

Impact assessment of water and nutrient reuse in hydroponic systems using Bayesian Belief Networks

Martin Zimmermann and Michaela Fischer

ABSTRACT

Water-saving agricultural practices can reduce negative environmental impacts in water-scarce regions all over the world. This study deals with an innovation that combines hydroponic crop production and municipal wastewater reuse for irrigation purposes. The research question was what impacts such hydroponic water reuse systems have on product confidence, economic viability, groundwater recharge, biodiversity and landscape quality. It should also be clarified under which conditions and with which measures these systems can be sustainable. To answer these questions, a number of generic hydroponic water reuse systems were modeled and assessed using a Bayesian Belief Network that included both numerical values and expert knowledge. The hydroponic water reuse systems with the most positive overall impacts are small-scale food production systems (tomatoes) equipped with lighting and heating whose products are marked with a quality label or with a label for regional products. The systems are located in a former industrial area. In addition, a wetland system and landscape integration are implemented as landscaping measures. Hydroponic systems can be operated economically viable, their products have a high level of product confidence and their ecological impacts can be positive. No tradeoffs have to be accepted between economic, social and ecological goals.

Key words | biodiversity, economic viability, landscaping, modeling, product confidence, social acceptance

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HIGHLIGHTS

- The study shows that hydroponic water reuse systems can be operated economically viable, that their products have a high level of product confidence and that their ecological effects can be positive if appropriate landscaping measures are taken.
- Landscaping as well as acceptance measures should be carried out to accompany hydroponic crop production to improve its social and ecological impacts.

INTRODUCTION

Agriculture accounts for approximately 70% of withdrawals of global freshwater resources and is thus by far the largest consumer of water compared with other sectors. In arid and semi-arid areas, the withdrawals can even be as high as 85%

(Chmielewski 2011). About 40% of the agricultural food produced is irrigated (Chmielewski 2011). Agriculture is dependent on irrigation not only in arid and semi-arid zones. Even in intensively cultivated agricultural areas in Germany, agriculture is confronted with problems of water scarcity. In total, 451,800 ha (or 1.3%) of agricultural land in Germany are irrigated (Statistisches Bundesamt 2017). In the German strategy for adaptation to climate change, it was found that

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regional water use conflicts could arise with regard to surface and groundwater during dry periods (BMU 2008). Therefore, new water-saving cultivation methods and additional water resources are of interest in Germany in order to avoid conflicts of use, but also for the protection of groundwater. Intensification of agriculture can reduce land use and therefore reduce negative environmental impacts (Ellis *et al.* 2013).

One option for the water-efficient cultivation of crops is hydroponic greenhouse production. In hydroponics, plants are grown without soil. Instead, mineral nutrient solutions dissolved in water are used (dos Santos *et al.* 2013). Crops are cultivated in such a way that only their roots are hanging in the nutrient solution. The roots can be physically supported by an inert medium such as mineral wool, volcanic stones or other substrates. One possibility of operation is that the nutrient solution continuously flows past the roots (continuous-flow solution culture). This particularly facilitates the adjustment of the nutrient concentration (Rockel 1997). The nutrients used in hydroponic systems can come from various sources, e.g. fish excrement, chemical fertilizers or nutrient solutions (Jones 2004). Crops that are usually grown hydroponically include tomatoes and lettuce, but also ornamental plants. The main advantage of hydroponics is the significantly lower water consumption compared with conventional agriculture (Zhang *et al.* 2018). In particular, water loss through evapotranspiration is low in a closed greenhouse. This enables the cultivation of food even in extremely dry areas.

One possible resource for feeding hydroponic systems is the reuse of wastewater. In water reuse, wastewater is treated with technical means, so that it can be reused for other purposes (e.g. agricultural irrigation). The use of recycled water instead of fresh water for corresponding purposes can be a water-efficient measure. Water reuse can thus be part of sustainable water management. This can reduce water scarcity and alleviate pressure on groundwater and other water resources (Andersson *et al.* 2016). In addition, not only can water be saved when reusing wastewater, but the nutrients contained in the wastewater can also be used to fertilize the plants.

Although studies have already been carried out on hydroponic systems in which reused wastewater is used, no large-scale implementation has yet been carried out. The use of treated wastewater as a nutrient solution has

so far been little investigated (Magwaza *et al.* 2020). In the HypoWave project, a new concept was tested, which deals with the connection of treated municipal wastewater and plant production (Bliedung *et al.* 2019). The key question was to what extent municipal wastewater has to be treated in order to be able to use it in hydroponic systems with as little additional nutrient input as possible. A pilot plant with a modular set-up of different wastewater treatment processes was implemented in Wolfsburg Hattorf, Germany, on the site of the municipal wastewater treatment plant (WWTP) (Bliedung *et al.* 2019). In addition to the option of using the biologically treated (activated sludge including nitrification and denitrification) WWTP runoff, a number of alternative treatment processes have been tested. These processes include an anaerobic expanded granular sludge bed reactor and an aerobic sequencing batch reactor for nitrification. In this way, a large part of the nitrate remains in the treated water. In addition, a biological activated carbon biofilter for the removal of trace substances and, if necessary, ozonation to eliminate pathogens was used. Depending on the process combination, water of different quality could be produced for the hydroponic system, which among other things resulted in different nutrient levels.

The hydroponic system of the pilot plant consisted of several parallel rows of pipes in which lettuce plants were cultivated. The pipes were fed with different water qualities. In addition, lettuce was grown in one pipe in a conventional Hoagland solution with a 50% concentration for comparison. The hydroponic system was designed as a mixture of nutrient film technique and deep water culture.

