Significant factors affecting the economic sustainability of closed backyard aquaponics systems. Part IV: autumn herbs and polyponics

[1]Ulrich Knaus, [2]Samuel Appelbaum, [1]Harry W. Palm

[1] University of Rostock, Faculty of Agricultural and Environmental Sciences, Aquaculture and Sea-Ranching, Justus-von-Liebig-Weg 6, 18059 Rostock, Germany; [2] French Associates Institute for Agriculture and Biotechnology of Drylands, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, Midreshet Ben-Gurion, 8499000, Israel. Corresponding author: U. Knaus, ulrich.knaus@uni-rostock.de

Abstract. Two identical coupled ebb-and-flow gravel substrate aquaponics units (each 3.81 m^3 – domestic backyard) were tested for extensive fish and herb productivity under autumn conditions in northern Germany (Mecklenburg-Western Pomerania). Common carp (*Cyprinus carpio*) were stocked in unit I with 10,033.3±305.5 g (number 226, initial weight 35.0±18.1 g) and Nile tilapia (*Oreochromis niloticus*) in unit II with 10,333.3±757.2 g (number 309, initial weight 26.5±9.9 g) initial biomass and a daily feed input of 200 g or 52.5 g m^{-3} of system water volume (19.9 g feed per kg fish day^{-1} and 2.0% feed for *C. carpio*; 19.4 g feed per kg fish day^{-1} and 1.9% feed for *O. niloticus*). Fish growth parameters were higher in *O. niloticus* (final biomass 19,450.0±50.0 g, SGR 0.91±0.10% d^{-1}, FCR 1.54±0.14) than in *C. carpio* (final biomass 18,000.0±50.0 g, SGR 0.84±0.05% d^{-1}, FCR 1.76±0.07). Mint yield (*Mentha piperita*) was 1.8 times higher (20.7±18.0 g) in the *O. niloticus* unit (II), and basil (*Ocimum basilicum*) yield was slightly higher in combination with *C. carpio* (22.1±17.5 g) than with *O. niloticus* (16.1±13.8 g). Parsley production (*Petroselinum crispum*) was below expectations, but yield was 2.4 times higher combined with *C. carpio* (1.2±1.1 g) than with *O. niloticus* (0.5±0.5 g). The different fish species affected the aquaponics system's stability with higher dissolved oxygen levels, a longer steady state phase and higher nitrate levels in the *C. carpio* unit. This experiment demonstrates a different influence of *C. carpio* and *O. niloticus* on plant growth expressed by the Aquaponic Growth Factor (AGF), which was higher for *O. niloticus* only with mint (0.84) in contrast to *C. carpio* with basil (0.37) and parsley (1.44). The combined use of different fish species in one coupled aquaponics system can compensate for lower growth rates of fish (*C. carpio*) with a better plant growth of basil and parsley with regard to economical gross output. This form of aquaponics production combines polyculture with aquaponics (POLYPONICs) and can increase the overall yield of the system for sustainable production in aquaponics.

Key Words: aquaponics, polyponics, Aquaponic Growth Factor, ebb-and-flow, fish and plant combination, tilapia, carp.

Zusammenfassung. Zwei identische gekoppelte Ebbe und Flut Kies-Substrat Aquaponik-Einheiten (jeweils 3,81 m^3 – „Hinterhofaquaponik“) wurden auf Fisch- und Kräuterproduktivität unter Herbstbedingungen in Norddeutschland (Mecklenburg-Vorpommern) getestet. Karpfen (*Cyprinus carpio*) wurden in Einheit I mit 10.033,3±305,5 g Initialbiomasse gehalten (Anzahl 226 Stück, Initialmasse 35,0±18,1 g) und Nil-Tilapia (*Oreochromis niloticus*) in Einheit II mit 10.333,3±757,2 g (Anzahl 309 Stück, Initialmasse 26,5±9,9 g) und einer täglichen Fütterung von ca. 200 g oder 52,5 g m^{-3} des Systemwasservolumens (19,9 g Futter pro kg Fisch Tag^{-1} und 2,0% Futter für *C. carpio*; 19,4 g Futter pro kg Fisch Tag^{-1} und 1,9% für *O. niloticus*). Die Fischwachstumsparameter waren für *O. niloticus* vergleichbar besser (Endbiomasse 19.450,0±50,0 g, SGR 0,91±0,10% d^{-1}, FCR 1,54±0,14) im Gegensatz zu *C. carpio* (Endbiomasse 18.000,0±50,0 g, SGR 0,84±0,05% d^{-1}, FCR 1,76±0,07). Der Ertrag von Minze (*Mentha piperita*) war 1,8-mal höher (20,7±18,0 g) in Kombination mit *O. niloticus* und der Ertrag von Basilikum (*Ocimum basilicum*) war nur gering höher in der Einheit mit *C. carpio* (22,1±17,5 g) im Vergleich zur kombinierten Haltung mit *O. niloticus* (16,1±13,8 g). Die Petersilienproduktion (*Petroselinum crispum*) war allgemein unter den Erwartungen, der Ertrag war jedoch 2,4-mal höher kombiniert mit *C. carpio* (1,2±1,1 g) im Vergleich zur *O. niloticus* Einheit (0,5±0,5 g). Die unterschiedlichen Fischarten beeinflussten die Systemstabilität der Aquaponiksysteme mit höheren Anteilen an gelöstem Sauerstoff, einer längeren Produktionsphase und höheren Nitratgehalten in der *C. carpio* Einheit. Dieses Experiment zeigt den unterschiedlichen Einfluss von *C. carpio* und *O. niloticus* auf das Pflanzenwachstum anhand des Aquaponischen Wachstums Faktors (AGF), der für *O. niloticus* nur bei Minze (0,84) größer war im Vergleich zur *C. carpio* Einheit mit jedoch höheren Werten für Basilikum (0,37) und Petersilie (1,44). Die kombinierte Verwendung verschiedener Fischarten in einem gekoppelten aquaponischen System kann niedrigere Wachstumsraten (*C. carpio*) durch ein besseres Pflanzenwachstum von Basilikum und Petersilie hinsichtlich der ökonomischen Gesamtleistung kompensieren. Diese Form der aquaponischen Produktion verbindet Polykultur mit Aquaponik (Polyponik) und kann den Gesamtertrag des Systems für eine nachhaltige Produktion in der Aquaponik steigern.

Schlüsselworte: Aquaponik, Polyponik, Aquaponischer Wachstums Faktor, Ebbe-und-Flut, Fisch und Pflanze Kombination, *Tilapia*, *Karpfen*.

Introduction. Culinary herbs may be a good choice of cultivated plant species in aquaponics (Rakocy 2012), owing to their fast growth potential and market acceptance. For extensive fish production in aquaponics, plants with a low nutrient demand are important, including basil (*Ocimum basilicum*), mint (*Mentha* spp.) and parsley (*Petroselinum crispum*) (Somerville et al 2014). Basil was reported to be the most cultivated plant by commercial aquaponics producers (Love et al 2015) and has repeatedly been used as a model plant (Rakocy et al 2003; Palm et al 2014b; Appelbaum & Kotzen 2016; Knaus & Palm 2017a). For diversification of plant production, other crop species were also tested. E.g. mint (*Mentha* spp.) was used by Shete et al (2016) combined with common carp (*Cyprinus carpio*) with the best yield at a moderate water flow rate of 500 L h^{-1} (12 m^3 day^{-1}), and was used effectively as biological filters by Moya et al (2016) with Nile tilapia (*Oreochromis niloticus*). Parsley is a new plant in aquaponics and can be cultivated in nutrient film technique (NFT) systems (Somerville et al 2014). Kotzen & Appelbaum (2010) reported a good yield of parsley in fresh and brackish water environments combined with Nile tilapia red strain (*Oreochromis niloticus* x *O. aureus*).

For an improved market presence as well as a reduction in the producer risk, different fish species should be used in aquaponics. The diversification of aquaponics production is in its initial stages and should also extend to the use of different plant species. Previous investigations showed differences in plant growth with the use of different fish species. Significantly better plant growth was observed in lettuce (*Lactuca sativa*) and cucumber fruits (*Cucumis sativus*) combined with *O. niloticus* than with *Clarias gariepinus* (Palm et al 2014b). The same effect was found with the cultivation of basil and parsley by Knaus & Palm (2017a) during wintertime. The fresh weight of basil and parsley was 2.5 and 2.0 times greater combined with *O. niloticus*, respectively. In the same aquaponics system, under optimal spring-summer conditions, tomato yield (*Lycopersicon lycopersicum*) was better with *O. niloticus*, whereas the combination with *C. carpio* showed a slightly better cucumber yield (Knaus & Palm 2017b). These investigations suggested differences in plant growth under aquaponics production with distinct selections of fish species. For a better crop yield, the combination of different fish species in one aquaponics system seems to be advantageous. This constitutes the integration of polyculture into aquaponics, described as POLYPONICs by Knaus & Palm (2017b).

