Model-based management strategy for resource efficient design and operation of an aquaponic system

Daniel Reyes Lastiri[a], Caspar Geelen[a], Hans J. Cappon[a], Huub H.M. Rijnaarts[b], Daniela Baganz[c], Werner Kloas[c], Divas Karimanzira[d], Karel J. Keesman[a,]

[a] *Biobased Chemistry and Technology, Wageningen UR, Bornse Weilanden 9, 6708 WG, Wageningen, the Netherlands*
[b] *Environmental Technology, Wageningen UR, Bornse Weilanden 9, 6708 WG, Wageningen, the Netherlands*
[c] *Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Müggelseedamm 301 and 310, 12587, Berlin, Germany*
[d] *Department of Surface Water and Maritime Systems, Fraunhofer IOSB-AST, Am Vogelherd 50, 98689, Ilmenau, Germany*

Abstract

Aquaponics is a technique that combines *aqua*culture with hydro*ponics*, i.e. growing aquatic species and soilles plants in a single system. Commercial aquaponics is still in development. The main challenge consists in balancing the conditions required for the growth of multiple species, leading to dynamic a system with high complexity. Mathematical models improve our understanding of the complex dynamics in aquaponics, and thus support the development of efficient systems.

We developed a water and nutrient management strategy for the production of Nile tilapia (*Oreochromis niloticus*) and tomato (*Solanum lycopersicum*) in an existing INAPRO aquaponic demonstration system in Abtshagen, Germany. This management strategy aims for improved water and nutrient efficiency. For this purpose, we developed a system-level mathematical model and simulation.

In our simulations, we found that the existing configuration and water management of the Abtshagen aquaponic system results in an excessive amount of water discharged from the RAS. Therefore, sending more nutrient-rich water from fish to plants can help reducing water and fertilizer consumption. However, this water transfer may lead to excess concentrations of some nutrients, which could stress fish, plants or both. For the Abtshagen system, our simulations predicted excess concentrations of total suspended solids (TSS) for the fish, and sodium (Na^+) and ammonium nitrogen (NH_4^+-N) for the plants. Furthermore, our simulations predicted excess calcium (Ca^{2+}) and magnesium (Mg^{2+}) for plants, due to the use of local fresh water with relatively high concentrations of those ions.

Based on our simulations, we developed an improved management strategy that achieves a balance between resource efficiency and water quality conditions. This management strategy prevents excess levels of TSS for fish, and Na^+ and NH_4^+-N for plants. Under the improved management strategy, simulated water requirements (263 $L/kg\ fish$ and 22 $L/kg\ tomato$) were similar to current commercial RAS and greenhouse horticulture. Simulated fertilizer requirements for plants of N, Ca and Mg (52, 46 and 9 $mg/kg\ tomato$, respectively) were one order of magnitude lower than in high efficient commercial closed greenhouse production.

Keywords: aquaponics, mathematical model, resource efficiency

1. Introduction

Land-based aquaculture can help increasing local fish production, and its development has led to systems with low water consumption. Intensive recirculating aquaculture systems in the Netherlands can require less than 1 $m^3\ water/kg\ fish$, competing with livestock levels. Recirculating aquaculture production is increasing worldwide, but operational requirements like energy and water purification are still a challenge resulting in high investment costs [1]. High cost for water purification is due in part to the accumulation of excess nutrients. Hydroponic horticulture has been suggested and tested to utilise excess nutrients from aquaculture [2]. In the Netherlands, greenhouse horticulture is very well developed, but it depends on external fertilizer. Therefore, the current technological status of aquaculture and greenhouse horticulture represents an opportunity to balance their mutual needs.

Aquaponics is a production technique that combines aquaculture with hydroponics. This combination has been long known: as rice fields combined with fish culture in South-East Asia [3], and as *chinampas* by the Aztecs [4]. Researchers of recirculating aquaculture introduced the modern concept of aquaponics in the mid-1970's as a combination of intensive production systems (with low land and water use); but commercially competitive aquaponics is yet to be achieved [5]. The main challenge lies in balancing the water quality and the nutrients required by three

*Corresponding author
Email address: karel.keesman@wur.nl (Karel J. Keesman)

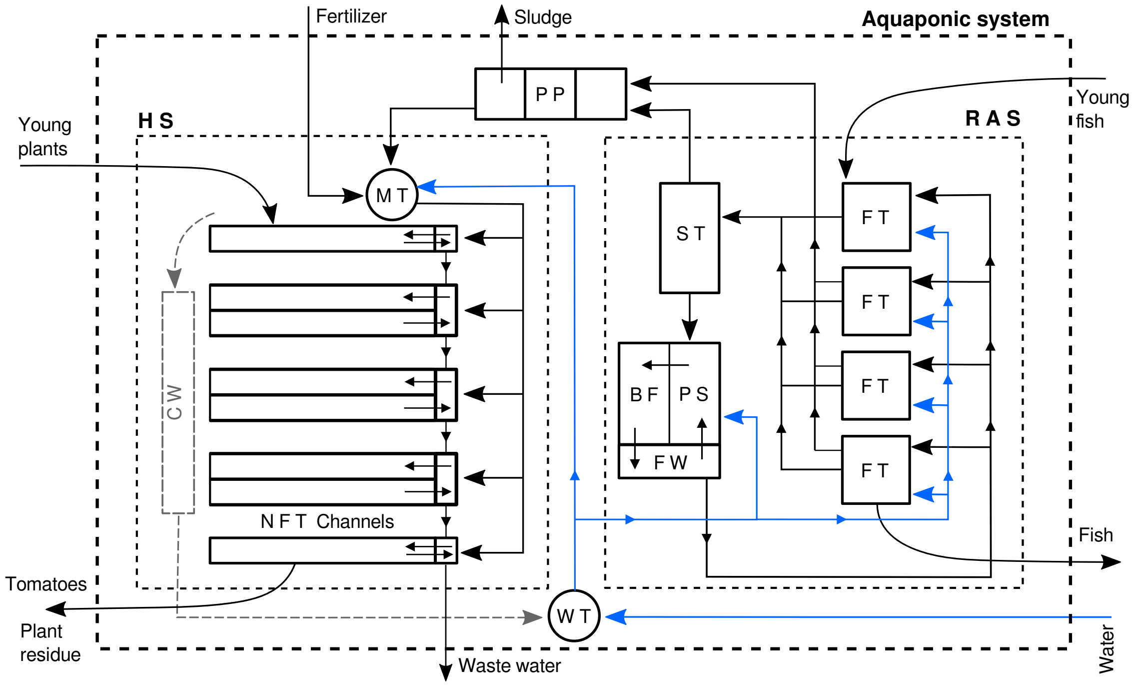

Figure 1: INAPRO demonstration aquaponic system in Abtshagen, Germany. Dashed rectangles represent the boundaries of RAS, HS, and aquaponic system. See components in Table 1.

or more biological systems (fish, plants and biodegradation bacteria) [6]. There is growing research based on mathematical models aimed at understanding the dynamics of water and nutrients in aquaponics for improved production. However, due to the large number of variables involved in a system-level analysis of aquaponics, each study has limitations.

For example, Karimanzira et al. [7] developed a detailed dynamic model for water and macronutrients of a decoupled aquaponic system. However, their study only presents the results of one system design and configuration. Reyes Lastiri et al. [8] presented a dynamic model comparing two management strategies for water and nitrogen (N), showing that it is theoretically possible to achieve stable nitrate levels for the fish by controlling the times when water is sent from fish to plants, based on amounts of fish feed introduced to the system. However, their study only models N dynamics. Goddek et al. [9] developed an agent-based model showing that it is theoretically possible to reduce nutrient consumption based on system-level sizing and design. However, their model only includes N and P, and it is based on a single management strategy.

Controlling the amount and frequency of water sent from fish to plants, fertilizer and water consumption can be reduced, but this water transfer can lead to accumulation of some nutrients to stressful levels for fish, plants or both. Therefore there is a trade-off between water transfer from fish to plants, and excessive nutrient concentrations that may result.

To balance the trade-off, one approach could be the introduction of additional (novel) technologies into aquaponics. For example, Goddek and Keesman [10] proposed desalination to treat excess nitrate, but desalination units can either be energy intensive or limited to large-scale applications. An alternative approach consists of evaluating the resource efficiency of the aquaponic system under multiple management strategies, and then selecting the most adequate. This alternative approach may not reach maximum resource recovery, but it does not introduce additional costs and it may help improving the productivity of an existing aquaponic system.

In this study, we propose a strategy for system design and management aimed at achieving a balance between reduced resource requirements and water quality conditions. For this purpose, we developed a mathematical model describing the system-level dynamics of water and multiple relevant nutrients in an existing aquaponic system.

2. Methods

The decoupled aquaponic system consists of two separate production loops: a recirculating aquaculture system (RAS) and a hydroponic system (HS).

2.1. Description of the aquaponic system

We studied one of the demonstration systems built and operated for semi-commercial and research purposes as part of INAPRO, a European Union (EU) project aimed at further developing aquaponics towards a commercial scale [11]. The system design is based the ASTAF-PRO configuration [12], and it is located in Abtshagen, Mecklenburg-West Pomerania, Germany. It consists a fish farm with 7.2

Table 1: Components of the aquaponic system.

Component	Size	Comments
Fish tanks (FT)	$4 \times 1.84\ m^3$	with 175 $fish/tank$
Settling tank (ST)	$1.32\ m^3$	-
Pump sump (PS)	$2.38\ m^3$	-
Biofilter (BF)	$2.29\ m^3$	with 445 m^2/m^3
Filtered water compartment (FW)	$0.02\ m^3$	negligible volume, not modelled
Post-purge (PP)	$9.0\ m^3$	3-chamber pit
Mixing tank (MT)	$1.1\ m^3$	-
Nutrient film technique channels (NFT)	$8 \times 10\ m$	with 2.4 $plants/m$
Fresh water tank (WT)	$2\ m^3$	modelled as constant concentrations

m^3 of total fish tanks volume in a RAS area of 43 m^2, and a Venlo type greenhouse of 139 m^2 for hydroponic cultivation in nutrient film technique (NFT) channels with a net cultivated area of 62.6 m^2. We studied the production of Nile tilapia (*Oreochromis niloticus*) and tomatoes (*Solanum lycopersicum cv. Pureza*).