In addition to the above-mentioned advantages of hydroponic water reuse systems in terms of water and nutrient efficiency, a number of impacts are also unclear, such as questions about the social acceptance of the produced crops, as well as ecological consequences and economic viability. Accordingly, the key research questions are: (1) What are the social, economic and ecological impacts of selected hydroponic water reuse systems? (2) Under which conditions are hydroponic water reuse system socially, economically and ecologically sustainable? To answer these questions, a number of generic hydroponic water reuse systems were modeled and assessed using a software-based modeling process that can make use of both numerical values and expert knowledge.

METHODS AND MATERIALS

General methodology and state of the art

The assessment of social, ecological and economic impacts of hydroponic water reuse systems was carried out using Bayesian Belief Networks (BBNs). BBNs are statistical multivariate models based on the theorem of Thomas Bayes (1740) for calculating conditional probabilities. BBNs combine a qualitative, graphical representation of a system with a quantitative, probabilistic evaluation of the interactions between the variables of such a system (Castelletti & Soncini-Sessa 2007; Barton *et al.* 2012). BBNs are particularly suitable for depicting complex systems in a comprehensible way (Molina *et al.* 2013), can process qualitative and quantitative data (Chen & Pollino 2012) and allow the inclusion of stakeholder and expert knowledge (Bergmann *et al.* 2010). BBNs consist of a directed acyclical graph containing variables and nodes. These are connected by directional arrows that represent cause–effect relationships between the nodes. Conditional probability tables (CPTs) assigned to each node reflect the conditional probabilities for the values of a node as a function of the values of the parent nodes (Cain 2001). A disadvantage of conventional BBN is that feedbacks cannot be mapped. Furthermore, spatial and temporal dynamics are difficult to represent (Uusitalo 2007).

BBNs are used as versatile tools for the investigation of interactions between variables of a system and as decision support systems for the development of management strategies (Kuikka *et al.* 1999; Cain 2001; Castelletti & Soncini-Sessa 2007; Jensen & Nielsen 2007; Pagano *et al.* 2013; Reichert *et al.* 2015), in the fields of water resource management and ecology (Cain 2001; Bromley 2005; Marcot *et al.* 2006; Castelletti & Soncini-Sessa 2007; Pollino *et al.* 2007; Aguilera *et al.* 2011) and on environmental impact assessment

and risk assessment (Voie *et al.* 2010; Liu *et al.* 2012; Tighe *et al.* 2013; Money *et al.* 2014; Brandmayr *et al.* 2015).

The structure of the BBN (i.e. system variables and their interrelations) was pre-developed together with external experts and project partners. For this purpose, a total of six expert interviews with researchers from different disciplines (e.g. civil and environmental engineering, plant science, ecology and landscape architecture) were carried out. Five social, economic and ecological impact variables were jointly chosen, namely product confidence, economic viability, groundwater recharge, biodiversity and landscape quality. The data required to model the BBN were collected through qualitative or semi-quantitative expert surveys in the case of product confidence, biodiversity and landscape quality (Table 1). Other impacts, namely economic viability and groundwater recharge, were calculated or assessed based on literature values and assumptions (Table 1). The relations among system variables (nodes) were expressed in the form of a CPT in the case of probabilistic values and in the form of a function table in the case of deterministic values (Supplementary Material, Appendix A). The BBN was finally evaluated using the software Netica. The BBN eventually shows which social, ecological and economic impacts the experts attributed to various hydroponic water reuse systems and selected measures.

Calculation of the economic viability

The economic viability was determined for a total of 16 different generic hydroponic water reuse systems. These systems differed in terms of product (food vs. non-food crops), size (small-scale vs. large-scale), production process (with or without lighting and heating) and the water regime applied (open vs. closed mode of operation). Furthermore, landscaping measures (i.e. wetland systems and landscape integration) were considered in the cost calculation.

Table 1 | Methods used to assess specific impacts of hydroponic water reuse systems

Impact dimension	Social impacts	Economic impacts	Ecological impacts		
Impacts	Product confidence	Economic viability	Groundwater recharge	Biodiversity	Landscape quality
Method	Expert survey	Calculation	Qualitative estimation	Expert survey	
Type of parameter	Probabilistic	Deterministic	Deterministic	Probabilistic	

Tomatoes were selected as food crops and Chrysanthemum as non-food crop or ornamental plants. The size of the hydroponic systems corresponded either to the water quantity of 1,000 (small-scale) or 10,000 (large-scale) population equivalents. The greenhouses were either equipped with lighting and heating for improved growing conditions or not. Finally, an open and a closed water regime were distinguished. In the first case, the water flows continuously through the hydroponic system which makes it nutrient-efficient (e.g. regarding micro- and macronutrients). In the second case, the water is circulated in the system which makes it water-efficient. Fertilizer, however, has to be added regularly. The water is circulated until a certain salinity threshold (e.g. 8 mmol NaCl) is reached. It can then be treated by reverse osmosis for further reuse.

Based on these preconditions, investments and operating costs (e.g. labor costs, energy costs, overhead and additional water treatment) of the 16 systems were determined. A depreciation period of 10 years has been applied. Capital costs have been calculated on the basis of an interest rate of 3%. Literature values for expenses and revenues were taken from the KWIN model (WUR 2018). Additional costs for the water reuse treatment steps and the landscaping measures were added. Finally, the economic viability was measured based on the annual rate of return which represents the profit expressed as the proportion of the investments and costs.

