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Minimising emissions to water bodies from NW European greenhouses; with focus on Dutch vegetable cultivation

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A B S T R A C T

In large parts of the Netherlands surface water quality does not meet the chemical and ecological standards as indicated by the EU Water Framework Directive (WFD). The largest exceedances were found in areas with greenhouse horticulture, flower bulbs, fruit trees and ornamental trees. Several regulations have been implemented to improve water quality in greenhouse areas, leading finally to a target for zero emission of nutrients by 2027 in soilless cultivation and rules to minimise losses in soil bound cultivation. In addition to that an obligation exists to remove plant protection products (PPPs) from drain water by 2018 onwards. For soilless cultivation a Zero Liquid Discharge (ZLD) system gives the best options to reach these goals. For soil-bound cultivation the situation is more complicated and a combination of tools and measurements to help the farmer to tune irrigation to crop demand is most promising. These approaches will lead to a substantial decrease in losses of nutrients and PPPs to surface water. However, it is uncertain whether this will lead to the desired reduction in emissions and the water quality standards of the WFD in 2027. Obstacles might be problems with soil-bound cultivation, leakages in soilless cultivation and sodium limitations in certain crops.

1. Introduction

1.1. Greenhouse horticulture in north western Europe

Greenhouse horticulture in the Netherlands covers an area of nearly 10,000 ha (Raaphorst, 2017), mainly in the western part of the country. Compared to other Northwest European countries the area and the concentration of greenhouses is much larger. Surrounding countries have 500 – 3,500 ha of greenhouses scattered over a larger area (Germany (3,500 ha), Belgium (2,000 ha), Sweden (500 ha), Denmark (< 500 ha), UK (< 500 ha)).

The sector is characterised by high production rates and accordingly a high input of nutrients (Sonneveld, 1995, 2000) and plant protection products (PPPs) per ha compared to other agricultural use (Tiktak et al., 2019). These high inputs of nutrients and PPPs induce emissions to ground and surface water by leaching from soil bound cultivation and by discharge and leakage from soilless cultivation systems.

1.2. Legislation on emission of nutrients and plant protection products

In large parts of the Netherlands surface water quality does not meet the chemical and ecological standards as indicated by the EU Water Framework Directive (EU-WFD, 2000). In 2014, concentrations for both nitrogen (N) and phosphorous (P) were exceeded in 45 % of the water bodies and exceedances of PPPs were found at 60 % of the locations (Van Gaalen et al., 2016). This is amongst others caused by the combination of intensive agriculture, shallow groundwater tables and intensive drainage systems. The largest exceedances were found in areas with greenhouse horticulture, and cultivation of flower bulbs, fruit trees and ornamental trees.

The first legislation to reduce pollution of surface waters came into effect in 1994 within the Water Pollution Act (Roos-Schalij et al., 1994), following the EU Nitrate Directive (EU-ND, 1991). Enforcement of this regulation was assigned to the Water Authorities (regional semi-governmental bodies responsible for water quantity and quality). However, due to the large number of enterprises, local conditions as well as the impracticability of the control, the operation was unsuccessful. In 2002 this resulted in an official agreement (Besluit Glastuinbouw, 2002) with

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controllable obligations for greenhouse growers: 1. obligatory collection and reuse of drain water; 2. obligatory collection and storage of rain water for irrigation, with a minimum size of 500 m^3 ha^{-1}, or use of water from a source with comparable quality; and 3. permission to discharge drain water only if crop specific sodium (Na) levels in drain water are exceeded or in case of emergencies (outbreak of diseases, incidental technical failures). For soil bound greenhouse horticulture the reuse of drainage water became obligatory depending on the hydrological situation (absence of seepage).

Implementation of the EU Water Framework Directive (EU-WFD, 2000; detailed programme by 2009) and disappointing results from monitoring of surface water quality (Baltus and Volkers-Verboom, 2005; Teunissen, 2005; Kruger, 2008; Beerling, 2011), created an incentive for the central government to tighten the regulations again. Previous legislation appeared inadequate because growers had too many reasons to discharge drain water next to Na-accumulation (Van Paassen and Welles, 2010; summarised by Beerling et al., 2014).

This led to a whole new approach focusing more on the targets to be reached and less on how these targets are realised (Van Paassen and Welles, 2010). This new regulation was based on an agreement between authorities and the growers' organisation. New rules were set with a final target of (nearly) zero emission for (soilless) greenhouse horticulture in 2027 and crop (and company) specific norms for the emission of N, which will be gradually decreased until 2027. It is assumed that a reduction in N emission will be mainly achieved by a reduction in the discharge of water and will thus also reduce the emissions of P and PPPs. The first step (standard 2015, Table 1) was set in such a way that at least 70 % of the companies should be able to comply and was based on a survey of N emission carried out by the growers' organisation (Van Paassen and Welles, 2010). In Table 1, the nitrogen emission standards for 2015 are presented as well as the conversion to an equivalent discharge volume. The latter is based on an average nitrate level per crop and gives the growers practical guidance to formulate a discharge strategy.

For soil grown greenhouse crops a different approach was chosen, since emission standards were not feasible. The solutions were directed towards optimising irrigation and a sustainable use of fertilisers, together with the former regulations on crop-specific maximal nutrient usage.

However, the nitrogen emission standards were not expected to lead to a sufficient and rapid improvement of the water quality with respect to PPPs before 2027 (Van Eerdt et al., 2012). Therefore authorities and the growers' organisations developed an additional approach for PPPs, resulting in a Purification Decree (Hoofdlijnenakkoord Glastuinbouw, 2015) for greenhouse discharge water from 2018 onwards. This urgency was initiated by the growers' organisation because of expected stricter (approval and renewal) registration demands for PPPs, which would drastically decrease the availability of PPPs for growers. The Purification Decree states that at least 95 % of the PPPs have to be removed from discharge water by using purification equipment. Rules apply for both soilless and soil-bound greenhouse cultivation (Van Ruijven et al., 2020b) and for discharge to surface water and sewer systems as PPPs are normally not removed in sewage treatment plants and might even damage these systems (STOWA, 2010).

The UK and Germany have no specific legislation or action for emissions from greenhouse horticulture. In Denmark, recommendations are being prepared for how to manage wastewater and other waste from greenhouses with respect to PPPs. The horticulture industry has drawn up a voluntary action plan to promote a broad basis for follow-up initiatives (Danish NAP on Pesticides, 2017). Also in Sweden the focus is on voluntary information and training campaigns with respect to safe handling and application of PPPs to solve problems with diffuse leakage (Sweden's NAP on PPPs, 2019), because it is believed that excessively detailed legislation would not be efficient. But Sweden is also considering measures to reduce PPP pollution in surface water coming from greenhouses (pers. comm. K. Löfkvist, 2018). In Belgium greenhouses are not allowed to discharge water containing nutrients since 2006 (Berckmoes et al., 2013, 2014). Exception is that it is allowed to bring the discharged solution to a nearby agricultural field as fertiliser, during the (outdoor) growing season. This is similar to The Netherlands, however the density of greenhouses in a large part of the Netherlands is that high that a neighbouring field is not available.

This paper gives an overview of approaches implemented by Dutch greenhouse growers to comply with the above regulations. Although the majority of crops are grown soilless, still about 10–12 % (Raaphorst, 2017) of the crops are grown in soil. These growing systems strongly differ in the issues and the nature of the problem of emissions which necessitates to deal with them separately. A number of examples are given and the bottlenecks are discussed. Finally, we will discuss a number of options to tackle these bottlenecks.

2. Approaches to reduce emissions

2.1. Soil grown crops

Soilless culture is nowadays by far the main cropping system in Dutch greenhouse horticulture. Nevertheless, a reasonable area is still used for soil-grown crops. The majority is used for growing cut-flowers. Whereas the area of soil-grown vegetables is relatively small, enlisting leafy vegetables like lettuce types and radish (250 ha), and organically grown crops, which include mainly tomato, sweet pepper and cucumber (100 ha) (Voogt, 2015). As the mechanisms and processes behind the leaching problem of nutrients and PPPs are applicable for all soil bound crops and the approaches for fertigation are similar for flowers and vegetables as well, many studies and observations from soil bound flower production systems are highly relevant to vegetable

Table 1
Nitrogen emission standards for 2015* and related (estimated) volume of discharge.

Crop category	Soilless grown crops	Allowed Nitrogen Emission (kg N ha^{-1} yr^{-1})	Estimated allowed Discharge Volume (m^3 ha^{-1} yr^{-1})
1	Other vegetables	25	100
2	Anthurium, bedding plants	50	300
3	Cymbidium	75	950
4	Tulip, annual summer cutflower	100	600
5	Tomato, herbs	125	300
6	Cucumber	150	600
	Potted plants, starting material ornamental crops, other ornamental crops	150	900
7	Strawberry, aubergine, sweet pepper	200	650
8	Rose, gerbera, starting material vegetables	250	1,050
9	Phalaenopsis**, potted orchids	300	3,600

* Mentioned allowed N discharge will be linear reduced in 3-year periods to zero in 2027.

** Phalaenopsis only had an open drainage system at that time.

production.