In the present study, we compared the growth of basil (*Ocimum basilicum*), mint (*Mentha piperita*) and parsley (*Petroselinum crispum*) in combination with common carp (*Cyprinus carpio*) and Nile tilapia (*Oreochromis niloticus*) in two identical coupled gravel aquaponics units in the northern hemisphere (Germany, Mecklenburg-Western Pomerania). For the late summer production from August until October 2014, we discuss the effects on aquaponics system stability and performance. This was another experiment in a domestic backyard aquaponics system with two identical aquaponics units (see Palm et al 2014a, b; Palm et al 2015; Knaus & Palm 2017a, b), which investigates the influence of different fish species selection on plant growth, allowing conclusions to be made on the diversification of extensive aquaponics.

Material and Method

Experimental design and data collection. Two identical coupled warmwater ebb-and-flow aquaponics units (unit I, unit II) with gravel hydroponics in each system were constructed in a temperate glasshouse for the production of *C. carpio* in unit I and *O. niloticus* in unit II (Figure 1). Each unit contained a fibreglass fish tank (3.90 m^3, 2.05 x 2.05 x 0.93 m, AquaLogistik, Möhnesee-Wippringsen, Germany) filled with approx.

1,800.00 L, a clarifier (1.00 m^3, Intermediate Bulk Container: IBC) filled with nearly 800 L, five plant boxes (5 x 1.00 m x 2.00 m x 0.30 m) filled with 0.20 m water height at the maximum flood status (120 L per box) and a sump (0.61 m^3). The total amount of water in each unit was 3.81 m^3. The component ratio of the fish tank (1,800 L), clarifier (800 L), hydroponic unit (600 L) and the sump (610 L) was 2.25:1.00:0.75:0.76 (fish tank:hydroponic unit = 3.00). The water was moved with a single pump (UP 150, 9,000 L h^{-1}, 160 W, Seerose Pumpentechnik Turkowski GmbH, Germany) with a single flow-type heater (3.00 KW) and an automatic temperature control at 25°C. Air was provided by a linear forcer pump LA-120A (Nitto Kohki GmbH, Germany) 118 W with the same number (4) of air outlets in the fish tanks of unit I and II.

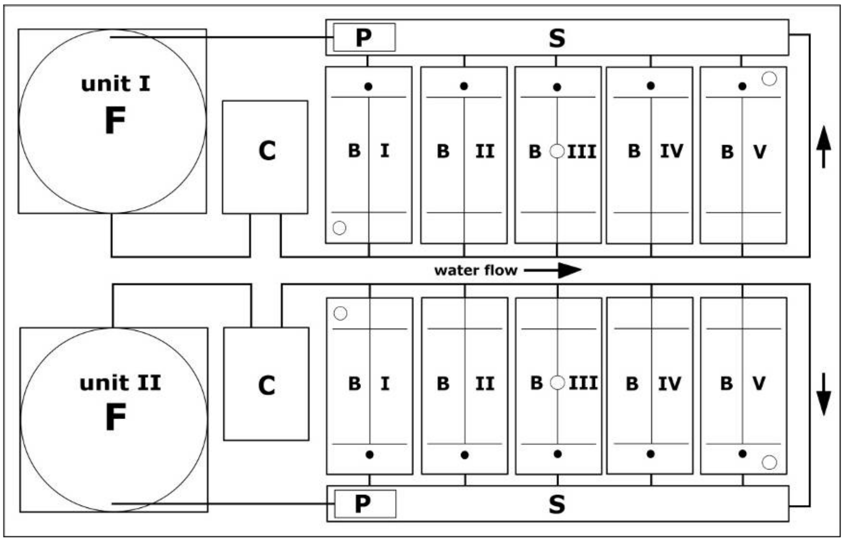

Figure 1. Schematic overview of the two identical coupled aquaponics units (unit I with *C. carpio*, unit II with *O. niloticus*) at the University of Rostock (F: fish tank; C: clarifier; B I–V: hydroponic subsystems with ebb-and-flow gravel media bed; S: sump, P: pump).

Each plant box was laid out with polyethylene foil (1.50 mm). The water inflow of each plant box was adjusted to 2 L min^{-1}. The outflow of each plant box was constructed as a bell siphon with a combination of three polyvinyl chloride (PVC) tubes and auto-mechanical water out-movement initiating the ebb status under water pressure after Bruno et al (2011). Each plant box was filled with a gravel substrate (400 kg), totalling 2,000 kg gravel media in each hydroponics unit (grain size of 16-32 mm, coarse gravel, pebble). The plant boxes were equipped with an overhead PVC irrigation system, filled with nutrient water from the main water pipe with 14 water outlets, six at the lower horizontal pipe, two at the communicating vertical pipe and six at the upper horizontal pipe. Three plant boxes (I, III, V) of each unit were equipped with three rows of PVC test tubes for collecting physical and chemical water parameters. The test tubes were situated at the front of the box, the middle and the end with n = 3 in each row. Each plant box was equipped with two neon light tubes (Gro-Lux 58 W/T8, wavelength 350-700 nm, Osram Sylvania, USA) for illumination at night 0.70 m above the gravel substrate.

Fish and plant species. The experiment was carried out from 08.08.2014 until 16.10.2014 (70 days). All fish were stocked in the two aquaponics units at the same time. Mixed sex *C. carpio*, originating from a local fish farm “Fischzucht Grambek” (Germany), were stocked in the fish tank of unit I (N = 226). An all-male population of *O. niloticus*, originating from Kirschauer Aquakulturen (Germany), were stocked in the fish tank of unit II (N = 309). For growth evaluation, fish were weighed every 14 days. Fish were fed with the tilapia feed Aller Aqua 37/10 float (crude protein: 37%; crude fat: 10%; NFE [nitrogen-free extractives, e.g. carbohydrates]: 36.7%; ash: 6.9%; and fibre: 4.4%, Emsland-Aller Aqua GmbH) over 24 h with automatic feeders (Aquacultur GmbH, Germany) and a daily feed input of 200 g or 52.5 g m^{-3} of system water volume. Based on fish initial biomass, the feed used for *C. carpio* was 19.9 g feed per kg fish day^{-1} and

2.0% feed per day fish biomass. For *O. niloticus*, the amount was 19.4 g feed per kg fish day^{-1} and 1.9% per fish biomass.

Three weeks before the experiment, three different plant species (basil [Kiepenkerl, BALDUR Garten GmbH, Germany]; mint [Kiepenkerl, BALDUR Garten GmbH, Germany]); and parsley [Mooskrause 2/Smaragd, Sperli GmbH, Everswinkel, Germany] were seeded in rockwool cubes and planted consecutively in the plant boxes at the beginning of the study with N = 12 per species in each box (36 plants per box, 180 plants per unit) with a distance of 25 cm.

Physical and chemical parameters. The physical water parameters were measured every day (five days a week) in the fish tank, the clarifier and the sump of each unit, and twice every week inside the PVC test tubes of the plant boxes. The physical parameters of temperature [°C], oxygen [mg L^{-1}], oxygen [%], conductivity [µS cm^{-1}], pH and redox potential [mv] were measured with a HQ40D multimeter (HACH LANGE GmbH, Germany). The chemical water parameters of NH_3-N [mg L^{-1}], NO_2-N [mg L^{-1}], NO_3-N [mg L^{-1}] and phosphorus [mg L^{-1}] were analysed twice a week with a spectral photometer DR-3900 (Hach Lange GmbH, Germany). Light was measured twice a week above the PVC test tubes inside the plant boxes with a Digital Lux Meter (Dr. Meter DM-LX1330B), and Photosynthetically Active Radiation light [µmol m^{-2} s^{-1}] (PAR) was measured with a Solar Electric Quantum Meter (Spectrum Technologies, Inc, USA).

Statistical and mathematical analyses. Significant differences ($p < 0.05$) were noted by creating the means of fish growth parameters and water parameters of the fish tank, the clarifier, the sump and the PVC test tubes inside the plant boxes of units I and II. If the Shapiro-Wilk test showed normality of the data set, a *t*-test was used; otherwise the Mann-Whitney test identified differences. All data were analysed using Microsoft Excel (2010) and the SPSS 22.0 statistical software package (IBM).