The market price for tomatoes was set at 1.86 EUR with lighting and heating and 1.74 EUR for tomatoes without lighting and heating as suggested by the KWIN model for European conditions (WUR 2018). The market price for Chrysanthemum Santini with lighting and heating was adjusted due to recent market fluctuations from 0.38 EUR to 0.28 EUR per stem. For Chrysanthemum Santini without lighting and heating, the price remained as suggested by the model at 0.17 EUR per stem. Wages were set at 12.00 EUR per hour for workers, 18.75 EUR for trained staff and 20.00 EUR for operators. For the landscaping measures, a land value (lease) of 800 EUR per ha and year was applied according to a related case study (Mohr *et al.* 2019). Additional costs for construction and operation of the landscaping measures, however, were not considered due to the diversity of possible options (e.g. wetland systems, hedges and trees).

Expert surveys and estimations of social and ecological impacts

A total of 12 experts from research and practice were surveyed using questionnaires regarding product confidence, biodiversity and landscape quality, covering different disciplines and sectors. Even if the number of 12 experts cannot be representative, their positions and experience mean that they are multipliers who can provide a well-founded appraisal of the impacts surveyed.

Consumer acceptance of the food and non-food products made using the hydroponic water reuse system was considered an important factor. The decision of food and flower retailers to add products to their range depends heavily on how they assess consumer acceptance. Therefore, the product confidence of corresponding retailers was chosen as an indicator of consumer acceptance. Additionally, measures to increase product confidence were taken into account. In addition to taking no action, these measures comprise products with a quality label (e.g. products are harmless to health, sustainable or without genetic engineering), products that are labeled as regionally produced as well as branded products (e.g. Bonduelle and Ardo).

The product confidence was determined by using standardized expert surveys. In particular, grocery retailers from organic supermarkets and farmers' markets as well as florists were interviewed. The interviewees were asked to rate the product confidence on a 5-level Likert scale from 1 to 5, with 1 meaning that the respondent would include the product in their range without hesitation and 5 that the respondent would under no circumstances do so. Two separate questionnaires for two separate groups of interviewees were used for vegetables (tomatoes) and ornamental plants (Chrysanthemum). One question, for example, was: 'Would you include foods (e.g. tomatoes) produced with the described hydroponic system in the assortment of your market if they are labelled as regional products?' The responses were converted to probabilities by first calculating the mean and then performing a linear interpolation where a mean of 1 corresponded to a product confidence of 100% and a mean of 5 to a product confidence of 0%.

The implementation of hydroponic greenhouses can have adverse ecological impacts, for instance increased land consumption or impervious surfaces. Landscaping

measures to mitigate these effects can be the creation of wetland systems around the greenhouses and the integration of greenhouses into the landscape by using hedges, trees or extensive farming elements such as short rotation forestry. Both measures can also be combined and might have positive impacts on biodiversity and landscape quality.

Similar to the case of product confidence, the impacts of landscaping measures (i.e. wetland systems and landscape integration) on biodiversity and landscape quality were determined by means of standardized expert surveys. In particular, experts from science and practice (e.g. ecologists and landscape architects) were interviewed. The interviewees were asked to rate the likelihood of positive impacts of the landscaping measures on biodiversity and landscape quality on a scale from 0 to 100% where 100% represents the strongest positive effect. Two questionnaires were presented to the interviewees – one for the impacts on biodiversity and one for the impacts on landscape quality. It was assumed that wetland systems would expand the area of the hydroponic systems (including the greenhouses) by 20%. Measures for landscape integration would expand the area by 40% and both measures combined by 60%. These values were derived from the proposal to keep more than 50% of the area free from intensive use in order to preserve biodiversity in the long term (Ellis 2019). Furthermore, the questionnaires also took into account whether the hydroponic systems were implemented in former industrial or agricultural areas and whether they were small-scale (approximately 3–6 ha or 1,000 population equivalents) or large-scale systems (approximately 27–58 ha or 10,000 population equivalents). One question, for example, was: ‘What is the probability that greenhouses built on a former agricultural area with a size of 100 ha and a continuous green area with wetland systems of an additional 20 ha have a positive and/or negative impact on biodiversity?’

Impacts on the local groundwater recharge were qualitatively estimated on the basis of land consumption and impervious surface of the hydroponic systems as well as the capacity of the considered measures to support rainwater infiltration. Five qualitative levels of groundwater recharge were distinguished, namely highly reduced, reduced, neutral, improved and highly improved. Different rates of groundwater recharge were assessed on the basis of two different initial situations, namely former agricultural areas (pervious) and former

industrial areas (impervious). The implementation of various landscaping measures (i.e. wetland systems and landscape integration) was then considered for these areas. The area used for landscaping measures is assumed to be permeable.

RESULTS AND DISCUSSION

Structure of the BBN

The expert discussions resulted in a BBN that consists of five system variables describing properties of hydroponic water reuse systems, two measures relating to product confidence and landscaping as well as the pre-defined five social, economic and ecological impact variables. The system variables each have two instances, namely food production systems (tomatoes) vs. systems for the production of ornamental plants (Chrysanthemum), small-scale (1,000 population equivalents) vs. large-scale systems (10,000 population equivalents), systems with lighting and heating vs. systems without lighting and heating, systems with a closed water regime (water-optimized) vs. systems with an open one (nutrient-optimized), and finally systems implemented in a former industrial area vs. systems in a former agricultural area. Furthermore, the BBN includes two measures which represent possible interventions to avoid or mitigate undesirable impacts. The measures are aimed at social and ecological impacts and consist of the four above-mentioned instances each.

