Quantitative comparison between soil based cultivation systems and stone wool systems

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Introduction

The term “Sustainability” can be defined in several ways, in essence the term points to endurance of systems and processes to sustain the well-being of future generations. Usage of resources per unit horticultural product e.g. water, land and fertilizer usage, can be used as indicators for sustainability. Grodan® as part of the ROCKWOOL Group has commissioned the chair group Horticulture and Product Physiology of Wageningen University to conduct a literature review and develop a calculation tool. The tool allows a comparison between soil based and stone wool based cultivation systems and makes an estimation of water, fertilizer and land use in three distinct climate zones for the crops tomato and cucumber.

Rationale behind the sustainability parameters

There are many measures for sustainability, but in relation to sustainability of substrates in horticultural systems usage of resources like water, land, pesticides and fertilizers, are key. Yield as such is also reported as it is an important indicator of overall cultivation system performance. This study focuses on sustainability of the crop production system and does for instance not include the whole chain of the horticultural products until use by consumers. In particular in greenhouse production systems, sustainability also depends on energy use. Note that this study/calculator does not include an energy or carbon footprint. In the following paragraphs the background of the data and guideline for data interpretation for each sustainability parameter is provided.

Yield per unit land area when cultivating on stone wool is potentially much higher than in soil bound (conventional) systems. Cultivation on stone wool, allows for a much more accurate control of the root environment (e.g. water and nutrient availability, EC, pH, oxygen availability, root temperature) compared to cultivation in soil bound systems. Other reasons for higher yields when grown on stone wool are: (1) roots are isolated from soil-borne pests and diseases, and (2) often when growing on stone wool the greenhouse soil is covered with white plastic foil, which reflects light thus increasing crop light interception and potential production. Reported yield improvements vary between 15 and 40%. However, yields can be as much as 10 to 20 times higher, when comparing soil bound cultivation in the field, with cultivation on stone wool in greenhouses. This difference is almost completely the result of comparing greenhouses, i.e. optimal growth environment and longer cultivation season, with open field.

Water use efficiency (WUE) is important as access to fresh water is crucial in agricultural, industrial, household, recreational and environmental activities. WUE is defined as the amount of product per unit of water used (kg per m^3). Irrigation practices have big impact on overall water use in a horticultural system, e.g. frequency, moment of the day, drip irrigation - spray etc. Here averages are taken of different irrigation practices. It is generally known that both the world's supply of usable groundwater is steadily decreasing and that the "water footprint" of human food consumption itself is unsustainable. Therefore water use efficiency must increase, as demand for irrigated crops grows while water and land resources are constrained (Stanghellini 2014). Soilless systems using stone wool can help improve water use on two levels. (1) irrigation efficiency itself can be increased by recirculating drain water and narrowly monitoring and matching crop demands; (2) yields per cubic meter of water used can be increased by the use of soilless systems (Olympios 1993; Putra and Yuliando 2015; Barrett et al. 2016).

In this study, data on water use efficiency (WUE) are generally directly taken from literature papers. In addition to this, for The Netherlands, where very detailed information is available, we have conducted a calculation with the following rationale:

Stone wool with 100% recirculation uses 15 litres water per kg tomatoes (Van Kooten et al. 2008). This is in agreement with Pronk et al. (2007) who report 1050 litres per m^2, which equals 15 litres per kg times 70 kg per m^2. In turn 70 kg per m^2 represents a "good tomato yield" according to KWIN Glastuinbouw, (2016-2017).

Water use of cultivation in a soil bound system is often higher than a soilless system. Pronk et al., (2007) report, for example, that 1250 litres of water is irrigated per m^2; yield is assumed to be 10% lower on soil than on stone wool hence 70 * 0.9 = 63 kg m^{-2}; this means 1250/63 = 20 litres water per kg tomatoes for conventional cultivation in soil. Please note that conventional cultivation of tomatoes in soil hardly exists anymore in the Netherlands.

To accommodate for a certain drain water recirculation percentage in the calculation tool, the following rationale was used: Van Kooten et al. (2008) reported that with 100% recirculation 15 litres per kg product was used and that 22 litres per kg was used for a free drainage system. Hence, e.g. 85% recirculation would mean (22-15)*(1-0.85)= 1 litre of disposed drain water per kg product. Thus water use efficiency equates as 15 litre (100% recirculation) + 1 litre additional use by 85% compared to 100% recirculation is a water use of 16 litres per kg tomatoes with 15% drain.

Nitrogen (N) is an essential element for crop growth and is roughly 1 to 5% of total plant dry matter and makes up 40-50% of all minerals in a plant. Nitrogen serves as building block for proteins, (co-) enzymes, nucleic acids, chlorophyll, phytohormones and secondary metabolites and is thereby a key steering element in crop management (Marschner 2011). Although a sufficient supply of N benefits crop growth, high N levels running off in the environment (water, soil and air) near cultivation areas are a serious global problem. Apart from nitrogen, fertigation water also contains other potentially polluting elements like phosphorus (P). Nitrogen and phosphorus emissions are both key measures when estimating the sustainability of an agricultural system. Crops receive phosphorus and nitrogen fertilizers in a ratio of roughly 1:10. It is, however, hard to rigorously quantify the phosphate use in soil based systems compared to soilless systems. Therefore the focus here is on nitrogen use.