The Aquaponic Growth Factor (AGF) was calculated according to Knaus & Palm (2017a), representing the deviation from the best possible growth (DFIGF), calculated as a quotient (with DFIGF ideal = 1.00 if the final biomass values of both fish and plants [g] were equal) of the maximum achieved fish and plant yield (biomass in g) during an experiment, under comparison of two identically built aquaponic units or identical experimental conditions. The AGF is described as the absolute value of a number (|x|) and compares the biomass development directly. For calculation of the AGF, the following formula was used:

$$\mathrm{AGF}_{fish}\ factor\ \mathrm{I} = |((\text{fish I final biomass of unit I}) \times (\text{fish II final biomass of unit II})^{-1}) - \mathrm{DFIGF}|,$$

$$\mathrm{AGF}_{fish}\ factor\ \mathrm{II} = |((\text{fish II final biomass of unit II}) \times (\text{fish I final biomass of unit I})^{-1}) - \mathrm{DFIGF}|,$$

$$\mathrm{AGF}_{plant}\ factor\ \mathrm{I} = |((\text{plant biomass of unit I}) \times (\text{plant biomass of unit II})^{-1}) - \mathrm{DFIGF}|,$$

$$\mathrm{AGF}_{plant}\ factor\ \mathrm{II} = |((\text{plant biomass of unit II}) \times (\text{plant biomass of unit I})^{-1}) - \mathrm{DFIGF}|,$$

with DFIGF = 1.00,

$$\text{AGF quotient} = |\mathrm{AGF}_{\text{plant growth fish species I}} \times \mathrm{AGF}_{\text{plant growth fish species II}}{}^{-1}|.$$

The specific growth rate (SGR) was calculated by:

$$\mathrm{SGR}\ (\%\ d^{-1}) = (\ln W_t - \ln W_0) \times t^{-1} \times 100,$$

with W_t = final biomass, W_0 = initial biomass, t = time in days.

The feed conversion ratio (FCR) was calculated by:

$$\mathrm{FCR} = \text{fish feed quantity (g)} \times \text{weight gain (g)}^{-1}.$$

Results

Fish and plants. The initial weight and length of *C. carpio* were significantly higher (35.0±18.1 g; 12.9±2.4 cm) than of *O. niloticus* (26.5±9.9 g; 11.9±1.4 cm); however, the initial stocked biomass values of both fish species were comparable (Table 1, Figure 2). *C. carpio* showed better growth in final weight (84.0±27.1 g), whereas *O. niloticus* showed a better feed conversion ratio (1.54±0.14) and specific growth rate (0.91±0.10% d^{-1}). Final biomass values in *C. carpio* and *O. niloticus* were significantly different (18,000.0±50.0 g; 19,450.0±50.0 g) in contrast to comparable biomass weight gains with 7,966.7 g (± 340.3) in *C. carpio* and 9,116.7 g (±765.4) in *O. niloticus* at the end of the experiment.

Table 1

Fish growth parameters in means (±SD) between the two aquaponics units with *C. carpio* (unit I) and *O. niloticus* (unit II)

Parameter	*Unit I - C. carpio*	*Unit II - O. niloticus*
Initial weight [g]	35.0±18.1[a]	26.5±9.9[b]
Final weight [g]	84.0±27.1[a]	66.5±22.7[b]
Initial length [cm]	12.9±2.4[a]	11.9±1.4[b]
Final length [cm]	16.9±1.9[a]	14.9±1.7[b]
Initial biomass [g]	10,033.3±305.5[a]	10,333.3±757.2[a]
Final biomass [g]	18,000.0±50.0[b]	19,450.0±50.0[a]
Initial stocking density [kg m^{-3}]	5.6±0.2[a]	5.7±0.4[a]
Final stocking density [kg m^{-3}]	10.0±0.0[b]	10.8±0.0[a]
Biomass weight gain [g]	7,966.7±340.3[a]	9,116.7±765.4[a]
SGR [% d^{-1}]	0.84±0.05[a]	0.91±0.10[a]
FCR	1.76±0.07[a]	1.54±0.14[a]
Initial number of fish [no.]	226	309
Mortality [%]	19.0	1.9

Different letters represent significantly different groups ($p < 0.05$).

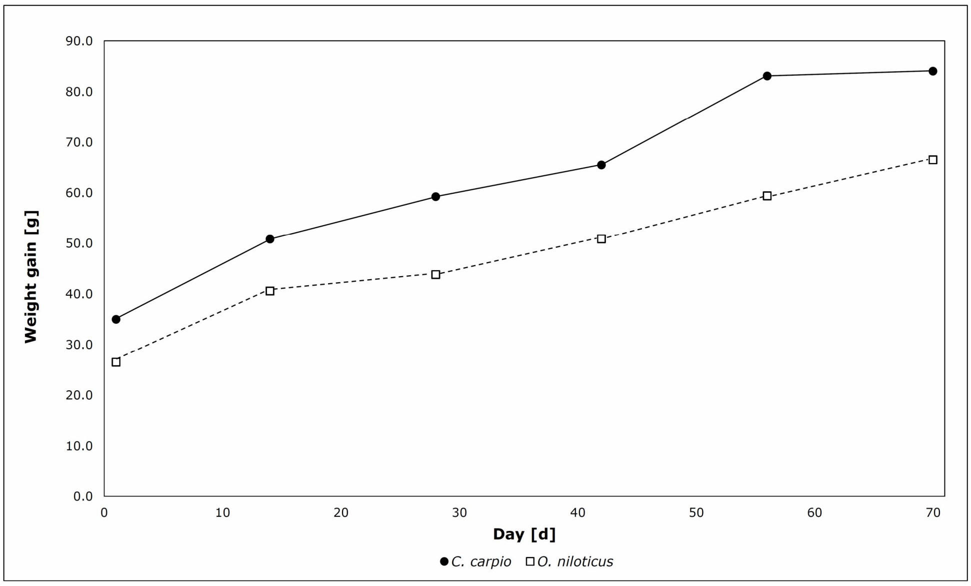

Figure 2. Weight gain of *C. carpio* (unit I) and *O. niloticus* (unit II) over 70 consecutive days.

The fresh biomass yield of mint was higher in the *O. niloticus* aquaponics unit (20.7±18.0 g), in contrast to parsley which showed a higher fresh biomass yield in the *C. carpio* unit (1.2±1.1 g, Table 2, Figure 3).

Table 2

Plant growth parameters of basil, mint and parsley in means (±SD) between the two aquaponics units with *C. carpio* (unit I) and *O. niloticus* (unit II)

Parameter	*Unit I - C. carpio*	*Unit II - O. niloticus*
Basil fresh biomass [g]	22.1 ± 17.5^{a}	16.1 ± 13.8^{a}
Basil length [cm]	30.7 ± 17.2^{a}	22.9 ± 13.4^{a}
Mint fresh biomass [g]	11.3 ± 8.3^{b}	20.7 ± 18.0^{a}
Mint length [cm]	59.2 ± 15.1^{a}	63.2 ± 13.9^{a}
Parsley fresh biomass [g]	1.2 ± 1.1^{a}	0.5 ± 0.5^{b}
Parsley length [cm]	11.4 ± 4.1^{a}	7.6 ± 3.5^{b}

Different letters represent significantly different groups ($p < 0.05$).

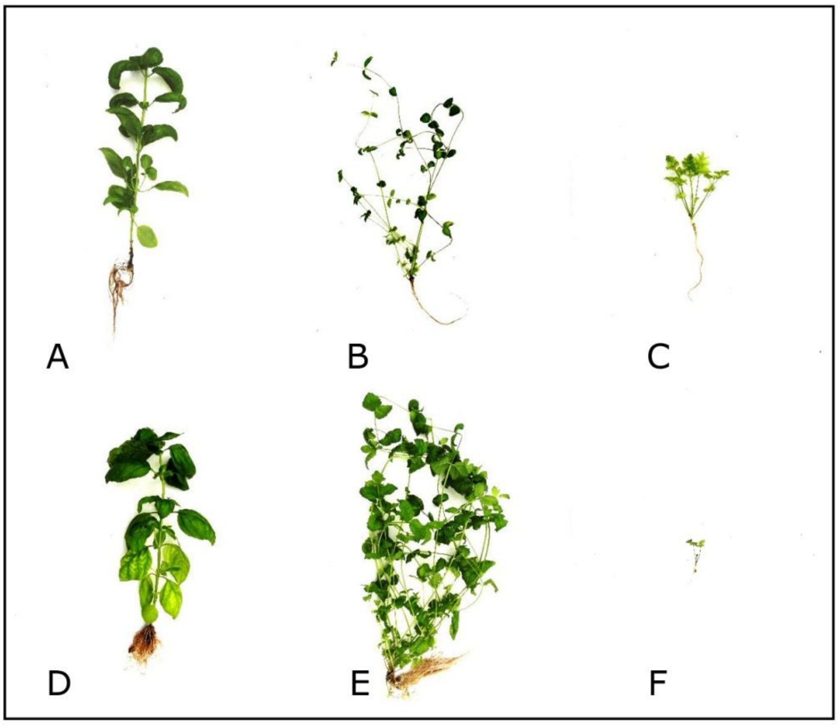

Figure 3. Plant yield examples of the two coupled aquaponics units of the University of Rostock (unit I with *C. carpio*: A: basil, B: mint, C: parsley; unit II with *O. niloticus*: D: basil, E: mint, F: parsley).

