EIP-AGRI Focus Group CIRCULAR HORTICULTURE Mini-paper – *Monitoring and metrics to boost circularity in horticulture*

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Introduction

Tracking production processes is strategic to monitor productive factor streams and improve crop sustainability by maximization of resource circularity in horticultural systems. The latter concept implies that production waste and waste streams are efficiently minimized or totally removed from the system thus maximizing material value through its reuse and recycle. The definition (what), the characterization (quality) and the quantification (amount and timing) of both inputs and outputs are the basal information to reach high degree of circularity and consequently economic and environmental sustainability in intensive horticultural cropping systems such as greenhouse horticulture. On the contrary, lack of proper monitoring of the cultivation process can lead to excess costs, waste, low input use efficiency, and poor produce quality with lower incomings and higher environmental burdens.

In this context, we must precisely define what is important and useful to be accounted and monitored taking into consideration a set of performance indicators directly related to: i) crop management (e.g., water quality, salt or agrochemical accumulation in the system, substrate status), ii) input factor use (e.g., water, agrochemicals, energy quantity per product unit), iii) output factors (e.g., wastewater) and boundary conditions (e.g., indicators for material flow analysis, life cycle assessment).

A potential approach consists in grouping same subjects into clusters, i.e., similar farm types in the same area with similar agro-ecological conditions and needs, to have a standardized reuse of waste (e.g., drainage water, substrates, plastics, etc.). Metrics and indicators should be also based on crop type and geographic area (i.e., Southern vs Northern Europe, dry and wet climatic conditions), from which mostly depend the different product and factor use on the medium-long period. This allows to annually assess progresses or inefficiencies in the input-output use against more global targets/standards of efficiency (e.g., water and carbon footprint).

This paper provides an overview of possible metrics, indicators and available technologies to support measurements in order to increase circularity in intensive greenhouse horticulture. Major critical gaps and opportunities, which can contribute for a wider implementation of recycling and reuse activities and processes, are also discussed taking into account a heterogeneous scenario (i.e., high tech vs low tech, crops, growers' needs and know-how) of the European greenhouse horticulture.

Current implementation of monitoring and metrics at farm level and beyond

In an ideal world, all inputs and outputs of a greenhouse would be monitored providing at all-time a clear view of the current status of all elements of the production process. All these data would be clustered providing the general overview of the status of all horticultural companies in a specific region. These data would be the starting point for growers to discuss and optimize their production processes. At the regional level, these data would benefit all growers as combined and more cost-efficient regional initiatives would be possible. This is more or less the idea behind internet of things, which more and more finds its way to the horticultural sector and might as well support the implementation of the circular economy.

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Where are growers standing today when it comes to monitoring and metrics?

In general, we expect that continuous inputs like water, fertilizers, phytochemicals, energy, plastics are continuously registered, and that growers are clearly aware on these consumables at any time. But is this actually the case? In 2016, the thematic network FERTINNOWA carried out a survey amongst 371 European growers regarding their fertigation practices and the applied technologies in both soil grown and soilless crops, as well as protected and open field cultivation. When these growers were asked about the yearly water consumption per m², only 83% of the growers responded. The remaining 17% did not answer to the question or were unable to provide any answer. Amongst the growers answering the question, huge variation was found in the responses, even within the same region and the same crop. This raised the question again if there is indeed a huge variation of irrigation practices, under similar climate conditions and crops, or if there is a lack of monitoring and accounting. The survey showed that only few growers monitored the water inputs in their farm. Similar results are often obtained in surveys carried out to assess the use of fertilizers and pesticides.
When it comes to effluents, 20% of the respondents replied that they measure the nitrogen content of the effluents produced by their practices. But a regional trend was found as 45% of the respondents in the North Western part of Europe measured the nitrogen content of their emissions, while this was done only by 11% of the Mediterranean and 4% of the Central Eastern respondents. This trend seems to relate to whether the growers are experiencing external control regarding their emissions.
Growers answered that cheaper and more reliable tools (like sensors) would support them to monitor water and nutrient streams. Moreover, growers indicated that sensors with a longer lifespan and minimal needs for calibration are needed.
The minor costs with fertilizers and water in the total production cost (Figure 1) could explain the lower efforts of growers to monitor for example water and fertilizer usage. A Dutch study (Ruijs 2018) showed that the costs for fertilizers and water counted for only 2% of the production cost of a soilless grown tomato crop (Figure 1). Similar scenarios are observed in Mediterranean countries for the cost of fertilizers and water. The same study showed that the main production costs for a Dutch greenhouse tomato crop are mainly energy, labor, and depreciation. Only a few growers of the FERTINNOWA survey could indicate the percentages that fertilizers and water take in the total production cost.

