RADIANT-Metrics: Conceptual framework

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Lead Author(s): David Styles

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- **Deliverable description:**

This deliverable report outlines the conceptual framework for *RADIANT-Metrics,* a novel approach to more holistically evaluate the comparative sustainability and resilience of underutilised crops and/or dynamic value chains.

- **Contributors (Institution)**
  - Chiara Bassignana, UNISG
  - Elena Bortolazzo, CRPA
  - Marie-Fleur Bremaud, WUR
  - Marko Debeljak, JSI
  - Yann de Mey, WUR
  - Paola Migliorini, UNISG
  - Sophie Saget, TCD
  - Mike Williams, TCD
  - Marta Vasconcelos

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Executive Summary

Life cycle assessment (LCA) brings rigour in terms of clear scope and boundary definition to capture environmental impacts across whole value chains in relation to specific functionality. However, this increasingly used approach is often based on "snapshots" of system performance that fail to represent critical long-term and cumulative sustainability and resilience attributes that are increasingly recognised as key areas of vulnerability for industrial food systems.

The *RADIANT* project is specifically evaluating the potential contribution of underutilised crops (UC) and dynamic value chains (DVC) to support a sustainable and resilient food (and bioenergy/biomaterial) system transition. This deliverable report proposes a conceptual framework for a *RADIANT-Metrics* approach capable of benchmarking the sustainability and resilience of UC DVC against conventional industrial value chain counterparts. The framework is underpinned by life cycle *thinking,* and incorporates quantitative LCA methodology, but includes a wider suite of semi-quantitative metrics under the themes of: environmental burdens, ecosystem services delivery, resilience, and economic performance. It was developed based on experience assessing the environmental sustainability of legume value chains in the recent *TRUE* project, and through two workshops bringing together core stakeholders from the *RADIANT* project. These workshops identified important attributes and appropriate sub-indicators to incorporate within *RADIANT-Metrics*.

In line with the core objective of identifying (ranking) relative sustainability and resilience across comparator crops, farms, value chains and deployment scenarios, the framework can operate at multiple levels depending on user-defined scope (in line with LCA principles) and appropriate data collection. Furthermore, the framework can be applied using different combinations of sub-indicators depending on data availability, translated into final comparative 0-1 scores across each theme to provide an indication of relative strengths and weakness of UC and/or DVCs. These scores can be presented in parallel with more quantitative LCA and economic indicators that can be calculated based on well-defined methodologies.

The proposed *RADIANT-Metrics* conceptual framework presented here is a starting point for more holistic assessment. It will be tested, revised and (re-)applied to *RADIANT* AURORA case studies and participatory farms over the remaining three years of the RADIANT project in order to improve sustainability and resilience assessment of food (and biomaterial/bioenergy) systems.

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1. Purpose of the Deliverable

1.1 Industrialised food systems

Industrialised food systems are characterised by high levels of technical efficiency along individual stages of the chain (cultivation, processing), at the expense of high levels of waste (especially from consumers), low profit margins on farms, and loss of non-provisioning ecosystem service delivery. Industrialised food systems are associated with a low level of resilience (e.g. drought vulnerability owing to depletion of soil organic matter and low capacity of farms and value chains to anticipate and respond to shocks and stresses) (Berti & Mulligan, 2016). The premise of the *RADIANT* project is that the wider cultivation of underutilised crops (UC) across agricultural systems could be a key component, and possibly a driver, of the transformative change needed to realise a sustainable and resilient food (and biomaterial/bioenergy) system. Underutilised crops are highly diverse, including, *inter alia*, legumes, horticultural crops, traditional fruit trees, landraces. By definition, UC are not widely cultivated in particular regions, so that their introduction will necessitate new and adapted value chains to process and distribute outputs to consumers, potentially as unique products. Thus, UC deployment is linked with the concept of dynamic value chains (DVC). There is an urgent need to develop better metrics capable of evaluating the prospective sustainability and resilience attributes of UC products, and the food system transformation associated with a shift away from industrialised value chains towards UC DVC.