Physicochemical parameters. Differences in chemo-physical water parameters were found in the *C. carpio* unit with higher values in oxygen (6.9±0.7 mg L^{-1}, Figure 4), saturation (84.1±9.6%), electrical conductivity (718.9±71.9 µS cm^{-1}) and nitrate (23.30±9.85 mg L^{-1}, Figure 5) compared to the *O. niloticus* unit (6.2±1.1 mg L^{-1}; 76.2±11.8%; 618.4±50.0 µS cm^{-1}; 15.57±8.39 mg L^{-1}, respectively, Table 3). In contrast, light intensity was slightly higher in the *O. niloticus* unit (17,891.5±10,273.0 lx) than in the *C. carpio* system (12,888.7±2,959.9 lx). In the hydroponics units, higher values were found in the *C. carpio* aquaponics unit in oxygen saturation (79.6±5.8%), electrical conductivity (712.9±76.0 µS cm^{-1}) and nitrate (26.84±8.55 mg L^{-1}) compared to the *O. niloticus* unit (72.9±12.1%; 623.4±57.1 µS cm^{-1}; 15.90±8.41 mg L^{-1}, respectively). Phosphate evolutions were more similar between unit I (*C. carpio*) and unit II (*O. niloticus*, Figure 6) during the experiment and showed no significant differences in means of global parameters at the relatively low level of approximately 5 mg L^{-1} (Table 3).

Table 3

Global chemo-physical water parameters in means (±SD) of the whole systems and the hydroponics units between the two aquaponics units with *C. carpio* (unit I) and *O. niloticus* (unit II) over the experimental time of 70 days

Parameter	*Unit I - C. carpio*	*Unit II - O. niloticus*
Global parameters of aquaponic unit I and II[1]		
Dissolved oxygen [mg L^{-1}]	6.9±0.7^a	6.2±1.1^b
Oxygen saturation [%]	84.1±9.6^a	76.2±11.8^b
Temperature [°C]	25.9±2.3^a	26.3±2.1^a
pH	7.9±0.3^a	8.0±0.3^a
Electric conductivity [µS cm^{-1}]	718.9±71.9^a	618.4±50.0^b
Redox potential [mv]	133.2±32.8^a	132.2±31.8^a
NH_3-N [mg L^{-1}]	0.13±0.10^a	0.21±0.16^a
Nitrite [mg L^{-1}]	0.07±0.09^a	0.08±0.07^a
Nitrate [mg L^{-1}]	23.30±9.85^a	15.57±8.39^b
Phosphate [mg L^{-1}]	5.17±2.38^a	4.93±2.23^a
Natural light intensity [lx]	12,888.7±2,959.9^b	17,891.5±10,273.0^a
Natural PAR [µmol m^{-2}s^{-1}]	111.2±36.9^b	146.6±35.4^a
Light intensity at night [lx]	582.9±229.8^a	622.0±210.2^a
PAR at night [µmol m^{-2}s^{-1}]	11.2±6.0^a	11.6±5.7^a
Parameters of the hydroponic units (unit I and II)[2]		
Dissolved oxygen [mg L^{-1}]	6.6^a±0.6	6.1^a±1.1
Oxygen saturation [%]	79.6^a±5.8	72.9^b±12.1
Temperature [°C]	25.0^a±2.0	25.2^a±1.4
pH	7.9^a±0.3	8.0^a±0.3
Electric conductivity [µS cm^{-1}]	712.9^a±76.0	623.4^b±57.1
Redox potential [mv]	133.1^a±41.9	130.1^a±41.8
NH_3-N [mg L^{-1}]	0.13^a±0.09	0.16^a±0.08
Nitrite [mg L^{-1}]	0.12^a±0.11	0.07^a±0.07
Nitrate [mg L^{-1}]	26.84^a±8.55	15.90^b±8.41
Phosphate [mg L^{-1}]	4.91^a±2.09	4.30^a±1.69

[1] Means calculated from values of the fish tank, clarifier and sump; [2] Hydroponic means calculated from values of three different pvc test tubes from plant box 1, plant box 3 and plant box 5. Different letters represent significantly different groups ($p < 0.05$).

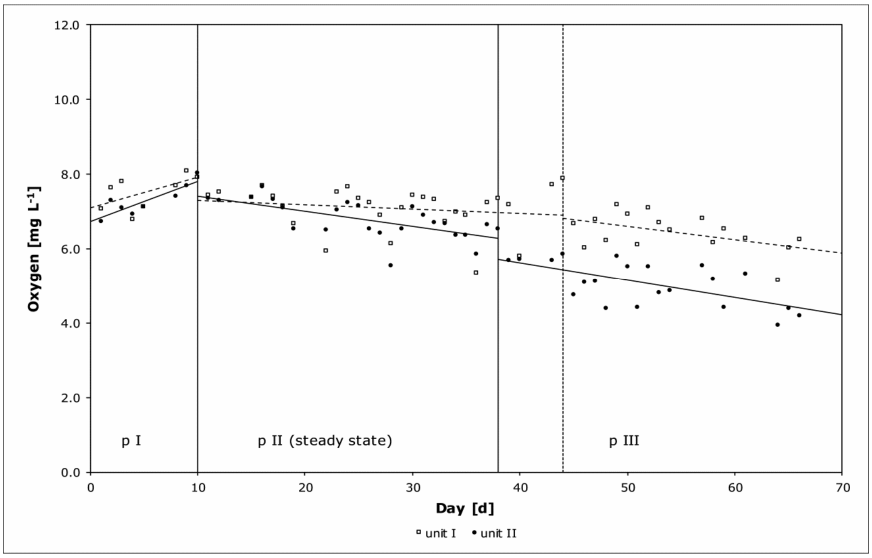

Figure 4. Oxygen distribution [mg L^{-1}] of the aquaponics unit I (*C. carpio*) and unit II (*O. niloticus*) during the three phases (pI: run-in phase, days 1-10; pII: steady state, unit I days 10-44, unit II days 10-38; pIII: accumulation phase, unit I days 44-70, unit II days 38-70) over 70 consecutive days.

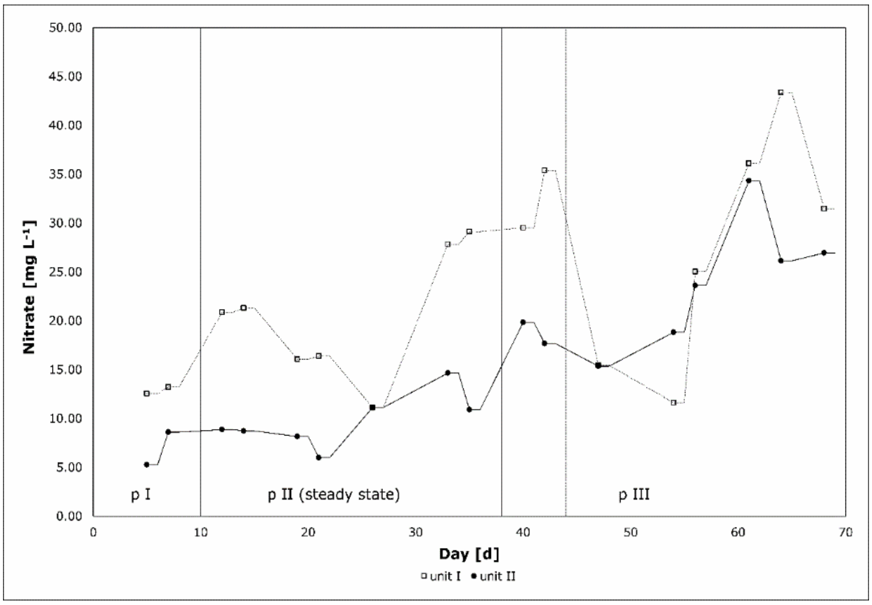

Figure 5. Distribution of nitrate [mg L^{-1}] of the aquaponics unit I (*C. carpio*) and unit II (*O. niloticus*) during the three phases (p I: run-in phase, pII: steady state, pIII: accumulation phase) over 70 consecutive days.