Inputs to the system were young tilapia, young plants, water and fertilizer. Outputs from the system were market-size tilapia, tomatoes, sludge, wastewater and plant residue.

RAS and HS were operated as separate loops. Water was transferred from the RAS to HS to provide some of the nutrients required by the plants. RAS and HS loops are described below and illustrated in Fig. 1. Component sizes are listed in Table 1.

RAS. Fish grew in 4 fish tanks (FTs) with circulating water. Water effluent from the FTs was directed to a settling tank (ST) to remove solids. Clean water from the ST was taken to a nitrification unit consisting of a pump sump (PS), a biofilter (BF), and a small compartment catching filtered water (FW). Water from the filtered water compartment was circulated back to the FTs. Settled sludge from the ST was removed periodically and directed to a post-purge unit (PP), consisting of a 3-chamber pit outside the building for secondary removal of solids by sedimentation. Clean water is added to the system from a fresh water tank (WT).

HS. Water with dissolved nutrients was received from the RAS after separation of solids at the PP. This water was stored inside the greenhouse in a mixing tank (MT). If needed, fertilizer was added to the MT to match minimum concentrations required by plants. The nutrient solution from the MT was recirculated in 5 small tanks that feed a set of NFT channels (3 double and 2 single). The single NFT channels were located near the greenhouse walls to maintain similar shading conditions in the double channels (condition required for other experimental studies). At the end of a plant production cycle, remaining water with low nutrient concentration was discarded. The aquaponic system includes a plan to recirculate condensed water from the HS back to the RAS loop (CW). However, this process was not yet available at the time of this study and therefore was not included in the model.

2.2. Description of the mathematical model

The mathematical model was developed following a dynamic, deterministic and modular approach, and based on algebraic and ordinary differential equations. Each module represents a component of the aquaponic system. The modules were modelled and calibrated based on data available from literature and gathered at the INAPRO demonstration site. Model and calibration routines were programmed in Python 3.4.

We modelled production of Nile tilapia in the RAS coupled with tomato in the HS. Design, configuration and flows between units were based on the operation of the demonstration system in Abtshagen.

Each module comprises mass balances for 3 state variables: 1) water volume (V), soluble components (nutrients) (m_S), and total suspended solids (m_{TSS}). The state variables constitute model outputs (y). The state variable m_S consists in turn of macronutrients considered relevant for plant hydroponic cultivation: NO_3^--N, TAN, PO_4^{3-}-P, K^+, Ca^{2+}, Mg^{2+}, and Na^+. We abbreviated these components as: NO_3, TAN, P, K, Ca, Mg, and Na

Mass balances for each module were expressed in terms of inflows (ϕ_{in}) and outflows (ϕ_{out}) (Eqn. 1). Concentrations at effluents were calculated from the resulting states of each unit $C = m/V$. The simulation time step (Δt) was 15 min.

$$\frac{dy}{dt} = \phi_{in} - \phi_{out} \qquad (1)$$

Equations describing mass balances for each module are shown in Table 5. Auxiliary equations are listed in Table 6. Values for parameters used in this model are listed in Table 7.

The filtered water compartment (FW) has a negligible volume, therefore it was not modelled. The fresh water tank (WT) is only modelled as a supply with constant concentrations.

Assumptions for the system-level model were:

- Negligible volume of pipes.

- Constant density of water $\rho = 1000\ kg/m^3$ (neglecting effect of soluble and suspended matter).
- Chemical reactions only take place in the BF.
- Fresh water composition was constant, based on measurements by REWA [13].
- Ideal fish and plant growth, justified by expert management from successful commercial operation in the region for individual tilapia aquaculture and tomato horticulture.

2.2.1. Fish tank (FT)

Fish was grown and harvested in FTs. Recirculating water enters at rate $\phi_{v,in}$. Ideally, a FT should be fully refreshed twice per hour. Outflow occurs by overflow on a standing pipe at rate $\phi_{v,out}$. To start production, fish is added to the 4 tanks in a staggered sequence spaced by 45 days. Each tank was harvested once every 180 days alternating between tanks, providing 1 harvest every 45 days. At harvest, a tank is emptied at rate $\phi_{v,harvest}$ in 1 Δt (to the PP). During the same Δt, flow through the FT stops ($\phi_{v,in} = \phi_{v,out} = 0\ m^3/hr$), and fresh water refilled the FT at rate $\phi_{v,fresh} = V_{FT}/\Delta t$. After harvest, flow through the FT resumed and an additional FT volume of fresh water is added through a period of 2 days to clean the FT ($\phi_{v,fresh} = V_{FT}/2day$). Since the additional water in the 2 day period stays relatively clean, it is kept in the RAS loop. New fish is then added to the harvested tank. Growth conditions are reported in [6].

Each FT was modelled as an ideally mixed tank.

Fish growth and nutrient uptake was included as a sub-model of the FTs. Total fish in one tank was modelled as a single mass m_{fish} assuming ideal growth, based on a least-squares, second order polynomial regression from data of average growth per fish estimated by Autosoft [14] (see Table 6 in Appendices). Fish constitutes up to 7% of the water volume in the FT and was therefore neglected in the calculation of V.

It was assumed that all fish feed is consumed.

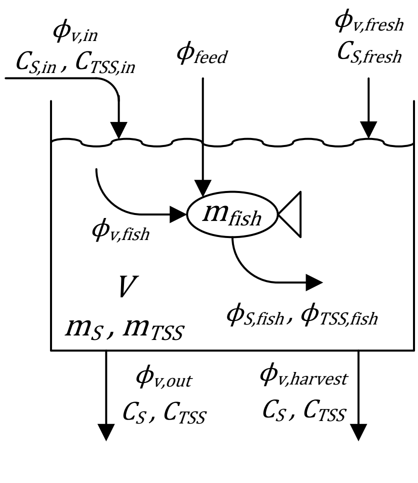

Figure 2: Model of the fish tank (FT).

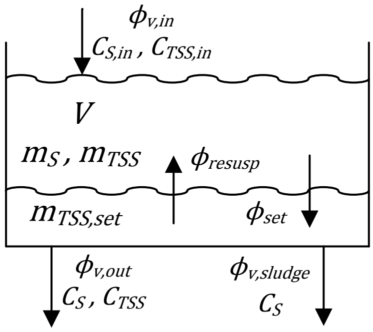

Figure 3: Model of the settling tank (ST).

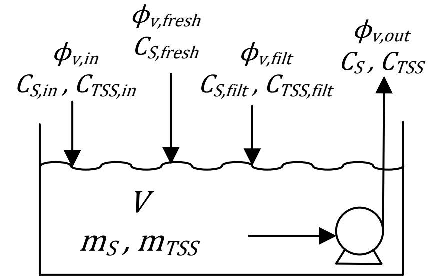

Figure 4: Model of the pump sump (PS).

2.2.2. Settling tank (ST)

The ST was used to remove solids. Recirculating water enters at rate $\phi_{v,in}$ and leaves by overflow at rate $\phi_{v,out}$. Sludge was removed at rate $\phi_{v,sludge}$ once every time interval $\Delta_{t,clean}$ in 1 single time-step. TSS settle at a rate ϕ_{set}, and undergo resuspension during sludge removal at a rate ϕ_{resusp}. Therefore, an additional mass balance for settled solids was included in the model (TSS_{set}).

For soluble components S, the ST was modelled as an ideally mixed tank. For TSS, settling and resuspension rates were assumed linearly related to the mass of TSS in the water and sludge respectively.

2.2.3. Pump sump (PS)

The pump sump was used to balance water deficit and to pump water through the system. Recirculating water enters at rate $\phi_{v,in}$ and it is pumped up at a constant rate $\phi_{v,out}$ (to the BF). Water also enters from the filtered water compartment of the biofilter at rate $\phi_{v,filt}$. When inflows are not sufficient to keep the PS full, fresh water is added at a rate $\phi_{v,fresh}$ (from the WT).

The PS was modelled as an ideally mixed tank.

2.2.4. Biofilter (BF)

The BF consisted of a trickling filter used for nitrification, i.e. conversion of ammonia (NH_4^+), which is toxic for the fish, into less toxic nitrate (NO_3^-). Recirculating water enters at a rate $\phi_{v,in}$ and leaves at a rate $\phi_{v,out}$. Biofiltered water is received in the FW compartment (of negligible volume). Part of the effluent goes back to the

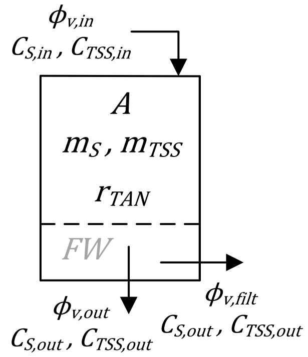

Figure 5: Model of the nitrification biofilter (BF).

PS ($\phi_{v,out,PS}$) and the rest is circulated back to the FTs ($\phi_{v,out}$).

The BF was modelled as a continuously stirred tank reactor (CSTR). Only 2.4% of the TAN mass is converted into bacteria biomass [15], and this loss of N was thus neglected. The simplified chemical reaction modelled was:

$$NH_4^+ + 2O_2 + 2HCO_3^- \rightarrow NO_3^- + 3H_2O + 2CO_2$$

The reaction rate of TAN was assumed linear. It was assumed that water and TSS do not change through the BF, i.e. $^{dV}/_{dt} = 0$ and $^{dm_{TSS}}/_{dt} = 0$. It was also assumed that the BF is well aerated, therefore O_2 does not become a limiting factor in the reaction, and CO_2 leaves as it is produced.

Nitrification consumes alkalinity and results in a pH decrease. To correct this, pH buffers like $NaHCO_3$ are commonly added in RAS before circulating water back to the fish. However, the system in Abtshagen showed no decrease in pH after nitrification. Therefore, addition of a pH buffer was not included in the model.