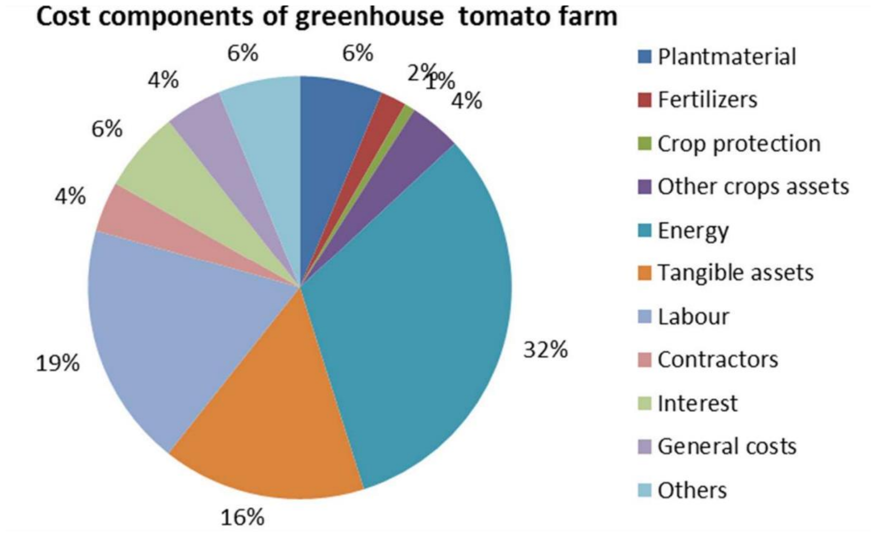

Figure 1 Cost components of Dutch greenhouse tomato crop (from Ruijs 2018).

Some examples of data collection and sharing on larger scale

In the last years, several initiatives have been implemented to foster monitoring at farm level. A Dutch example can be found in the Waterson Company (https://www.waterson.nl). This company is providing growers with a mobile service to remove pesticide residues from horticultural drainage water. When drain water needs to be treated a truck passes by and cleans the water. To improve the company's logistics, Waterson built a large-scale monitoring network measuring the water level in the wastewater tanks of Dutch greenhouses. At any time, Waterson has a complete overview of the water levels in the different storages. Based on this monitoring system, Waterson organizes its logistics as efficient as possible. Moreover, growers are now more aware of their wastewater production since this wastewater streams are monitored continuously. The Waterson Company expects growers to reduce their wastewater production in the coming years. Indeed, metrics not only should be applied to the productive aspects of horticulture, but also to the environmental management of it. For instance, Cáceres et al. (2017) set up a system for monitoring continuously the nitrate/phosphorous of a constructed wetland that removes these ions from nursery wastewater.

The relevance of horticultural statistics in EU: update and good quality data

According to the European Commission, agricultural statistics aim to produce data on agriculture that meet the current and future user needs in an efficient manner with a bearable burden on data producers (EUROSTAT 2015). Statistics make available reliable and up-to-date information on a specific subject or agricultural domain and enable more objective decision making, at farm, regional, country and even EU level. In addition, it enables companies and regions benchmarking for input use efficiency, waste production and/or recycling. Indeed, the importance of statistical data recording and of robust and up-to-date statistics must be clearly emphasized near the stakeholders of the greenhouse horticulture supply chain, from growers to politicians and consumers.

In order to achieve higher input use efficiency and higher profits with minimal environmental impact greenhouse managers must have a detailed and accurate recording system to support more efficient management and related decisions.

Therefore, robust records (frequent in time and detailed) can help horticultural managers not only to better plan and grow their crops but also to support growers/managers to better predict quantities of inputs and outputs. Additionally, such type of data recording will allow identification of major limitations influencing circularity and will help to pin point efficiencies and inefficiencies along the production process. This goal for the greenhouse industry will be accomplished when employees and greenhouse managers have a better and more positive perception on the value of data gathering.

In parallel, wise and correct policies for the greenhouse sector depend on well informed politicians (EUROSTAT 2015). Update and uniform statistics or more practical and robust indicators are needed to support implementation of the most correct policies e.g., for environmental impact and sustainability. This can be considered at different governance levels: from the local government to the European Commission officers.

Good quality data recording is crucial to establish proper metrics and robust quantification of inputs and outputs in agricultural systems and standard operating procedures should be implemented for data collection. Indeed, expansion of greenhouse horticulture sector and the lack of a national registration system pose difficulties to obtain reliable quantitative data for some South- European countries (e.g., Portugal, Italy, Greece) namely in terms of certain types of inputs e.g. water (Costa et al. 2017; AQUASTAT 2017; OECDstat 2017).

Therefore, more detailed and more homogeneous set of indicators and data collection/analysis procedures is on demand by the industry. This will avoid conflicting statistics within the EU, will minimize misunderstandings and wrong perceptions on the sector and will make easier data analysis and the comparison of the performance of regions and countries. In the context of circular horticulture, the precise quantification of both inputs and outputs from greenhouse farms assumes particular relevance and may consider different levels:

- main inputs:
  - greenhouse construction materials: cover materials and greenhouse structures, plastic films, cladding and mulching materials, substrates and pots irrigation pipes;
  - agrochemicals (fertilizers and biocides) and related machinery;
  - energy: electricity and gas expenses related to irrigation and climate control;
  - water (irrigation and other uses);
- main outputs:
  - yield and biomass;

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- organic solid wastes (low quality fruits, biomass, etc.);
- inorganic solid waste (covering plastics, plastic strings/clips, pots, irrigation pipes, etc.);
- liquid waste (waste waters from washing, exhausted nutrient solution).