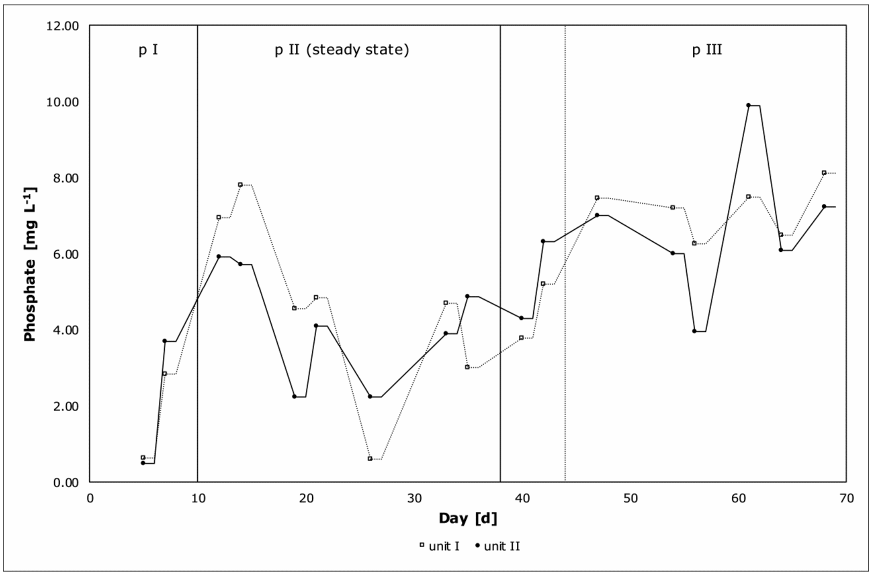

Figure 6. Distribution of phosphate [mg L^{-1}] of the aquaponics unit I (*C. carpio*) and unit II (*O. niloticus*) during the three phases (pI: run-in phase, pII: steady state, pIII: accumulation phase) over 70 consecutive days.

Discussion

Fish and plant growth. The growth of the two fish species, *C. carpio* and *O. niloticus*, showed generally good results although the daily feed input was limited. The growth of *O. niloticus* in biomass weight gain was slightly better than that of *C. carpio*. With nearly the same initial biomass of both fish species and a 26.9% higher initial fish number in the *O. niloticus* unit (39.6% difference in the final fish number), the biomass weight gain was 12.6% higher in the *O. niloticus* aquaponics unit. This agrees with the findings of Knaus & Palm (2017b) who described a better growth potential of *O. niloticus* under the same experimental aquaponics system design during summer, but with a contrasting fish stocking of the tanks and units and an only moderate feed acceptance of *C. carpio*. In the present study, the specific growth rate and feed conversion ratio were slightly better in *O. niloticus* than in *C. carpio*, which might be an indication of better feed digestibility and acceptance by *O. niloticus* with the use of a tilapia-designed feed (Aller Aqua 37/10 float).

The observed feed conversion ratio of *O. niloticus* (1.54) was better than that of the older fish described by Rakocy (2012) for *O. niloticus* (1.7) and red tilapia (1.8), and a little lower than that reported by Knaus & Palm (2017b) with nearly the same initial weight and the same aquaponics experimental design. However, for *C. carpio*, a much lower feed conversion ratio was reported by Knaus & Palm (2017b), strongly influenced by a lower feed acceptance of the tilapia-designed floating feed with reduced growth at the beginning of the experiment. Generally, the specific growth rate in *C. carpio* was reduced and was more comparable to the younger fish described by Hussain et al (2015) in *C. carpio* var. 'koi' (5.9 g) with 0.83% d^{-1} and with 0.70% d^{-1} by Nuwansi et al (2016). Differences in fish growth parameters could have been affected by the slightly lower water temperature compared to the spring-summer cultivation (Knaus & Palm 2017b), the acceptance of the feed (custom-made for *O. niloticus*) and the restricted feeding regime of 200 g d^{-1}, as well the genetically fixed growth potential of the fish species used. Results from the present experiment suggest that although the growth of *C. carpio* was better than observed by Knaus & Palm (2017b), *O. niloticus* had still a higher growth potential also under autumn conditions observed by the overall value in total higher biomass weight gain.

The physico-chemical water parameters did not negatively influenced the growth of either fish species, and they were in their optimal ranges. As described for *C. carpio* by Somerville et al (2014), optimal temperature was considered to be from 25-30°C, total ammonia nitrogen and nitrite < 1 mg L^{-1} and dissolved oxygen concentration > 4 mg L^{-1}. For *O. niloticus*, Somerville et al (2014) recommended a marginally higher optimal water temperature between 27 and 30°C and total ammonia nitrogen < 2 mg L^{-1}, nitrite < 1 mg L^{-1} and dissolved oxygen concentration > 4 mg L^{-1}. The lowest dissolved oxygen level with a very short duration was found at the end of the experiment on day 64 in unit II with 3.93 mg L^{-1}, however, followed again by higher oxygen values.

Plant growth was generally below expectations (strongly influenced by a high alkaline pH) and differed between the fish species and aquaponics units. Previous experiments showed a more reduced yield of basil during wintertime with 8.8 g $plant^{-1}$ and a very low stocking density of 18 plants per unit (Palm et al 2014b) or 0.30 g fresh weight with an increasing daily feed input (Knaus & Palm 2017a), making comparisons difficult. However, light intensity and water temperature values were slightly higher in the present experiment, explaining the better harvest of culinary herbs. Generally, the height of basil was at the minimum level (30 cm) in the *C. carpio* unit as described by Somerville et al (2014) in contrast to a lower height in the *O. niloticus* system. Growth of mint was moderate with a significantly better yield in the *O. niloticus* aquaponics unit. Kotzen & Appelbaum (2010) described good plant development of *Mentha* sp. in freshwater and brackish water aquaponics, although with a slightly greater plant height of 70 cm and some chlorosis as also observed in the present study in freshwater. The growth of parsley was generally low and showed a more than two times higher yield in the *C. carpio* aquaponics unit. Parsley is known to be easy to grow with low nutrient requirements (Somerville et al 2014). However, our experiments did not reach the described yields, even under a higher nutrient supply with a low comparable mean yield in the *O. niloticus* unit at 0.55 g (Knaus & Palm 2017a).

Influence of fish species choice. Fish species choice had a significant influence on the aquaponics system stability and on plant growth. The use of *C. carpio* in aquaponics unit I extended the steady state or production phase by means of stable dissolved oxygen concentrations for six days. This effect was also described by Knaus & Palm (2017b) with a different stocking with *O. niloticus* in tank I and *C. carpio* in tank II, in the same aquaponics experimental setup. The steady state conditions of phase II were seven days longer in the *C. carpio* unit than in the *O. niloticus* aquaponics unit. This effect basically originates from the differences in the specific activity (feeding, locomotion) and metabolic rate between the two fish species with consumption of dissolved oxygen. The feeding activity and movement of *C. carpio* was generally lower compared with *O. niloticus*, which has a higher oxygen demand based on a longer feeding activity period and feeding time. This resulted in a reduced dissolved oxygen concentration in the *O. niloticus* aquaponics unit with clear evidence of the impact of fish species onto water parameters and thus on system stability. Oxygen was used by Palm et al (2014a) and Knaus & Palm (2017a) as an indicator for coupled aquaponics system stability. During a continuous increase of the daily feed input, three phases of production were recognized: *i*) "run-in phase", *ii*) "exponential phase", also described as "steady state phase" by Knaus & Palm (2017a) and *iii*) "accumulation phase" (Knaus & Palm 2016). The abovementioned production phases are obviously present in media bed gravel aquaponics and greatly alter the operational intervals through the choice of fish species. In our experiments, which were carried out under nearly the same aquaponics system design, we found the shortest steady state and lowest water oxygen levels with *O. niloticus* (Knaus & Palm 2017a) followed by *C. carpio* (Knaus & Palm 2017b) and *C. gariepinus* (Knaus & Palm 2017a).