1.2 Metrics for sustainability & resilience

Existing metrics based on conventional economic analyses and life cycle assessment (LCA) relate to narrow definitions of "efficiency" that disregard systemic challenges to the sustainability and resilience of agri value chains (Eyhorn et al., 2019). More sophisticated multi-level analyses are required to accurately quantify the potential contribution of disruptive change driven by UC to agri value chain sustainability and resilience, and to consider cumulative impacts in relation to critical "planetary boundaries" (Steffen et al., 2015).

Life cycle assessment is the quantification of inputs, outputs and environmental impacts arising along a value chain in relation to the delivery of a funcional unit – a specified quantity of a good or service (Rebitzer et al., 2004). It forms the basis of product environmental foot-printing (Famiglietti et al., 2019; JRC, 2018), underpinning business-to-consumer (B2C) and business-to-business (B2B) labelling, and more active forms of supply chain management (Schönberger et al., 2013; Styles et al., 2012). Recently it has

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become the leading framework to assess the sustainability of food value chains. Attributional LCA is improving in precision owing to the development of databases with higher resolution across thousands of "unit processes" (the building blocks of value chain LCA) (Moreno-Ruiz et al., 2018) and detailed methodological recommendations, such as the European Commission's Product Environmental Footprint product category rules (JRC, 2018). However, the utility of attributional LCA in identifying sustainable food system transitions in inherently limited (Costa et al., 2021; Costa et al., 2020). On one hand, some LCA practitioners recommend application of consequential LCA when evaluating the environmental effects of prospective system changes (Weidema et al., 2018). On the other hand, there are inherent limitations to the sensitivity of life cycle impact assessment methods that do not reflect long-term ecological functioning nor resilience in agri-food chains (Meuwissen et al. 2020). Important weaknesses in LCA methodology that must be addressed to better inform sustainable food system transitions include poor representation of: (i) inter-crop and pan-rotation agronomic effects; (ii) delivery on non-provisioning ecosystem services; (iii) over-consumption and waste linked with particular business models; (iv) economic value added, and its distribution among value chain actors. In combination, all these effects, but especially (ii) and (iv), are linked with resilience.

Recent studies have attempted to address the weakness of LCA by integrating LCA metrics with simple indicators of ecosystem services delivery at farm level. For example, Grassauer et al. (2021) proposed four different functions of agriculture defined by Nemecek et al. (2005): (i) generating income for the farmers, (ii) providing energy and protein as food, (iii) preserving an attractive landscape by utilizing ecologically valuable land, and (iv) providing further ecological services. In a subsequent paper assessing the multi-functionality of dairy farms, the authors propose inclusion of a "high nature value" farmland indicator as a farm "output", to represent the value of maintaining low-input, comparatively biodiverse grasslands on dairy farms (Grassauer et al., 2022). Whilst useful, such approaches have tended to focus on livestock systems, and to apply statistical methods across relativly large data sets to compare performance, e.g. using data envelopment analysis (DEA) to caluclate an "efficient frontier". There remains an urgent need for a more holistic yet flexible sustainability and resilience assessment framework that can be applied across diverse farm systems, including isolated case studies (which may be the only source of data for specific UCs and DVCs).

Thus, *RADIANT-Metrics* will incorporate specific suites of indicators within a coherent assessment framework to address the aforementioned weaknesses, without requiring "calibration" against a large dataset of similar farms – thereby providing a stronger evidence base on the sustainability of underutilised crops and dynamic value chains in relation to multi-functional outputs (Fig. 1).

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The purpose of this deliverable is to scope out a conceptual framework for *RADIANT-Metrics* that can be refined and applied to evaluate the wider sustainability and resilience of UC (DVC) throughout the *RADIANT* project.

