Impact of Deep Flow Cultivation Systems on Sustainability of Field Vegetable Production

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Abstract

In 2009, a research program was initiated in the Netherlands to develop soilless cultivation systems for outdoor crops, with the objective to design cost effective cultivation systems with minimal emissions of fertilizers and pesticides. To test whether these objectives have been achieved, a sustainability impact assessment of growing vegetable crops on a deep flow system was performed. We developed a conceptual framework consisting of a set of quantitative and qualitative environmental, economic and social indicators. Application of the framework showed that compared to field cultivation, deep flow cultivation performs better on land use, pesticide use, nutrient use and water use. However, profitability decreases, and greenhouse gas emission and direct energy use increase considerably. Sustainability gains and losses vary between crops. Uncertainties and opportunities were revealed, thereby directing further optimization of the deep flow system in crops where its performance is promising. Moreover, transparency about the system's sustainability is crucial for the systems' social and political acceptance and for its adoption by farmers.

INTRODUCTION

In 2009, a research program was initiated in the Netherlands to develop soilless cultivation systems for outdoor crops, including tree nursery crops, flowers, flower bulbs, vegetables and fruit crops. The initial driver behind this program was to improve compliance of outdoor horticultural production with European regulations for water quality (EU, 2000; EU, 1991). Particularly nutrient and pesticide emissions need to be considerably reduced in order to meet the new regulations. The aim was therefore to design cost effective cultivation systems with minimal nutrient and pesticide emissions, while maintaining economic perspectives for farmers.

Inspired by modern greenhouse horticultural production, a range of soilless cultivation systems were designed and tested during the course of the program. The potential for implementing these systems is being evaluated for the following (groups of) crops: leaf vegetables, leek, cabbages, strawberry, apple, blueberry, tree nursery crops, summer flowers, perennial plants, and flower bulbs. Some of the new systems are currently in an advanced stage of implementation and are being adopted by growers for commercial crop production.

Scientific underpinning of emission reduction is important for achieving social, political and commercial support for soilless systems. Also, for farmers to adopt the systems requires evidence of their economic performance. However, comparison between the conventional and new systems is not straightforward since they often differ in terms of production scale, duration of the growing season or product characteristics. Moreover, improvements may go at the cost of other aspects. Such trade-offs should be accounted for when assessing the performance of a new cultivation system.

In order to do so, we developed a conceptual framework for assessing the impact of soilless cultivation systems on sustainability of outdoor horticultural production. Sustainability is most commonly defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). In our context, this implies that growers should be able to make a living from their farming activities, while safeguarding other functions and future availability of the natural resources used and without negatively affecting their own and others' well-being. The framework is structured according to the three generally acknowledged dimensions of sustainability: People, Planet, and Profit (Kuhlman and Farrington, 2010). In the following sections, we present the framework and apply it to four field vegetable crops: leek, head lettuce, spinach and cauliflower.

Based on the case study results, we identify strengths and weaknesses of the new systems as well as opportunities for further improvement. Since we are interested in the impact of changing from a field cropping system to a soilless cropping system, we discuss performance of the soilless cropping systems *relative* to their reference field cropping systems, without making any judgments about sustainability of producing a particular crop in general.

CONCEPTUAL FRAMEWORK

In order to assess the impact of changing from a typical field cropping system to a soilless cropping system, a reference system had to be defined. Cropping practices can strongly vary among growers and assumptions regarding such aspects affect the outcome of the comparison. Therefore, systems were defined on a case by case base using crop-specific production data representative for the Netherlands (Anonymous, 2012), comple-0mented with expert consultation.

To determine changes in economic, environmental and social performance, different themes were selected. The Planet dimension contains the largest set of themes, which is due to the fact that environmental performance is the driver behind development of soilless cropping systems. In the Profit dimension, different types of costs and benefits can be efficiently merged into one theme, as profitability captures costs of all inputs as well as shifts in costs and revenue due to a change in product quality or quantity. More insight into costs and revenues is provided by De Haan et al. (2014). Labour and landscape valuation were included as social themes. Labour directly relates to labour costs, which are accounted for in the economic theme profitability. Other social issues such as food safety and occupational health and safety were not included as horticultural production in the Netherlands complies with high legal and extralegal standards for these themes.