The challenge of identifying an appropriate methodology —extensive data collection or indirect estimation— is evident and demands study and investments (see for example, USGS 2000).

Improved data management and record keeping are essential for monitoring and evaluation. These processes demand standardized data collection procedures to avoid variability among regions/countries (e.g., ISO norms). Such approach should be considered for both qualitative and quantitative data.

Moreover, combination of qualitative and quantitative data (e.g., perception and values and attitudes for farmers, consumers, distribution, consumers) will contribute to increase the overall reliability and validity of the survey and evaluation as well as to support confidence in conclusions and allow for complementarity and triangulation.

Ultimately, the EU should promote and support transnational strategies to develop a more standardized statistical survey and data quality assurance for the agricultural sector. In particular, for greenhouse horticulture in the different EU countries namely in what concerns: i) classification system and sector coverage (which thresholds to use); ii) statistical concepts, units of measure and definitions (specific to greenhouse sector); iii) reference area and period; iv) frequency and type of dissemination.

Metrics and indicators of factor use

To comply with the goals of circular economy, it is necessary to understand what are the inputs and where do they come from, how effectively the production phase turns the inputs into products and how waste generated during the production phase and the phase of using the products is managed. Therefore, it is necessary to monitor, measure, combine measurements into metrics and interpret metrics into indicators that represent the level of circularity of the system or process. The overall aim is to improve performance by comparison with a target and the study of the processes involved, so that better management practices can be adopted to gain efficiency and lower the environmental impact. Therefore, positive economic and environmental effects on the farm activity will be achieved.

On the other hand, monitoring can be applied at plant level during the growing cycle for adjusting the crop management. In this case, certain variables are measured in representative control points which allow taking decisions aimed at the optimization of the management. The objective is to improve the production, reduce input use and increase their use efficiency. To apply monitoring in automatic control is the best way of optimization. This is the case of automatic irrigation systems based on an evapotranspiration model and/or soil water content measurements (Casadesus et al. 2012). However, sometimes monitoring has to be done manually and data must be interpreted after collection, so that automation is not possible.

At farm level, there is a large number of performance indicators suitable to be applied (van Halsema and Vincent 2012). For the specific case of irrigation water, a guideline for benchmarking performance in the irrigation and drainage sector was published by FAO and proposes several key metrics classified in different categories (Malano and Burton, 2001). An extended measure is the irrigation water supplied per irrigated unit area (expressed as $m^3\ ha^{-1}$), although it does not give an exact idea of how good the irrigation management is. For this objective, it is remarkable the Relative Irrigation Supply (RIS), which is the ratio between the measured water inflow to the irrigation system and the irrigation water demand, being RIS = 1 the optimal value. Management will be less efficient the higher the value of the indicator, so that a value of, for example, RIS = 1.5 indicates an excess of supply of 50% in relation to crop water requirements. However, metrics can vary along the crop cycle, being important to achieve a good performance throughout the whole growing period, so that it is necessary to analyze the different phases of the crop independently.

A comparative way of measuring the water use efficiency is relating production and irrigation supply, thus obtaining the water productivity (kg m^{-3}). These parameters can be also inversely related as water use per production unit ($m^3\ t^{-1}$), which is a useful metric for growers since they have awareness of the mean final production. Moreover, this metric can be quickly related to the total volume of water

required per cultivation cycle. This metric allows comparing the efficiency in different areas or growing systems. However, some agronomic strategies, such as the deficit irrigation, could improve use efficiency while reducing the economic profitability, which is a relevant aspect for growers. Thus, it is necessary to consider not only the use efficiency but also the profitability (gross profit per unit of irrigation water; € m^{-3}) for the selection of the best practices.
In greenhouses, rain and condensation water can be collected and used for irrigation as a very sustainable water source. This reduces the use of other types of water, especially ground water. The relation between the amount of rain and condensation water used in irrigation and the total water use indicates to what extent the growing system is independent of external water sources.
Regarding the nutrient use, it can be also evaluated in relation to the yield (nutrient use efficiency). It is often expressed as the amount of a nutrient applied by fertilisation (kg or fertilizer unit) necessary to produce one tonne of fresh yield. If the nutrient discharge is measured (in soilless systems or in soil bound crops where leaching can be controlled), it is possible to determine the percentage of nutrient discharge as the relation between the amount of wasted nutrient and the total applied. This metrics gives an idea of how big are the nutrient losses to the environment are and the potential to improve management.
Plant waste can be supplied to the soil and atmospheric nitrogen fixation can be promoted as a source of nutrients. Likewise, some microorganisms can be used for the mobilization of the nutrient reservoir in the soil. In this way, the ratio between the supply of nutrients by external fertilizers and the total nutrient extraction of the crop gives an idea of the level of self-sufficiency of the growing system referred to the nutrient use.
Regarding the energy use, it can be expressed per surface unit (MJ m^{-2}) or in relation to the yield (Global Energy Requirement or GER; MJ kg^{-1}). The energetic sustainability of the production system can be evaluated based on CO_2 emissions (Global Warming Potential, GWP, kilograms of emitted CO_2 per kilogram of yield).
Besides GWP, different indicators derived from the life cycle assessment (LCA) can be used to evaluate the environmental impact of the growing system such as: Abiotic Depletion Potential (ADP, expressed as the consumption of antimony per ton of yield), which measures the consumption of resources in the greenhouse ecosystem; Air Acidification Potential (AAP, expressed as kilograms of sulfur dioxide emissions into the atmosphere per ton of yield), which measures air pollution; Eutrophication Potential (EUP, expressed as kilograms of phosphates per ton of yield), which represents the nutrient enrichment of the ecosystem; and Photochemical Oxidation Potential (POP, expressed as kilograms of ethylene emissions (into the atmosphere per ton of yield). For example, Valera et al. (2016) compiled information about the above performance indicators for tomatoes grown in different greenhouse types and countries.
In the Annex, two tables have been reported that show i) web-available tools and ii) a summing up of measures, metrics, indicators and indexes, as a roadmap example for improving circularity in horticulture.