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2. Materials and Methods

2.1. Approach to conceptual development

The objective of Task 4.1 is to develop holistic assessment framework (*RADIANT-Metrics*) to quantify the sustainability & resilience of multifunctional UCs and DVCs, and to benchmark these against conventional, industrialised crops & value chains. This will involve moving beyond state-of-the-art environmental footprints to capture prospective sustainability and resilience attributes of UC & DVC configurations, considering multi-functionality. Figure 1 provides an illustration of important factors, and indicates how the framework will need to operate at different scales (related to tasks within WP4).

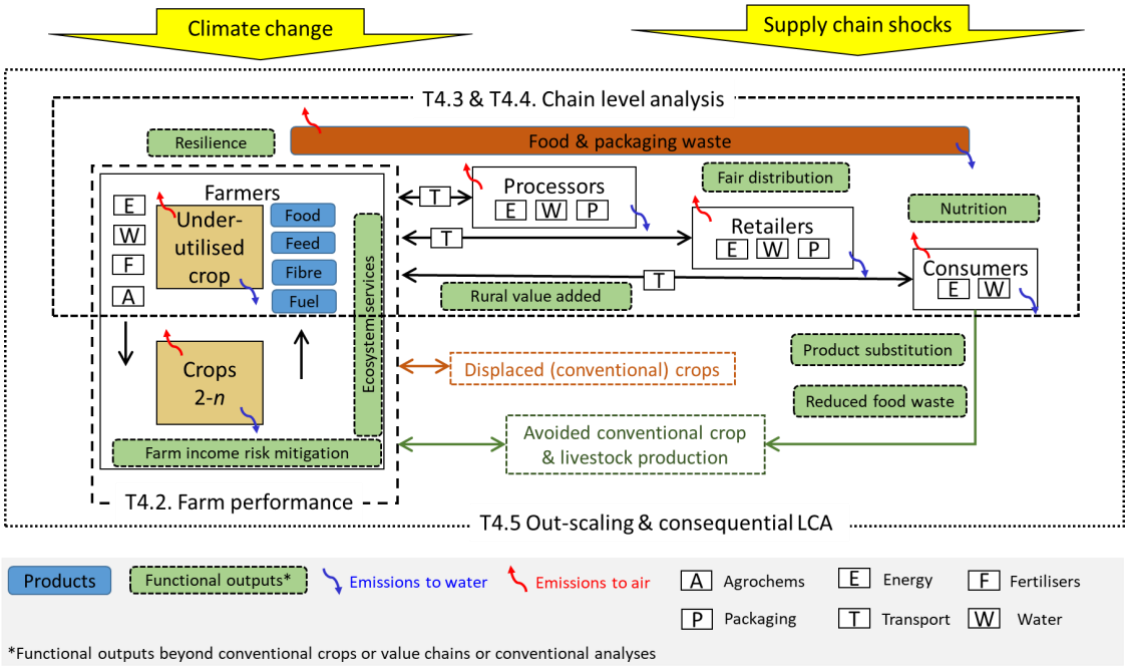

Figure 1. Schematic overview of the key factors to be captured within different tasks (T4.1-T4.5) of work package 4 in *RADIANT*, including: multi-functionality of underutilised crops and associated dynamic value chains; different levels of analysis – crop, farm, value chain and scenario; inputs & outputs driving environmental impact and economic performance.

RADIANT-Metrics conceptual development began at the proposal phase of the *RADIANT* project, evolving out of experience gained in environmental assessment of legume-modified value chains during the *TRUE (TRansition paths to sUstainable legume based systems in Europe)* project (Costa et al., 2021; Costa et al., 2020; Lienhardt et al., 2019; Saget et al., 2020; Saget et al., 2021; Saget et al., 2021). Whilst the concept is grounded in LCA thinking, it is expanded to consider critical ecosystem services, resilience and economic distribution of value added (Figure 1). Whilst there is some overlap between

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environmental footprints and ecosystem (*dis-)*services, there are ecosystem services that can potentially be delivered by UCs that are simply not represented in the life cycle impact assessment used to quantify environmental footprints.