To make a theme measureable, one or more quantitative or qualitative *indicators* had to be defined. Selection of indicators was based on previous studies (De Haan et al., 2002; Boone et al., 2007; Boone et al., 2012). Where possible, quantitative indicators were used as they can objectively and transparently be measured following commonly agreed standards, while qualitative indicators often lack a standardized approach and are subject to interpretation. Emission of pesticides and nutrients was (partly) quantified indirectly through indicators expressing the application of corresponding inputs. Some themes were qualitatively measured due to lack of appropriate methods or quantitative data. This applies particularly for People themes, where quantitative alternatives (e.g., contingent valuation or hedonic pricing method for landscape valuation) are very comprehensive and time-consuming. Table 1 provides an overview of themes and corresponding indicators. Further information on the methodology can be provided by the authors upon request.

System boundaries were defined in order to determine which impacts are attributable to the cultivation system. In our calculations, the system included all input factors and processes directly related to the cultivation of the crop under investigation. Other crops on the same farm were excluded. Farm property and on-farm post-harvest processes were only included if they were fully attributable to the investigated crop and differed between the conventional and soilless cropping system. Capital goods such as machinery and equipment used in multiple crops were proportionally attributed to the system. In line with LCA methodology (Guinée et al., 2002), indicators were expressed per functional unit, which is a particular amount or volume of harvested, marketable product.

SUSTAINABILITY ASSESSMENT

The framework was applied to measure sustainability performance of leek, head lettuce, spinach and cauliflower grown in a deep flow cultivation system (DF system). This type of cultivation system is described by De Haan and Van Dijk (2013). Figure 1 shows the performance of the DF system per crop for most sustainability themes, relative to the performance of a field cultivation system. A value of 100% implies equal performance of both systems. Presented results are preliminary as optimization of the systems is still on-going and commercial implementation is still rare.

The DF system performs consistently better (i.e., value lower than 100%) on land use, use of pesticides, water usage, and labour demand. More efficient harvesting causes labour savings in all crops. Land use efficiency is increased due to a higher planting density or frequency, or both. Fewer pesticides are applied due to lower disease pressure under more controlled circumstances, resulting in lower pesticide emissions. Emissions are further reduced because the DF system is better isolated from the environment; e.g., production takes place without interaction with the soil. The net effect on pesticide emission, expressed in Environmental Impact Points (Reus and Leendertse, 2000), is considerably, particularly for soil life and groundwater (results not shown).

Nevertheless, experience with soilless cultivation in greenhouses learns that occasional high point emissions can occur when the water from the system is discharged. The required discharge frequency for optimal crop growth is not known yet (De Haan and Van Dijk, 2013). Current results are based on a discharge frequency of once in three years; changes in this frequency will also affect the relative performance on water usage. Particularly for spinach, conclusions regarding performance on water usage are sensitive to assumptions on discharge frequency as savings are rather small relative to the field cultivation system.

The DF system has a higher greenhouse gas emission and direct energy use per unit product than a field cultivation system. This is explained by the high electricity use for pumping the nutrient solution. Electricity use per m^2 is independent of planting density or frequency, causing the negative impact on greenhouse gas emission and energy use to be relatively lower for crops with high land use efficiency. The DF system also performs poorer than the field cultivation system in cost price. Particularly capital costs are much higher (De Haan et al., 2014). As with electricity use, capital costs per m^2 are not directly related to the planting density, causing their relative magnitude to decrease as production efficiency increases. For the moment, product prices are assumed to be the same for both systems. As a result, impacts of the DF system on profitability are negative.

Both positive and negative relative performances of the DF system are observed for nutrient usage (N and P). On the whole N and P use are better in the DF systems compared to the soil systems. The increase in P use in leek is due the fact that production in a DF system cannot benefit from the high P supplies that are still present in soils in major leek producing regions. The relative performance of the DF system for leek will gradually improve as P supply in the soil becomes smaller over time.

Apart from the quantitative results presented here, a number of themes were qualitatively addressed, i.e. risk, physical work load, and landscape valuation. Due to the high level of mechanisation, a large initial investment is required when switching to a soilless cropping system. This brings along an investment risk. The so-called pay-back period of a system increases as its revenue-cost ratio is lower. Another risk is incidental crop failure. This risk is likely to be reduced in soilless cropping systems as production takes place in a more controlled environment.

Soilless cropping systems generally reduce the physical work load, as activities that used to be done manually can easier be automated or plants are grown at a more convenient working height. Particularly in crops where labour is currently physically demanding, as is the case with lettuce cultivation, growers highly value these improvements.

Finally, the impact of soilless cultivation on landscape valuation was qualitatively evaluated. Consultation of citizens revealed that the DF system scores poorer than field cultivation systems on this aspect because of its somewhat industrialized appearance. This impact can be moderated by using natural colours and material and adapting the height of the system to its surrounding. A strength of the DF system is that it looks very clean and neat, with straight rows and no weeds.