The expert discussions also revealed how the system variables, measures and impacts (i.e. product confidence, economic viability, groundwater recharge, biodiversity and landscape quality) are interrelated which eventually leads to the BBN (Figure 1 and Supplementary Material, Appendix C). A total of 512 combinations ($2^5 \times 4^2$) of the system variables and measures are possible. Figures with examples of the model's behavior are attached in Supplementary Material, Appendix B.

Selected hydroponic water reuse systems and their impacts

The hydroponic water reuse system with the most positive overall impacts is a small-scale food production system (3–6 ha, tomatoes) equipped with lighting and heating

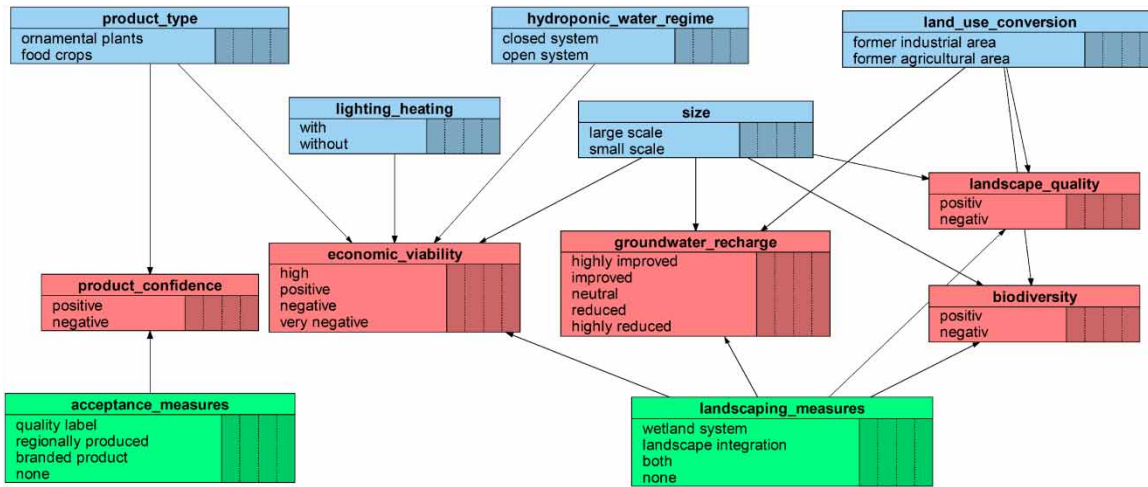


Figure 1 | BBN of hydroponic water reuse systems consisting of system variables (blue), measures (green) and impacts (red). Please refer to the online version of this paper to see this figure in color: <http://dx.doi.org/10.2166/wrd.2020.026>.

whose products are marked with a quality label (Table 2). The system is located in a former industrial area, and both above-mentioned landscaping measures (wetland system and landscape integration) are implemented. With regard to the investigated impacts, it is irrelevant whether it is a system in which the water is circulated (closed system) or through which the water flows only once (open system). Such a system would achieve a very high product confidence (90%), a high economic viability (6% rate of return), a greatly improved groundwater recharge, a very positive impact on biodiversity (77%) and a very positive effect on

the landscape quality (84%). A slight variation in this system in which the tomatoes are marked with a label for regional products would achieve a slightly lower product confidence (70%). Apart from that, the system achieves the same very positive results. Small-scale food production systems without lighting and heating, however, have a very poor economic viability (−12% rate of return).

Large-scale food production systems (tomatoes with quality label) in former industrial areas also perform fairly well but only without lighting and heating (Table 2). In this case, the economic viability is just positive (Table 2).

Table 2 | Hydroponic water reuse systems with most positive impacts

Systems	Measures	Product confidence	Economic viability	Groundwater recharge	Biodiversity	Landscape quality
Food production (tomatoes); small-scale; lighting and heating; open or closed system; former industrial area	Quality label; wetland system, landscape integration	90%	High	Greatly improved	77%	84%
Food production (tomatoes); small-scale; lighting and heating; open or closed system; former industrial area	Labeled as regional product; wetland system, landscape integration	70%	High	Greatly improved	77%	84%
Food production (tomatoes); large-scale; no lighting and heating; open or closed system; former industrial area	Quality label; wetland system, landscape integration	90%	Positive	Greatly improved	76%	80%
Food production (tomatoes); large-scale; no lighting and heating; open or closed system; former industrial area	Labeled as regional product; wetland system, landscape integration	70%	Positive	Greatly improved	76%	80%

Apart from this, the large-scale system scores slightly worse than the small-scale system with regard to the criteria biodiversity (76 instead of 77%) and landscape quality (80 instead of 84%) (Table 2). Large-scale food production systems with lighting and heating, however, do not appear to be economically viable (rate of return -5% , Table 5).

As in the case of small-scale systems, product confidence drops from 90 to 70% if the tomatoes are labeled as regionally produced. Food systems without consumer acceptance measures (regardless of whether they are large- or small-scale) lead to a loss of product confidence (56 instead of 90 or 70%). Branded products even lead to a product confidence of only 42%.

In the case of food production systems in former agricultural areas, the positive ecological effects are not so pronounced. Assuming that both landscaping measures are carried out, the groundwater recharge is neutral in small-scale systems with lighting and heating, the biodiversity is 55 instead of 77% and landscape quality 67 instead of 84%. For large-scale systems without lighting and heating, groundwater recharge is also neutral, the biodiversity is 53 instead of 76% and landscape quality 53 instead of 80%.