Technologies available to support measurements

Monitoring technologies are developing fast (e.g., climate conditions, crop stress, etc.) and there is an increasing number of high and low-cost technologies that will help the sector in proper and fast assessments and indirectly quantify input use and needs, improve input use efficiency and minimize waste and pollution in greenhouse horticulture (Incrocci et al. 2017; Thompson et al. 2017).
In an ideal horticultural system, each stream of a productive factor should be monitored for evaluation. To this purpose, in the "computer era", electronic devices can automatically accomplish much of the work otherwise manually done by humans. This allows high-throughput monitoring of data regarding material streams and their quantity and quality. Interactions between different tools for monitoring production systems are moreover facilitated by wireless connections that can improve much data exchanges in flexible (i.e., modular) sensing frameworks.
QR codes can be applied and scanned by laser to monitor the logistic of different productive factors. Many sensing technologies are instead available for monitoring productive factor use and quality for their maintenance and reuse in the same production cycle or recycle for other purposes.
Water balance, and then water use, can be directly calculated by electronic water meters allowing simple measurements of water volumes supplied and drained out from the horticultural system in the

time unit. This procedure is particularly simple and effective in soilless cultivation (hydroponic or pot) systems.

However, water losses due to the use of free drain systems in both protected and open field horticulture can be indirectly estimated by the difference between water supply and crop evapotranspiration. The last quantity can be directly or indirectly determined by installation of different "hard" and "soft" sensors, respectively. The former are mainly represented by electronic weighing gutters, lysimeters and moisture sensors. The latter is one of the most promising technologies. Although moisture sensors often require on-situ calibration, their use has been spreading much in the last years due to the impressive cost reduction from one hand and the many possibilities of application from the other hand. The most common type is represented by FDR (frequency domain reflectometry) sensors, which allow affordable measurements of the volumetric water content in the root zone. Indirect measurements of crop evapotranspiration can be furthermore accomplished through "soft" sensors consisting in simulation models. Indeed, mathematical models allow estimating crop evapotranspiration through algorithms based on more simply-to-measure variables such as climatic parameters that show high correlation with crop evapotranspiration. Other mathematical models can then also be adopted to estimate crop biomass and yield, plant growth and nutrient uptake, disease and pest occurrence. To run mathematical models, nets of sensors for the measurement of model-driving variables are required. Sensing technologies can be applied at different level in the horticultural system. Basic measurements consist in the monitoring of climatic variables fundamental for plant life such as radiation, air humidity and temperature. Historical climate datasets can be used to run prediction models to forecast cultivation scenarios and make economic and agronomic decisions in advance.

However, the recording and storage of climatic parameters is important not only for simulation purposes but also to calculate efficiency indices (e.g., radiation and temperature use efficiency), to manage climate in protected environment, to optimize energy fluxes. Basic instruments are radiometers (to measure direct and diffuse radiation), thermometers (to measure air, substrate and canopy temperature), wind speed meters, hygrometers (to measure vapor pressure deficit and relative humidity). For advanced temperature monitoring of the canopy, thermal imaging can be accomplished by increasing cheaper infrared thermal cameras.

All the above technologies can be applied to monitor and quantify material streams with the aim of reducing waste. However, when cultivation residues are collected to be reused in the same production cycle or recycled for other industrial sectors, the quality of residual materials must be measured and continuously monitored for proper management. In closed soilless systems, for example, the nutrient solution can be recirculated in successive irrigation cycle prior monitoring and adjustment of the nutrient solution drained out from the systems. To prolong as much as possible the recirculation of nutrient solution, the chemical characteristics can be automatically monitored through probes for the measurement of electrical conductivity, pH, ballast ions and nutrient concentration. For the latter, the most effective probes are based on photometry with visible light and ion-specific sensors such as ion selective optodes (ISOs), ion selective electrodes (ISEs), and ion-selective field effect transistors (ISFEs). Rapid kits for root zone (soil and growing media) and crop analysis are also commercially available for this scope (Incrocci et al. 2017).

Monitoring plant material is needed to optimize agronomic practice and to characterize cultivation residue and its successful recycle. An adequate quantification and characterization of green crop residues is for example strategic to recycle them as substrates and/or to use them in soil amendments, or to extract specific compounds valuable for other industrial sectors. Rapid kits for on-farm analysis commercially available for the characterization of green waste (Incrocci et al. 2017). Nowadays emerging imaging technologies are based on optical sensors allowing non-destructive measurements in the hyperspectral radiation range. In particular, imaging analysis, accomplished through digital RGB cameras, allows visual and chemical characterization of plant material, biomass quantification, and helps to monitor quality of both horticultural products and residues.

