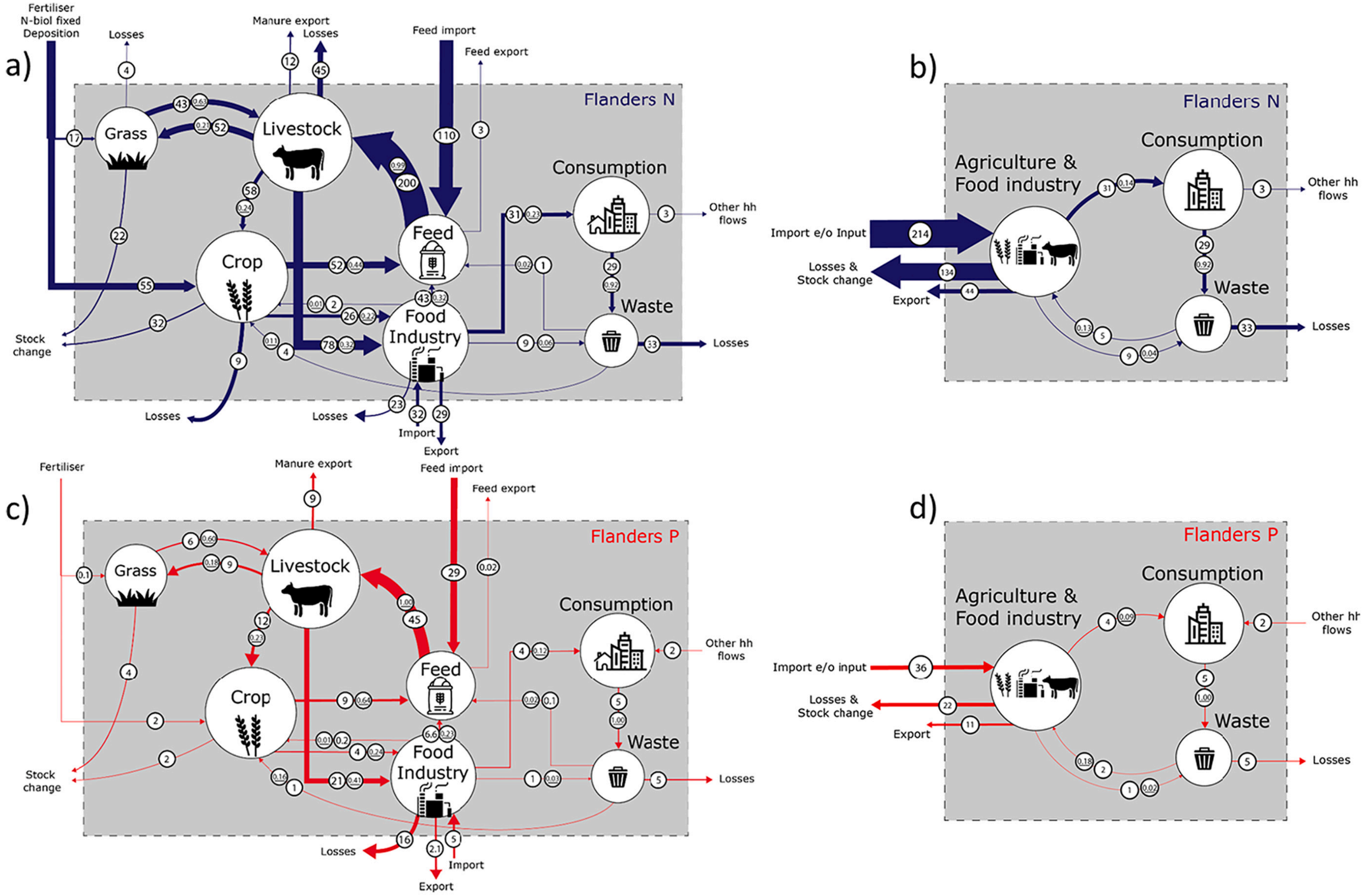

Fig. 6. Simplified representation of nutrient flows in the Flanders agro-food system. Values not underlined represent nitrogen (a,b) and phosphorus (c,d) flows in kt year^{-1}. Values underlined represent partitioning coefficients with reference to total inflow into the corresponding compartment (Eq. 1), values for outgoing arrows adding up to 1. Subfigures a and c represent the 'full scheme' after Papangelou and Mathijs (2021). In subfigures b and d, selected compartments were aggregated to show that the system can be approximated as being composed of compartments linked into a single cycle. Data source: Papangelou and Mathijs (2021).