To fully understand the approaches that may contribute to reduce emissions for soil grown greenhouse crops in the Netherlands it is necessary to consider the different hydrological situations in greenhouses (Voogt, 2015) as well as the Dutch approach of greenhouse fertilisation (Sonneveld, 1995). There are roughly two major hydrologically different situations:1) greenhouses located on soils with (relatively) deep ground water (> 1.5 m), in which the leaching will be primarily to groundwater; 2) greenhouses situated in areas with shallow ground water levels (often < 1 m). In the latter situation greenhouses are equipped with active and closed drainage systems, connected to a drainage pit with a pump to enforce lowering of the groundwater inside the greenhouse. The water pumped off is discharged to surrounding surface water. The enforced lower groundwater level may cause seepage from surrounding plots triggered by the difference in hydraulic pressure. The rate of seepage depends mainly on the difference in hydraulic pressure, the soil characteristics (saturated permeability) and the distance. In some cases, the hydrological situation varies throughout the year and in some periods of the growing season the groundwater level around the greenhouse will be lower than inside, whereas opposite situations may occur in other periods. Thus, depending on the hydrological situation, leaching resulting from irrigation surpluses will be drained off into the drainage system or will seep into the groundwater.

Seepage into the greenhouse drainage system may also be due to the natural geographical location of the greenhouse, for example a location in a valley or a deep polder. Thus, the net inflow into the drainage system in a greenhouse will be the result of the irrigation surplus percolating through the soil, the sideward seepage from surrounding plots, upward seepage from further away and leaching to the groundwater.

The approach of fertilisation of greenhouse crops differs substantially from that of field vegetables and can be characterised by targeting the EC-level and nutrient concentrations in the soil solution – except for P - in the root environment rather than applying certain amounts per unit area. This is driven by i) the high growth rates and the corresponding high nutrient demands, ii) the almost year round cropping cycles (fruit vegetables) or even continuous cropping (radish, leafy vegetables), iii) the use of fertigation as a way to control plant growth and development. Particularly in autumn and winter with poor light conditions, high osmotic potentials in the soil solution are maintained to prevent too lush growth (lettuce, radish), promoting flowering and fruit set (tomato) or to improve fruit quality (fruit vegetables). The current Dutch fertiliser recommendation system is therefore based on the concept of fertigation with target values for nutrient concentrations in the soil solution managed by regular sampling and analysing, using the 1:2 vol extract (Sonneveld and Van den Ende, 1971).

Generally spoken the approach to minimise emissions can be divided in four main directions: (i) changeover to soilless cultivation, (ii) reuse of drainage water, analogue to soilless systems, (iii) tune irrigation to crop demand and thus reduce leaching of water containing nutrients and PPPs, and (iv) tune N and P fertilisation to crop demand.

2.1.1. Change to soilless

An obvious solution for soil-grown crops would be a switch to soilless. However, for various technical and economic reasons this is not always feasible. Most of the crops grown in soil are characterised by a relatively short growing period (weeks or months) and a high planting density, with almost full coverage of the surface. To grow these crops in a soilless system a full surface coverage of a substrate or hydroponic system is needed. These modifications of the current system in combination with harvesting mechanisation necessitate high investments. As a result, a yield increase of at least 15 % for these crop types is needed to make soilless cultivation economically feasible (Ruijs, 1995). Although a change from soil to soilless usually leads to higher yields, this required increase could not be achieved for all crops.

2.1.2. Reuse of drainage water

Reuse of drainage water can only be implemented if it can be collected (hydrological situation 2 described above). Even in that situation, local hydrological conditions (high seepage) may limit implementation. Moreover, other than in soilless systems, soil bound systems can never be completely closed due to losses to groundwater. Nevertheless, reuse of drainage water has been successfully implemented in many soil-grown crop situations since the nineties. Baltus and Volkers-Verboom (2005) reported that 50 % of the greenhouses with soil grown crops reused drainage water, which resulted in serious reduction in the quantity of discharged drainage water and strong improvement of the water and nutrient use efficiency (Voogt and Korsten, 1996; Voogt et al., 2000).

2.1.3. Tuning irrigation to crop demand

The most effective way to reduce leaching is to reduce the inputs of water and fertilisers (Voogt, 2005), although a certain over-irrigation is the common strategy for soil grown crops to avoid salt accumulation. Voogt et al. (2000) demonstrated, in a number of experiments with chrysanthemum in a Dutch commercial greenhouse on a light clay soil with a drainage system at 90 cm (hence the groundwater level), that the irrigation could be safely reduced to approach zero leaching. However, the heterogeneity of stem length and weight was increased if the irrigation went below the point of zero leaching, where capillary rise contributed to the water supply of the crops. The approach of 'tuning to crop demand' as it is named, has been advocated by many stakeholders (water authorities, (local) governments, growers organisations) as the most effective and potent approach to minimise emissions. However, for the majority of the growers the crop water demand as well as important parameters as soil moisture conditions and water holding capacities are rather elusive. In fact, most growers are unaware of the crop water demand and do not know if and how much water is leaching from the topsoil. Accordingly, from the first regulations onwards, the focus was put on revealing the unknown and develop and implement tools to provide the growers with insight in the irrigation demand of crops, the soil moisture conditions and the processes of leaching (Voogt et al., 2000). There have been three approaches to this subject: 1) models, 2) sensors and 3) the use of lysimeters. Examples will be discussed in Section 3.1.

2.1.4. Tuning fertilisation to crop demand

The concept of fertigation solutions and target values for the soil solution was developed in the seventies and eighties and was aiming at optimum production and quality. For obvious reasons there is room for reduction of the levels of NO_3 and P without compromising yield or quality. However, this system is well established and widely accepted in the Dutch greenhouse industry. Nevertheless several experiments in this direction have been conducted as well as demonstrations at farms. This was carried out in close cooperation with the growers to investigate the possibilities of reduction of the N (NO_3) concentrations as well as lowering the P-buffer (Voogt, 2005), some examples will be shown in Section 3.2.

2.2. Soilless grown crops

Reduction of emissions is relatively easy in soilless cultivation compared to soil grown crops, as water flows can be controlled. The first approach that has been studied is reduction of the irrigation surplus. However, simply reducing irrigation has severe limitations as soilless systems are characterised by a small rooting volume. This requires a very accurate supply of water and nutrients, as the storage of water and nutrients in the substrate is very low and theoretically only sufficient for one or two days (Sonneveld, 1995). In practice a drain fraction of at least 0.2 is recommended to prevent problems of heterogeneity in release of drippers, transpiration and uptake. Vegetable growers mostly use a fraction of 0.3, flower growers 0.5 as these crops tend to be more heterogenous. As Dutch growers have fully climatised and computerised greenhouses, including measurement of global radiation, the irrigation is strictly related to the amount of (solar and artificial) radiation.

In the eighties hardly anybody was aware of the polluting effects of emissions on the aquatic environment, and the price of water and fertilisers was low compared to energy or labour (Raaphorst, 2017). Growers preferred an open system, as it was cheaper (lower investments; no pipework, control equipment or disinfection) and easier as adjustment of the applied fertilisers over time could be avoided.

Changes in legislation (as was described in Section 1.2) and along with that the development of new knowledge and dissemination programmes stepwise changed this behaviour over the years. To reduce emissions of nutrients and PPPs to the environment, and to comply with the increasingly stricter legislation, growers took the following two steps and are now considering the third:

1 Recirculation of drain water, to reduce emission of both nutrients and PPPs;
2 Purification of discharge water for the removal of PPPs, to reduce emission of PPPs;
3 Zero Liquid Discharge (ZLD) cultivation, to avoid emission of nutrients and PPPs.

2.2.1. Recirculation of drain water

To change the habit of leaching and discharging drain water, recirculation of the nutrient solution became obligatory for soilless cultivation systems, together with the use of rainwater as main source for irrigation water (see Section 1.2). The stricter legislation made growers change from open to semi-closed systems (Fig. 1; Van Os, 1998).

A semi closed system requires a change in the infrastructure and control of the cultivation system. Drain water needs to be collected, transported and stored. In the early open systems drain water flowed from the slabs directly into the soil. A first step was to make troughs to collect the drain water from the slabs and to bring it to a central place. In the greenhouse the troughs lie on a slope (around 0.2 – 0.5%). Drain water flows on gravity to a sub-surface drain tank ($< 1\ m^3\ ha^{-1}$). From here it is pumped to a central place, to be collected in a dirty water tank with a recommended size of about $35\ m^3\ ha^{-1}$. The water is treated by a disinfection unit (see Section 3.2.1) and stored in a tank for disinfected drain water with a size of $70\ m^3\ ha^{-1}$. The irrigation solution is prepared by a substrate unit (a small tank, $1 - 2\ m^3\ ha^{-1}$) with computer controlled equipment to add fertilisers and fresh water; Boesten et al., 2019). Often there is a day storage tank of $40 - 50\ m^3\ ha^{-1}$, from which irrigation to the plants takes place.

Next to controlling EC, pH and irrigation regimes, the irrigation computer shows the realised data for further adjustments. Supply water and drain water are generally analysed at least once every two weeks on nutrient composition. In an open system analysis of the nutrient solution is less important as growers always supply the standard solution; only control on the volume given to the plants is important (enough drain water).

With this semi-closed system the grower is always in control of the timing and the amount of water discharged. Water is periodically discharged for several reasons, but all reasons are related to actual or assumed insufficient water quality (Na accumulation, imbalances in the nutrient solution), inadequate hardware (too small storage tanks, discharge of filter rinsing water, calamities) or cultivation measures (first drain water after draining the slabs, risk of diseases just after planting) (see Beerling et al., 2014; Van Os et al., 2019).

2.2.2. Purification of discharge water

The water discharged from a semi-closed cultivation system still contains nutrients and PPPs (if applied in the cultivation) and needs to be treated to remove 95 % of PPPs (Purification Decree; see Section 1.2). Fig. 2 (left) gives a schematic overview of the water flows in a greenhouse in which purification of discharge water is included.