The oxygen contents of the process water also affected the availability of plant nutrients and significantly influenced the dynamics of nitrate via bacterial nitrification. Aquaponics with *C. carpio* generally showed a higher content of nitrate (≈ 1.5 more compared to *O. niloticus*), apparently supported by a higher proportion of dissolved oxygen in the process water as a result of lower oxygen consumption by the fish. In unit I with *C. carpio* and higher oxygen content, the higher proportion of nitrate was available to be utilized by the plants and a higher growth of parsley and by trend (average) in basil could be observed. However, nitrate level should have been higher in unit II with *O. niloticus* due to the better feed utilization and growth potential of tilapia (FCR) as well as the increasing tendency of NH_3-N. In global parameters, nitrite was similar in both units and nitrate 1.5 higher in unit I, suggesting that bacterial oxidation of nitrite to nitrate was more efficient in unit I with *C. carpio* and reduced in unit II with *O. niloticus*. The main effect of nitrate reduction in unit II with *O. niloticus* is still unclear because different factors worked together simultaneously. *O. niloticus* had a better growth potential with a higher body protein assimilation and obviously restrictive NH_3-N excretion. Mint production was 1.8 times higher with tilapia and consequently reduced significantly the amount of nitrate in the recirculation water by higher plant nutrient retention capacity. A lower oxygen content in unit II caused by higher fish locomotion of *O. niloticus* reduced the effectiveness of bacterial nitrate oxidation. Consequently, the accumulation phase started earlier, indicating accumulation of solids inside the system and supporting anoxic conditions, followed by an increased denitrification processes. Interestingly, mint grew very well under these conditions and, in contrast to basil and parsley, mint appears suitable for combination with *O. niloticus* in backyard aquaponics.

Phosphate was low and not significant between both aquaponic units. Fish stocking was extensive and the feed input was low with 200 g per day, resulting in low phosphate supply. The distribution of phosphate was similar and followed the same trend in both units with a sigmoid curve expression. During the run-in phase, the phosphate contents first increased. The P concentration reduced through plant growth during the steady state, until P accumulated during the accumulation phase. This sluggish effect of phosphorus with a sigmoid concentration curve as an indication of plant P nutrient retention was also described by Palm et al (2015) under the same experimental setup and different plant species choice.

Fish species affected electrical conductivity (EC) with significantly lower values in the *O. niloticus* unit, the general values as well as inside the hydroponic units. The EC was associated with the lower levels of nitrate in the *O. niloticus* unit, and consequently with the lower oxygen level inside the system. An earlier investigation by Knaus & Palm (2017b) had insignificant EC values by using *O. niloticus* in unit I and *C. carpio* in unit II under the same experimental design and spring-summer conditions (production of cucumber, tomatoes and lettuce). Thus the EC followed the opposite relationship, and was slightly higher in the *O. niloticus* unit during all three production phases in Knaus & Palm (2017b). We suggest that in the present study, nitrate reduction in the *O. niloticus* unit was influenced by a better feed conversion with a more restrictive NH_3-N excretion as the basis of bacterial nitrate production compared with Knaus & Palm (2017b), and a

1.8 times higher yield of mint. The higher reduction of nitrate also increased water quality inside the process water.

Influence of the culture period. For sustainable production in coupled aquaponics, the production time has a great influence. Steady state conditions in the present study were strongly influenced by the reduced nutrient retention capacity of the plants by lower natural light under late summer to autumn conditions and differed among the plant species in growth, described in nutrient total system removal for aubergine, tomatoes and cucumber by Graber & Junge (2009). The length of the steady state phase strongly demonstrates this influence as it was described by Palm et al (2014a) and Knaus & Palm (2017a, b). The natural light intensity and temperature are the most important factors at this northern locality, influencing the performance of aquaponics plant production. In the northern hemisphere, the change in light intensity and temperature leads to an adjustment of the steady state phase as demonstrated in the present study. An earlier study with a stable daily feed input showed the longest "steady state" interval during spring-summer conditions reaching over 45 days in the *O. niloticus* aquaponics unit (Knaus & Palm 2017b). In contrast, in the present study, the steady state during late summer and autumn also for *O. niloticus* was reduced to only 28 days. During wintertime, the steady state had the shortest time interval of only 12 days under a continuously increasing feeding regime (Knaus & Palm 2017a). Due to these findings, commercial producers have to select plants whose maximum performance occurs in the northern hemisphere during spring and summer. For this purpose, fast-growing plants such as culinary herbs or medicinal plants are most suitable. When the nutrient retention capacity decreases with season, artificial light can be used or the plant selection must change to low- light intensity and cold-adapted varieties.

Combined biomass production and polyponics. The combined biomass production (Aquaponic Growth Factor, AGF) of the present experiment clearly showed the better growth of basil and parsley in combination with *C. carpio* (Figure 7), although the biomass development of the fish species was nearly comparable. It is evident that *O. niloticus* and *C. carpio* have different effects on plant growth. An earlier experiment confirmed this assumption, with the growth of cucumber being better in combination with *C. carpio* in contrast to the better growth of tomatoes in combination with *O. niloticus* (Knaus & Palm 2017b). This is surprising since the natural diets of *O. niloticus* and *C. carpio* appear to resemble each other in contrast to more piscivorous fish species. Comparison of the more omnivorous-herbivorous *O. niloticus* (Lim & Webster 2006) with the more omnivorous-piscivorous *C. gariepinus* showed, in contrast, a higher plant biomass production in combination of *O. niloticus* and basil with a very high difference of 60% in fresh weight (AGF quotient $|1.50_{\text{basil-}\mathit{O.niloticus}} \text{ x } -0.60^{-1}_{\text{basil-}\mathit{C.gariepinus}}| = 2.50$; Knaus & Palm 2017a). In this study, the difference in basil growth was lower with 27.2% in fresh weight combined with *O. niloticus*, although with a higher plant growth combined with *C. carpio* (AGF quotient $|0.37_{\text{basil-}\mathit{C.carpio}} \text{ x } -0.27^{-1}_{\text{basil-}\mathit{O.niloticus}}| = 1.37$, Figure 7). This suggests that the digestive physiology of *C. carpio* and *O. niloticus* are more similar and the production of *C. carpio* causes a higher growth effect on basil compared to *O. niloticus*. In contrast, mint production was higher in the present study with *O. niloticus*, with a difference of 45.4% in fresh mint weight compared with *C. carpio*.

The difference in plant yield can be considered higher between different fish feeding guilds (herbivore to piscivore, *O. niloticus* to *C. gariepinus*), compared to more closely related feeding guilds (herbivore to omnivore, *O. niloticus* to *C. carpio*). *O. niloticus* was described as generally omnivorous but with a strong tendency to herbivory (Lim & Webster 2006). *C. gariepinus* seems to be, in general, omnivorous (de Kimpe & Micha 1974) or a bottom omnivorous fish (Gosse 1963 in de Kimpe & Micha 1974), but with an ontogenetic shift to a more piscivorous behaviour with a weight of 7–8 g (De Graaf et al 1996) or earlier with cannibalistic (piscivorous) behaviour at 8–80 mm length as described in Hecht & Appelbaum (1988). *C. carpio* was described as omnivorous and can feed 50% on natural food and 50% on supplementary food, e.g. cereal grain (Horváth et al 1992). Thus, the digestion physiology appears to be more similar between

O. niloticus and *C. carpio* compared with *C. gariepinus*, with considerable effects on plant growth.

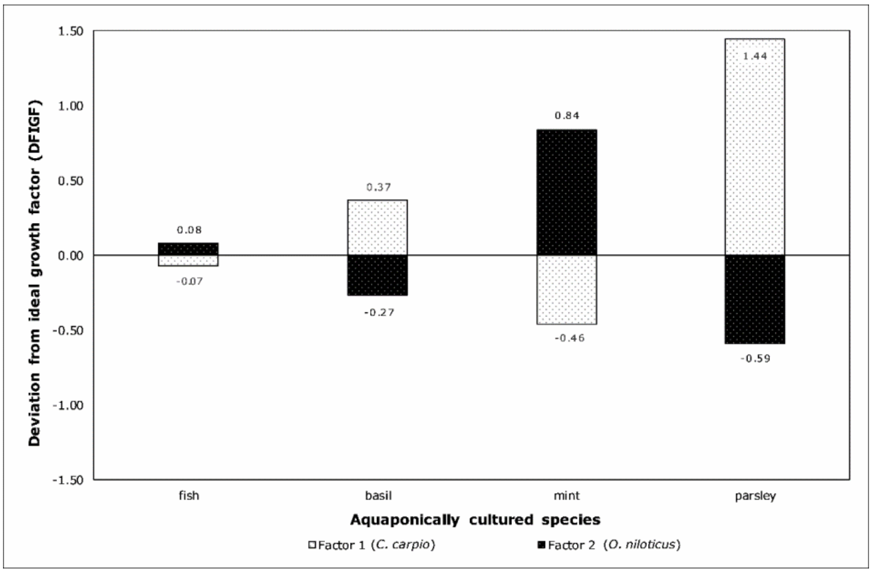

Figure 7. Aquaponic Growth Factor (AGF) as growth differences of aquaponics-cultivated species marked as the deviation from the ideal growth factor (DFIGF) in the relation of the final biomasses in fish (Factor I: *C. carpio*, Factor II: *O. niloticus*) to the final biomasses of the associated herbs (basil, mint, parsley) in two identical aquaponics units.