2.2.5. Post purge (PP)

The PP was used for secondary clarification by settling of solids and consists of a 3-chamber pit. It operated as the connection unit between RAS and RHS. Sludge from the ST enters at rate $\phi_{v,sludge}$. Water from the FTs emptied for harvest enters at rate $\phi_{v,harvest}$. Water is removed on demand to the RHS at a rate $\phi_{v,out}$. When RHS demand is low, water in the PP accumulates; if full, excess water is discharged at a rate $\phi_{v,discharge}$.

The 3 chambers were modelled as a single unit similar to the ST: an ideally mixed tank for S, and settling for TSS at a rate linearly related to its concentration.

2.2.6. Mixing tank (MT)

The MT received water from the RAS as well as fertilizer to match concentrations required by plants ($C_{S,required}$). RAS water enters at a rate $\phi_{v,in}$ and leaves after fertilizer addition at a rate $\phi_{v,out}$. When V drops below 55 %, fresh water is added at a rate $\phi_{v,fresh}$ to refill the MT in one Δt. Fertilizer is added at rate ϕ_{fert} in 1 time-step Δt, based

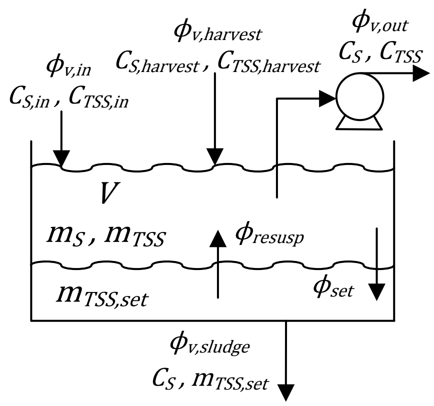

Figure 6: Model of the post purge tank (PP), consisting of a 3-chamber pit modelled as a single tank.

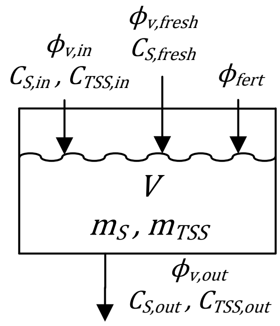

Figure 7: Model of the mixing tank (MT).

on the difference between required and present nutrient concentrations at the NFT tanks.

The MT was modelled as an ideally mixed tank. Fertilizer volume constitutes less than 0.1% of the flow rate leaving the MT. Therefore, V increase due to fertilizer addition was neglected.

It was assumed that nutrients are added in their soluble ionic form (in practice, salts are added), neglecting the presence of other elements. It was also assumed that N is only added as NO_3^- and no Na^+ is added.

2.2.7. Nutrient film technique (NFT) unit

The NFT unit consists of small tanks that store water recirculated in channels where plants were grown. Water enters the NFT tanks at a rate $\phi_{v,in}$. Plants take up water at a rate $\phi_{v,plants}$ in the channels. After a yearly production cycle, all remaining water is discharged from the NFT tanks at a rate $\phi_{v,discharge}$ in 1 Δt. Growth conditions in the greenhouse are reported in [6].

The group of NFT tanks and channels were modelled as a single ideally mixed tank. Changes in concentrations through channel length are thus neglected.

Plant growth and nutrient uptake was added as a submodel in the NFT unit. Tomato plant growth was modelled for two separate parts: vegetative and fruits.

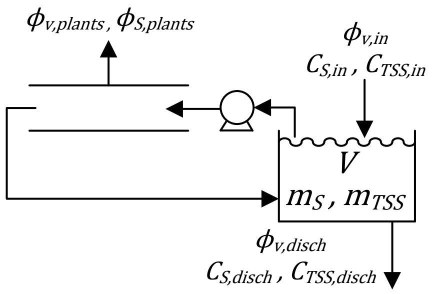

Figure 8: Model of the NFT tanks and channels.

Vegetative growth was modelled following an ideal logistic function and calibrated against data on final vegetative weight. Fruit growth was modelled assuming a second order polynomial function and calibrated against production data. Total water uptake was modelled assuming a third order polynomial function. Data for calibration was obtained from control groups grown under ideal conditions in experiments at the Abtshagen system [16] (see Appendices). Each nutrient uptake rate was assumed linearly related to the plant growth and the fruit composition.

2.3. Development of an improved management strategy

The simulation results from the existing configuration of the aquaponic system in Abtshagen were analysed to identify opportunities for increased resource efficiency, using an improved management strategy, following the next steps:

1. Water balance. Identify the largest (waste) streams in the system, and possibilities for reuse on plants.
2. Nutrient balance. Identify surplus or deficit streams of nutrients in the RAS water, and possibilities for reuse on plants (compared to fertilizer use).
3. Water quality. Identify water quality parameters near or above suggested limits for fish and plant growth. These parameters become limiting factors for the water reuse potential identified in the previous steps.
4. Response surface analysis. Select system operation parameters affecting the streams identified in previous steps. List the critical water quality parameters (limiting factors). Run a set of simulations with a range of system operation parameters and evaluate their effect on resource efficiency, accounting for limiting factors from water quality. Identify an improved management strategy.

3. Results and discussion

The aquaponic system was simulated for a period of 2 years. Year 1 is the starting phase of the system. From year 2 onwards, the system operates with similar yearly behaviour. Therefore, amounts of yearly production and consumption were calculated based on year 2.

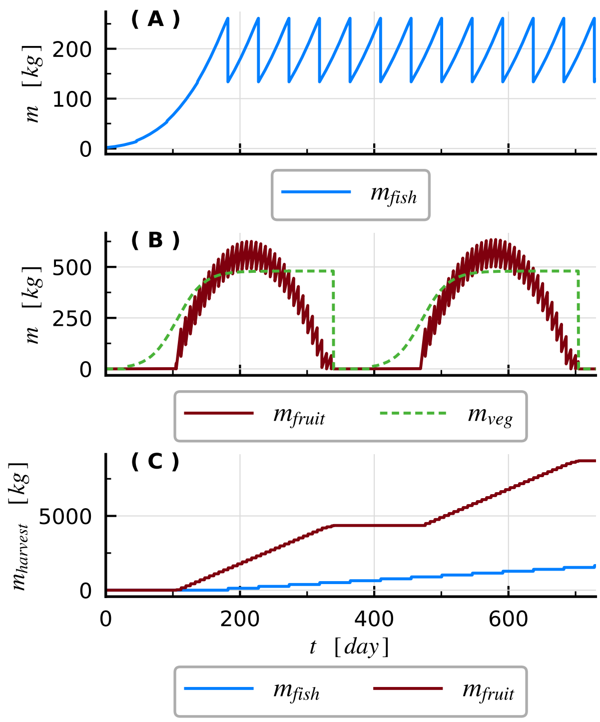

Figure 9: Simulated production. A) Fish growth. B) Plant growth. C) Cumulative harvest. After 1 start-up year, simulated production was 1034 kg/yr for fish, and 4350 kg/yr for tomato (fresh weights).

3.1. Production

Simulated growth and cumulative production of tilapia and tomato are shown in Fig. 9.

After 1 start-up year, fish is harvested 8 times per year at 129.3 kg per harvest for a total of 1034 kg/yr or 140 $kg/m^3/yr$ with a final stocking density of 70 kg/m^3. This simulated yearly production is higher than commercial production ($60 - 120$ $kg/m^3/yr$, [17]) due to the assumption of ideal growth with no mortality and expert management. At the time of this study, fish production in the actual system at Abtshagen was facing problems and comparison to simulated results is not possible.

Tomato is harvested weekly, for a simulated production of 4350 kg/yr or 69 $kg/m^2/yr$ (net cultivated area), at 22.5 $kg/plant$. This simulated yearly production matches by calibration the conventional production under expert management ($50 - 75$ $kg/m^2/yr$, [18, 19, 20]). An experiment in the actual Abtshagen system without measures for increased productivity only achieved a production of (32 $kg/m^2/yr$) [6], showing the relevance of expert management in our model assumptions.

3.2. Water balances

Simulated cumulative water balances for the RAS and HS are shown in Fig. 10.

After 1 start-up year, the RAS consumes $994 m^3/yr$ of fresh water, mainly to compensate for discharge from the

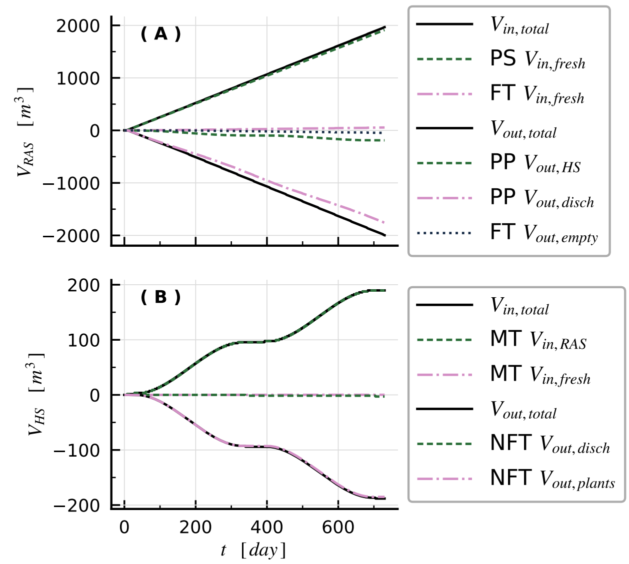

Figure 10: Simulated cumulative water balance. A) Recirculating aquaculture system (RAS). B) Hydroponic system (HS). Positive values represent water entering the system. Negative values represent water leaving the system. PS: pump sump. FT: fish tanks. PP: post-purge tank. MT: mixing tank for fertilizer. NFT: nutrient film technique channels and containers.

PP ($900 m^3/yr$). Discharge from the PP happens when removing sludge or when it overflows. The main flow filling up the PP to eventual overflow comes from cleaning the ST. These large flows confirm the assumption for a negligible volume of water corresponding to fish body mass.

In the HS, fresh water consumption is negligible: 0.18 m^3 during 1 start-up year, and 0 m^3 afterwards. This low consumption in the HS happens because the system was simulated to prioritize water use from the RAS (fresh water is added to the MT only if its volume drops below 55%).