2.2 What, for who and why?

Any meaningful attempt to improve comparative assessment of UCs and DVCs must be focussed on representation of potentially important attributes that could improve decision making by farmers, agri-suppliers, agri-advisors, processors, consumers, policy makers and wider stakeholders.

Expertise was drawn from across the project, with a particular emphasis on partners from WP3, WP4, WP6 in the first instance, to elucidate important factors (Fig. 1) and attributes (Table 1) to consider. This was done during proposal preparation meetings and subsequently via bilateral discussions and two workshops held in June and July 2022. Some key attributes of UC and DVC identified during a brainstorming session in the first workshop are listed in Table 1. This is a critical starting point for conceptual development of a metrics framework that should be capable of capturing these attributes, preferably in a quantitative or semi-quantitative format.

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Table 1. Potential attributes/benefits provided by underutilised crops and dynamic value chains at the different levels of scale (crop, farm, value chain and landscape). These attributes were identified to be of importance during two project workshops, and subsequently categorised according to relevant levels of analysis

Level	Underutilised crops	Dynamic value chains
Crop	• genetic diversity • resource use efficiency (water, nutrients, energy)	NA
Farm	• agri-biodiversity • resource use efficiency & break-crop effects • resilience via diversified income and rotation benefits • insurance against one crop failure • on-farm employment • intangible knowledge	• new and diversified markets • improved communication • resilience • faster return on investment
Value chain	• disruptive transformation of food systems • connectivity, community • networking • intangible knowledge	• reduce waste • better economic value & power distribution • more resilient to disruption •
Landscape	• agri-biodiversity • resource use efficiency & break-crop effects • resilience via diversified income and rotation benefits • disruptive transformation of food systems • socio-cultural ecosystem services (recreation, cultural, education…) • intangible knowledge • climate change mitigation	• reduce waste • shift consumption patterns (diet change) • regional/local gastronomy • food knowledge and local connection • better economic value & power distribution • more resilient to disruption • climate change mitigation

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3. Results

3.1 Goal, scope and boundaries

RADIANT-Metrics is underpinned by life cycle thinking, and is based around LCA, but is specifically designed to accommodate a diverse range of systems and to incorporate additional (non-LCA) indicators pertinent to wider sustainability and resilience. The framework is thus modular, and designed to be implemented flexibly depending on the system, the question being asked and the data available. In this regard, various functional units are relevant depending on the level of analysis and the comparison being made (Table 2). Choice of appropriate functional unit is fundamentally important in LCA studies, and can determine whether or not particular attributes (Table 1) are captured in benchmarking comparisons – thus potentially changing the order of apparent environmental efficiency.

Table 2. Examples of relevant functional units and potential end users related to different levels of analysis, and attributes listed in Table 1

Level	Functional units	Potential end users
Crop (farm-gate)	• kg main crop product (e.g. grain) • € revenue or net margin	• Farmers & farm advisors • Agri suppliers
Farm (farm-gate)	• € revenue or net margin • Nutritional output (e.g. NDU)	• Farmers & farm advisors • Agri suppliers • Agri policy makers
Value chain	• kg (or serving weight) main product • Nutrient density of a serving (e.g. NDU) • € of gross value added	• Food processors • Distributors • Consumers • Food policy makers • Nutrition & health policy makers
Landscape	• Million people fed for one year	• All stakeholders (civic society)

NDU = nutrient density unit (Saget, Porto Costa, et al., 2021)

The typical functional unit of a given mass (e.g. 1 kg), used to express most food footprints, is relevant and important when following UC burdens through to final products. However, this functional unit is narrow and often misses important crop-sequence and inter-crop effects associated with the introduction of different crop(s) into a rotation (Costa et al., 2020), or changes in nutritional characteristics associated with dietary substitution (Saget et al., 2021). These issues can be addressed by using e.g. € revenue or net margin, or nutrient density unit (NDU) to integrate multiple outputs at the farm or crop rotation level (Costa et al., 2021). NDU and gross value added are also good indicators of final product functionality or delivery at the value chain level. Finally, when assessing prospective scale-out of UC DVC,

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considering the number of people fed (or otherwise provided with energy, materials, etc) is an ideal functional unit that could capture wider interactions across multiple systems and factors such as potential waste reduction (Table 1).