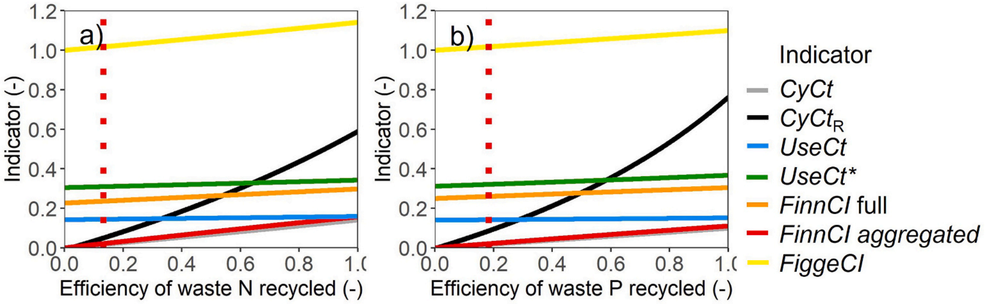

Fig. 7. Circularity indicator values for agro-food system of Flanders as function of the efficiency of internal waste bin N (a) and P (b) recycling to the 'Agriculture & Industry' subsystem. Dashed red line represents the original value based on Papangelou and Mathijs (2021) (see Fig. 6 for the complete system description). (For colours, the reader is referred to the web version of this article.)

properties, and – for *CyCt*$_R$ – to the retrieval of external waste flows. Second, within similar agricultural systems (e.g. dairy farms), the indicators can be used to benchmark nutrient cycling. Third, comparisons between *CyCt* and *CyCt*$_R$ may help prioritize among measures that minimize losses from within the system versus measures that increase the return of external waste N and P flows back to the system.

While nutrient use efficiency (*O/I*) is proportional to *UseCt*, these indicators themselves respond supra-proportionally to the nutrient retention fraction per cycle (1-*A*). This positive feedback is illustrated in Fig. 6 for the dairy farm. A larger fraction retained (by minimizing system losses) or returned (from external consumer waste) generates more product output, but also more residual flow from the Use compartment, and that flow in turn contributes to more product output, etc., ad infinitum. Thus, the new indicators help to quantify the contribution of cycled flow to *O/I*, which otherwise cannot be seen directly from the partitioning coefficients. This 'cycled' contribution can be relatively large, as shown for P in the dairy farm case.

4.2. Easy to calculate or measure

Among the indicators, *FinnCI* is the more complex to calculate or measure because all flows – both internal and external – must be known (Finn, 1980). In comparison, the other indicators can be assessed more easily, either by calculation (from retention coefficients $f_{i,\mathrm{ret}}$) or by measuring the flow through the compartment that first receives the fresh nutrient input (for *CyCt*, *FiggeCI*), or measuring the flow through the compartment that produces the main system output (for *UseCt*). Unlike *CyCt*, both *FiggeCI* and *UseCt* incorporate direct flow; but *UseCt* accounts for losses from direct flow, unlike *FiggeCI*. In the dairy farm case, for example, only 70% (weighted average over feed and fertiliser imports) of N input reaches the herd as direct flow.

4.3. Circularity indicators for P larger than for N, assuming steady state equilibrium

In two of the cases presented – the dairy farm and the Flanders agro-food system – virtually all circularity indicators show larger values for P than for N (Tables 4, 5). This is because N is more mobile and prone to losses (ammonia volatilisation, nitrate leaching, and denitrification) than P (e.g. Addiscott and Powlson, 1992; Bussink and Oenema, 1998; Hilton et al., 2010). For our crop-soil case, however, nutrient cycling was lower for P rather than N (Table 3). We attribute this to accumulation of P in the soil, which would violate the steady state condition. Indeed, P input was halted in this experiment in the year 2000 and from then onward, crops utilise soil P built up in previous years (Rothamsted Research, 2021).

4.4. Aggregation, complexity/scale, and retrieval of export flow

Our three cases – field, farm and food system – differ in complexity and scale. As already mentioned by Rufino et al. (2009), *FinnCI* responds strongly to aggregation of compartments (Table 5). The other indicators remain unaffected by aggregation (not shown).

A short comment on the impact of system boundary choice, i.e. of internalizing a component that was external at first, on circularity indicators. Because *CyCt*$_R$ presumes that all nutrients contained in outputs are returned to field or farm, (*CyCt*$_R$-*CyCt*) expresses the effect of extending the system boundaries. The size of this difference (e.g. Table 4 for dairy farm) confirms the notion that widening system boundaries increases opportunities for recycling and re-use. Returning consumer waste back to dairy farms contributes little to N cycling (as shown by the small difference between *CyCt* and *CyCt*$_R$). This is because large losses occur on the farm itself. Thus for N, the high environmental impact of intensive dairy farming cannot be resolved by recycling consumer waste. Rather, reducing inputs would be more effective, besides measures to increase N retention by the system. P cycling, on the other hand, could be dramatically increased by returning external consumer waste P to the farm (Table 4). Alternatively, arable cropping (Table 3) shows much larger potential for re-use of nutrients by returning consumer waste to the farm, both for N and P, because system losses are smaller and exports larger.