Hydroponic water reuse systems for the production of ornamental plants (in our case: Chrysanthemum) have a negative or very negative economic viability in all calculated scenarios (Table 5). However, these systems can still achieve positive social and ecological impacts. Ornamental plants (Chrysanthemum) show high product confidence if they are labeled with a quality label (100%) or as regionally produced (100%) and even if neither of these two consumer acceptance measures have been carried out (92%). The potential for very good ecological effects only exists if the system is implemented in a former industrial area and not on an agricultural one. Conclusions regarding the advantages and disadvantages of systems with an open or closed water regime cannot be drawn either for food production systems or for systems for the production of ornamental plants.

Specific impacts and their interdependencies

Social impacts

The highest product confidence is found in ornamental plants (Chrysanthemum) with (100%) and without (92%)

consumer acceptance measures (quality label and/or labeled as regionally produced) as well as in food products (tomatoes) with quality labels (90%) followed by ones that are labeled as regionally produced (70%). In general, food retailers were positive about potential products from hydroponic water reuse systems. They said that they could imagine including the products in their range. The best measure to improve the product confidence was a quality label which can be compared with labels that certify sustainable production or GMO-free labels. Labeling as a regionally produced product also improved product confidence. Branded food products even had a lower product confidence (42%) than products without any consumer acceptance measure (56%). A sensitivity analysis of the factors influencing product confidence shows that the influence of acceptance measures is significantly greater than that of the product type.

Florists did not mention concerns with selling ornamental flowers produced with hydroponic water reuse systems. The use of labels (quality label or labeling as a regional product) was preferred over no label. However, it was also argued that labels are not required in case of ornamental plants since customers would not be concerned. They were said to prefer quality and price over other factors. In some cases, it was said that costumers would ask where the flowers were made. This might indicate an interest in regional products and their social or environmental impacts.

The results indicate that the production of flowers from hydroponic water reuse systems would be well accepted. Flowers labeled as regionally produced could even influence the consumer's purchase decision in a positive way if they are interested in the social and environmental sustainability of the production. Apart from this, the attitude of grocery retailers towards food crops from hydroponic systems was predominantly positive. Nevertheless, quality labels or labeling as a regional product might be required to increase product confidence. Big supermarket chains could not be reached by means of this study. Further research is necessary to understand how the big players will position themselves towards the circular economy and future developments in food production. To our knowledge, there are no other detailed studies on product confidence concerning products from hydroponic systems with water reuse.

Ecological impacts

Implementing both landscaping measures (i.e. wetland system and landscape integration) leads to the most positive impacts in terms of biodiversity and landscape quality. This is irrespective of whether the hydroponic system was set up in a former industrial or agricultural area or whether it is a small-scale or large-scale system (Table 3). Undertaking no landscaping measures in a former agricultural area leads to the most negative effects in this regard.

Hydroponic systems in former agricultural areas need at least landscape integration measures to achieve positive impacts on landscape quality. In terms of biodiversity, both landscaping measures are necessary to achieve positive impacts. In contrast, hydroponic systems in former industrial areas have positive effects on landscape quality even without any landscaping measures. Regarding biodiversity, at least measures of landscape integration are necessary to reach positive impacts.

The evaluation of impacts on biodiversity and landscape quality can only provide first indications for decisions about landscaping measures. Activities to improve biodiversity need to be focused on a larger spatial scale than the rather narrow system boundaries, especially with a view to

mobile organisms such as birds (Söderström *et al.* 2001). From a legal point of view, nature conservation legislation in Germany, for instance, prohibits a deterioration of land to avoid negative effects on nature and landscape ('Verschlechterungsverbot'). According to the German Federal Nature Conservation Act, interventions which cannot be avoided need to be compensated. The landscaping measures considered here could play a role in connection with these compensations.

Hydroponic systems implemented in former industrial areas always show an improved or greatly improved groundwater recharge if landscaping measures are taken (Table 4). Systems implemented in former agricultural areas have at best a neutral effect on groundwater recharge if both landscaping measures are carried out. Without any measures or with only one of the considered measures, groundwater recharge is highly reduced or at least reduced.

For the assessment, it was assumed that former industrial areas are impervious. Therefore, there would be no further reduction of groundwater recharge in the case of the construction of a greenhouse. The surfaces of the landscaping measures mentioned above are regarded as pervious. Apart from surface infiltration, various construction measures can be taken to improve groundwater recharge such as infiltration basins or percolation trenches.

A sensitivity analysis of the influencing factors on all three ecological impact variables shows that the influence of landscaping measures and the former type of land use is significantly greater than that of the size of the greenhouses.

Table 3 | Impacts of landscaping measures on biodiversity and landscape quality

Size	Measures	Biodiversity (%)	Landscape quality (%)
Former agricultural area:			
Large-scale (27–58 ha)	No measures	0	0
	Wetland system	21	28
	Landscape integration	37	52
	Both measures	53	53
Small-scale (3–6 ha)	No measures	0	7
	Wetland system	34	35
	Landscape integration	41	58
	Both measures	55	67
Former industrial area:			
Large-scale (27–58 ha)	No measures	23	53
	Wetland system	47	63
	Landscape integration	62	70
	Both measures	76	80
Small-scale (3–6 ha)	No measures	26	57
	Wetland system	48	66
	Landscape integration	58	76
	Both measures	77	84

Table 4 | Impacts of landscaping measures on groundwater recharge

Measures	Groundwater recharge
Former agricultural area:	
No measures	Highly reduced
Wetland system	Reduced
Landscape integration	
Both measures	Neutral
Former industrial area:	
No measures	Neutral
Wetland system	Improved
Landscape integration	
Both measures	Highly improved

To our knowledge, there are no other detailed studies on the effects of hydroponic systems with water reuse on biodiversity, landscape quality or groundwater recharge. Studies dealing with the environmental impacts of hydroponic systems deal either with their general land requirements (Moore *et al.* 2020), water pollution (Tewolde *et al.* 2016), energy demand (Barbosa *et al.* 2015; Chen *et al.* 2020) or greenhouse gas emissions, respectively, their carbon footprint (Martinez-Mate *et al.* 2018; Vinci & Rapa 2019).