To be able to treat the water, it has to be stored separately. In general, growers will attempt to reduce the amount of discharge water as much as possible, to lower the required capacity of treatment equipment and thereby to lower costs. The water needs to be treated with approved purification equipment (see Section 1.2). This could be done with dedicated equipment (option 1), or with an installation with a dual function for purification of discharged water and disinfection of recirculation water (option 2). Contractors can also bring an approved mobile treatment installation to a grower, to treat stored discharge water (option 3). Regional collection of discharge water from neighbouring horticultural enterprises with treatment at a central location (option 4) can be a relevant solution, but only in concentrated greenhouse areas, as the infrastructure for transport of water is expensive. A complicating factor is that collectivity requires a strong commitment from all growers. Collective treatment of waste water flows (including nutrients) from these (semi-) closed systems has already been studied (Van der Velde et al., 2008), but implementation appeared to be rather expensive. Extensive investigations to the effectiveness of various available equipment is done by Van Ruijven et al. (2014) and is shortly summarised in Section 3.2.1.

2.2.3. Zero liquid discharge cultivation

To simultaneously solve emission problems for nutrients and PPPs, a next step is to look for options to avoid periodical discharge in a so called Zero Liquid Discharge system (ZLD; Fig. 2, right) (Beerling et al.,

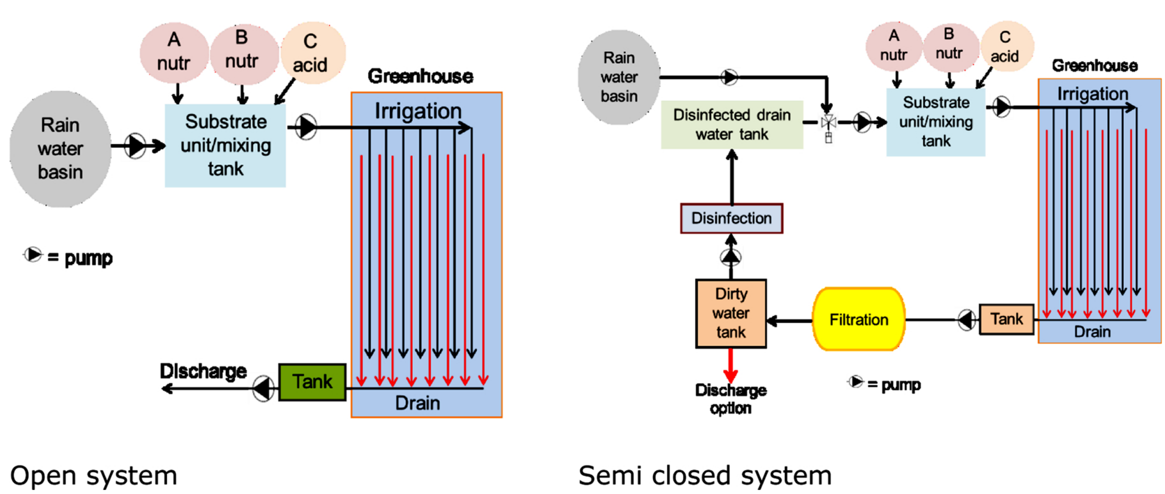

Fig. 1. Schematic overview of an open (left) and semi-closed system (right).

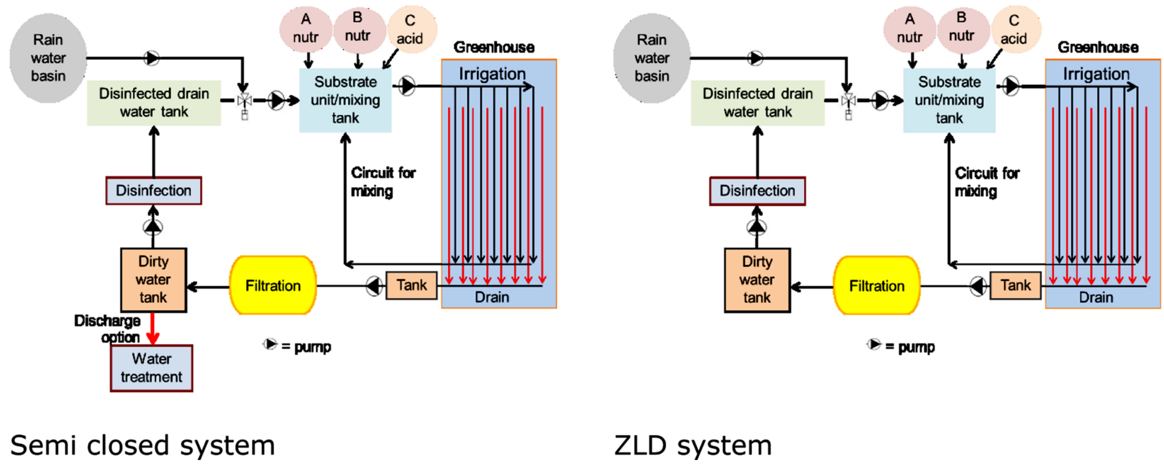

Fig. 2. Schematic overview of a semi-closed system with purification of discharge water (left) and Zero Liquid Discharge (ZLD) system (right).

2017; Van Os et al., 2019, 2020). Therefore, the cultivation systems and practices have been evaluated for reasons to discharge, followed by the development of solutions and the redesign of the soilless cropping system. Prerequisites for such a system are 1) good quality irrigation water (almost free of Na, see Section 3.2.4), 2) optimal control of the quality of the recirculating nutrient solution, using an adequate water treatment technique and filters (see Section 3.2.1) which produce less or no rinsing water, 3) prevent unbalances in nutrients by fertigation based on plant needs, and 4) sufficient storage volumes and adequate piping for irrigation and drain water reuse. ZLD systems solve the issues for discharge of nutrients and PPPs in semi-closed cultivation systems.

The above mentioned systems are for substrate grown crops. For lettuce and similar crops, grown in NFT or DFT, the principles are slightly different. From the beginning lettuce was grown in a closed system at which the surplus of water was recirculated. However, hardly any water treatment took place. In NFT, DFT, but also at sub-irrigation (ebb/flow), recirculating water volumes are very high and are often not disinfected for economic reasons (Ruijs et al., 1995).

3. Examples and bottlenecks

3.1. Soil grown crops

The water balances of several commercial greenhouses (Table 2) illustrate the variability in situations due to the complexity of the hydrological conditions at individual greenhouses (Voogt and Korsten, 1996; Voogt et al., 2006). Greenhouses (GH) 1 and 5 are typical for the hydrological situation with high groundwater and seepage and a resulting high input of water by capillary rise. The drainage quantity is very high (GH1) to extreme (GH5), although the irrigation surplus is negative as seepage quantities are high. In GH5 some drainage water is used for irrigation – in fact this cannot be considered as reuse, since there is virtually no irrigation surplus -, but this is only 16 %. For GH1 the grower decided not to use the drainage, as he feared salinity built-up, due to the high EC-value of the drainage water. High EC is also the reason that GH3 did not use all its drainage water and discharged one-third. GH4 and 6 did not have drainage as the groundwater table is more than 5 m below surface. For GH4 the irrigation surplus is rather limited, compared to the other chrysanthemum growers, which is not the case with GH6 with the highest irrigation of all radish growers.

GH7 and 9 both had a high drainage, much more than the irrigation surpluses, indicating substantial seepage. Both growers reused part of the irrigation surplus and the seepage, but a substantial part is still discharged. In both cases, as well for GH5, the seepage occurs during the autumn and winter seasons, when groundwater levels and the water levels in surrounding ditches rise due to rainfall. In this period only little irrigation is needed. Only for GH2 and GH8 all the drainage water could be reused, and this resulted in almost zero losses. However, even in these situations there is no guarantee that the amount of water drained derives only from the irrigation surplus. The overall annual balance might be just the net result of an irrigation surplus and (downward) seepage at one hand and upward seepage at the other hand, which occur at different moments in time. Hence, periods of upward seepage, will cause leaching of nutrients and PPPs to the environment. Such an effect can be illustrated by Fig. 3, showing the water fluxes (total drainage, irrigation surplus) over time. These data show that an average or a total value of these water fluxes over time can easily be misinterpreted as there are huge peaks in the actual fluxes. All by all it can be concluded that reuse of drainage water only in some cases will contribute to minimising emissions.

3.1.1. Tuning irrigation to crop demand

3.1.1.1. Models. To enable growers to tune irrigation to crop demand, tools have been developed to estimate the crop water demand. Basically, these DSS models calculate the cumulative uptake of water by the crop over a certain period, which is understandable since irrigation is primarily intended to replenish the soil water content. One of the first initiatives was the FERTIGATION model, which was based on calculation of the crop evapotranspiration (ET_c) over time and included even an estimation of the nutrient demand to tune also nutrient uptake (Voogt et al., 2000). This model was tested in experimental greenhouses (Voogt, 2001) and in commercial practice at three year-round chrysanthemum growers (Voogt et al., 2006). These three growers with modern greenhouses, were situated in a typical Dutch polder, with heavy clay soils, with approximately 5 % organic matter in the topsoil and very low salinity levels in soil and groundwater. The growers had a drainage system between 0.8 and 0.9 m below the surface. Irrigation was done by modern rotating overhead sprinklers and using 100 % (stored) rainwater for fertigation. Although the results differed among the growers, this DSS model showed to be applicable by growers and to lead to a serious reduction in the input of water and fertilisers (Table 3), without any effect on yield or quality. However, a disadvantage is that the model requires actual data from the greenhouse (e.g. radiation, temperature, heating pipes, use of screens), as well as basic soil physical parameters, and data on crop and greenhouse construction. The latter values were not always available or easy to obtain.