Plant yield is dependent on the specific digestive physiology of the fish species. Therefore, for sustainable aquaponics production under coupled conditions, it seems advantageous to compensate for the negative aspects of one fish species (for example, low fish growth, high plant growth, *O. niloticus*) with positive aspects of another fish species (high fish growth, low plant growth, *C. gariepinus*) as described by Knaus & Palm (2017a). This compensation maximizes the yield of the entire system, has an effect on system stability in terms to extend the steady phase, and stabilises aquaponics production for the market (risk diversification by using several species). This process of diversification is used in aquaculture, leading to the use of several fish species in one system (polyculture). Combined with aquaponics production techniques, this has been termed as POLYPONICs (polyculture + aquaponics, Knaus & Palm 2017b). Table 4 demonstrates the by far best plant growth in combination with *O. niloticus* in all previous experiments in contrast to *C. gariepinus* with the exception of the better growth of basil and parsley in combination with *C. carpio* of the present study. In contrast, plant growth in combination with *C. gariepinus* is widely reduced. Thus, the preliminary best plant growth results have the order *O. niloticus* > *C. carpio* > *C. gariepinus*, with the fish growth order *C. gariepinus* > *O. niloticus* > *C. carpio*. However, deviations were found, which were mainly based on the different cultivation periods between the experiments (winter, spring, summer, autumn) and certain plant species. Therefore, in future experiments, adjustments to environmental factors such as light and temperature should be made in order to achieve a better comparison of the possible yields and these results should be tested in a triplicate experimental design with at least three species of fish.

Table 4

High growth, low growth, AGF (Aquaponic Growth Factor), AGF quotient ($AGF_{plant\ growth\ fish\ species\ I} \times AGF_{plant\ growth\ fish\ species\ II}^{-1}$) and yield differences [%] of cultivated crops between produced fish species (*O. niloticus*, *C. gariepinus*, *C. carpio*) of previous experiments in coupled aquaponics

Plant species	*High growth*	*AGF |x|*		*Low growth*	*AGF |x|*	*AGF quotient |x|*	*Yield difference [%]*	*Reference*
Basil	*O. niloticus*^{1}	1.50	>	*C. gariepinus*	0.60	2.50	60.00	Knaus & Palm (2017a)
	C. carpio^1	0.37	>	*O. niloticus*	0.27	1.37	27.20	Present study
	O. niloticus^2	0.35	>	*C. gariepinus*	0.26	1.35	25.82	Palm et al (2014b)
Tomato	*O. niloticus*^{3}	1.12	>	*C. carpio*	0.53	2.11	52.76	Knaus & Palm (2017b)
	O. niloticus^2	0.08	>	*C. gariepinus*	0.07	1.14	7.10	Palm et al (2014b)
Cucumber	*O. niloticus*^{2}	0.18	>	*C. gariepinus*	0.16	1.13	15.50	Palm et al (2014b)
	C. carpio^3	0.14	>	*O. niloticus*	0.12	1.17	12.02	Knaus & Palm (2017b)
Lettuce	*O. niloticus*^{2}	0.93	>	*C. gariepinus*	0.48	1.94	48.31	Palm et al (2014b)
Parsley	*C. carpio*^{1}	1.44	>	*O. niloticus*	0.59	2.44	58.33	Present study
	O. niloticus^1	1.04	>	*C. gariepinus*	0.51	2.04	50.91	Knaus & Palm (2017a)
Mint	*O. niloticus*^{1}	0.84	>	*C. carpio*	0.46	1.83	45.40	Present study

^{1} = fresh weight [g]; ^{2} = plant gross biomass [g]; ^{3} = fresh biomass per plant (g plant^{-1}).

General aspects. In order to achieve sustainable production with modern aquaponics, main factors are system design, feed design, fish welfare, and parasite and pathogen control (Figure 8, Palm et al 2014a). Under coupled backyard aquaponics conditions (Palm et al 2018), we demonstrate that the different fish species *O. niloticus*, *C. carpio* and *C. gariepinus* alter plant growth and result in different fish yields. For this reason, the multiple species use of fish or other aquatic organisms (e.g. crayfish, shrimp, mussels) can optimize output of backyard aquaponics. POLYPONICs in the sense of Knaus & Palm (2017b) seem to be of high relevance for these domestic aquaponics in order to achieve the best possible results. On the other hand it challenges the farmer because he requires knowledge on more than single species in the aquatic animal as well as the plant units. Further investigations are needed to identify the relevant stocking densities of the respective fish species under coupled aquaponics conditions to optimise the best possible yield.

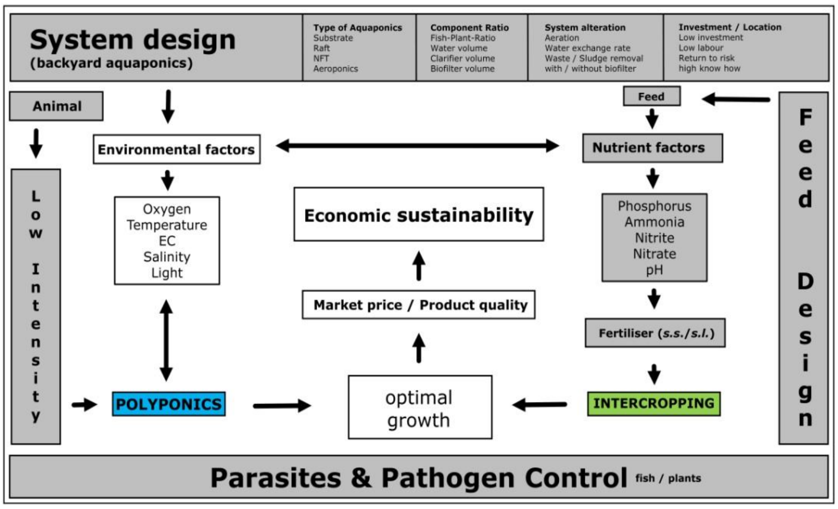

Figure 8. Principles of backyard aquaponics with POLYPONICS and INTERCROPPING (altered from Palm et al (2014a) and Palm et al (2018) with possible fertilisation of aquaponics *s.s.*/*s.l.*).

Similar to polyponics on the aquaculture side, "intercropping" (Rakocy 2012) combines different plant species with different growth properties within the same aquaponics (*s.s*, *s.l.*) subsystem (Palm et al 2018). To increase sustainable crop production, leafy crops and fruit crops can be combined in a minimum production area. Such pairs of aquaponics plants are tomato and lettuce, tomato and parsley, cucumber and lettuce, or strawberry and lettuce (Puteri Edaroyati et al 2017). It was also shown that the combined intercropped production of lettuce and red chicory, *Cichorium intybus* in a pangasius (*Pangasianodon hypophthalmus*) aquaponics system can affect plant growth. Intercropping with red chicory influenced plant biochemical body composition with an increase in lettuce sugar content, a decrease in lettuce caffeic acid content and a change in the bitter taste compounds (Maucieri et al 2017). Therefore, the intercropping cultivation principle must be taken into consideration under backyard aquaponics and is similar to the polyponics principle on the cropping side (Figure 8).

Conclusions. The present study describes the production of two different fish species (*C. carpio*, *O. niloticus*) under late summer to autumn conditions in combination with basil (*Ocimum basilicum*), mint (*Mentha piperita*), and parsley (*Petroselinum crispum*) in two identical coupled domestic backyard aquaponics units. The different fish species had an influence on the system stability of the system. In the *C. carpio* unit, generally higher oxygen values were obtained, which, in turn, extended the production phase (steady state of the system) and simultaneously shortened the accumulation phase. The proportion of nitrate in the process water was increased in combination with *C. carpio*. The growth of *O. niloticus* was slightly higher than *C. carpio*, but only a higher yield of mint was found in the *O. niloticus* system, in contrast to the higher yields of parsley and by trend (average) of basil in the *C. carpio* unit. These results demonstrate the different plant yields in the production of different fish species under extensive coupled aquaponics conditions. Comparison of the new results with previous experiments shows the following preliminary potential of fish growth: *C. gariepinus* > *O. niloticus* > *C. carpio*, and the resulting impact on plant growth: *O. niloticus* > *C. carpio* > *C. gariepinus*. Balancing this relationship between fish and plant growth inevitably leads to the use of several fish species (POLYPONICS) in smaller sized (domestic) extensive aquaponics. The relevance of these results for future system designs of extensive coupled aquaponics must be studied in future.