All information automatically acquired by sensing tools can be stored and elaborated by expert systems integrated into provisional computer programs and decision support systems (DSS), for optimized crop management with minimum waste and high recycle capacity of cultivation residues. The use of free image analysis software should be also promoted to make easier and faster image analysis.

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Data elaboration and storage

One of the main bottlenecks in the use of monitoring data is the lack in common acquisition protocols for their collection, storage and successive elaboration. In the EU, it is not possible to identify a standard protocol for the acquisition of data in the specific sector of horticulture. Common targets should be identified for different specialized cultivation systems and then the buildup of robust, up-to-date and transnational databases supported to define precisely input and outputs use in modern greenhouse horticulture. Some databases are indeed available at EU level for agricultural activity (AQUASTAT; OECDstat; FAOSTAT; see Annex I, Table I) but the profile of many countries is very often not kept up to date.

Depending on the scope, available data can be stored and used at farm, consortium, regional, and country level. One of the main drawbacks and limitations in data sharing consists in the possible concerns about the protection of individual farm data. To this purpose, the idea of grouping same subjects into clusters, i.e., similar farm types in the same area with similar agroecological conditions and needs, appears of great interest to achieve common objectives for increasing circularity in the economy of horticultural systems. Some projects in the Mediterranean area have been developed to create nets of farms for accurate climate monitoring. In this case, monitoring frameworks were created at local level in homogenous agricultural areas using principal nodes that collect information from other "satellite" farms. The elaboration of those data allows estimating many climate-based parameters that are basilar, for example, for plant nutrition and irrigation or pest and disease management. Web-based platforms are also useful tools to boost the elaboration climatic and other crop parameters for efficient fertirrigation of horticultural crops (e.g., Cahn et al. 2015).

Collected monitoring data are subjected to different use depending on their nature and application. These data can be handled at farm or at broader scale for different purposes such as the operative farm management, the implementation in prevision studies for making decisions, and the calculation of economic and environmental indices.

"Big data" and "smart farming" are relatively new concepts, so it is expected that knowledge about their application and implication for research and development is not widely spread yet (Kamilaris et al. 2017; Wolfert et al. 2017). Nevertheless, the new approach of "internet of things" and "cloud computing" are expected to leverage technologic development and introduce more robots and artificial intelligence in farming for advanced decision-making in the near future (Figure 2). Big data could be used to provide predictive insights in farming operations, drive real-time operational decisions, and redesign business processes for game-changing business models; therefore, this kind of approach could go beyond primary production.

On the other hand, monitoring data is crucial for effective understanding of the associated environmental impacts related to the horticultural systems. Life cycle assessment (LCA) model compilation of a greenhouse system firstly requires detailed information about the available annual quantities of natural resources (e.g., rainfall, well water, soil nutrient budget, radiation, temperature, and land) as well as materials (e.g., seedlings, fertilizers, pesticides, substrates) and energy (e.g., fuels, electricity) inputs for the system's operation. Information regarding structures and covering materials (types and life span) should also be available. Second fundamental point is related to the availability of data regarding the harvestable produce and residues. Produce quality and yield should be quantified to be related to the use efficiency of different productive factors. Annual waste (e.g., fertilizer and water losses, residual growing media, product losses, unmarketable products) should be quantifiable with special attention paid towards those chemicals or other residual substances that are potential pollutants or harmful factors for human and animal health (e.g., nitrates, phosphates, residual pesticides, etc.). However, since LCA outputs mostly depend on the boundary conditions delineated in the computation of the model chosen, more inclusive and global LCAs should consider transport and market characteristics.

Results by LCA can be managed through specific indices to assess the environmental impact of horticultural crops e.g. carbon and water footprint. The first one is an indicator of anthropogenic greenhouse gas emissions related to climate change (IPCC, 2007). The second is an indicator of direct and indirect fresh water consumption in the cropping system. The water footprint is a multidimensional indicator that quantifies volumes of water directly used by the crop and polluted due to the cultivation process. The indicator has three components, the green, blue, and gray water

footprints, which are respectively based on i) naturally available water (i.e., rainfall and soil budget), ii) irrigation water, and iii) water potentially polluted by the crop (Hoekstra et al. 2009). Carbon and water footprint are useful tools to quantify and locate input footprints, to evaluate sustainability of the cropping system and to identify strategies to reduce the impact of agricultural systems at local and global level.
In the Annex, two tables have been reported that show i) web-available tools and ii) a summing up of measures, metrics, indicators and indexes, as a roadmap example for improving circularity in horticulture.