3.1.1.2. Sensors. Initially, with the first attempts to tune irrigation to crop demand, the focus was on sensors measuring soil matric potential (tensiometers). These sensors were used to monitor the soil moisture conditions, as well as to initiate irrigation, using start/stop signalling.

Table 2
Water balance from four chrysanthemum crops and five radish crops, monitored for 24 to 30 months, expressed in mm year^{-1}; Irrigation (I), Drainage (D), and draiange reused in the irrigation (DR) are measured data, Evapotanspiration (ET_c) is derived from model calculations, Irrigation Surplus (IS) is the result of I-ET, the resulting assumed leaching to groundwater (DI) is calculated as the gap in the water balance D-DR (Voogt and Korsten, 1996; Voogt et al., 2006).

Greenhouse	Irrigation (I) mm	Evapo-transpiration (ET) mm	Irrigation surplus (IS) mm	Drainage (D) mm	Drainage-reuse (DR) mm	Discharged or leached to groundwater (DI) mm
Chrysanthemum						
1	677	789	−112	450	0	450
2	1,100	810	290	410	385	25
3	1,439	816	623	650	403	247
4	860	822	38	0	0	38
Radish						
5	490	527	−37	895	147	749
6	703	459	245	0	0	245
7	660	512	148	398	198	201
8	584	547	37	46	47	37
9	669	438	231	507	134	374

Soil and hydrological situations: GH1 Light clay on peat, groundwater 0.5 – 0.6 m, active drainage at 0.9 m depth.
GH2 Light clay, groundwater 0.8–1.0 m, active drainage at 0.9 m depth.
GH3 Moderate clay, groundwater 0.8–1.0 m, active drainage at 0.9–1.0 m depth.
GH4 Loamy sand, groundwater 3–5 m, no drainage system.
GH5 Sand, groundwater 0.5 – 0.8 m, active drainage at 0.8 m depth.
GH6 Loamy sand, groundwater 3–5 m, no drainage system.
GH7 Sand, groundwater 0.6 – 0.8 m, active drainage at 0.8 m depth.
GH8 Sand, groundwater 0.8 – 0.9 m, active drainage at 0.8 m depth.
GH9 Sand, groundwater 0.6 – 0.8 m, active drainage at 0.8 m depth.

This methodology was tested in a large number of crops, soils and hydrological situations during a number of years (De Veld, 1995). In some situations the results were successful in terms of adoption by growers, for others the adoption was pretty low. Other strong disadvantages of these sensors were maintenance, complicated sensor installation and the need for specific calibration.

Next to these sensors, volumetric soil water content sensors, like frequency domain reflectometry (FDR) sensors became popular. They did not need maintenance, were easier to install and the data were easier to interpret. Nevertheless, the same disadvantages as for tensiometers apply: calibration and application of the data is not straightforward. However, the most important disadvantage of using soil moisture sensors for irrigation management aiming at zero emission is that one cannot visualise or predict leaching. With soil moisture sensors one can only get a rough impression of soil water fluxes, when sensors are installed at several depths and by observing the trends in graphs. Voogt et al. (2018) studied the behaviour of soil moisture measurements by FDR-sensors in combination with a lysimeter in chrysanthemum (Fig. 4). The sensors showed a typical and expected response; at 15 cm depth the moisture content showed short peaks with irrigation events (irrigation by sprinklers, events of 6–15 mm), indicating water flow from the top to deeper levels. The sensor at 25 cm responded delayed, with small fluctuations and at 60 cm there was no response at all. Intensification of irrigation events, like the first weeks in August and in November show wetting at all three depths, but without a clear increase in the drain in the lysimeter. On the contrary, periods with relative decreasing soil moisture levels (early September and early October) had high peaks in drainage. Due to the vicinity to the

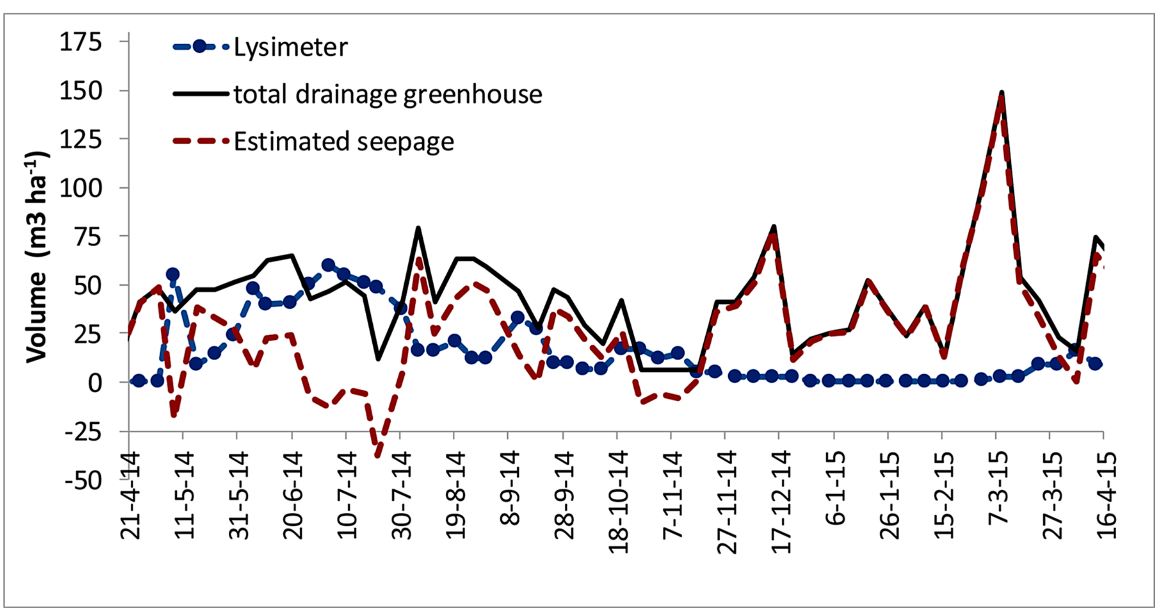

Fig. 3. Daily amount of drain collected in a lysimeter (LD), the total drainage of the greenhouse (GD) and the estimated seepage, as derived from GD-LD, during a one year cropping cycle in a commercial greenhouse in a polder area with a natural groundwater level at 0.6 m and an active drainage system at 0.9 m depth; data in $m^3\,ha^{-1}$.

Table 3
The calculated evapotranspiration (ET_c), the total irrigation (I), the calculated irrigation surplus (IS), in mm year^{-1}, and the Relative Irrigation Supply index (RIS) (I/ET_c) at three commercial greenhouses using the FERTIGATION model in a section of the greenhouse (M) compared to the reference (R), with irrigation according to the growers own insights.

		Evapo-transpiration (ET_c)	Irrigation (I)		Irrigation surplus (IS)		Relative Irrigation Supply index (RIS)	
Grower	Year	M/R	M	R	M	R	M	R
A	1	687	756	769	69	83	1.10	1.12
	2	779	874	1,026	95	247	1.12	1.32
B	1	799	918	1,254	119	455	1.15	1.57
	2	850	1,076	1,165	227	315	1.27	1.37
C	1	785	972	1,051	187	266	1.24	1.34
	2	843	868	893	25	50	1.03	1.06

saturated zone as well as the dispersion of the water flows, sensors at depths will lack dynamic changes and are therefore not useful as indicators for leaching (Balendonck et al., 2012).

3.1.1.3. Lysimeters. The only method by which the real leaching can be uncovered is by using lysimeters. These devices have demonstrated their functionality in scientific research for decades (Titus and Mahendrappa, 1996), but have never been used as such as a tool for irrigation control. Basic requirement of a lysimeter is that it represents as much as possible the conditions for crop growth and development, hydrology and thus ET_c in the greenhouse outside the lysimeter. In essence the lysimeter is only applicable in situations with no substantial contribution of capillary rise. Since in almost all Dutch greenhouses a smaller or larger irrigation surplus is the case, when considering periods of a week or longer, this is not a hindrance for using this tool. However, when growers are moving towards the point of zero leaching this will become increasingly problematic. To prevent this situation, the lysimeter was modified by installing additional drippers inside the lysimeter surface area with a known capacity, to increase the input with 10 % (or the like) which enforces some deliberate small drainage flow in the lysimeter, which then clearly can give the grower the indications he needs for aiming at zero leaching for his entire greenhouse. Surely relying on capillary rise as a source of additional water supply is not recommendable due to salinity build up in the soil. Voogt et al. (2014) designed a 'practical lysimeter' for use in commercial crops, which either manually or automatically measures the drainage. Application in a number of successive and various crops demonstrated that these lysimeters make leaching tangible (Fig. 5) This contributed highly to the awareness of growers with respect to the occurrence of emission and their options to control it.