In contrast to the above 'extending boundaries' exercise, direct comparison of *CyCt* values between field, farm and region clearly demonstrates that increasing system scale or complexity alone does not necessarily increase *CyCt*. The most complex system (Flanders agro-food) shows the lowest *CyCt*. In this case both losses and food exports are high, leading to very high fractions of nutrient removal per cycle, thus low *CyCt* and *UseCt* (Table 5). Only a small part of the internal waste flow is cycled back to the production compartments (Fig. 6). Further, accounting for exported food products – external consumption – roughly doubles (N, P) the use count (Table 5, cf. *UseCt** versus *UseCt*). It remains nevertheless remarkable that, all in all, only 31% (N) or 32% (P) of nutrient imports will ever be consumed by humans (Table 5). This is mainly due to high losses from the 'Agriculture & Industry' subsystem. So here *UseCt* and *UseCt** serve as indicators of whole system nutrient use efficiency, for lack of *O/I* as the regular efficiency indicator, now that humans are included.

4.5. Varying system properties and nutrient recovery from waste flows

The value ranges set for the various system parameters in our sensitivity analyses (Figs. 5 and 7) are only hypothetical. For example, it is unsure which level of consumer waste recycling to 'Agriculture & Industry' could actually be realised, and where (to which compartment) this flow would enter (Fig. 7). Recovering nutrients from waste flow is already difficult for P, it would be even more difficult for N without drastic systemic changes. Recent studies investigated the potential of such alternative waste-management to make improved recycling of consumer waste-streams possible (e.g. Van Dijk et al., 2017; Vijn and Weijma, 2020).

4.6. Limitations

Interpretation of the presented indicators can be challenging, especially if circularity is only assessed for a small section of an agro-food system. For example, while *UseCt* increases with increasing feed import on a dairy farm (Fig. 5a,c), importing feed should not be promoted as a strategy to increase circularity. Rather, this indicator can be used to compare farms with the same amount of feed import, or the nutrient flows associated with feed production must be included to make a meaningful comparison at a higher systems level. The choice of system boundaries is therefore crucial when assessing impacts of interventions on circularity.

4.7. Final note: multiple top trophic levels

The approach presented in this paper is largely confined to systems that can be represented by compartments connected in series, to form a single loop. Occurrence of parallel flows or local subsystem loops can violate this condition, but often these smaller flows can be incorporated by extending compartment boundaries, as in the Flanders agro-food system case. Moreover, there must be a clearly distinguishable top trophic level ('user' in our terminology): the crop, the herd or the human consumer in our respective cases. Systems with multiple 'users' are perhaps too complex to describe by our metrics. For example, a region with arable farming and animal farming but lacking the human consumer has no clear top trophic level, except when all arable products are fed to animals.

5. Conclusion

Nutrient cycle count (*CyCt*), expresses how many times a unit of nutrient input completes a full cycle in a circular system – such as an arable field, a dairy farm or a regional food system. With the help of *CyCt*, the overall nutrient use efficiency of a system (*O/I*) can be split into a part that is derived from direct flow, and a part that is derived from cycled flow. The ratio between the two contributions is 1:*CyCt*.

UseCt is the number of times a unit nutrient input passes through the top trophic compartment of a system, in arable systems represented by the crop, in dairy systems by the dairy herd, and in regional food systems possibly by the human consumer. Nutrient use efficiency is then proportional to *UseCt*.

We showed that arable systems can be highly linear but simultaneously efficient in terms of nutrient use efficiency. In the crop-soil system, nutrient use efficiencies are 74% and 66% for N and P, respectively, but cycled flow contributes only for 9% and 5% to these high efficiencies.

Cycling is higher in the Dutch intensive dairy farm example than in the other two cases. Yet, much lower *O/I* were found here (0.28 for N, 0.72 for P), with larger contributions of cycled flow to *O/I* than in the other two cases. In the dairy farm 35% (N) and 60% (P) of *O/I* comes from cycled flow, and a unit of P imported to the farm passes 2.39 times through the dairy herd. Furthermore, the small difference between *CyCt* and $CyCt_R$ for N shows that the large environmental impact of the dairy farm cannot be resolved by recycling consumer waste. Reducing N inputs would be more effective, besides measures to increase system N retention (reduce losses). P cycling, on the other hand, could be dramatically increased by returning external consumer waste P to the farm.

In the Flanders regional food system, cycled flow contributes least to system performance, with only 2% of total N and P flows that reach the human consumer being cycled flow. In total, about 30% of total N or P input (i.e. in feed and fertiliser imports) reaches human consumers in Flanders or elsewhere. About 70% is lost or accumulated.

When systems of different scale or complexity are ranked by increasing nutrient use efficiency, their corresponding circularity indicators *CyCt* or *UseCt* do not necessarily increase in the same order. Across different systems, higher circularity does not imply higher nutrient use efficiency, or vice versa. When aiming to reduce environmental impact and resource requirements, however, circularity indicators may help to prioritize between measures directed at minimizing losses from the system on the one hand, and measures to increase the returning of external waste flows on the other. In the quest for designing sustainable agricultural and food systems, other indicators besides circularity indicators are also needed.

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

Nutrient flows for the arable field system were obtained from long-term winter wheat experiment at Broadbalk, UK (Rothamsted Research, 2021); for the farm system from dairy farm De Marke at Hengelo, the Netherlands (Schröder et al. 2003; Oenema 2013; Aarts 2000). Nutrient flows for the Flanders regional food system were obtained from Papangelou and Mathijs (2021). See also SI excel sheet for all data used in this study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103610.

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