In terms of scope, *RADIANT-Metrics* will apply standard attributional LCA principles (Finkbeiner et al., 2006) to delineate system boundaries related to the delivery of the chosen functional unit. Performance may therefore be benchmarked at crop, farm, value chain (product) level by developing life cycle inventories that capture all major inputs and outputs up to the relevant point in the value chain related to the stated functional unit (Fig. 2).

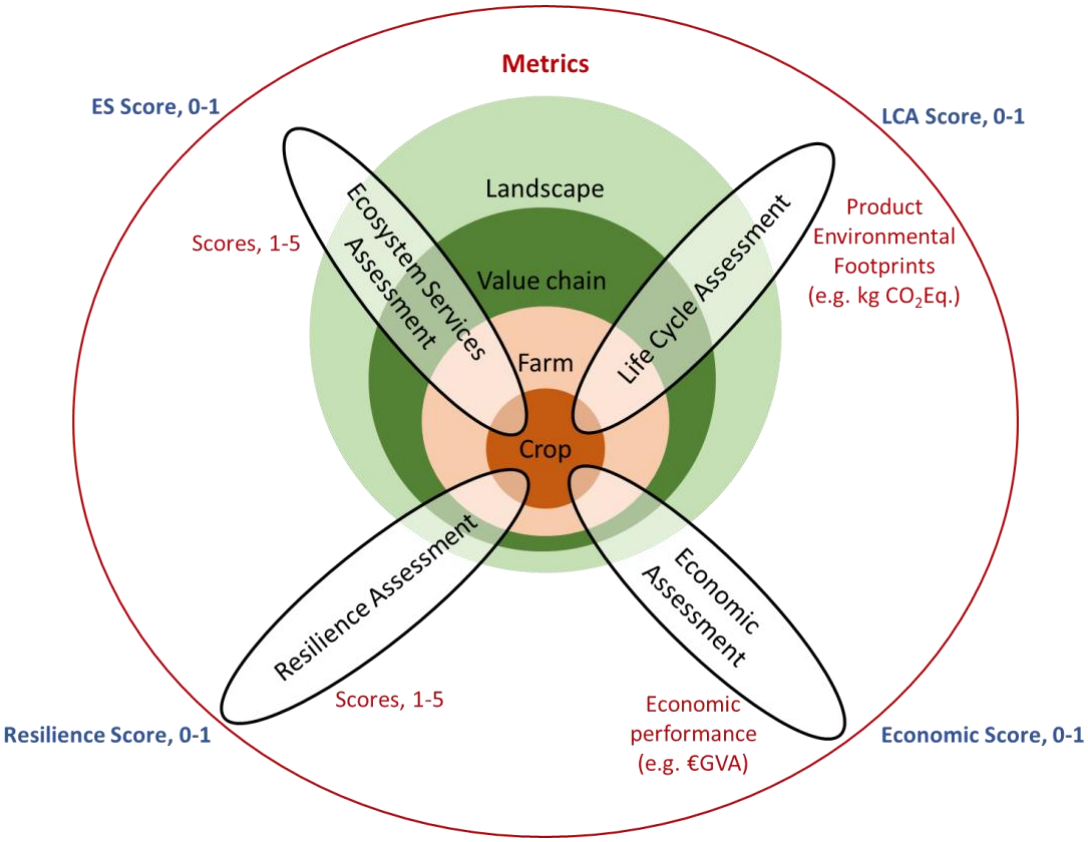

Figure 2. Conceptual representation of the *RADIANT-Metrics* framework, comprising parallel sub-indicator assessment for the four main themes, feeeding into four comparable aggregated scores

At landscape level, a consequential LCA approach (Schmidt, 2008; Weidema et al., 2018) is proposed, in order to explore scenarios of UC DVC out-scaling that capture wider inter-system effects indicated in Fig. 1 & Table 1.