Assuming 95% water content in tomato fruits [6] and 70% leaf relative water content [21] (generalized for stem and roots), given a production of 4363 kg/yr fruits and 480 kg/yr vegetative, a total of 4481 kg/yr water corresponds to plant weight (4.48 m^3/yr). This water content in the plant weight corresponds to 5% of the simulated yearly plant water uptake (92.60 m^3/yr), the rest being lost by evapotranspiration (88.12 m^3/yr). This evapotranspiration constitutes 9% of the total water consumption. Therefore, it is more important to reduce overall water input that to implement condensation recovery for water in the greenhouse.

The large amount of water discharged from the PP suggests that the RAS can provide water requirements for a much larger number of plants. But first, it is necessary to analyse the nutrient balances to determine the amount of nutrients that the fish water can provide to the plants.

3.3. Nutrient balances

Simulated nutrient balances are focused on the HS, where nutrient addition can be reduced using RAS water. Fig. 11 shows the simulated nutrient balances in the HS.

The RAS supplies 25% of the plant N requirements (as $TAN + NO_3$). P and K are mostly supplied as fertilizer (P excretion by fish was assumed negligible). Ca, Mg and Na are mostly supplied by RAS water. However, most of the Mg and Na enters the system in fresh water, not in fish feed. Excess Ca, Mg and Na is discharged in waste water at the end of the plant production cycle.

Based on excess nutrients and the water discharge from the PP, it could be suggested that fertilizer consumption for N, Ca, Mg and Na could be reduced using RAS water for an even larger number of plants. However, due to the excess of some nutrients, transferring a high amount of water from fish to plants could result in water quality conditions that may hinder plant growth. On the other hand, transferring low amounts of water could result in accumulation of nutrients that may hinder fish growth. Therefore, in the next section we analyse whether the water quality would be adequate for fish and plant growth.

3.4. Water quality

According to the simulation, concentrations of soluble and suspended matter can become limiting factors for the amount of water that can be sent from RAS to HS.

3.4.1. RAS water quality

Simulated nutrient concentrations in water of the first FT are shown in Fig. 12. These simulated concentrations contained high noise due to the recirculating nature of the system and because mixing dynamics was not modelled. Therefore, the resulting concentrations were filtered using an order 3 lowpass Butterworth filter (normalized critical frequency 0.05) applied in a forward-backward linear digital filter (scipy functions *signal.butter* and *signal.filtfilt*). A comparison between filtered simulated values and recommended levels is shown in Table 2.

During the start-up year, concentrations build up in the first FT and change suddenly every 45 days as tanks 2, 3, and 4 start operation. Afterwards, and every 180 days, the first FT is harvested. Once all 4 FT operate, one FT is harvested every 45 days. With every harvest, concentrations drop and subsequently build up with time due to fish waste, resulting in the characteristic saw-tooth

Table 2: RAS water quality. Simulated minimum & maximum values after 1 start-up year vs. recommended levels

Nutrient	Simulated [mg/L]	Recommended [mg/L]	References
TSS	$73 - 104$	< 200	[22, 23, 24]
NO_3	$7.5 - 9.0$	< 300	[25]
Ca	$55 - 60$	$50 - 160$	[25, 15]
NH_3	$0.023 - 0.036$	< 0.1	[26]
Mg	5.5	< 15	[15]
Na	15	< 75	[15]

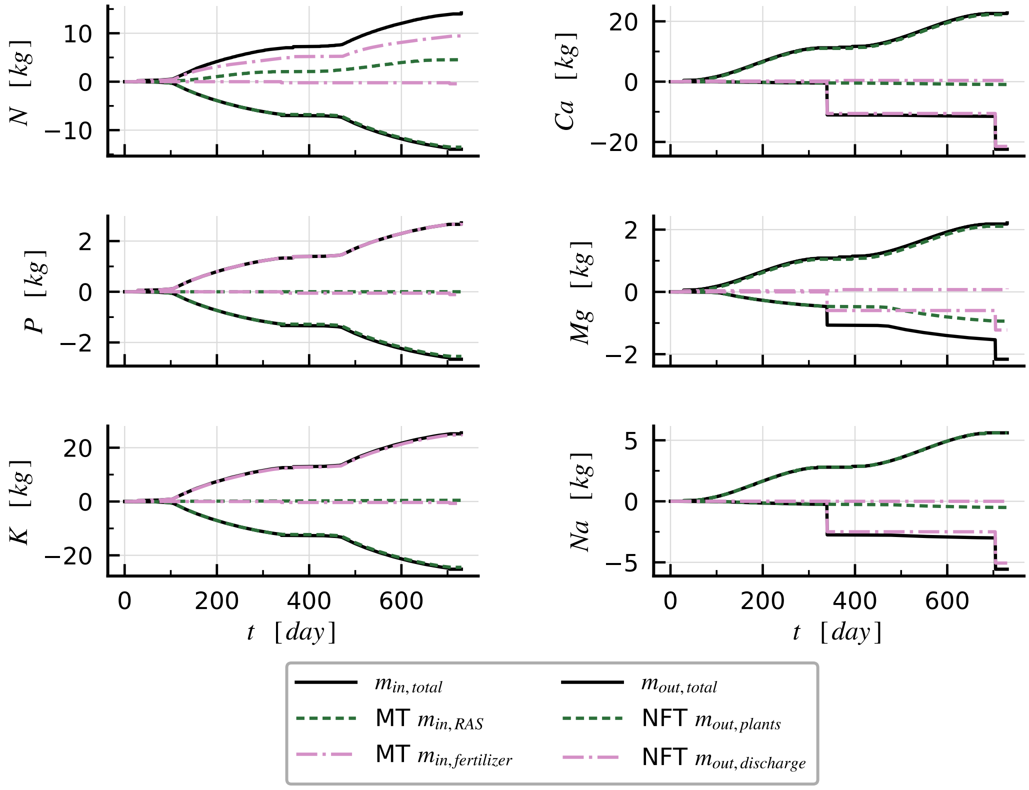

Figure 11: Simulated cumulative nutrient balance in the hydroponic system (HS). Positive values represent nutrients entering the system in the mixing tank (MT). Negative values represent nutrients leaving the system after harvest, discharged from the nutrient film technique (NFT) containers. N refers to TAN + NO_3-N.

pattern of a RAS. Concentrations of Ca, Na and Mg show small oscillations because their levels are governed by fresh water (their input is higher from fresh water than from fish feed).

Special attention must be given to TAN levels, because in the form of unionized ammonia (NH_3-N) it is very toxic for fish. For tilapia, De Long et al. [25] suggested to maintain NH_3-N below 1 mg/L. However, El Shafai et al. [26], found negative effects of NH_3-N on tilapia growth rate with long term exposure at concentrations as low as 0.144 mg/L, and suggested levels below 0.1 mg/L. NH_3 concentration depends on pH and TAN. Tilapia has been reported to grow best at pH between $6-9$. However, nitrifying bacteria requires a minimum pH of 6.8. Therefore, we assumed a controlled pH of 7.0 in the RAS. Under these conditions, based on $Ka = [NH_3 - N][H^+]/[NH_4^+ - N] = 10^{-9.25}$, and assuming activity of water equal to 1 [27], the simulated TAN levels oscillating between $4.6 - 6.5$ mg/L after the start-up year, are equivalent to $0.023 - 0.036$ mg/L of NH_3-N. Therefore, NH_3-N levels are kept safe throughout the production cycle.

Special attention must also be given to TSS levels, because the RAS only has one settling tank to remove solids, as opposed to the combination of mechanical filter and settling tank suggested in literature [28]. It has been suggested to maintain TSS levels below 80 mg/L in RAS [15]. Ebeling reported growing fish in RAS with up to 100 mg/L TSS, in absence of other stress factors [22]. However, tilapia has a high tolerance to solids, and it has been reported to grow at 200 mg/L [24] and up to 900 mg/L [23]. We chose to aim for TSS levels below 200 mg/L.

3.4.2. HS water quality

Simulated nutrient concentrations in the NFT channels are shown in Fig. 13. A comparison between simulated and recommended levels is shown in Table 3.

Table 3: HS water quality. Simulated maximum values vs. recommended levels

Nutrient	Simulated [mg/L]	Recommended [mg/L]	References
NO_3-N	160	$151-465$	[6, 29, 30, 31]
NH_4-N	$56-825$	$0.1-200$	[6, 29, 30, 31]
P	37	$15-66$	[6, 29, 30, 31]
K	234	$117-380$	[6, 29, 30, 31]
Ca	$255-7288$	$100-800$	[6, 29, 30, 31, 32, 33]
Mg	428	$24-104$	[6, 29, 30, 34]
Na	$32-1713$	< 1150	[35]

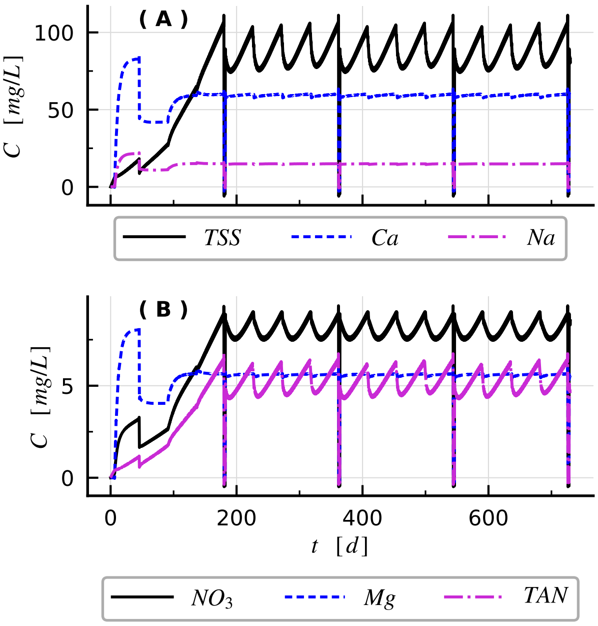

Figure 12: Simulated water quality in one fish tank (FT). A) TSS, Ca and Na. B) NO_3, Mg and TAN. Concentrations oscillate due to fish harvest every 45 days. Once every 180 days the FT depicted is harvested, shown as a concentration drop to 0. Ca, Na, and Mg concentrations are mainly governed by fresh water addition, therefore they stabilize after starting up all 4 FTs. TSS, NO_3, and TAN concentrations are mainly governed by fish excretion, therefore they oscillate with each harvest.