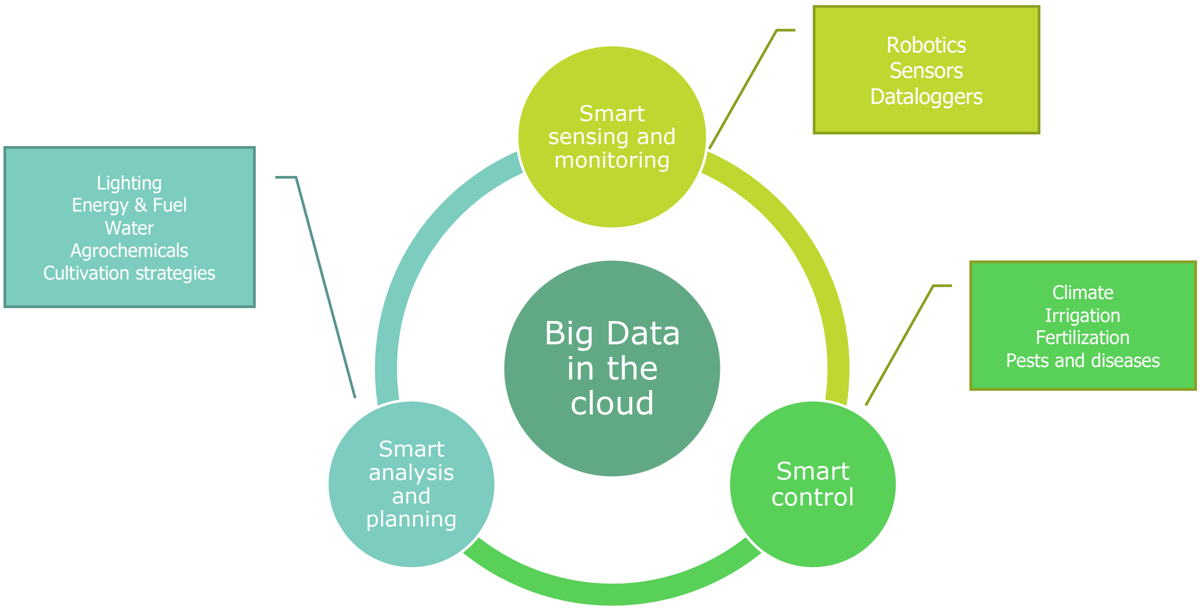

Figure 2. Examples of big data application: the cycle of smart farming in horticulture (rearranged from Wolfert et al. 2017).

Proposal for potential operational groups

- Operational groups focusing on the training of technicians and growers for improved education about monitoring and metrics in agriculture.
- Operational groups on the effective use of monitoring devices and data handling.
- Operational groups to support data analysis.
- Operational groups on water accountability in farming.
- Operational groups for data collection of every type of crop.

Proposals for (research) needs from practice

The collection of reliable data and the adoption of effective monitoring systems is currently limited by many factors that could be addressed in specific research programs focusing on the following topics.

- Low-cost and affordable technologies: the cost of monitoring devices can be reduced by the adoption of low-cost technologies derived by studies of new and recyclable materials.
- Standardized metrics for greenhouse horticulture and other intensive farming systems.
- Increase perception of growers and managers for "data value".
- Effective use of sensors in horticulture.
- No autonomous data analysis software or procedure is available: standardize procedures of big data analysis have to be implement to help farmers.

Conclusions and recommendations for further development

Horticultural systems are complex and intensive agricultural production systems that allow high standard produce quality and yield, and high input efficiency when properly understood, managed and

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monitored. Nevertheless, the high demand for inputs per unit area can easily lead to inefficiencies thereby compromising the economic and the environmental sustainability. The way to minimize waste and maximize the use efficiency of productive factors lies in a deep knowledge of material characteristics and related streams involved in the greenhouse production cycle, which in turn makes it possible to optimize material reuse and recycling potential. To achieve this goal, a fine and precise monitoring action is required from the farm to a broader scale level. Notwithstanding its importance, many knowledge gaps are identified when dealing with data gathering and monitoring at farm, region and even country levels. Very often, growers have scarce awareness of the importance of metrics and data monitoring to characterize and quantify the use of or the amount of waste materials involved in the greenhouse production chain. Therefore, exceeding materials are merely perceived as waste rather than as resources that could potentially be reused in successive production cycles in the greenhouse or outside it. Specific politics should encourage effective and constant monitoring of horticultural system for example by grouping same subjects into clusters (clustering) with similar characteristics and exigencies. The greenhouse horticulture has ideal conditions (know-how, technical, economical) to reach high level of "circularity" if compared, for example, with other subsectors of intensive agriculture in open field that show less capacity to assess and control the flow of materials and waste. Therefore, and attending to its importance, data monitoring in EU greenhouse horticulture needs to be economically sustained through specific support programs. Indeed, precise data monitoring and storage appears a worthwhile practice to improve circular economy in this agricultural subsector.

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Annex I

Table 1. Examples for different web-available tools to boost data monitoring and elaboration in horticultural systems.