This can be illustrated by the results of the water balance data of four organic growers, where lysimeters were installed (Fig. 6). Each of the greenhouses had long term (10 months) crop cycles with tomato, cucumber or sweet pepper in rotation. Growers used the lysimeter to adjust their irrigation strategies to aim leaching reduction. During five successive years the irrigation and lysimeter drainage was monitored and ET_c was calculated from crop- and greenhouse climate data. Irrigation and ET_c differed substantially among growers, due to differences in cropping cycle, local conditions, as well as the grower's own judgements. For some growers the maximum irrigation was even lower than the maximum evapotranspiration, (which is likely due to additional supply through capillary rise), for others peak irrigations were higher than ET_c. All by all this resulted in differences of + and – 15 % in the calculated irrigation surplus. The calculated positive surplus corresponded quite well with the real drainage in the lysimeter (obviously negative surpluses cannot be measured by a lysimeter (Fig. 5)). Despite these large annual differences, the average measured leaching was low with values between 2 % and 12 % for all years and growers. These relatively low values demonstrate the intention of these growers to tune the irrigation to crop demand. Nevertheless, these data also show that even for motivated growers, in this case organic growers that deliberately strive to zero emission, it is hardly possible to tune irrigation to crop demand without any leaching.

A serious bottleneck for the use of lysimeters for direct irrigation control is the time delay between the occurrence of irrigation events and the moment of registration of leaching in the lysimeter. Data analysis has revealed that this is at least several days and makes it complicated for direct irrigation control.

3.1.1.4. Combination of tools. In an approach to overcome the various bottlenecks of the above mentioned three approaches, a modular system was developed, consisting of a combination of an irrigation model, soil moisture sensors and a lysimeter (Voogt et al., 2012; Balendonck et al., 2012; Heinen et al., 2012). In this model, EMAN3G, irrigation events and quantity were predicted by the

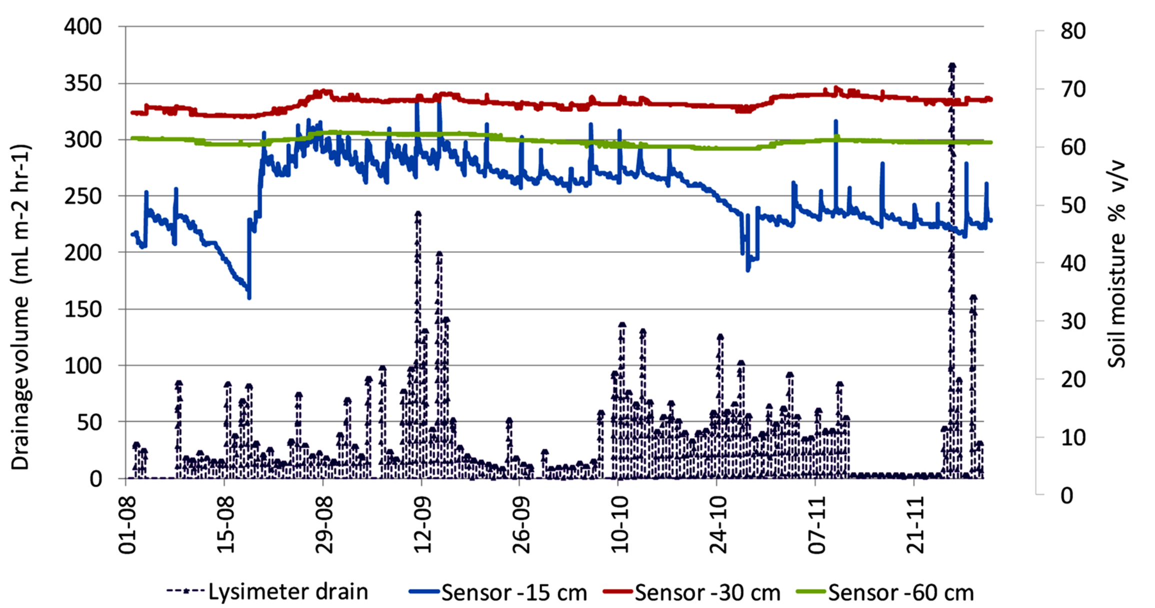

Fig. 4. Course of the soil moisture content, measured with FDR-sensors at 15, 25 and 60 cm depth, time interval of 10 min and the measured drainage in a lysimeter (surface 2 * 1.60 m, depth 0.9 m), with time interval of 1 h in a commercial greenhouse with chrysanthemum during five months.

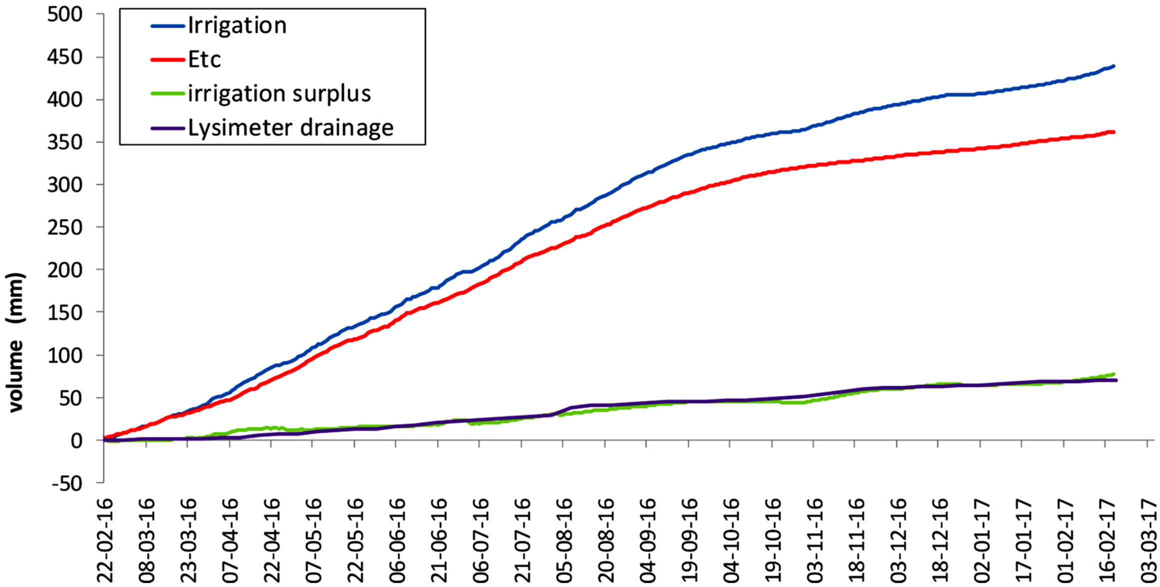

Fig. 5. The cumulative irrigation and evapotranspiration (ET_c) and the resulting cumulative irrigation surplus and the cumulative lysimeter drain in a commercial alstroemeria greenhouse during a full year.

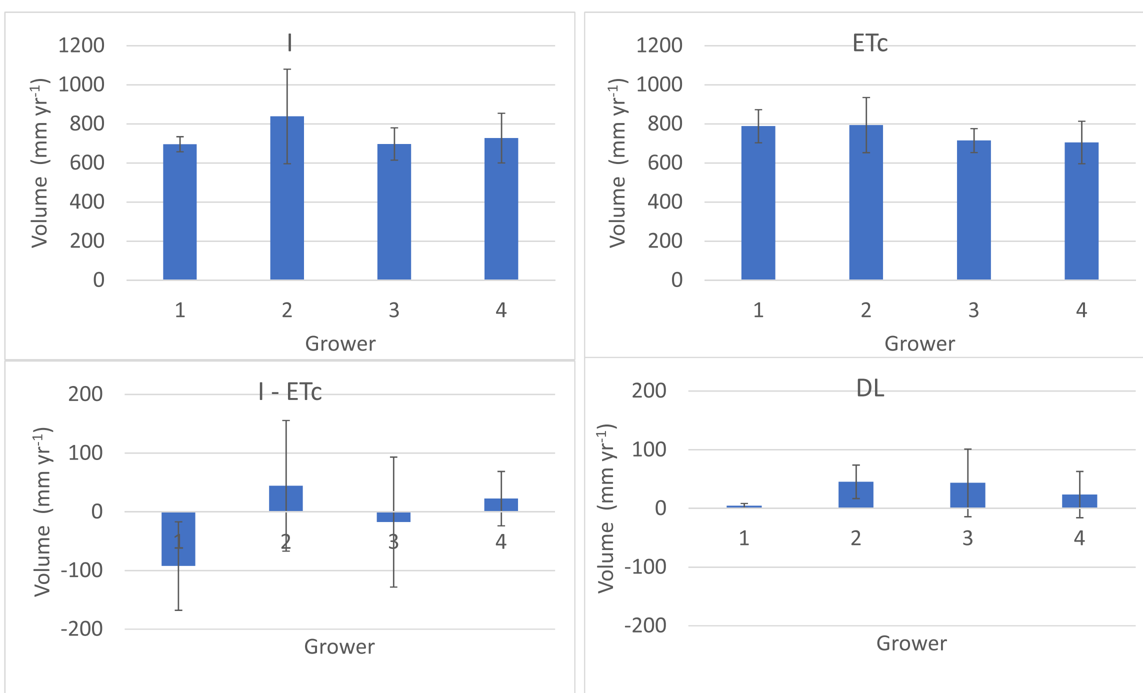

Fig. 6. Results of the water balance at four organic growers that used a lysimeter for irrigation control, monitored during five successive years, all with long term tomato, cucumber and sweet pepper crops in rotation, showing the average values over the years of the irrigation (I), evapotranspiration (ET_c), irrigation surplus (I-ET_c) and the lysimeter drainage (Dl), all expressed in mm year^{-1} (data derived from Voogt et al., 2017). Vertical bars represent ± standard deviation.

FERTIGATION model. The lysimeter drainage data were used for feedback control on the fertigation model. Then, soil moisture sensors were used as a safe-guard to check both the irrigation events and to prevent that the lysimeter would dry-out in case of less irrigation than ET_c and even modify some of the parameters settings automatically, like soil or crop parameters. This approach was initially tested in an experimental greenhouse, followed by implementation at thirteen different commercial greenhouses, with a variety of cut-flower and vegetable crops.