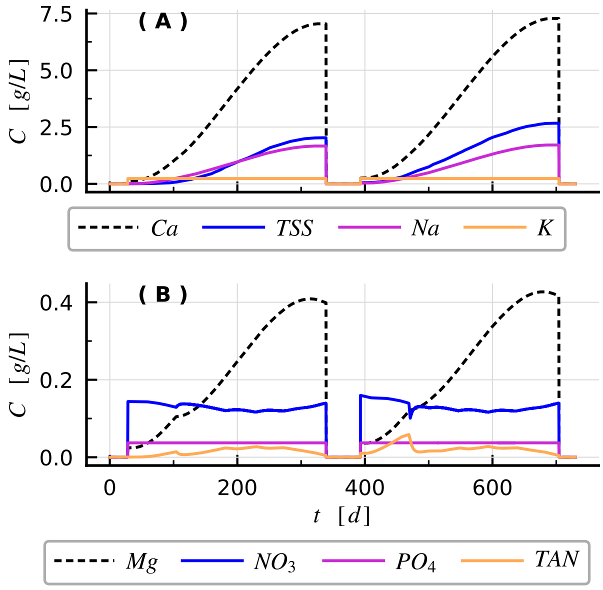

Figure 13: Simulated water quality in one NFT channel. A) Ca, TSS, Na, and K. B) Mg, NO_3, PO_4, and TAN. The greenhouse stops production during winter, shown as a concentration drop to 0. Plant requirements for P and K are not covered from RAS water, therefore their levels are almost entirely determined by the controlled addition of fertilizer (constant levels). Plant requirements for N are partially covered by RAS, therefore its levels are partly determined by the addition of fertilizer and remain stable. Plant requirements for Ca, Mg and Na are provided in excess by RAS water and they accumulate in the HS.

Special attention must be given to NH_4-N levels. Similarly to the NH_3-N in the RAS, its levels depend on TAN and pH, but in the case of tomato plants, we assumed controlled pH at 6 [36]. Simulated TAN levels oscillate between $4 - 59$ mg/L after 1 start-up year, equivalent to $56 - 825$ mg/L of NH_4-N. Borgognone et al. [29] reported adverse effects on tomato production with decreased ratios of NO_3-N:NH_4-N for N supply. They observed higher productivity with a 70:30 ratio. Based on this observation, and on the recommended levels for NO_3-N, we chose a maximum recommended concentration of 200 mg/L for NH_4-N for this study. The simulated levels exceed this maximum recommended level by a factor of 4.

Special attention must also be given to levels of Ca, Mg, and Na. Ca has been reported to reduce K and Mg uptake, but tomato production was achieved at Ca levels up to 20 mM (800 mg/L) [33, 37]. Mg has been reported to reduce fruit yield at 1 mM (24 mg/L), but under saline conditions negative effects appeared only at 5 mM (121.5 mg/L) [34]. Na levels have been reported to cause stress on tomato plants at 50 mM (1150 mg/L), but seedlings have been grown for 37 days with up to 100 mM Na with no significant differences from 50 mM Na nutrient solution [35]. Simulated Ca levels exceed the maximum concentrations found in literature by up to a factor of 10, and simulated Na is close to stress levels.

Although the water and nutrient balances suggest the possibility to increase the number of plants and the amount of water provided by the RAS, excess of Ca, Mg, and Na present limiting factors for the system. In the next section, different strategies to operate the water supply from RAS to HS are evaluated.

3.5. Response surface analysis. Selecting a management strategy

The water and nutrient balances suggested the possibility to reduce water and fertilizer addition by increasing 1) the number of plants and 2) the amount of water sent from RAS to HS. However, some concentrations in the FT and in the NFT channels may (further) exceed recommended levels when doing so. Therefore, we evaluated the effect of these system parameters on 1) Water consumption and discharge, and fertilizer consumption (N and Mg), 2) Concentration of TSS and NH_3-N in FT as well as NH_4-N, Ca, and Na in NFT channels. The objective was to select an improved system size and management strategy.

The model was simulated for different numbers of plants and for different ST cleaning intervals (related to the amount of water sent from RAS to HS). The number of plants was simulated for $92 - 768$ $plants$, and the shortest ST cleaning interval ($\Delta t_{clean,min}$) was simulated for $0.5 - 6.5$ $days$. Both parameter ranges were split in 13 points, for a total

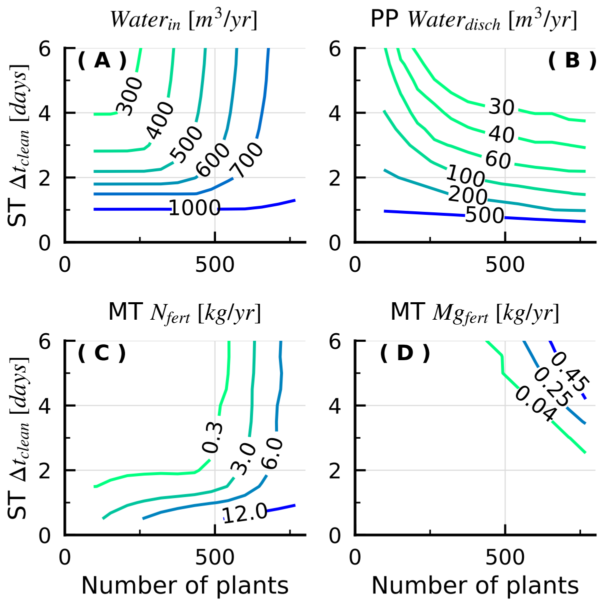

Figure 14: Response surface analysis from simulations. Effect of the number of plants and cleaning interval of the settling tank (ST) on yearly resource consumption. A) Fresh water addition to the system. B) Water discharge from the post-purge tank (PP). C) Fertilizer addition to the mixing tank (MT) for N. D) Fertilizer addition in the mixing tank (MT) for Mg. The given system configuration operates with 192 plants, and a 0.5 day ST cleaning interval.

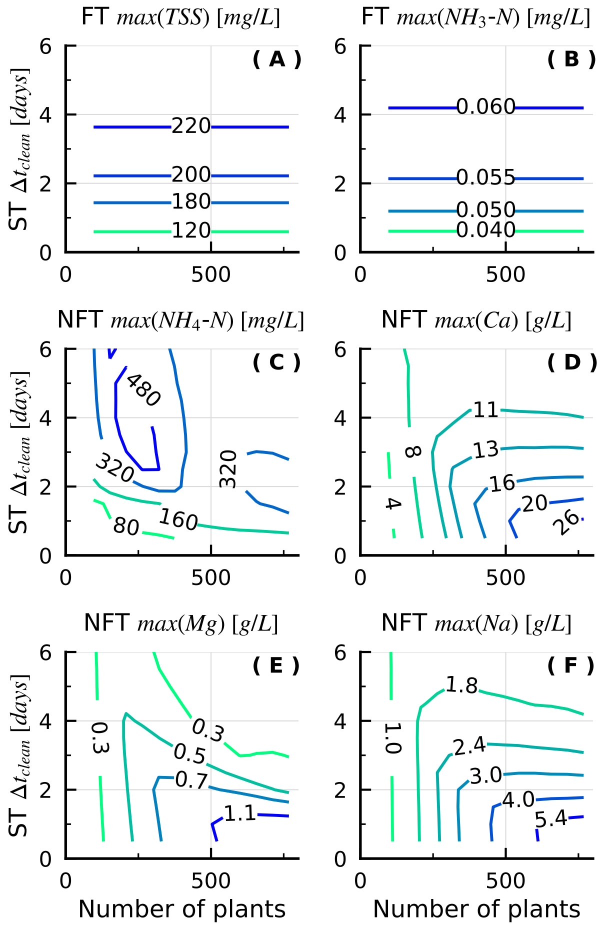

Figure 15: Response surface analysis from simulations. Effect of the number of plants and cleaning interval of the settling tank (ST) on maximum concentrations. A) TSS in the fish tanks (FT). B) NH_3-N in the fish tanks (FT). C) NH_4-N, in the NFT channels. D) Ca in the NFT channels. E) Mg in the NFT channels. F) Na in the NFT channels. The given system configuration operates with 192 plants, and a 0.5 day ST cleaning interval.

of 169 simulations. The results are shown as contour plots of Figs. 14 and 15.

Fertilizer consumption was only analysed for N and Mg because it can be reduced using RAS water (Fig. 14). Water quality was only analysed for the components that resulted in (near) excessive levels when simulating the given system configuration (Fig. 15).

Based on the contour plots in Fig. 15, it is first possible to determine that maximum Ca and Mg concentrations cannot be brought down to recommended levels. But it is still possible to decrease them using a lower number of plants (not desirable for improved productivity) or a higher ST cleaning interval. We therefore suggest to take additional measures to decrease Ca and Mg levels, such as filtration or an alternative fresh water source. However, minerals in the given fresh water source may be providing alkalinity that acts as a pH buffer, which may be the reason why pH control is not needed after the BF (nitrification would normally result in a pH drop).

Continuing with the analysis of the contour plots in Fig. 15, the main limiting factors are the concentrations of TSS in the FT, and Na in the NFT channels. To maintain TSS concentrations within recommended levels for fish ($< 200\ mg/L$), the shortest interval for cleaning of the ST must be smaller than 2 $days$. And to maintain Na concentrations below excessive levels ($< 2\ mM$ or $< 2300\ mg/L$), the number of plants can only be increased to about 222 $plants$. Tomato plants may be stressed at 1 mM of Na, but based on Fig. 13 it would only be expected to reach the maximum simulated concentration during the last third of the plant growth period.