Resource/Tool/Database	Description	Main inputs/Based on	Link/Available at
		Calculators	
Various web tools to support decisions greenhouse cultivation	Strategies, substrates, quality control, economics	Various parameters	http://backpocketgrower.com/calculators.asp
Air exchange monitor	Excel spreadsheet for air exchange rate of multi-tunnel natural ventilation	Number of spans and ventilators characteristics	https://www.wur.nl/en/Research-Results/Projects-and-programmes/Euphoros/Calculation-tools/Air-exchange-monitor.htm
Daily light integral calculator (DLICALC)	Web tool to calculate supplemental daily light	Lamp type and operation	https://extension.unh.edu/Agric/AGGHFL/dlicalc/index.cfm
Fertilizer calculator	Excel spreadsheet to calculate nutrient supply and efficiency	Crop characteristics	https://www.wur.nl/en/Research-Results/Projects-and-programmes/Euphoros/Calculation-tools/Fertilizer-Calculator.htm
Fertilizer concentration calculator (FERTCALC)	Web-based nutrient solution calculator	Fertilizer type, crop, location, date, injector parameters	https://www.ces.ncsu.edu/depts/hort/floriculture/software/FERTCALC.htm
Open-field fertilization calculator (Agrosat)	Web tool to manage open-field fertilization	Geographical references and crop parameters	https://www.agrosat.it/
Plant growth regulator calculator (PGRCALC)	Excel spreadsheet to calculate plant growth regulator mixing rates and final solution costs	Plant dimensions, application rate per unit areas	https://www.ces.ncsu.edu/depts/hort/floriculture/software/PGRCALC.htm
Various mobile device applications	Web page collecting many simple applications for greenhouse growers	Depending on application	https://ag.umass.edu/greenhouse-floriculture/fact-sheets/apps-useful-apps-for-greenhouse-growers
		Simulators and decision support systems (DSS)	
Fertigation manager (Hydrotools)	Nutrient solution calculator and simulation tool to manage water and mineral relations of soilless crops	Various parameters	https://www.wur.nl/en/Research-Results/Projects-and-programmes/Euphoros/Calculation-tools/Hydrotools.htm
Economic and environmental simulator	The excel spreadsheet allows evaluating inputs and outputs and the potential environmental impacts of the product system basing on LCA approach	Crop characteristics, pesticide applications, energy use and livestock data	https://www3.lei.wur.nl/euphoros/

Resource/Tool/Database	Description	Main inputs/Based on	Link/Available at
Cool Farm Tool	Web tool to estimate the possible reduction in carbon and greenhouse gas emissions depending on growers' cultivation strategies	Crop characteristics, fertilizer applications, number of pesticide applications, energy use and livestock data, manure management, energy use	https://coolfarmtool.org/coolfarmtool/greenhouse-gases/
EcoModules	Web-based service for calculating environmental impacts of products for their whole lifecycle.	Material characteristics	https://www.luke.fi/palvelut/osaamisalueet/kiertotalous-ja-kestavyys/ecomodules-palvelu/
PrHo 2.0	DSS to calculate the water requirements of greenhouse vegetable crops	Crop and climate data	http://www.publicacionescajamar.es/series-tematicas/centros-experimentales-las-palmerillas/prho-v-20-programa-de-riego-para-cultivos-horticolas-en-invernadero-2/
VegSyst-DSS	DSS to calculate the nitrogen requirements of greenhouse vegetable crops	Crop and climate data, nitrogen content of the soil at the beginning of the crop	http://www.ual.es/GruposInv/nitrogeno/VegSyst-DSS%20-%20ESP.shtml
Performance indicators and indices			
Agro-environmental indicators	These indicators monitor agricultural and environmental change in England and are updated as new information becomes available		https://www.gov.uk/government/statistical-data-sets/agri-environment-indicators
WATER use	Provides standards and guidance for measuring, estimating, collecting, and analyzing water-use data		http://water.usgs.gov/pubs/chapter11/
Water footprint	SO 14046:2014 specifies principles, requirements and guidelines related to water footprint assessment of products, processes and organizations based on life cycle assessment (LCA). ISO 14046:2014 provides principles, requirements and guidelines for conducting and reporting a water footprint assessment as a stand-alone assessment, or as part of a more comprehensive environmental assessment.		https://www.iso.org/standard/43263.html
Databases and statistics			
AQUASTAT	Includes tools and databases providing information on water use and related parameters		http://www.fao.org/nr/water/aquastat/main/index.stm
FAOSTAT	Includes tools and databases providing information for agricultural system		http://www.fao.org/faostat/en/
EUROSTAT	Includes tools and databases providing information for agricultural system		http://ec.europa.eu/eurostat
OECDstat	Includes tools and databases providing information for agricultural system		http://stats.oecd.org/

Table 2. Examples of circular economy measures, metrics, indicators and indexes. Tomato production was considered as a model system. A1-n. Circular measures, metrics, indicators and indexes in the strict sense, measuring the degree of closed loops and restorative processes (degree of circularity on company level). B1-n. Environmental performance or competitiveness metrics are associated with sustainability but not with circularity in a strict sense of the concept[1].