Implementation was guided by intensive data collection by research staff as well as exchange of results by automatic data uploading to an internet platform, with access to all participants, and through regular discussions of the results in small groups of growers (Voogt et al., 2012). Results of one of the chrysanthemum growers in this project (Fig. 7) showed that initially the irrigation surplus (I minus ET_c) was 25 % for a cropping cycle, but gradually it decreased to around 10 % and finally even went down to almost zero. This illustrates the learning process of this grower. In this particular case he learned to adjust the irrigation by watching the reaction of the sensors and learned under which conditions the lysimeter starts to produce drainage (Fig. 7). However, the approach as described above was only adopted by few growers. The majority qualified the systems as too complicated,

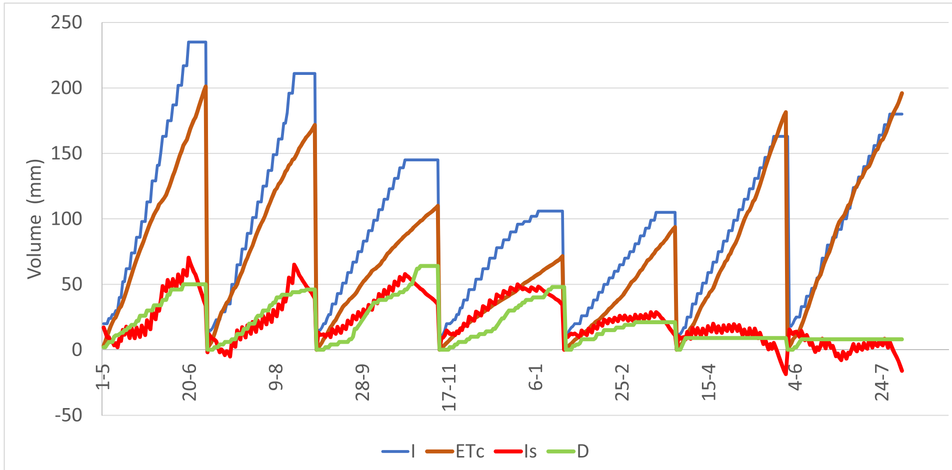

Fig. 7. Cumulative data of irrigation (I), calculated ET_c, calculated irrigation surplus (IS), and the measured lysimeter drainage (D) at a chrysanthemum crop during 1.5 year (seven successive crops).

moreover, many of them were too much dedicated to their own experience and common irrigation strategies. Therefore it was not easy to convince them to use these alternative approaches.

3.1.1.5. Adoption of technology. Reusing drainage water has been adopted widely in commercial soil grown greenhouses, if applicable, given the quality (electrical conductivity, EC) and the hydrological conditions. Application of this methodology is rather easy and inexpensive. The adoption of other technologies to obtain the goals for emission reduction was not entirely successful. Generally spoken, the lack of incentives and the increased risks of yield losses and loss of quality can be mentioned as the main reasons for the low adoption by farmers. Moreover, all of these technologies require investments and operational costs including additional labour, which are perhaps only compensated by some small savings on water and fertilisers.

Eventually, only a handful of growers made use of the DSS model for tuning fertigation to crop demand. Apart from the consideration mentioned above, growers have quite some reservations against model calculations in general and rely more on their own experience. This was in particular the case when the recommended values for irrigation were below their own expectations and judgements of crop demand. The same, or even more hesitation was observed when more sophisticated DSS-models, with a combination of tools were introduced. The adoption of soil moisture sensors was more successful. Initially both sensors for soil matric potential and volumetric soil water content were installed by many growers after introduction. However, after a while it appeared that only few of them actually used the sensors for steering irrigation. Next to some technical issues, like maintenance, failures (with limited service by supplying companies), the complicated sensor installation and the need for specific calibration was seen as an important drawback. A disadvantage was also the time needed for adequate use of these sensors i.e. to learn about soil-moisture behaviour in response to irrigation events and evapotranspiration. However, the most important disadvantage of using soil moisture sensors for irrigation management aiming at zero emission is that one cannot visualise or predict leaching. With soil moisture sensors one can only get a rough impression of soil water fluxes, when sensors are installed at several depths and by observing the trends in graphs.

Although the lysimeter was appraised by growers as a very useful tool for feedback on the irrigation strategy and a means to aim at zero leaching, the system was considered as not applicable in commercial practice. The main reasons were the high costs, estimated at €7,000 per unit for the simple version and over €10,000 for a fully automated version (Voogt et al., 2015), as well as that the lysimeter was too much an obstacle in the course of harvesting, soil tillage and planting cycles of crops for commercial practice.

3.1.2. *Tuning fertilisation to crop demand*

The current Dutch fertiliser recommendation system is based on the concept of targeting the nutrient concentrations in the soil solution (section 2.1), which is managed by regular sampling and analysing by the 1:2 vol extract (Sonneveld and Van den Ende, 1971). Control of the osmotic potential, using the EC as parameter is considered as a key factor to control crop development and also fruit quality (Sonneveld and Voogt, 2009). Since this concept is well established and widely accepted in the Dutch greenhouse industry, it would not be easy to convince growers to reduce NO_3-levels to obtain reduction in the emission of nutrients. Experiments and demonstrations at farms have been conducted, in close cooperation with the growers to investigate the possibilities of reduction of the N and P supply (Voogt, 2005). For example, Van den Bos (2003) showed clearly that neither yield nor quality of lettuce was negatively affected by substantial reduction of the N-target values and, consequently, the N-supply (Table 4). As a result the N-target values were reduced substantially. In other trials with several crops, reduction in the NO_3-concentration was also shown to be possible without causing any problems (Voogt et al., 2002). Although the effects on leaching could not be determined in these experiments, logically a reduction of the NO_3-concentration in the soil solution would at least reduce the risk of NO_3-leaching. In specific crops for which the EC value is important for quality, the reduction in N-supply must be compensated by application of other salts. For instance Van den Bos (pers. comm.) has reported fertiliser trials with radish, in which N was successfully partly replaced by SO_4 and Cl. Seasonal effects, related to the change in irradiation should be taken into account. Sonneveld

Table 4
The average soil mineral N at the start, N-supply, yield (average head weight, relative to treatment 1) and N-uptake of four successive lettuce crops, in an investigation of lettuce in soil, at four target levels of soil-N at the start of the crop, with 9 mmol L^{-1} as the reference value (Van den Bos, 2003), the N-concentrations (mmol L^{-1}) refer to the 1:2 vol extract and are the sum of NH_4 and NO_3.

Treatment	N target value (mmol L^{-1})	Mineral N in soil (mmol L^{-1})	N-supply (kg ha^{-1})	Yield (%)	N-uptake (kg ha^{-1})
1	3	2.1	72	100	138
2	5	3.6	123	103	143
3	7	5.8	189	102	149
4	9	7.4	238	102	147

Table 5
Results of a 3-year fertiliser trial with thirteen successive lettuce crops. Average P-content in the soil expressed as: P in the 1:2 vol extract, P_w value and P-Al content, the P-fertiliser supply, yield (average head weight), P-content and P-uptake. Treatment 2 is the standard recommended value for P for this soil (Voogt and Van den Bos, 2016).

Treatment	P supp. (kg ha^{-1})	P (1:2) (mmol L^{-1})	P_w[1]	P-Al[2]	Yield (g $head^{-1}$)	P cont. (mmol kg^{-1} d.m.)	P-uptake (kg ha^{-1})
1	0	0.03	48	122	320	186	641
2	340	0.07	73	133	331	214	739
3	680	0.11	101	146	330	231	789
4	1,020	0.16	132	152	331	242	825
5	1,360	0.22	162	165	332	248	848

1 P in water extraction, expressed as mg P_2O_5 /l dry soil 2 P in extraction of Al− acetate, expressed as mg P_2O_5/100 g dry soil.

and Van den Bos (1995) clearly showed with radish that the uptake concentrations of all nutrients in winter (under poor light condition) were four to five times higher than in summer (under abundant light conditions).

For phosphate, the P-buffer of the soil is much more important than the concentration (Van der Paauw, 1969; Roorda van Eysinga, 1971; Sonneveld and Voogt, 2009). A long term experiment was therefore set up with P-buffer levels with lettuce and with chrysanthemum for five and three years respectively. Voogt and Van den Bos (2016) found that even with zero-P treatments no significant effect on crop yield could be established (Table 5). This shows that the vast buffer of P built up in the soils during many years of over-fertilisation in most greenhouse soils could deliver sufficient P. However, reduction in the P fertilisation will hardly contribute to improvement of the environment, since the leaching of P from greenhouse soils is already very limited (Voogt and Bloemhard, 1995; Voogt and Korsten, 1996). This is likely caused by the high content of either Fe and Al or else $CaCO_3$ in the subsoil, causing sorption to Fe-Al oxides or precipitation as Ca-phosphates (Geelhoed et al., 1988).

Reduction of the high concentrations of nutrients (NO_3) in the soil solution will certainly contribute to a potential reduction in the nutrient emission. Nevertheless, the vertical water flow through the soil, due to irrigation and subsequent net over-irrigation will affect not only the emission of NO_3 but of other nutrients and PPPs as well. Moreover, precise control over the NO_3 concentrations is much more complex, due to less predictable processes of the soil-N cycle (mineralisation, denitrification, immobilisation) and plant-N uptake rates than the evapotranspiration. On top of that, the control over PPP-emission requires also a reduction in the water flow from the soil, which leads to the conclusion that focussing on managing the water balance will be a preferable first step.