DISCUSSION AND CONCLUSIONS

The relative sustainability assessment of the DF system in four crops showed mixed results. Moderate to large gains are achieved with respect to land use, pesticide use, nutrient use and water use. On the other hand, greenhouse gas emission and direct energy use increase considerably. It is currently investigated whether these impacts can be reduced, e.g., by analysing how energy consumption for water circulation can be reduced. Also, the decrease in profitability is a major drawback of the DF system as product margins in vegetable production are already very small. For lettuce and leek, it is expected that DF cultivation can over time become profitable through further optimization of the system and increased product price (De Haan et al., 2014). The latter improvement should be achieved by more flexibility in supply period and promoting superior quality (e.g., no soil attached).

While Figure 1 provides insight into the *relative* performance of the DF cultivation system, observed differences between crops are not necessarily representative for the absolute impacts per crop. For instance, DF cultivation decreases labour demand for cauliflower while labour demand for lettuce increases almost fivefold. However, absolute labour demand is still higher for cauliflower (113 h per 10,000 heads) than for lettuce (93 h per 10,000 heads). Also, the decrease in land use is minor for spinach, because land use efficiency is already very high in field production and there is little room for improvement. Therefore, no conclusions can be drawn on absolute sustainability of cultivation of individual crops in either of the two systems. Furthermore, the interpretation of absolute values is crop-specific. A higher labour demand may be justified by a higher value of the crop, or compensated by low other inputs such as land use. Conclusions on the sustainability of a crop should thus be based on an integrated assessment, and account for the importance stakeholders attach to particular themes. Methods such as multi-criteria analysis are suitable for performing such assessments (Sadok et al., 2008).

In measuring the performance of different cropping systems, we came across several methodological limitations. For certain impact categories, indicators commonly used for measuring performance of field cropping systems appeared difficult to quantify for soilless cropping systems. For instance, current standards for expressing nutrient emissions are based on existing quantitative models, which are not adapted to innovative systems as evaluated here. Nutrient application was considered a representative proxy as nutrient uptake by the crop will not significantly differ between systems in and out of the soil. For measuring landscape valuation, no suitable indicator was available at all as this theme has never been accounted for in the design of cropping systems before. Therefore, conditions favourable for integration in agricultural landscape were identified from on-site workshops with consumers.

Another methodological pitfall was the risk of confounding intrinsic system characteristics with grower's implementation. Examples of such biases are the assumption that in soilless cropping systems non-marketable crop parts can efficiently be collected and used as by-product for e.g., energy production and that less water would be required due to the use of rain water. While soilless cropping systems facilitate such sustainability gains, they can also be realized in field cultivation systems. As a compromise, farming practices and techniques were only taken into account if they are common practice on representative farms and their implementation is closely associated with the type of cultivation system.

At this stage, some soilless cropping systems are at a more advanced stage of development than others, and adoption differs per sector. Data were scarce for some crop-system combinations, and quantified sustainability impacts are subject to high uncertainty. This is particularly true for the crops spinach and cauliflower, and for the indicators energy use, water use and profitability. Reducing these uncertainties requires still numerous questions to resolve, such as: which planting densities and frequency are optimal? How long can water be recirculated in hydroponic systems? How will disease pressure in soilless systems evolve over time? Can added value be created on the market? Some of these questions are currently addressed in technological research aimed at further optimization of the systems. Other questions can only be answered by monitoring commercial use of the systems over time.

The potential of the soilless systems also depends on exogenous factors, such as institutional circumstances and macro-economic trends. For instance, growers who intend switching to soilless crop production face a diversity of legal criteria and preconditions, which may even vary per region depending on local policy. Particularly with respect to spatial planning, policies may need to be adapted to facilitate the establishment of soilless cropping systems in a region. On the other hand, increasing restrictions to pesticide use and decreasing availability of healthy soils will make soilless cropping systems more attractive.

A sustainability assessment as presented in this paper serves multiple purposes. It provides insight into the performance of soilless cropping systems on a number of themes in different dimensions. We have identified strengths and weaknesses, uncertainties to be resolved, and opportunities for improvement. Results of our assessment direct further optimization towards a system that is sustainable from an environmental, economic and social perspective. Transparency about sustainability also determines the system's social and political acceptance, offering adopters a licence to operate. Most importantly, a sustainability assessment identifies whether the objectives underlying the design of soilless cultivation systems have been met. For the DF system, this is true with respect to the objective of improving compliance with European legal requirements for water quality. Yet, economic perspective for farmers is reduced and requires further improvement. For this reason, it is unlikely that the majority of Dutch crop production will take place out of the soil in the near future. Nevertheless, soilless cultivation systems can serve specific demands of growers, such as complying with specific product demand (e.g., period of supply, quality) or meeting environmental legislation if this cannot be achieved in field cultivation. Therefore, we believe that soilless crop production *complementary to* field cropping systems offers new opportunities for growers and is worth further development and implementation.