After fixing TSS and Na limits, the next limiting factors are NH_4-N levels in the NFT channels (Fig. 15), together with water consumption and discharge (Fig. 14). Lowering the shortest ST cleaning interval decreases NH_4-N. However, it increases both water consumption and discharge. Increasing the maximum cleaning interval from 1.5 to 2 $days$ could decrease water consumption by 150 m^3/yr, but it will not guarantee NH_4-N levels for the NFT channels within recommended values. However, they would still decrease with respect to the given system configuration, from 825 to ca. 320 mg/L. Furthermore, based on Fig. 13, TAN levels (and thus NH_4-N) only peak during the first third of the plant growth period and decrease afterwards. Therefore, it could be safe to operate at a 2 day ST cleaning interval.

Finally, fixing the HS size to 222 plants and the short-

Table 4: Simulated resource productivity of the INAPRO aquaponic system in Abtshagen in its given and improved management strategies, compared to commercial RAS and greenhouse hydroponic production. INAPRO figures are based on simulated results after 1 start-up year.

Resources	Units	INAPRO given	INAPRO improved	Commercial	References
$Freshwater$	$[L/kg\ fish]$	961	263	$40-240$	[38]
$Freshwater$	$[L/kg\ tomato]$	≈ 0	22	$4-21$	[19]
N	$[mg/kg\ tomato]$	1031	52	$728-3822$	[19, 39]
P	$[mg/kg\ tomato]$	305	305	$28-586$	[19, 39]
K	$[mg/kg\ tomato]$	2831	2831	$782-4105$	[19, 39]
Ca	$[mg/kg\ tomato]$	44	46	$800-4200$	[19, 39]
Mg	$[mg/kg\ tomato]$	8	9	$292-1351$	[19, 39]

We do not compare water discharge and energy requirements to those in commercial systems because the INAPRO system in Abtshagen did not introduce changes for those aspects that could deviate from current production techniques.

est ST cleaning interval to 2 $days$, fertilizer Na and Mg addition is reduced to the minimum (Fig. 14), and NH_3-N levels in the FT are still kept within recommended levels ($< 0.1\ mg/L$) (Fig. 15).

It is important to notice that even if Ca and Na are decreased from the fresh water input, which could allow for more plants, other variables would still get affected by an increase in the number of plants. NH_4-N levels in the NFT channels could increase above the maximum recommended level (320 vs. 200 mg/L). Beyond 500 plants, consumption of fertilizer N would increase drastically (Fig. 15).

3.6. Operation under improved management strategy

The given aquaponic system size and management consisted of 192 *plants* and a shortest ST cleaning interval of 0.5 $days$. We found a new management strategy consisting of an increase to 222 *plants* (10 NFT channels with 22 plants each), and an increase of the shortest ST cleaning interval to 2 $days$. This new management strategy could improve the resource productivity and the water quality for fish and plants.

With the new management strategy, simulated tomato production increased from 4350 to 4990 kg/yr. Water consumption decreased with respect to the given configuration, from 994 to 380 m^3/yr (272 m^3/yr in the RAS and 108 m^3/yr in the HS). Waste water discharge from the PP decreased from 900 to 164m^3/yr. Fresh water consumption in the HS becomes necessary due to the reduced water discharge from the aquaponic system.

The simulated system productivity is summarized in Table 4. Water supply for fish can be similar to current commercial RAS systems in the Netherlands (240 $L/kgfish$ commercially). New developments in RAS such as denitrification could reduce water supply even further, to 40 $L/kg\ fish$ [38], but this could reduce N availability from fish to plants. Water supply for tomato can also be similar to some commercial systems in the Netherlands (21 $L/kg\ tomato$). However, current production in closed greenhouse system can operate using only 4 $L/kg\ tomato$ [19].

Nutrient supply to commercial greenhouse horticulture was calculated based on the range of water supply [19] and recommended levels for hydroponic solution. Simulated P and K requirements lie somewhere between the standard and high efficient closed greenhouse in the Netherlands. N Ca and Mg requirements are one order of magnitude lower than those of commercial systems.

Recirculating water for the NFT could help decreasing further N, P, and K requirements. However, due to the high concentrations of other nutrients, this may result in stressful conditions for plant growth.

In summary, experimental-scale aquaponic production by the system in Abtshagen can operate with a resource efficiency that competes with large scale commercial production of tilapia and tomato in separate, specialized systems.

3.7. Analysis of the system configuration

The aquaponic system in Abtshagen has a small experimental size with unique characteristics.

- Solids removal in the RAS is only done in 1 settling tank, aiming at a reduced initial investment.

  It has been suggested for a RAS to include a mechanical filtration unit, followed by a secondary sedimentation unit [28].

  As a result of the single settling tank (ST), the RAS in Abtshagen requires frequent cleaning and a large storage unit to store water for further use in the HS: the post-purge tank (PP). Large residence times in the PP may have led to anaerobic conditions which resulted in nitrogen losses by denitrifcation. Aeration of in the PP could help solving this problem [6].

  Commercial-scale RAS operating with both mechanical filtration and sedimentation, would result in different water quality limitations when developing a management strategy.

- The RAS required no pH buffer during operation.

  Controlling pH with buffers is frequently necessary after nitrification [15]. But in the Abtshagen system, using fresh water with high alkalinity may have helped controlling the pH.

  Commercial-scale systems may require the addition of a pH buffer, leading to higher concentrations of Na, Ca or K, depending on the buffer choice, which would also result in different water quality limitations when developing a management strategy.

3.8. Limitations of the model

This model assumed ideal growth for both fish and plants, provided by expert management. However, any deviation from ideal growth, could result in changes on the nutrient balances. These changes may require different parameters for the water and nutrient management strategy.

Plant nutrient uptake was modelled based on mineral composition of fruits, assuming that vegetative parts have the same composition and uptake. Therefore, predicted nutrient uptake may differ from reality during vegetative growth.

Settling of suspended solids was modelled linearly with respect to their mass in a tank. This could hold for low concentrations. But increased concentrations may result in lower settling than predicted.

Except for the BF, (bio)chemical reactions were neglected.

Measures for pH control were not modelled, such as addition of salts to increase alkalinity after nitrification in the BF.

The model was developed using a system-level approach and it was based on one existing aquaponic system. Further work is necessary to provide the model with more flexibility for the analysis of other systems. Particularly, detailed dynamics could improve the modularity of each component, allowing to change the overall system configuration while maintaining reliability in the simulations. To improve modularity, we suggest to model mixing dynamics in the tanks, particle size distribution effect on solids removal, effects of water quality on fish and plants, and possible reactions outside of the nitrification biofilter.

Finally, our selection for a management strategy was based on the response to 2 parameters. This allows to visualise the presence of local minima. To evaluate multiple parameters, we suggest the use of numerical algorithms for sensitivity analysis and optimisation (up to 5 parameters). This would first require the development of an objective function comprising water quality parameters and resource efficiency.

4. Conclusions

The main challenge in the development of aquaponics consists in balancing the requirements for growth of different species.

We developed a dynamic mathematical model with a system-level approach to understand water and nutrient dynamics, and improve resource efficiency. The model describes the dynamics of an existing aquaponic system with two connected loops based on the INAPRO configuration. Model simulations allowed to identify the operation parameters that have a significant impact on resource efficiency: number of plants and frequency of water exchange from fish to plants.

Sending more water from fish to plants can help reducing water and fertilizer consumption. However, it may also result in excessive concentrations of some nutrients, which may stress fish, plants or both. We developed a management strategy that achieved a balance between resource efficiency and water quality. With this strategy, we demonstrated the possibility to re-size and operate an existing aquaponic system in a way that improves its resource efficiency while maintaining the required water quality conditions.

Based on our simulations, water supply for fish and plant production (263 $L/kg\ fish$ and 22 $L/kg\ tomato$) is similar to commercial RAS and greenhouse hydroponic systems. N, Ca, and Mg supply for plant production (52, 46 and 9 $mg/kg\ tomato$, respectively) was one order of magnitude lower than in commercial systems. P and K supply was similar to current commercial systems.

Funding

This work was done as part of the project INAPRO, with funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 619137.

References

[1] FAO, Aquaculture topics and activities. aquaculture resources (December 2015).
URL http://www.fao.org/fishery/countrysector/naso_netherlands/en

[2] W. M. Lewis, J. H. Yopp, H. L. Schramm Jr, A. M. Brandenburg, Use of hydroponics to maintain quality of recirculated water in a fish culture system, Transactions of the American Fisheries Society 107 (1) (1978) 92–99.

[3] A. Coche, Fish culture in rice fields a world-wide synthesis, Hydrobiologia 30 (1) (1967) 1–44.

[4] A. E. Turcios, J. Papenbrock, Sustainable treatment of aquaculture effluents—what can we learn from the past for the future?, Sustainability 6 (2) (2014) 836–856.

[5] D. C. Love, J. P. Fry, X. Li, E. S. Hill, L. Genello, K. Semmens, R. E. Thompson, Commercial aquaponics production and profitability: Findings from an international survey, Aquaculture 435 (2015) 67–74.

[6] J. Suhl, D. Dannehl, W. Kloas, D. Baganz, S. Jobs, G. Scheibe, U. Schmidt, Advanced aquaponics: Evaluation of intensive tomato production in aquaponics vs. conventional hydroponics, Agricultural Water Management 178 (2016) 335–344.

[7] D. Karimanzira, K. J. Keesman, W. Kloas, D. Baganz, T. Rauschenbach, Dynamic modeling of the inapro aquaponic system, Aquacultural Engineering 75 (2016) 29 – 45. doi:http://dx.doi.org/10.1016/j.aquaeng.2016.10.004.

[8] D. Reyes Lastiri, T. Slinkert, H. J. Cappon, D. Baganz, G. Staaks, K. J. Keesman, Model of an aquaponic system for minimised water, energy and nitrogen requirements, Water Science and Technology 74 (1) (2016) 30–37. doi:10.2166/wst.2016.127.

[9] S. Goddek, C. A. Espinal, B. Delaide, M. H. Jijakli, Z. Schmautz, S. Wuertz, K. J. Keesman, Navigating towards decoupled aquaponic systems: A system dynamics design approach, Water 8 (7).