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3.2 Selection of metrics

The primary challenge lies in the integration of different approaches and different metrics into a coherent framework. During the *RADIANT-Metrics* development consultation process, various ideas were explored to integrate ecosystem services into the assessment framework, for example as functional outputs with economic values that could be aggregated with the value of main products, or conversely costing the economic damage associated with environmental impacts and ecosystem dis-services in the true cost of production (Nature, 2020). However, it was decided that economic valuation of environmental impacts and ecosystem services is too uncertain and narrow in approach to accurately represent important effects. The conceptual framework proposed in Fig. 2 therefore involves parallel assessment according to best practice across four dimensions: LCA, economics, resilience & ecosystem services. An LCA approach is taken to express burdens and/or credits in relation to appropriate functional units, such as those indicated in Table 2, but there is flexibility in the selection and calculation of specific indicators (either quantitatively or semi-quantitatively) in order to accommodate different levels of application in accordance with specific objectives and data availability.

Whilst the LCA and some of the economic indicators are quantitative, based on well-defined methodology and indicator sets such as Product Environmental Footprint (European Environmental Bureau et al., 2018), other are qualitative or semi-quantitative based on survey or expert-judgement scores (Table 3). Furthermore, for ecosystem services indicators applicable only at crop or farm level, scores applied at the relevant level can simply be carried through to the next level up if necessary for integration with LCA scores. In this way, important aspects can be combined in a flexible manner, irrespective of the level at which benchmarking is undertaken.

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Table 3. Summary of sub-indicators across the four themes, and aggregated metrics to be integrated in the *RADIANT-Metrics* framework, indicating relevant levels of analysis

	Sub-indicator	Unit	Unit	Aggregated metric	Applicable Levels
Environmental burdens	Climate change		kg CO_2	Single score, scaled as ratio of largest summed value arising from [1/characterised score] for each impact catgegory	Crop Farm Value chain Landscape
	Freshwater and terrestrial		mol H+		
	Freshwater ecotoxicity		CTU		
	Freshwater eutrophication		kg P Eq		
	Marine eutrophication		kg N Eq		
	Terrestrial eutrophication		mol N Eq		
	Human health - carcinogenic effects		CTUh		
	Human health - ionising radiation		kg U235		
	Human health - non-carcinogenic		CTUh		
	Ozone layer depletion		kg CFC-		
	Photochemical ozone creation		kg		
	Respiratory effects, inorganics		disease		
	Resources - dissipated water		m^3 water		
	Resources - fossils		MJ		
	Resources - land use		Points		
	Resources - minerals and metals		kg Sb Eq		
Ecosystem services	Enhanced soil fertility		1-5	Aggregated score, scaled as ratio to larger / largest summed value compared	Crop Farm Landscape
	Pest and disease control		1-5		
	Hydrological cycle and water flow regulation		1-5		
	Reg. temperature, light, humidity, transpiration		1-5		
	Increased animal welfare		1-5		
	Recovery of marginal areas		1-5		
	Pollination and or seed dispersal		1-5		
	Wind protection		1-5		
	Fire protection		1-5		
	Biodiversity		1-5		
	Educational value		1-5		
Resilience	Max use stress-tolerant species, breeds, cultivars		1-5	Aggregated score, scaled as ratio to larger / largest summed value compared	Crop Farm Value chain Landscape
	High level of diversification of products		1-5		
	High level of diversification of clients		1-5		
	Good temporal distribution of revenue		1-5		
	Low share of subsidies in gross farm income		1-5		
	Ability to attract and keep motivated workforce		1-5		
	High level of autonomy from commercial inputs		1-5		
Economics	Net margin		€	Aggregated score, scaled as ratio to larger / largest value compared	Crop Farm Value chain Landscape
	Gross value added		€		
	Minimised variable costs		1-5		
	Minimised fixed costs - investments		1-5		
	High proportion local or self-processed products		1-5		
	Short marketing chain		1-5		
	Local marketing chain		1-5		
	High level of diversification of activities		1-5		
	Satisfaction with economic benefits from farming		1-5		
	Similar or higher benefits vs other farmers		1-5		