Economic impacts

As mentioned above, good economic viability (6% rate of return) is associated with small-scale food production systems with lighting and heating (Table 5). Large-scale food production systems without lighting and heating are at least barely economically viable. Other studies confirm that hydroponic systems can be economically viable under various conditions (Waldhauer & Soethoudt 2015; Becraft 2017; de Franca Xavier *et al.* 2018; Souza *et al.* 2019). Systems for ornamental plant production or small-scale food production systems without lighting and heating, however, always have a poor economic viability. A sensitivity analysis of the factors influencing the economic viability shows that the influence of the product type, the size of the greenhouses as well as lighting and heating is greater than that of the water regime and landscaping measures.

Additional water treatment costs are lowest for systems producing ornamental plants. Corresponding costs range between 0.2 and 0.5% of the production costs in systems with an open water regime and between 2.0 and 4.6% in closed ones. In food production systems, they range between 2.0 and 5.5% in open systems and between 2.4 and 6.5% in closed ones.

Market prices of the products and energy costs have a big influence on the profitability. The calculations presented in Table 5 are based on rather conservative assumptions. A further sensitivity analysis was made with different assumptions considering energy supply and market prices. If prices and energy production are used as initially suggested by the model, six scenarios are highly profitable (15–35%), further four scenarios are positive, two scenarios are negative, and four scenarios are very negative (–6 to –13%). Furthermore, a combined heat and power plant for the

Table 5 | Annual rate of return and size of hydroponic water reuse systems

		Food production (tomatoes) Lighting and heating		Ornamental plant production (Chrysanthemum) Lighting and heating	
		with	without	with	without
Large-scale	Open system	27 ha –5%	27 ha 1%	33 ha –10%	33 ha –4%
	Closed system	58 ha –5%	58 ha 0.5%	51 ha –14%	51 ha –8%
Small-scale	Open system	3 ha 6%	3 ha –12%	3 ha –17%	3 ha –12%
	Closed system	6 ha 6%	6 ha –12%	5 ha –19%	5 ha –13%

production of heat and electricity would result in a surplus and therefore an income from sales of electricity. The market prices for Chrysanthemum (with lighting and heating) were assumed to be 0.38 EUR according to the model.

Costs for disposal of residues from water treatment were not considered in the calculations. In systems with closed water regimes, reverse osmosis is suggested to recycle the greenhouse runoff. It would be possible to irrigate a short rotation plantation in the landscape park which is much less sensitive to salinity than crops in hydroponic systems. In this way, water treatment costs and the question of disposal of residue would not arise.

CONCLUSIONS

The results of the study show that hydroponic water reuse systems can be operated in an economically viability way, that their products have a high level of product confidence and that their ecological effects can be positive if appropriate landscaping measures are undertaken. This applies in particular to the small-scale food production system described above. The results mean that no tradeoffs have to be accepted between economic goals on the one hand, as well as social and ecological goals on the other. In order to achieve this, however, the results suggest that landscaping as well as acceptance measures should be carried out to accompany hydroponic crop production. Land use through the construction of greenhouses should be

compensated in particular by measures such as wetland systems and landscape integration in order to avoid or at least mitigate undesirable effects on the environment.

The BBN method allowed a rough, but nevertheless comprehensive and quick overview of the interdependencies of generic hydroponic systems. On the one hand, the modeling of generic systems has the advantage that the results can offer a general orientation and can be transferred to a specific case under certain conditions. On the other hand, the circumstances of a specific case can be such that the effects of the modeled systems might not apply. From a business perspective, however, such a model can serve as a decision support for companies (e.g. horticultural companies) or investors for a pre-feasibility study. The advantage of using a method such as the BBN is that quantitative assessments (e.g. cost-benefit analysis) are expanded to integrate qualitative expert knowledge. This means that impacts that are difficult to assess and to quantify can be included, which are often neglected in purely quantitative assessments.

Further investigations could address questions that remained open. One of these aspects is to clarify how an adequate quality management for hydroponic crop production including water reuse should be. In connection with this, the possibilities for the certification of the products with regard to consumer acceptance could be examined in more detail. Another aspect would be to include further assessment criteria such as measuring the carbon footprint in order to get a more complete picture of the impacts of hydroponic systems. A life cycle analysis could, in particular, provide insights into energy and material consumption for water reuse and hydroponic crop production in greenhouses. Unfortunately, this was not possible within the scope of the study. Nevertheless, the findings of this work may contribute to a successful take-off of the discussed innovation and the associated transformation processes in agriculture and water management.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