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Literature Cited

Anonymous, 2012. KWIN: Kwantitatieve Informatie Akkerbouw en Vollegrondsgroenteteelt 2012 (in Dutch). Applied Plant Research, Lelystad.

Boone, K., De Haan, J.J. and Goddijn, S. 2007. Evaluatie opzet van LEer Instrument Duurzaamheid (LEID) (in Dutch). LEI, The Hague. 43p.

Boone, K., Dolman, M., Jukema, G., Van Kernebeek, H. and Van der Knijff, A. 2012. Duurzame landbouw verantwoord: Methodologie voor het kwantitatief meten van de duurzaamheid van de Nederlandse landbouw (in Dutch). LEI, The Hague. 169p.

De Haan, J.J. and Garcia Diaz, A. (eds.) 2002. Manual on Prototyping Methodology and Multifunctional Crop Rotation. VEGINECO Report 2. Applied Plant Research, Lelystad. 96p.

De Haan, J.J. and Van Dijk, S. 2013. Soilless cultivation of outdoor horticultural crops in The Netherlands to reduce nitrogen emissions. Extended Abstract Nutrihort Conference, 16-18 Sept., Ghent. (In press.)
De Haan, J.J., Spruijt, J. and Vermeulen, T. 2014. Farm Management and Economic Drivers for Implementation of Soilless Cultivation of Outdoor Horticultural Crops in The Netherlands. Acta Hort. 1034:177-184.
EU. 1991. Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. Official Journal of the European Communities 34 L375:1-8.
EU. 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities 43 L 327:1-72.
Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., De Koning, A., Van Oers, L., Wegener Sleeswijk, A., Suh, S.,. Udo de Haes, H.A., De Bruijn, H., Van Duin, R., Huijbregts, M.A.J., Lindeijer, E., Roorda, A.A.H., Van der Ven, B.L. and Weidema, B.P. (eds.). 2002. Handbook on Life Cycle Assessment; Operational Guide to the ISO Standards. Institute for Environmental Sciences. Leiden University, Leiden, The Netherlands.
Kuhlman, T. and Farrington, J. 2010. What is sustainability? Sustainability 2010 (2): 3436-3448.
Reus, J.A.W.A. and Leendertse, P.C. 2000. The environmental yardstick for pesticides: a practical indicator used in the Netherlands. Crop Protection 19(8-10):637-641.
Sadok, W., Angevin, F., Bergez, J.-E., Bockstaller, C., Colomb, B., Guichard, L., Reau, R. and Doré, T. 2008. Ex ante Assessment of the Sustainability of Alternative Cropping Systems: Implications for Using Multi-criteria Decision-Aid Methods – A Review. Agronomy for Sustainable Development 28(1):163-174.
WCED. 1987. Our Common Future. World Commission on Environment and Development. Oxford University Press, New York, NY, USA.

Tables

Table 1. Sustainability themes with selected indicators and method of quantification.

Theme	Indicator	Expression[1]	Quantification method
Planet			
Land use	Required acreage	m^2	Empirical measurement, farm reference data (Anonymous, 2012)
Nutrient emission	N-application	Kg	Empirical measurement, farm reference data (Anonymous, 2012)
	P- application	Kg	Empirical measurement, farm reference data (Anonymous, 2012)
Pesticide emission	Use of active ingredient	Kg	Empirical measurement, farm reference data (Anonymous, 2012)
	Burden on surface water	EIP[2]	Environmental Yardstick (Reus and Leendertse, 2000)
	Burden on ground water	EIP	
	Burden on soil	EIP	
Water use	Supply of water	m^3	Empirical measurement
Climate change	GHG emissions direct and indirect	Kg CO_2-equivalents	Life Cycle Assessment according to ISO standards (Guinée et al., 2002)
Energy use	Direct energy use	MJ-equivalents	Empirical measurement, farm reference data (Anonymous, 2012)
Profit			
Profitability	Product price	€	Empirical measurement, farm reference data (Anonymous, 2012)
	Cost price	€	Partial budgeting
	Revenue-cost ratio	%	Follows from product price and cost price
People			
Labour	Labour demand	Hours	Empirical measurement, farm reference data (Anonymous, 2012)
	Physical work load		n/a (Qualitative)
Landscape valuation	Height of the system		n/a (Qualitative)
	Material and colour use		n/a (Qualitative)

[1] Indicators are expressed per functional unit, i.e., a specified amount or volume of harvested, marketable product.
[2] EIP = Environmental Impact Points, determined by the active substance, volume used, and drift percentage.