Acknowledgements. We thank the Ministry of Agriculture, Environment and Consumer Protection of Mecklenburg-Western Pomerania (Germany) for supporting research in aquaponics fish and plant production and EIP-AGRI operational groups for supporting research in aquaponic fish and plant production (‘Aquaponik in MV’, BNRZD: 13 903 000 0103;WM-EIP-0007-15). This project was funded through the pilot project “FishGlassHouse: Innovationsinitiative zur ressourceneffizienten Nahrungsmittel-produktion in MV” (European Fisheries Fund-EFF, grant number: VI-560/730-32616-2013/025). We acknowledge financial support by Deutsche Forschungsgemeinschaft and Universität Rostock within the funding programme Open Access Publishing.

References

Appelbaum S., Kotzen B., 2016 Further investigations of aquaponics using brackish water resources of the Negev desert. Ecocycles 2(2):26-35.

Bruno R., Chen W., Cottle P., Lai V., Loc H., Delson N., 2011 Aquaponics ebb and flow mechanisms ECOLIFE foundation. MAE 156B: Fundamental Principles of Mechanical Design II. University of California, 85 pp.

De Graaf G., Galemoni F., Banzoussi B., 1996 Recruitment control of Nile tilapia, *Oreochromis niloticus*, by the African catfish, *Clarias gariepinus* (Burchell 1822), and the African snakehead, *Ophiocephalus obscuris*. I. A biological analysis. Aquaculture 146(1):85-100.

De Kimpe P., Micha J. C., 1974 First guidelines for the culture of *Clarias lazera* in Central Africa. Aquaculture 4:227-248.

Gosse J. P., 1963 Le milieu aquatique et l'écologie des poissons dans la région de Yangambi. Tervuren: Musée Royal de l Afrique Centrale (MRAC), Annales in-8°, Sciences zoologiques, n°116, pp. 113-270, 10 pl.

Graber A., Junge R., 2009 Aquaponic systems: nutrient recycling from fish wastewater by vegetable production. Desalination 246(1-3):147-156.

Hecht T., Appelbaum S., 1988 Observations on intraspecific aggression and coeval sibling cannibalism by larval and juvenile *Clarias gariepinus* (Clariidae: Pisces) under controlled conditions. Journal of Zoology 214(1):21-44.

Horváth L., Tamás G., Seagrave C., 1992 Carp and pond fish culture including Chinese herbivorous species, pike, tench, zander, wels catfish and goldfish. Fishing News Books Ltd., 170 pp.

Hussain T., Verma A. K., Tiwari V. K., Prakash C., Rathore G., Shete A. P., Saharan N., 2015 Effect of water flow rates on growth of *Cyprinus carpio* var. koi (*Cyprinus carpio* L., 1758) and spinach plant in aquaponic system. Aquaculture International 23(1):369-384.

Knaus U., Palm H. W., 2016 A new method to assess the steady state conditions of a coupled small-scale ebb-and-flood aquaponic system. Aquaculture Europe Edinburgh, UK, 2016, meeting abstract. EAS Oostende Belgium.

Knaus U., Palm H. W., 2017a Effects of fish biology on ebb and flow aquaponical cultured herbs in northern Germany (Mecklenburg Western Pomerania). Aquaculture 466: 51-63.

Knaus U., Palm H. W., 2017b Effects of the fish species choice on vegetables in aquaponics under spring-summer conditions in northern Germany (Mecklenburg Western Pomerania). Aquaculture 473:62-73.

Kotzen B., Appelbaum S., 2010 An investigation of aquaponics using brackish water resources in the Negev Desert. Journal of Applied Aquaculture 22(4):297-320.

Lim C., Webster C. D., 2006 Tilapia: biology, culture, and nutrition. The Haworth Press, New York, 678 pp.

Love D. C., Fry J. P., Li X., Hill E. S., Genello L., Semmens K., Thompson R. E., 2015 Commercial aquaponics production and profitability: findings from an international survey. Aquaculture 435:67-74.

Maucieri C., Nicoletto C., Schmautz Z., Sambo P., Komives T., Borin M., Junge R., 2017 Vegetable intercropping in a small-scale aquaponic system. Agronomy 7(4):63.

Moya E. A., Angel Sahagún C. A., Mendoza Carrillo J. M., Albertos Alpuche P. J., Álvarez-González C. A., Martínez-Yáñez R., 2016 Herbaceous plants as part of biological filter for aquaponics system. Aquaculture Research 47(6):1716-1726.

Nuwansi K. K. T., Verma A. K., Prakash C., Tiwari V. K., Chandrakant M. H., Shete A. P., Prabhath G. P. W. A., 2016 Effect of water flow rate on polyculture of koi carp (*Cyprinus carpio* var. koi) and goldfish (*Carassius auratus*) with water spinach (*Ipomoea aquatica*) in recirculating aquaponic system. Aquaculture International 24(1):385-393.

Palm H. W., Seidemann R., Wehofsky S., Knaus U., 2014 Significant factors affecting the economic sustainability of closed aquaponic systems. Part I: system design, chemo-physical parameters and general aspects. AACL 7(1):20-32.

Palm H. W., Bissa K., Knaus U., 2014 Significant factors affecting the economic sustainability of closed aquaponic systems. Part II: fish and plant growth. AACL Bioflux 7(3):162-175.

Palm H. W., Nievel M., Knaus U., 2015 Significant factors affecting the economic sustainability of closed aquaponic systems. Part III: plant units. AACL Bioflux 8(1):89-106.

Palm H. W., Knaus U., Appelbaum S., Goddek S., Strauch S. M., Vermeulen T., Jijakli M. H., Kotzen B., 2018 Towards commercial aquaponics: a review of systems, designs, scales and nomenclature. Aquaculture International 26(3):813-842.

Puteri Edaroyati M. W., Siti Aishah H., Al-Tawaha A. M., 2017 Requirements for inserting intercropping in aquaponics system for sustainability in agricultural production system. Agronomy Research 15(5):2048-2067.

Rakocy J. E., Shultz R. C., Bailey D. S., Thoman E. S., 2003 Aquaponic production of tilapia and basil: comparing a batch and staggered cropping system. Acta Horticulturae 648:63-69.

Rakocy J. E., 2012 Chapter 14: Aquaponics - integrating fish and plant culture. In: Aquaculture production systems. Tidwell J. H. (ed), Wiley-Blackwell, Oxford, UK, pp. 344-386.

Shete A. P., Verma A. K., Chadha N. K., Prakash C., Peter R. M., Ahmad I., Nuwansi K. K. T., 2016 Optimization of hydraulic loading rate in aquaponic system with common carp (*Cyprinus carpio*) and mint (*Mentha arvensis*). Aquacultural Engineering 72: 53-57.

Somerville C., Cohen M., Pantanella E., Stankus A., Lovatelli A., 2014 Small-scale aquaponic food production. Integrated fish and plant farming. FAO Fisheries and Aquaculture Technical Paper No. 589, FAO, Rome, 262 pp.

*** Microsoft, 2010 Microsoft Excel [computer software]. Redmond, Washington: Microsoft.

*** SPSS Inc., 2013 Statistic Software Package, Chicago, IL, USA.

Received: 20 August 2018. Accepted: 29 October 2018. Published online: 18 November 2018.

Authors:
Ulrich Knaus, University of Rostock, Faculty of Agricultural and Environmental Sciences, Aquaculture and Sea-Ranching, Justus-von-Liebig-Weg 6, D-18059 Rostock, Germany, e-mail: ulrich.knaus@uni-rostock.de
Samuel Appelbaum, French Associates Institute for Agriculture and Biotechnology of Drylands, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, Midreshet Ben-Gurion, 8499000, Israel, e-mail: sappl@bgu.ac.il
H. W. Palm, University of Rostock, Faculty of Agricultural and Environmental Sciences, Aquaculture and Sea-Ranching, Justus-von-Liebig-Weg 6, D-18059 Rostock, Germany, e-mail: harry.palm@uni-rostock.de

How to cite this article:
Knaus U., Appelbaum S., Palm H. W., 2018 Significant factors affecting the economic sustainability of closed backyard aquaponics systems. Part IV: autumn herbs and polyponics. AACL Bioflux 11(6):1760-1775.