- Aguilera, P. A., Fernández, A., Fernández, R., Rumí, R. & Salmerón, A. 2011 *Bayesian networks in environmental modelling*. *Environmental Modelling & Software* **26** (12), 1376–1388.
- Andersson, K., Rosemarin, A., Lamizana, B., Kvarnström, E., McConville, J., Seidu, R., Dickin, S. & Trimmer, C. 2016 *Sanitation, Wastewater Management and Sustainability: From Waste Disposal to Resource Recovery*. United Nations Environment Programme and Stockholm Environment Institute, Stockholm.
- Barbosa, G. L., Almeida Gadelha, F. D., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. M. & Halden, R. U. 2015 *Comparison of land, water, and energy requirements of lettuce grown using hydroponics vs. conventional agricultural methods*. *International Journal of Environmental Research and Public Health* **12**, 6879–6891.
- Barton, D. N., Kuikka, S., Uusitalo, L., Henriksen, H. J., Borsuk, M. & Linnell, J. D. C. 2012 *Bayesian networks in environmental and resource management*. *Integrated Environmental Assessment and Management* **8** (3), 418–429.
- Becraft, A. 2017 Potential for home-use hydroponic systems to increase food security in Cape Eleuthera, Bahamas. *i-ACES* **3** (1), 12–18.
- Bergmann, M., Jahn, T., Knobloch, T., Krohn, W., Pohl, C. & Schramm, E. 2010 *Methoden Transdisziplinärer Forschung. Ein Überblick mit Anwendungsbeispielen (Methods of Transdisciplinary Research. An Overview with Application Examples)*. Campus Verlag, Frankfurt am Main.
- Bliedung, A., Dockhorn, T., Ebert, B., Germer, J., Mohr, M., Schramm, E. & Winker, M. 2019 Hypowave – Ressourceneffiziente Nutzung von gereinigtem Abwasser in hydroponischen Systemen (HypoWave – resource-efficient use of treated wastewater in hydroponic systems). *Zentralblatt für Geologie und Paläontologie* **I**, 95–104.
- Brandmayr, C., Kerber, H., Winker, M. & Schramm, E. 2015 *Impact assessment of emission management strategies of the pharmaceutical Metformin and Metoprolol to the aquatic environment using Bayesian networks*. *Science of the Total Environment* **532**, 605–616.

- Bromley, J. 2005 *Guidelines for the use of Bayesian Networks as a Participatory Tool for Water Resource Management*. Wallingford, UK.
- Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU) 2008 *Deutsche Anpassungsstrategie an den Klimawandel (German Adaptation Strategy to Climate Change)*. Available from: https://www.bmu.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/das_gesamt_bf.pdf (accessed 24 March 2020)
- Cain, J. 2001 *Planning Improvements in Natural Resources Management*. Center for Ecology & Hydrology, Wallingford.
- Castelletti, A. & Soncini-Sessa, R. 2007 *Bayesian networks and participatory modelling in water resource management*. *Environmental Modelling & Software* **22**, 1075–1088.
- Chen, S. H. & Pollino, C. A. 2012 *Good practice in Bayesian network modelling*. *Environmental Modelling & Software* **37**, 134–145.
- Chen, P., Zhu, G., Kim, H.-J., Brown, P. B. & Huang, J.-Y. 2020 *Comparative life cycle assessment of aquaponics and hydroponics in the Midwestern United States*. *Journal of Cleaner Production* **275**, 122888.
- Chmielewski, F.-M. 2011 *Wassernutzung und Eingriffe des Menschen in den Wasserhaushalt. Wasserbedarf in der Landwirtschaft*. In: *WARNSIGNAL KLIMA: Genug Wasser für alle?* 3rd edn (J. L. v. Lozán, H. Graßl, P. Hupfer & K. L. Schönwiese, eds). Wiss. Auswertungen, Hamburg.
- de Franca Xavier, J., Vieira de Azevedo, C. A., de Q.A. Azevedo, M. R., Fernandes Monteiro Filho, A. & Rocha da Silva, C. 2018 *Economic viability and profitability of lettuce in hydroponic system using different effluents*. *Journal of Agricultural Science* **10** (7), 342–351.
- dos Santos, J. D., Lopes da Silva, A. L., da Luz Costa, J., Scheidt, G. N., Novak, A. C., Sydney, E. B. & Soccol, C. R. 2013 *Development of a vinasse nutritive solution for hydroponics*. *Journal of Environmental Management* **114**, 8–12.
- Ellis, E. 2019 *To conserve nature in the anthropocene, half earth is not nearly enough*. *One Earth* **1**, 163–167.
- Ellis, E. C., Kaplan, J. O., Fuller, D. Q., Vavrus, S., Klein Goldewijk, K. & Verburg, P. H. 2013 *Used planet: a global history*. *Proceedings of the National Academy of Sciences of the United States of America* **110** (20), 7978–7985.
- Jensen, F. V. & Nielsen, T. D. 2007 *Bayesian Networks and Decision Graphs*. Springer Science + Business Media, New York.
- Jones Jr., J. B. 2004 *Hydroponics: A Practical Guide for the Soilless Grower*, 2nd edn. CRC Press, Boca Raton, London, New York, Washington, DC, pp. 153–166.
- Kuikka, S., Hildén, M., Gislason, H., Hansson, S., Sparholt, H. & Varis, O. 1999 *Modeling environmentally driven uncertainties in Baltic cod (*Gadus morhua*) management by Bayesian influence diagrams*. *Canadian Journal of Fisheries and Aquatic Sciences* **56**, 629–641.
- Liu, K. F.-R., Lu, C.-F., Chen, C.-W. & Shen, Y.-S. 2012 *Applying Bayesian belief networks to health risk assessment*. *Stochastic Environmental Research and Risk Assessment* **26**, 451–465.
- Magwaza, S. T., Magwaza, L. S., Odindo, A. O. & Mditshwa, A. 2020 *Hydroponic technology as decentralised system for domestic wastewater treatment and vegetable production in urban agriculture: a review*. *Science of the Total Environment* **698**, 134154.
- Marcot, B. G., Steventon, J. D., Sutherland, G. D. & McCann, R. K. 2006 *Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation*. *Canadian Journal of Forest Resources* **36** (12), 3064–3074.
- Martinez-Mate, M. A., Martin-Gorriç, B., Martínez-Alvarez, V., Soto-García, M. & Maestre-Valero, J. F. 2018 *Hydroponic system and desalinated water as an alternative farm-productive proposal in water scarcity areas: energy and greenhouse gas emissions analysis of lettuce production in southeast Spain*. *Journal of Cleaner Production* **172** (20), 1298–1310.
- Mohr, M., Koch, M., Schramm, E., Ebert, B., Germer, J. & Bürgow, G. 2019 *Nutzung des Ablaufs einer Teichkläranlage zum Anbau von Gemüse im hydroponischen System im Landkreis Gifhorn*. *Zentralblatt für Geologie und Paläontologie Teil I* **2019**, 131–138.
- Molina, J.-L., Pulido-Velázquez, D., García-Aróstegui, J. L. & Pulido-Velázquez, M. 2013 *Dynamic Bayesian networks as a decision support tool for assessing climate change impacts on highly stressed groundwater systems*. *Journal of Hydrology* **479**, 113–129.
- Money, E. S., Barton, L. E., Dawson, J., Reckhow, K. H. & Wiesner, M. R. 2014 *Validation and sensitivity of the FINE Bayesian network for forecasting aquatic exposure to nano-silver*. *Science of the Total Environment* **473–474**, 685–691.
- Moore, E., Ward, J. & Lennard, W. 2020 *End-of-pipe horticultural reuse of recirculating aquaculture system effluent: comparing the hydro-economics of two horticulture systems*. *Water* **12**, 1409.
- Pagano, A., Vurro, M., Giordano, R., Portoghese, I., Fratino, U., Berardi, F., Duro, A., Campopiano, F., Fiori, G., Vitucci, G. & Palmieri, V. 2013 *A DSS risk management on drinking water infrastructures during extreme events*. *Environmental Engineering and Management Journal* **12** (S11), 125–128.
- Pollino, C. A., Woodberry, O., Nicholson, A., Korb, K. & Hart, B. T. 2007 *Parametrisation and evaluation of a Bayesian network for use in an ecological risk assessment*. *Environmental Modelling & Software* **22**, 1140–1152.
- Reichert, P., Langhans, S. D., Lienert, J. & Schuwirth, N. 2015 *The conceptual foundation of environmental decision support*. *Journal of Environmental Management* **154**, 316–332.
- Rockel, P. 1997 *Growth and nitrate consumption of sunflowers in the rhizostat, a device for continuous nutrient supply to plants*. *Journal of Plant Nutrition* **20** (10), 1431–1447.
- Söderström, B., Svensson, B., Vessby, K. & Glimskär, A. 2001 *Plants, insects, birds in semi-natural pastures in relation to local habitat and landscape factors*. *Biodiversity and Conservation* **10** (11), 1839–1863.
- Souza, S. V., Toesca Gimenes, R. M. & Binotto, E. 2019 *Economic viability for developing hydroponic system in emerging*