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3.3 Integration and proposed application

In essence, the proposed *RADIANT-Metrics* framework can be summed up by the following principles:

1. Four key themes capture priority sustainability and resilience attributes – environmental burdens (footprints); ecosystem services; resilience; economic performance
2. A life cycle approach is adopted to define system boundaries that capture relevant upstream effects at a level of analysis (crop, farm, value chain/product or landscape/scenario) appropriate to the question being asked and the subjects of comparison
3. Quantitative sub-indicators are calculated for each theme where possible, in accordance with best practice guidelines for that theme, and can be presented as stand-alone or parallel metrics (e.g. product environmental footprints)
4. Qualitative methods are used to score performance across themes for which quantitative methods are not possible owing to e.g. data constraints
5. Summing scores across sub-indicators for each theme and scoring as a ratio of the higher/highest scoring comparator generates a suite of simple but easy-to-interpret *relative performance* scores
6. The objective of assessment is to generate comparative scores across alternative options (e.g. an UC DVC compared with a conventional, industrialised counterpart value chain). Whilst a higher level of comprehensiveness across proposed metrics is better, the over-riding rule is that the same metrics are applied consistently to all comparators

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4. Conclusions

There is increasing concern about the long-term sustainability and resilience of industrialised food systems that have evolved in response to short-term cost-minimisation under the prevailing paradigm of economic efficiency. In many cases, this has been aligned and reinforced by narrowly-defined resource and environmental efficiency indicators that measure environmental *intensity* per unit of output – typically based on life cycle assessment (LCA). Whilst LCA brings rigour in terms of scope and boundary definition to capture environmental impacts across whole value chains, it is often based on "snapshots" of system performance that fail to represent long-term and cumulative sustainability and resilience attributes that are increasingly recognised as key vulnerabilities in agro-industrial food (or biomaterial/bioenergy) systems. In this context, there is an urgent need for an assessment framework capable of robust representation of wider sustainability and resilience attributes yet based on readily-available data sets and expertise.

The RADIANT project is specifically evaluating the potential contribution of underutilised crops (UC) and dynamic value chains (DVC) to support a sustainable and resilient food (and biomaterial/bioenergy) system transition. This deliverable report proposes a conceptual framework for a *RADIANT-Metrics* framework capable of benchmarking the sustainability and resilience of UC DVC against conventional industrial value chain counterparts. The framework is underpinned by life cycle *thinking,* and incorporates quantitative LCA methodology and, but includes a wider suite of semi-quantitative metrics under the themes of: environmental burdens, ecosystem services delivery, resilience, and economic performance.

In line with the core objective of identifying (ranking) relative sustainability and resilience across comparator crops, farms, value chains and deployment scenarios, the framework can operate at multiple levels depending on user-defined scope (in line with LCA principles) and appropriate data collection. It is thus flexible and applicable to the diverse range of prospective UCs and DVC configurations. Furthermore, the framework can be applied using different combinations of sub-indicators depending on data availability, translated into final comparative 0-1 scores across each theme to provide an indication of relative strengths and weakness across UC and/or DVC comparators. These scores can be presented in parallel with more quantitative LCA and economic indicators that can be calculated based on well-defined methodologies.

The proposed *RADIANT-Metrics* conceptual framework will be tested, revised and (re-)applied across RADIANT AURORA case studies and participatory

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farms in order to improve sustainability and resilience assessment of food (and biomaterial/bioenergy) systems.

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