[10] S. Goddek, K. J. Keesman, The necessity of desalination technology for designing and sizing multi-loop aquaponics systems, Desalination 428 (2018) 76 – 85. doi:https://doi.org/10.1016/j.desal.2017.11.024.

[11] INAPRO, Innovative aquaponics for professional applications. URL http://www.inapro-project.eu/

[12] W. Kloas, R. Groß, D. Baganz, J. Graupner, H. Monsees, U. Schmidt, G. Staaks, J. Suhl, M. Tschirner, B. Wittstock, et al., A new concept for aquaponic systems to improve sustainability, increase productivity, and reduce environmental impacts, Aquaculture Environment Interactions 7 (2) (2015) 179–192.

[13] Analysenbefund zum untersuchungsauftrag nach trinkwasserverordnung vom 21.5.2001, zwva steinhagen - seniorenheim negast. URL http://www.rewa-stralsund.info/fileadmin/Dateien/Dokumente/Wasserqualitaet/steinhagen.pdf

[14] R. Jancke, Personal communication (2016).

[15] M. B. Timmons, J. M. Ebeling, Recirculating aquaculture, 2nd Edition, Coyuga Aqua Ventures, 2010.

[16] J. Suhl, Personal communication (2015).

[17] FAO, Cultured aquatic species information programme. oreochromis niloticus (May 2018). URL http://www.fao.org/fishery/culturedspecies/Oreochromis_niloticus/en#tcNA00EA

[18] A. De Gelder, E. Heuvelink, J. Opdam, Tomato yield in a closed greenhouse and comparison with simulated yields in closed and conventional greenhouses, Acta Horticulturae 2005 (691) (2005) 549–552.

[19] M. Ruijs, Soilless culture in dutch greenhouse tomato.

[20] H. M. Resh, Hydroponic food production: a definitive guidebook for the advanced home gardener and the commercial hydroponic grower, CRC Press, 2016.

[21] A. L. Tuna, C. Kaya, M. Ashraf, H. Altunlu, I. Yokas, B. Yagmur, The effects of calcium sulphate on growth, membrane stability and nutrient uptake of tomato plants grown under salt stress, Environmental and Experimental Botany 59 (2) (2007) 173 – 178. doi:http://dx.doi.org/10.1016/j.envexpbot.2005.12.007.

[22] J. M. Ebeling, B. Vinci, Recirculating aquaculture systems, short course.

[23] J. E. Rakocy, D. S. Bailey, E. S. Thoman, R. C. Shultz, Intensive tank culture of tilapia with a suspended, bacterial-based, treatment process, in: New Dimensions on Farmed Tilapia: Proceedings of the Sixth International Symposium on Tilapia in Aquaculture, 2004, pp. 584–596.

[24] M. Dominguez, A. Takemura, M. Tsuchiya, S. Nakamura, Impact of different environmental factors on the circulating immunoglobulin levels in the nile tilapia, oreochromis niloticus, Aquaculture 241 (1) (2004) 491–500.

[25] D. P. DeLong, T. Losordo, J. Rakocy, Tank culture of tilapia, Southern Regional Aquaculture Center, 2009.

[26] S. A. El-Shafai, F. A. El-Gohary, F. A. Nasr, N. van der Steen, H. J. Gijzen, Chronic ammonia toxicity to duckweed-fed tilapia (oreochromis niloticus), Aquaculture 232 (1) (2004) 117 – 127. doi:https://doi.org/10.1016/S0044-8486(03)00516-7.

[27] Metcalf-Eddy, G. Tchobanoglous, H. D. Stensel, R. Tsuchihashi, F. Burton, Wastewater engineering: treatment and resource recovery, 5th Edition, McGraw-Hill, New York, NY, 2014.

[28] S. J. Cripps, A. Bergheim, Solids management and removal for intensive land-based aquaculture production systems, Aquacultural engineering 22 (1-2) (2000) 33–56.

[29] D. Borgognone, G. Colla, Y. Rouphael, M. Cardarelli, E. Rea, D. Schwarz, Effect of nitrogen form and nutrient solution ph on growth and mineral composition of self-grafted and grafted tomatoes, Scientia horticulturae 149 (2013) 61–69.

[30] A. Komosa, J. Piróg, Z. Weber, B. Markiewicz, Comparison of yield, nutrient solution changes and nutritional status of greenhouse tomato grown in recirculating and non-recirculating nutrient solution systems, Journal of plant nutrition 34 (10) (2011) 1473–1488.

[31] H. R. Roosta, M. Hamidpour, Mineral nutrient content of tomato plants in aquaponic and hydroponic systems: Effect of foliar application of some macro-and micro-nutrients, Journal of plant nutrition 36 (13) (2013) 2070–2083.

[32] M. Zahedifar, A. Ronaghi, A. Moosavi, S. Safarzadeh Shirazi, Influence of nitrogen and salinity levels on the fruit yield and chemical composition of tomato in a hydroponic culture, Journal of plant nutrition 35 (14) (2012) 2211–2221.

[33] E. A. S. Paiva, R. A. Sampaio, H. E. P. Martinez, Composition and quality of tomato fruit cultivated in nutrient solutions containing different calcium concentrations, Journal of Plant Nutrition 21 (12) (1998) 2653–2661.

[34] M. Carvajal, V. Martinez, A. Cerda, Influence of magnesium and salinity on tomato plants grown in hydroponic culture, Journal of plant nutrition 22 (1) (1999) 177–190.

[35] S. M. Shiyab, M. A. Shatnawi, R. A. Shibli, N. G. Al Smeirat, J. Ayad, M. W. Akash, Growth, nutrient acquisition, and physiological responses of hydroponic grown tomato to sodium chloride salt induced stress, Journal of plant nutrition 36 (4) (2013) 665–676.

[36] J. E. Rakocy, M. P. Masser, T. M. Losordo, Recirculating aquaculture tank production systems: aquaponics—integrating fish and plant culture, SRAC publication 454 (2006) 1–16.

[37] H. Yamazaki, S. Kikuchi, T. Hoshina, T. Kimura, Effect of calcium concentration in nutrient solution before and after inoculation with ralstonia solanacearum on resistance of tomato seedlings to bacterial wilt, Soil science and plant nutrition 45 (4) (1999) 1009–1014.

[38] C. Martins, E. H. Eding, M. C. Verdegem, L. T. Heinsbroek, O. Schneider, J.-P. Blancheton, E. R. d'Orbcastel, J. Verreth, New developments in recirculating aquaculture systems in europe: A perspective on environmental sustainability, Aquacultural Engineering 43 (3) (2010) 83–93.

[39] C. Sonneveld, W. Voogt, Plant Nutrition of Greenhouse Crops, Springer. doi:10.1007/978-90-481-2532-6.

Appendices

Plant growth calibration

Calibration was done on the solution of the differential equation ${dm_{veg}}/{dt} = \mu \; m_{veg} \left(1 - {m_{veg}}/{m_{veg,max}}\right)$:

$$m_{veg} = \frac{n_{plants} \; m_{veg,max} \; m_{veg,0} \; e^{\mu(t - t_{0,veg})}}{m_{veg,max} + m_{veg,0} \left(e^{\mu(t - t_{0,veg})} + 1\right)} \tag{2}$$

The function was fitted to the final mass m_veg_{max} obtained in the Abtshagen site.

Fruit growth calibration

Fruit growth was modelled based on a least-squares, second order polynomial regression from data of average fruit harvest collected in the demonstration system in Abtshagen:

$$\begin{aligned} m_{fruit} = n_{plants} \; Y_{fruit} \; \big[& p_{1,fruit} \left(t - t_{0,fruit}\right)^2 \\ & + p_{2,fruit} \left(t - t_{0,fruit}\right) \big] \end{aligned} \tag{3}$$

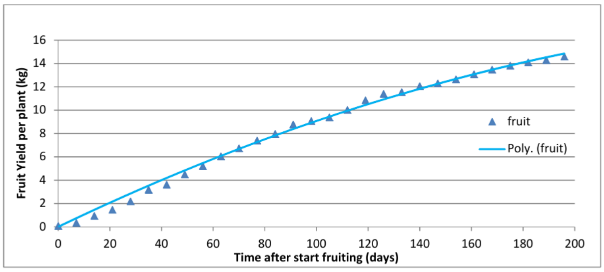

Figure 16: Least squares regression for fruit production to a second order polynomial function. Data from Suhl [16].

Plant water uptake calibration

Water uptake by the plants was modelled based on a least-squares, third order polynomial regression from data of cumulative water uptake collected in the demonstration system in Abtshagen.

$$V_{plants} = n_{plants} Y_{fruit} m_{veg,max} \left[p_{1,w} \left(t - t_{0,veg} \right)^3 + p_{2,w} \left(t - t_{0,veg} \right)^2 + p_{3,w} \left(t - t_{0,veg} \right) \right] \quad (4)$$

which allows to calculate the water uptake for each time-step as $\phi_{v,plants} = V_{w,plants} \left(t + 1 \right) - V_{w,plants} \left(t \right)$.

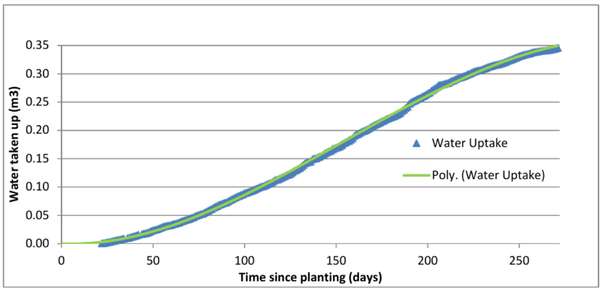

Figure 17: Least squares regression for cumulative water uptake to a third order polynomial function. Data from Suhl [16].

Table 5: Mass balances for the models of each module (unit) in the aquaponic system (Eqn. (1)). Variable names in each module are independent, even if shared between modules.