Monitoring tool and reasons for its use	Requirements to be measured /calculated according to the principles of circularity (reusing, recycling, recovery)[2]
Measures: Provide quantitative indication of the extent, amount, dimension, capacity, size etc. of some attribute of a process or a product. **Why do you need measures?** ✓ To operationalize a process at a practical, concrete level with a number or value. ✓ Measured values do not provide enough information to guide decisions. They must be fed into a metrics for that.	***How efficient is the use of materials and energy to deliver the value proposition?*** ✓ How many m^2 of water/N/P/kWh of energy are used per ha to grow tomatoes? ***Reducing input and use of natural resources and increasing share of renewable and recyclable resources:*** ✓ How many m^3 of water comes from blue, green and grey sources? ✓ How many kg of nutrients are synthetic, excavated from the lithosphere or are animal, plant or manure based? ✓ How much of the energy/material inputs is derived from renewable sources? ***Reducing valuable material losses:*** ✓ How much water is drained per ha? How tight do materials and products circulate? ✓ How much waste is reduced as a result of the value proposition? ***Product and by-product outputs:[3] How much material inputs are needed to deliver a unit of value?*** ✓ How many kg of saleable tomatoes are produced/ha? ✓ How much by-product biomass per ha do you sell to other production processes where they are used as raw material? ***Reducing non-product outputs (solid waste, wastewater, air emissions):*** ✓ How much waste is generated to deliver a unit of value? ✓ How many kg of produced biomass other than the end product are recycled/sold as raw material to other processes, and taken to the landfill as waste? ✓ How much nutrients and CO_2 are discharged/emitted to the environment per weight unit of tomatoes? ***Business model:*** [4] ✓ How much of the value proposition is derived from recycling/repairing/reusing and circular business models? ✓ How much do costs increase/decrease by implementing circularity?
Metrics: a system or standard of measurement by which you assess the efficiency/ performance/progress/ quality of your production process/ products. **Why do you need metrics?** ✓ To take decisions for changing the process if it is has not reached target value(s)	**A1. *The Fraction of a Product that Comes from Used Products:*** [1] ✓ What is the ratio between recirculated and total economic value of products? **A2. *Eco-efficient Value Ratio:*** [5] ✓ How much environmental impacts accrue per euro spent for production? **B1. *Water use efficiency (WUE):*** [6] ✓ How many liters of water are needed to produce one kg of tomatoes? **B2. Relative Irrigation Supply (RIS)** ✓ How much water is used compared to the irrigation water demand of the crop? RIS = 1 is optimal, RIS > 1 indicate excess of water use **B3. Nutrient use efficiency (NUE)** ✓ How many kg tomatoes are produced per kg nutrient uptake by plants? **B4. *European nitrate directive:*** [7] ✓ How much $N\text{-}NO_3^-$ can you have per unit volume of wastewater that reaches surface or groundwater? **B5. *Material flow analysis:*** [2] ✓ How much material (substances and goods) enters your tomato production process as inputs and how much material leaves it as outputs? **B6. *Data Envelopment Analysis:*** [8] ✓ How efficient is your company in using inputs and transforming them into outputs? **B7. Global Energy Requirement** (GER, $MJ\ kg^{-1}$) ✓ How much energy is used in relation to the produced yield?
Indicator: A measurable variable used as a	***What is the degree of circularity of your tomato production process? To which extent does it close the material loops, maximize value***

Monitoring tool and reasons for its use	Requirements to be measured /calculated according to the principles of circularity (reusing, recycling, recovery)[2]
representation of an associated (but non-measured or non-measurable) quantity or factor. **Why do you need indicators?** ✓ Indicators help to measure a company's transition towards a CE and provide actionable information used for bench-marking.	***(natural, financial, human, social), lead to positive resource and emission footprints and contribute to future based orientation?*** [4] **A1. *Circle Economy:*** [9] ✓ How well is your company upholding CE principles and implementing their policies and intentions to move towards a CE? **A2. *Material Circularity Indicator: How to maximize restorative flows and minimize linear flows?*** [10] ✓ How much can you reduce input and use of natural resources/increase the share of renewable and recyclable inputs in your tomato production process? ✓ How much waste goes to landfill, is used as energy or raw material in other processes, and is recycled via composting? ✓ How much can you increase the value durability of tomatoes to reduce food losses? **B1. *Water footprint (WF)*** (L of water per one kg of tomatoes based on life cycle analysis in the full supply chain): [6] ✓ How much does your tomato production contribute to freshwater scarcity in your area/country? **B2. *Carbon footprint:*** [2] ✓ How much does the production of one tonne of tomatoes contribute to climate change? **B3. Global Warming Potential (GWP, kg emitted CO_2 per kg yield)** ✓ How much does production contribute to global warming? **B4. Air Acidification Potential** (AAP, kg sulfur dioxide emissions into the atmosphere per ton of yield) (LCA based) ✓ How much does your production system contribute to air pollution? **B5. Eutrophication Potential** (EUP, kg phosphates per ton of yield) ✓ How much does your production system enrich ecosystems with nutrients? (LCA based) **B6. Photochemical Oxidation Potential** (POP, kg ethylene equivalent emissions into the atmosphere per ton of yield) ✓ How much does your production system contribute to secondary air pollution through photochemically reactive substances? (LCA based)
Index: A set of related indicators, expressed as a single value, for comparing performance across programs/processes that are similar in content or have the same goals and objectives. **Why do you need indices?** ✓ For same reasons as Indicators	**A1. *Circular economy index (CEI):*** [11] ✓ What is the recycling rate in economic terms (material value from recycling in percent of material value of new product)? **B1. *Water stress index:*** [6] ✓ How much water is withdrawn from the water sources of one particular area compared to its water availability that varies according to monthly and annual precipitation?

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