- countries: a differentiated risk adjustment proposal. *Land Use Policy* **83**, 357–369.
- Statistisches Bundesamt (Destatis) 2017 *Land- und Forstwirtschaft, Fischerei. Bewässerung in landwirtschaftlichen Betrieben/ Agrarstrukturerhebung 2016 (Agriculture, Forestry and Fisheries. Irrigation on Agricultural Holdings/Agricultural Structure Survey 2016)*. Available from: https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Landwirtschaftliche-Betriebe/Publikationen/Downloads-Landwirtschaftliche-Betriebe/betriebe-bewaesserung-5411205169004.pdf?__blob=publicationFile (accessed 30 March 2020)
- Tewolde, F. T., Takagaki, M., Oshio, T., Maruo, T., Kozai, T. & Kikuchi, Y. 2016 Environmental impact of tomato production under different hydroponic systems. *Acta Horti* **1112**, 267–271.
- Tighe, M., Pollino, C. A. & Wilson, S. C. 2013 Bayesian networks as a screening tool for exposure assessment. *Journal of Environmental Management* **123**, 68–76.
- Uusitalo, L. 2007 Advantages and challenges of Bayesian networks in environmental modelling. *Ecological Modelling* **203** (3–4), 312–318.
- Vinci, G. & Rapa, M. 2019 Hydroponic cultivation: life cycle assessment of substrate choice. *British Food Journal* **121** (8), 1801–1812.
- Voie, O. A., Johnsen, A., Stromseng, A. & Longva, K. S. 2010 Environmental risk assessment of white phosphorus from the use of munitions – a probabilistic approach. *Science of the Total Environment* **408**, 1833–1841.
- Waldhauer, N. & Soethoudt, H. 2015 *Metropolitan Food Supply in Egypt. Market Analysis Hydroponics Production for Selected Urban Areas. Report 1551*. Wageningen UR Food & Biobased Research, Wageningen.
- WUR 2018 *Quantitative Information on Dutch Greenhouse Horticulture 2016–2017*. 'KWIN'. English Version. Wageningen University and Research.
- Zhang, H., Asutosh, A. & Hu, W. 2018 Implementing vertical farming at university scale to promote sustainable communities: a feasibility analysis. *Sustainability* **10** (12), 4429.

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