Module	d/dt	ϕ_{in}	ϕ_{out}
FT	V	$\phi_{v,in} + \phi_{v,fresh}$	$\phi_{v,out} + \phi_{v,harvest} + \phi_{v,fish}$
	m_S	$C_{S,in}\phi_{v,in} + \phi_{S,fish} + C_{S,fresh}\phi_{v,fresh}$	$\left(m_S/V\right)\phi_{v,out} + \left(m_S/V\right)\phi_{v,harvest}$
	m_{TSS}	$C_{TSS,in}\phi_{v,in} + \phi_{TSS,fish}$	$\left(m_{TSS}/V\right)\phi_{v,out} + \left(m_{TSS}/V\right)\phi_{v,harvest}$
ST	V	$\phi_{v,in}$	$\phi_{v,out} + \phi_{v,sludge}$
	m_S	$C_{S,in}\phi_{v,in}$	$\left(m_S/V\right)\phi_{v,out} + \left(m_S/V\right)\phi_{v,sludge}$
	m_{TSS}	$C_{TSS,in}\phi_{v,in} + \phi_{resusp}$	$\left(m_{TSS}/V\right)\phi_{v,out} + \phi_{ret} + \phi_{v,sludge}$
	$m_{TSS,set}$	$\phi_{ret} + \phi_{resusp}$	$m_{TSS,set}\ \phi_{v,sludge}$
PS	V	$\phi_{v,in} + \phi_{v,filt} + \phi_{v,fresh}$	$\phi_{v,out}$
	m_S	$C_{S,in}\phi_{v,in} + C_{S,filt}\phi_{v,filt} + C_{S,fresh}\phi_{v,fresh}$	$\left(m_S/V\right)\phi_{v,out}$
	m_{TSS}	$C_{TSS,in}\phi_{v,in} + C_{TSS,filt}\phi_{v,filt}$	$\left(m_{TSS}/V\right)\phi_{v,out}$
BF	V	$\phi_{v,in} + r_{H_2O}A_{BF}/\rho_{H2O}{}^{\dagger}$	$\phi_{v,out} + \phi_{v,filt}$
	m_S	$C_{S,in}\phi_{v,in} + r_{TAN}A_{BF}{}^{\dagger}$	$\left(m_S/V\right)\phi_{v,out} + \left(m_S/V\right)\phi_{v,filt}$
	m_{TSS}	$C_{TSS,in}\phi_{v,in}$	$\left(m_{TSS}/V\right)\phi_{v,out} + \left(m_{TSS}/V\right)\phi_{v,filt}$
PP	V	$\phi_{v,sludge} + \phi_{v,harvest}$	$\phi_{v,out} + \phi_{v,discharge}$
	m_S	$C_{S,sludge}\phi_{v,sludge} + C_{S,harvest}\phi_{v,harvest}$	$\left(m_S/V\right)\phi_{v,out}$
	m_{TSS}	$+C_{TSS,harvest}\phi_{v,harvest}$	$\left(m_S/V\right)\phi_{v,out} + \phi_{ret}$
MT	V	$\phi_{v,in} + \phi_{v,fresh}$	$\phi_{v,out}$
	m_S	$C_{S,in}\phi_{v,in} + C_{S,fresh}\phi_{v,fresh} + \phi_{fert}$	$\left(m_S/V\right)\phi_{v,out}$
	m_{TSS}	$C_{TSS,in}\phi_{v,in}$	$\left(m_{TSS}/V\right)\phi_{v,out}$
NFT	V	$\phi_{v,in}$	$\phi_{v,plants} + \phi_{v,discharge}$
	m_S	$C_{S,in}\phi_{v,in}$	$\phi_{S,plants} + \left(m_S/V\right)\phi_{v,discharge}$
	m_{TSS}	$C_{TSS,in}\phi_{v,in}$	$\left(m_{TSS}/V\right)\phi_{v,out}$

† We assumed reaction only takes place in the BF. For simplicity, this term is added as an inflow.

Stoichiometric coefficients in Table 7 reflect production and consumption.

Table 6: Auxiliary equations for the mass balances of each module in the aquaponic system (Table 5). Variable names in each module are independent, even if shared between modules.

Module	Auxiliary equations
FT	$\phi_{S,fish} = k_{S,feed}\, k_{S,excretion}\, \phi_{feed}$
	$\phi_{TSS,fish} = k_{TSS,excretion}\, \phi_{feed}$
	$\phi_{feed} = FCR\, \Delta m_{fish}/\Delta t$
	$\phi_{v,fish} = k_{water,fish} \Delta m_{fish}/\Delta t$
	$FCR = FCR_0 + k_{FCR} t$ if t in Δt_{growth} else 0
	$m_{fish} = n_{fish} \left(p_{1,fish} t^2 + p_{2,fish} t + m_{0,fish}\right)$ if t in Δt_{growth} else 0
ST	$\phi_{set} = k_{set}\, m_{TSS}$
	$\phi_{resusp} = k_{resusp}\, m_{TSS,set} \quad if \quad t = t_{clean} \quad else \quad 0$
PS	$\phi_{v,out} = 2\phi_{v,in,RT}$
BF	$r_{H2O} = \xi_{H2O} r_{TAN}$
	$r_{TAN} = k_{TAN}\, C_{TAN,in}$
	$\xi_{H2O} = M_{H2O}/M_N$ (ratio of molecular weights)
	$\phi_{v,out} = \phi_{v,filt} = \phi_{v,in,RT}$
PP	$\phi_{set} = k_{set}\, m_{TSS}$
MT	$\phi_{fert} = (C_{S,required} - C_{S,NFT})\, V_{NFT}/\Delta t$
NFT	$\phi_{v,plants} = V_{plants}(t+1) - V_{plants}(t)$
	$V_{plants} = n_{plants} Y_{fruit} m_{veg,max} \left[p_{1,w} \left(t - t_{0,veg}\right)^3 + p_{2,w} \left(t - t_{0,veg}\right)^2 + p_{3,w} \left(t - t_{0,veg}\right)\right]$
	$\phi_{S,plants} = k_{S,plants} \left(\Delta m_{veg}/\Delta t + \Delta m_{fruit}/\Delta t\right)$
	$dm_{veg}/dt = \mu_{veg} m_{veg} \left(1 - m_{veg}/m_{veg,max}\right)$
	$dm_{fruit}/dt = n_{plants} Y_{fruit} \left[2 p_{1,fruit}(t - t_{0,fruit}) + p_{2,fruit}\right]$

Table 7: Values for the parameters used to model the aquaponic system.

Module	Parameter	Value	Units	Description
FT	V	1.84	m^3	Maximum volume of a fish tank
	$\phi_{v,in}$	3.68	m^3/hr	Recirculating water flowrate
	Δt_{growth}	180	day	Growth period between fish harvests
	$k_{water,fish}$	0.8	kg/kg	Water content in fish mass
	n_{fish}	175	-	Number of fish per tank
	$m_{0,fish}$	0.01	kg	Initial mass of one fish
	$p_{1,fish}$	1.89×10^{-3}	kg/day^2	Estimated parameter for fish growth
	$p_{2,fish}$	6.41×10^{-4}	kg/day	Estimated parameter for fish growth
	FCR_0	0.8	kg/kg	Initial feed conversion ratio (fresh weight fish per dry mass feed)
	$k_{S,feed}$	(0.064, 0.010, 0.003, 0.010, 0.001, 0.002)	kg/kg	Content in feed dry mass of N, P, K, Ca, Mg, Na, respectively
	$k_{S,excretion}$	(0.32, 0, 0.02, 0.47, 0.14, 0.06)	kg/kg	Mass excreted per mass of nutrient eaten: N, P, K, Ca, Mg, Na, respectively
	$k_{TSS,excretion}$	0.25	kg/kg	Mass excreted per mass of feed eaten
ST	V	1.32	m^3	Volume
	k_{set}	0.97	$1/day$	Solids (linear) settling constant
	k_{resusp}	0.97	$1/day$	Solids (linear) resuspension constant (during cleaning only)
PS	V	2.38	m^3	Volume
BF	k_{TAN}	2.18×10^{-3}	$m^3/m^2/day$	(Linear) reaction constant for TAN
	A	1020.4	m^2	Surface area of the biofilter ($V = 2.29m^3$, $a = 445m^2/m^3$)
PP	V	9	m^3	Volume
	k_{set}	1.8	$1/day$	Solids settling constant
MT	V	1.1	m^3	Volume
	$C_{S,required}$	$(151, 37, 234, 128, 24)$	mg/L	Target concentration for plants of soluble nutrients: N, P, K, Ca, Mg, Na, respectively
NFT	V	0.3	m^3	Volume per NFT channel
	n_{plants}	192	-	Total number of plants
	Y_{fruit}	22.72	kg	Fruit yield per plant
	$m_{veg,max}$	2.5	kg	Maximum vegetative mass per plant
	$p_{1,w}$	$-1.46 \times 10-9$	$m^3/kg/day^3$	Estimated parameter, plant water uptake
	$p_{2,w}$	$6.75 \times 10-7$	$m^3/kg/day^2$	Estimated parameter, plant water uptake
	$p_{3,w}$	$-7.25 \times 10-6$	$m^3/kg/day$	Estimated parameter, plant water uptake
	$t_{0,veg}$	28	day	Start time for plant growth, days after 01/Jan
	$t_{end,veg}$	339	day	End time for plant growth, days after 01/Jan
	$k_{S,plants}$	(140, 26, 252, 9.8, 9.7, 5.2) $\times 10^{-5}$	-	Mass fraction of fruits: N, P, K, Ca, Mg, Na, respectively
	μ_{veg}	0.05	$1/day$	Plant (logistic) growth rate
	$p_{1,fruit}$	-9.51×10^{-6}	$1/day^2$	Estimated parameter, fruit growth
	$p_{2,fruit}$	6.49×10^{-3}	$1/day$	Estimated parameter, fruit growth
	$t_{0,fruit}$	104	day	Start time for first harvest, days after 01/Jan
WT	$C_{S,fresh}$	(3.1, 0.04, 0.054, 2.4, 115.0, 11.2, 30.1)	mg/L	Concentrations in fresh water for NO_3, TAN, P, K, Ca, Mg, Na, respectively