3.2. Soilless cultivation

3.2.1. Water treatment

Soilless cultivation requires a high and constant quality of water to avoid any problems with clogging, leaking or leaching. Filters are used to eliminate large particles in the water before disinfection (Fig. 1 and 2). Mostly another filter is used before the water is supplied to the drippers to eliminate substances from the fertilisers which may block the drippers. Sometimes additional small filters are used for special equipment (disinfection, fertiliser supply, other water sources). Sand filters used to be common to eliminate the coarse particles coming from the plants and substrate and they still meet the demands for disinfection equipment. However, these filters have to be (automatically) rinsed if clogging appears. The water used for rinsing the filters (by changing the direction of the flow) was automatically discharged, leading to a discharge of about 200 – 500 m^3 ha^{-1} yr^{-1}. To minimise this amount other filter types were investigated. Metal screen filters use only 25 % filter rinsing water compared to a sand filter, and flatbed filters eliminate particles > 10 to > 40 μm, depending on the cloth which is used, and use no rinsing water at all (Van Os et al., 2020). The cloth and the dirt can be removed as solid waste and composted.

Recirculation of drain water means that the risk of spreading root-borne pathogens increases dramatically, disinfection of the drainwater is a good solution (Van Os, 2009). Spreading of pathogens within rows (gutter) can be minimised by separation of individual slabs (troughs) and using gutter systems with sideward collection and transport of drainage to prevent contact with other slabs or root system. Heat treatment is very efficient by use of heat exchangers but still requires additional energy (Runia et al., 1988). Best performance was found with 95 °C during 30 s or 85 °C during 3 min. A newer alternative is UV light by means of high pressure or low pressure lamps. Both perform well if a dosage of 100 mJ cm^{-2} is given against fungi and bacteria or 250 mJ cm^{-2} against viruses (Runia, 1995; Ehret et al., 2001). Ozone treatment now makes a comeback, it was used in the 90 s (Runia, 1995), disappeared because of safety issues and high investment costs. Recently, new and safer technology was introduced; dosing of ozone is controlled using redox sensors, measuring the oxidisable load of the water. With a redox potential of > 750 mV, the nutrient solution is disinfected for bacteria, fungi and viruses (Van Os et al., 2020). For small farms slow sand filtration might be a cheaper solution. It combines a good effectivity with low investments and a high space requirement (Van Os et al., 1998). Much cheaper but also less effective are chemicals such as hydrogen peroxide, bleach, chlorine dioxide to eliminate pathogens. Mentioned products are meant for cleaning pipework and not for eliminating pathogens for which a much higher dosage of the product is required (Stijger et al., 2020). These products may be well suitable to eliminate biofilm in the pipework (Van Ruijven et al., 2020a).

3.2.2. Fertigation control

In an open system with concentrated stock solutions (A and B tank, Fig. 1) the irrigation computer always supplies the correct solution to the plants. When recirculation takes place (disinfected) drain water has to be mixed with fresh water. Mostly the irrigation solution is composed in such a way that 30 % of EC in the irrigation water is derived from drain water and additional fresh water and fertilisers from A and B tank are supplied to achieve the setpoint EC. Alternatively mixing can take place on a volume basis. In the latter case all the drain water of the last day is used. This is not the case when the irrigation solution is mixed on EC basis, as EC of the drain water varies. This method may thus lead to unneeded overflow of storage tanks.

3.2.3. Purification of discharge water

When the biological or chemical quality of the recirculating nutrient solution is no longer sufficient, growers can decide to discharge within the limits of the Nitrogen Emission Standards, but PPPs need to be removed from the discharge water. Several techniques have been developed for the removal of PPPs from discharge water (Van Ruijven et al., 2014), that could be applied either at the scale of an individual company or a group of companies. Adding an additional treatment to a sewage treatment plant could also be a collective solution, but water volumes to be treated will increase drastically.

Techniques can be divided in three groups: 1. Oxidative technology to breakdown organic PPP molecules (Chiron et al., 1999); 2.

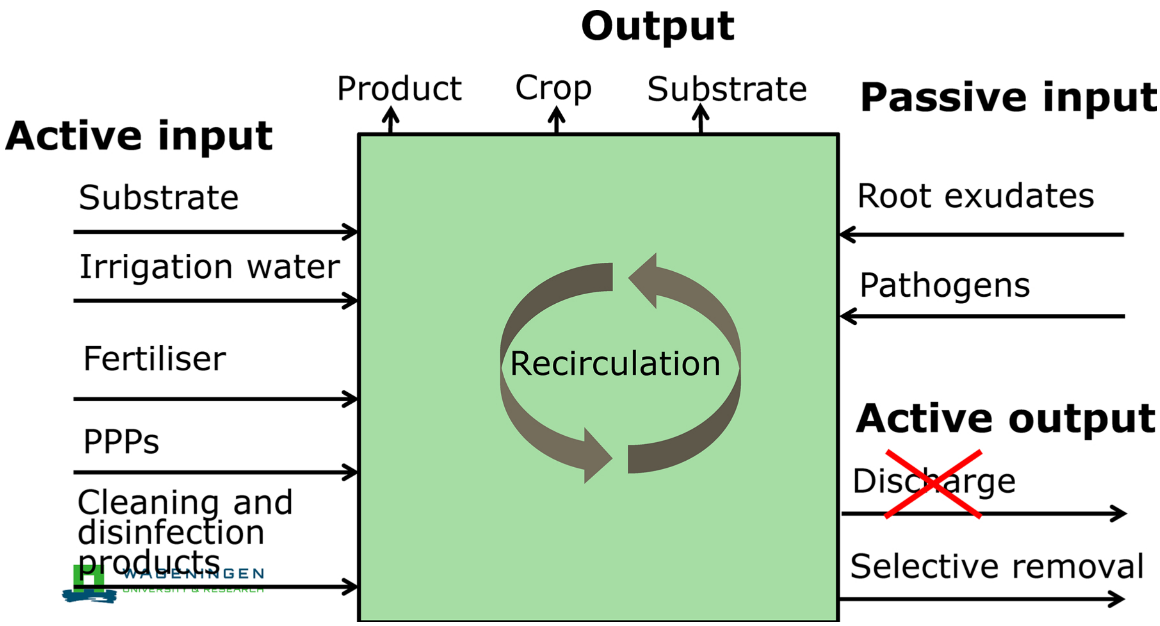

Fig. 8. Balance of inputs and outputs in a Zero Liquid Discharge cultivation system.

Separation technology to selectively filter PPPs from discharge water (Cougnaud et al., 2005; Jiang and Adams, 2006); or 3. Biological treatment (Debaer and Jaeken, 2006; De Wilde et al., 2007). Oxidative technology makes use of either ozone or advanced oxidation by combinations of hydrogen peroxide, UV or ozone, to breakdown PPP molecules into smaller molecules. Removal of PPPs by separation could be done effectively by either activated carbon or membrane filtration. However, saturated activated carbon needs to be handled as chemical waste after its lifespan, but in general can be regenerated with 80 % recovery (https://activated-carbon.com/); the filtered residue from membrane filtration containing the PPPs needs further treatment before discharge is possible. Biological treatment is difficult for some of the organic molecules, as long treatment times are required to reach 95 % efficacy, which translates to large installations. Next to that, conditions need to be controlled very carefully for biological treatment to be effective at all (Koeman et al., 2020 (in press)).

Equipment used for the removal of PPPs needs approval from a special governmental committee. A standardised efficacy test is performed by an independent research institution, to check the efficacy of the installation for the removal of PPPs from Standardised Water (Van Ruijven et al., 2020b). The committee checks the test results, as well as the implementation strategy for the installation, before approval is granted (or not). Enforcement (municipality and water authorities) checks whether approved technology is used (and maintained) correctly. In 2019, 47 % of the growers used, according to interviews, an individual system for purification, 29 % joined a collective purification initiative, 14 % used a mobile system (Leendertse et al., 2019). The remaining 10 % does not need any system for various reasons (for example use of ZLD or plans to close down).

The implementation of the regulation has not yet led to a reduction in the number of locations with exceedances of the water quality standards in 2018 (De Weert et al., 2019). This is not surprising as purification systems are not yet implemented at all companies. For example, companies that have opted for a collective system can postpone the implementation to the end of 2020. Next to the implementation and enforcement of purification techniques, intensive local measurement and communication campaigns in close cooperation with growers have been started by water authorities. This has led to a reduction in unconscious leaching and a decrease in concentration and number of PPPs in surface water in some polders (Waterkwaliteitsrapportage Delfland, 2019).

The implementation of the obligation to remove PPPs from discharge water will theoretically lead to a considerable reduction in concentrations of PPPs in surface water, as soon as measures are completely implemented. Leakages in the piping system or leaching via soil may still lead to unexpected losses. Moreover, at the moment only drainage water from soil grown crops or drain water from soilless cultivation and filter rinsing water containing nutrients have to be purified. Other water flows, like filter rinsing water without nutrients or water used for cleaning at the end of the cultivation, do not have to be treated. Besides, it remains to be seen how efficient the purification equipment will work in practice as efficacy depends on the maintenance and proper use of the equipment. Finally, there is a risk that a removal rate of 95 % will not be enough to reduce the concentrations of PPPs with very low water quality standards such as spinosad, abamectine, methiocarb and teflubenzuron to an acceptable level. For imidacloprid this was foreseen, hence the obligation to use equipment with a 99.5 % purification rate.