Land Use Efficiency, i.e. the cultivation area used for the production of a unit of product is an important resource use measure. In the calculation tool differences between soilless (stone wool) and soil bound systems are estimated by looking at the yield per unit area. As a calculation example, if a soilless system produces 70 kg tomatoes per m^2 then it requires 1.4 m^2 for 100 kg tomatoes. If yield in a soil bound system produces 10% less compared to soilless (stone wool) system because of less optimal root environment, then 70 * 0.9 = 63 kg m^2 hence 1.6 m^2 needed for 100 kg tomatoes. Thus because of the lower yield more land area is required to establish the same amount of tomatoes, i.e. 100 kg in this example.

It is important to note that cultivation on stone wool allows for the use of land that would otherwise not be suitable for horticulture. This hidden sustainability asset has not been included in the calculation tool.

Emissions of plant protection products (pesticides use) contribute considerably to the present suboptimal surface and groundwater water quality. In soil-grown crops emissions occur via leaching of plant protection products to ground and surface water. Runoff of pesticides strongly depends on irrigation strategy (Voogt et al. 2012), but the emission from soil-bound systems will never be zero. In principle, soilless cultivation systems can obtain zero emission, because the nutrient solutions are recirculated and there is no interaction with water flows in the soil (Beerling et al. 2014). In the Netherlands, for the top 20% tomato growers the emission (discharge) is almost zero, whereas for the bottom 20% tomato growers it is 746 m^3 ha^{-1} $year^{-1}$ which is about 10% of the annually overall used nutrient solution (Beerling et al. 2014).

Methodology

To optimally balance simplicity and details, the amount of input parameters is kept as limited as possible, but still aims to provide a robust estimation of resource use. Data underlying the quantification of water, fertilizer and land use was derived from scientific experiments and renowned trustworthy sources. Documentation of these sources is provided in Portable Document Format (PDF) files which are included with the calculation tool.

Data gathering

Search strategy used for this literature review mainly followed general practices for literature reviews. To prevent too narrow search results, cross-referencing was done by screening references in meta-analyses and review papers.

Cultivation system definition

In this study several horticultural systems in different climate zones are compared (Table 1). The quantification of the four sustainability parameters, i.e. yield, water, fertilizer and land use can be done using the calculation tool. Note that comparison between full soil systems and substrate systems using stone wool is made on a system level. This means that resource use differences between soil and stone wool cultivation systems are confounded with general systems differences, e.g. substrate heating, level of climate control, fertigation regimes, technology level and other general cultivation practices. The cultivation systems are defined as follows:

"Open Field (soil)" is defined as production in the natural soil without any cover. This is also commonly referred to as unprotected horticulture, i.e. no plastic tunnel, greenhouse or glasshouse is used.

"Low tech greenhouse (soil)" is defined as production in natural soil or imported soil that is ground bound (e.g. enarenado in Almeria); greenhouse with natural ventilation, no heating system, no active cooling system.

"High tech greenhouse (soil)" is defined as production in natural soil or imported soil that is ground bound (e.g. enarenado in Almeria); these greenhouses are high tunnels, multi-tunnels, single or multispan glasshouses with heating systems and these may also contain active cooling systems.

"High tech greenhouse (stone wool)" are in all aspects defined similar to "High tech greenhouse (soil)" except for the used substrate.

Climate zone definition

To have commonly accessible and accepted definitions of the climate zones, the definitions conform to Wikipedia websites (01-04-2018), i.e.:

Temperate: https://en.wikipedia.org/wiki/Temperate_climate
Mediteranian: https://en.wikipedia.org/wiki/Mediterranean_climate
Arid: https://en.wikipedia.org/wiki/Desert_climate

Table 1: Combination of climate zones and cultivation systems.

	Temperate	Mediterranean	Arid
Open Field (soil)	+[1]	+	-
Low tech greenhouse (soil)	+	+	-
High tech greenhouse (soil)	+	+	+
High tech greenhouse (stone wool)	+	+	+

[1] Relevance is questionable as there is no commercial open field tomato cultivation in N-W Europe
+ Data available
- No data available

Information on chair group Horticulture and Product Physiology

Currently Wageningen University (WU) is ranked as No. 1 in agriculture & forestry among the world's leading universities according to QS World University Rankings. The WU chair group Horticulture and Product Physiology (HPP) is the only academic group focused on horticulture in the Netherlands, which possesses a leading position in horticultural research worldwide. The chair group, led by Prof. Marcelis, explores and exploits the combination of physiology of horticultural crops as well as the combination of experimentation and process-based modelling. The HPP chair group has not only large experience in working with hydroponics in greenhouses and vertical farming, it is also well known for its systems analytical approach, questions from horticultural practice are translated into fundamental research topics, aiming to explain mechanisms. The mission of the HPP chair group is to provide the scientific foundation for sustainable crop production and high product quality in horticulture. The HPP group publishes yearly on average 20-25 peer-reviewed papers in international scientific journals with high impact factors. The quality of the research has been evaluated as excellent by the latest peer review committee.

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