Figures

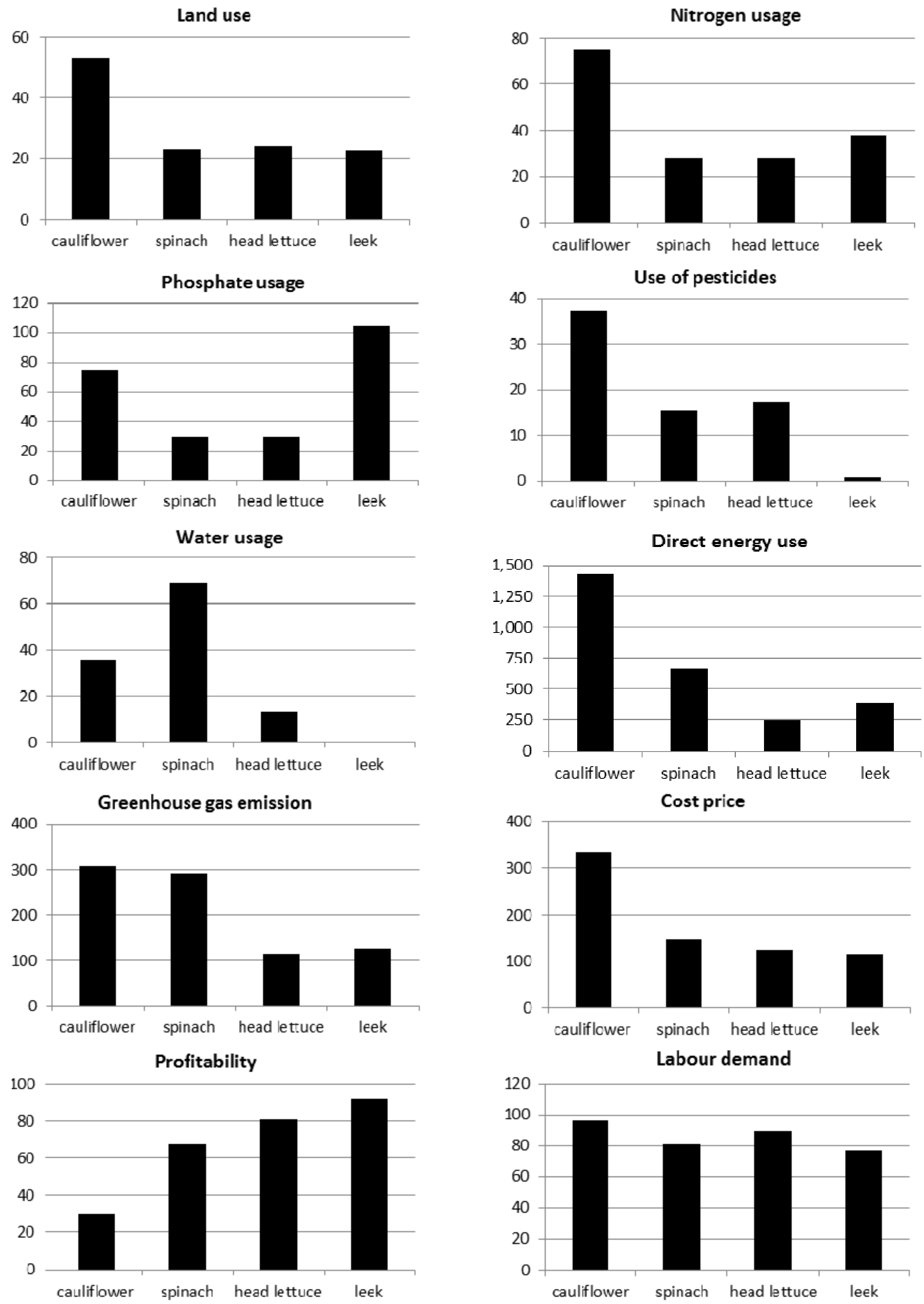

Fig. 1. Relative performance of a DF system on ten sustainability indicators, in cauliflower, spinach, head lettuce and leek. Performance of the field cultivation system is set at 100%; a lower score implies that the DF system performs better, except for profitability where interpretation is the opposite.