3.2.4. Zero liquid discharge

Zero Liquid Discharge (ZLD) is a solution that both meets the regulations for PPPs (2018) and nutrients (2027), and also improves the water use efficiency of greenhouse cultivation. It is therefore an interesting option for growers to consider before they decide on investing in PPP purification equipment. However, as the nutrient solution is no longer refreshed, quality of inputs into the irrigation system becomes more important (Fig. 8). If the uptake of a substance by the crop is lower than the input into the irrigation system, the concentration in water will increase if it is not actively removed from the system. Increased concentrations of Na (Voogt and Van Os, 2012) and heavy metals have been reported to affect the crop. A ZLD cultivation system therefore requires even more attention to the quality of inputs and the recirculating nutrient solution, compared to a semi-closed system.

ZLD was investigated during a four-year period for cucumber and sweet pepper (Beerling et al., 2017; Van Os et al., 2019, 2020) and crop yield and water flows were measured. To achieve ZLD (Fig. 2*)* the following steps were taken:

- Use of water low in Na (< 0.1 mmol L^{-1}), supplied by rainwater or brackish well water treated with reverse osmosis;
- Use of a flatbed filter (no rinsing) or a fibre filter (with reuse of rinsing water) before disinfection;

Table 6
Water balance and yield (kg m-2) of crops grown in zero liquid discharge experiments.

	2014 (Jul-Oct) Cucumber		2015 (Dec-Nov) Sweet pepper		2016 (Jan-Oct) Sweet pepper		2017 (Jun-Oct) Cucumber	
	Ref Stone wool[1]	ZLD Stone wool[1]	Ref Stone wool	ZLD Stone wool	ZLD Stone wool	ZLD Coir	ZLD Coir Buffered	ZLD Coir Non-Buffered
Water balance (%)								
Rainwater	Nav.	Nav.	74	73	72	66	60	63
Irrigation water	Nav.	Nav.	100	100	100	100	100	100
Drain	Nav.	Nav.	26	27	28	34	44	41
Discharge	Nav.	Nav.	4	0	4	1	1	0
Yield (kg m^{-2})	19.1	18.5	26.3	27.4	28.1	26.5	43.9	48.2
Product water use Efficiency (L kg^{-1})		Nav.	22.5	24.0	22.4	22.5	8.8	8.1

[1] Nav. Not available.

- Disinfection of the recirculating nutrient solution using ozone;
- A quick response irrigation system with 3 L h^{-1} pressure compensated drippers in combination with a 16 mm pipe and a low pressure recirculation system to bring added substances immediately at all drippers;
- Recirculation of the first drain after start of the cultivation;
- Weekly analysis of the nutrient solution and adjustment of concentrated nutrient stocks;
- End of cultivation strategy to avoid drain and prevent water losses via removal of the substrate (Leyh et al., 2020).

Yields in the reference situation were generally comparable to the ZLD greenhouse (Table 6). Slight differences occurred in 2016 due to the fact that the growth was more vegetative on coir compared to stone wool. There was no clear explanation for the difference in yield in 2017.

Zero drain water discharge could not be completely achieved in all ZLD experiments. In the 2016 crop, the nutrient solution had to be discharged during a few days due to a broken disinfection installation and limited storage facility. In the experiments with coir some water was lost as the coir was washed with calcium nitrate before use. The rinsing water was discharged. In 2017 the rinsing water from the coir was not discarded and the calcium concentration in the nutrient solution was increased to compensate for the higher Na. Data showed that this worked well and further accumulation of Na during the experiment did not take place.

3.2.5. Bottlenecks of zero liquid discharge

The above-mentioned experiments showed that ZLD is a serious option to prevent or at least strongly reduce emissions of nutrients and PPPs to surface waters. However, there are a number of bottlenecks that might restrain growers to use a ZLD approach such as: substrate quality, technical failure, losses during and after crop interchange (Leyh et al., 2020), crops susceptible for Na accumulation or certain substances leading to an inhibition of growth.

Probably the most serious impediment for ZLD is Na accumulation in the recirculating water. Even when using the most optimal water sources available some background concentration of Na via water sources is unavoidable, as well as some input through fertilisers (Voogt and Van Os, 2012). Since Na is only taken up by crops in low amounts, Na accumulation in the recirculating solution will occur. Eventually this may result in unbalanced nutrient solutions due to lower concentrations of other nutrients compared to Na (Voogt and Sonneveld, 1997) and/or increase in the total salt concentration, which may reduce growth and yield or induce physiological disorders (Sonneveld, 2000).

Since the uptake of Na by plants is a linear function of the prevailing Na concentration in the root environment, it is recommended to let Na accumulate to the maximum acceptable concentration. Recent studies with sweet pepper, tomato and gerbera have shown that Na may accumulate much higher than the prevailing opinion among growers (Kierkels, 2018; Van Staalduinen, 2020) without causing problems. Nevertheless, based on previous work, it is to be expected, that for crops with a very low tolerance for Na, or crops with a low Na uptake capacity, like rose, cymbidium and other orchids, Na accumulation will remain an important bottleneck.

The experiments showed that ZLD is possible both with relatively inert substrates like stone wool, but also with more challenging substrates like coir. The first drain of the stone wool slabs could be reused without any problems in pepper and cucumber crops. Also, the coir could be used without discharging the rinsing water at the start of cultivation. However, coir can differ substantially in quality and growers have to be careful and ask for information from the supplier.

Technical failure may cause a need to discharge water, as most growers do not have (additional) capacity to store the nutrient solution for a couple of days to solve problems. Moreover, a frequent and careful analyses of the nutrient solution is needed to avoid nutrient imbalances, in combination with a fertigation strategy tuned to plant needs and prevailing climate/radiation.

Losses of water, nutrients and PPPs still occur at the end of the cultivation when the remaining drain solution is discarded. To minimise these losses, an end-of-cultivation strategy was developed (Blok et al., 2017; Van Os et al., 2019; Leyh et al., 2020). The strategy aims at reducing the water content in the slab from 80 % v/v to 30 % v/v by reducing irrigation in the last weeks of cultivation. This results in less drain water to be reused and empty drain tanks for the start of a new growing season. It also lowers the amount of nutrients and PPPs emitted from the company by removal of the substrate slabs. Furthermore, the N and P concentration in the irrigation solution are gradually reduced to almost zero and replaced by Cl to further reduce these losses. This strategy led to reduction in discharge from 36.8 kg N ha^{-1} to 11.6 kg N ha^{-1}. The strategy can still be improved to further reduce discharge and to be resilient to changes in weather conditions during the last weeks of cultivation. Moreover, the knowledge has to be translated to guidelines to help growers to implement such a strategy.

Another argument to discharge water is the accumulation of growth inhibitors, either originating from the crop, the cropping system (zinc), rest products (silver) or metabolites of disinfection products like chlorate or perchlorate. Van Os et al. (2014) demonstrated that root exudates in rose can be broken down with advanced oxidation (UV with peroxide). Yet, the discharge at the start of a new cultivation, especially in fruit vegetables, is related to the fear for growth inhibition. The young crop is very sensitive and therefore during the first months the water is often not re-used, although it has been shown there may be no scientific ground for that (Lee, 2011).

The presence of growth inhibitors in drain water can be detected with a bioassay (Phytotox kit; Blok et al., 2014). This is a useful tool when doubting the quality of their recirculation water. In combination with the application of advanced oxidation this may decrease the amount of discharge significantly, as has been demonstrated in practice for several crops (Raaphorst et al., 2014).

4. Conclusions and way forward

The above-mentioned approaches have and will lead to a substantial decrease in losses of nutrients and PPPs to ground- and surface water bodies. However, it is uncertain whether this is sufficient to reach the goals set for the Dutch greenhouse industry (zero-emission by 2027) and eventually to achieve the water quality standards of the ND and WFD.

For soil bound greenhouses, the goal of zero emission will most probably not be reached. For those greenhouses where seepage is limited, drainage collection and reuse is an option, but still diffuse leaching of nutrients and PPPs may occur. This solution is not feasible in areas with high seepage quantity or input of undesired salts into the drainage through seepage. For those greenhouses, growers either have to change over to soilless or stop with greenhouse cultivation. In the current regulation this is also foreseen.

Tuning irrigation to crop demand is the best option to minimise losses from soil grown crops. Various methods are available such as models and various sensors. A combination of tools, for example a virtual lysimeter combined with sensors, seems currently the most promising approach. This approach combines technical feasibility and acceptance by growers with achievable goals.

For soilless cultivation systems the emission goals set for the greenhouse industry are within reach by adoption of ZLD. Potential obstacles are leakages and accumulation of undesired salts and other growth inhibiting compounds in the water systems.

Leakages in soilless cultivation (Groen, 2015) is one of the causes of ongoing emissions to water bodies, even within a ZLD strategy. Greenhouses contain extended and complex piping for irrigation, and furthermore gutters and piping for drainage collection and transport. Most growers lack a good documentation of the piping and changes/ renovation may cause unexpected pathways to surface water. Moreover, small defects or clogging of irrigation lines, loose hanging drippers, overflowing drain gutters easily lead to undetected spills. Currently a standard leakage rate of 1.5% (Vermeulen et al., 2010) is assumed, but adequate data to support this value is missing.

To prevent discharge due to accumulated Na in the recycling solution, growers should learn to deal with increasing Na. Accepting higher Na concentrations and to make use of the space in ion concentrations between the recommended EC level in the root environment and the minimum required nutrient concentrations to feed the plant (Voogt, 2020).

Declaration of Competing Interest

The authors report no declarations of interest.

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