Optimal hydroponic growth of *Brassica oleracea* at low nitrogen concentrations using a novel pH-based control strategy

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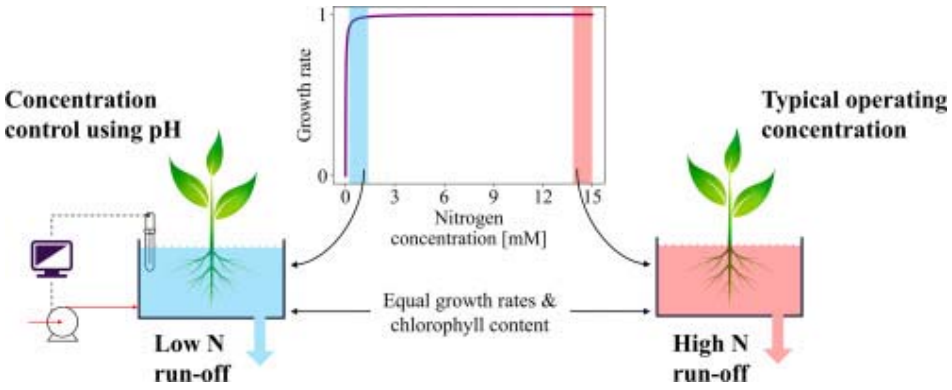
Highlights

- Nitrogen spillage from soilless agriculture harms the environment.
- Nitrogen concentration control at lower levels is key.
- *Brassica oleracea* exhibits a near constant proton-to-nitrate uptake ratio.
- Nitrate concentration is controlled using pH as the sole measurement.
- Optimal hydroponic growth is achieved at nitrate concentrations 100 times lower.

Abstract

Aquatic nitrogen pollution from conventional agriculture contributes severely to the degradation of numerous ecosystems and is considered one of the main contributors to earth's alarming rate of biodiversity loss. Soilless agriculture, in contrast to conventional agriculture, has the advantage of discharge control since the nutrient solution is contained. However, periodic replacement of the nutrient solution is dictated by inert build-up over time resulting from transpiration. As the spent solution is usually discharged, the nutrient concentrations are proportional to the load of nutrient spillage to the environment. This study investigates a novel pH-based control strategy to minimise the nitrate concentration while maintaining optimal plant growth and nutrition. Experiments were performed where the nitrate concentration was controlled at 11 mM (representing standard protocol), 1 mM, 0.5 mM, and 0.1 mM. This was accomplished by controlling the pH with a mixture of HNO_3 and $NaNO_3$. A molar ratio of 3:2 (HNO_3:$NaNO_3$) resulted in relatively stable nitrate profiles with slow depletion of nitrate in solution, owing to a near-constant ratio between proton dosing required for pH homoeostasis and nitrate absorption. Small manual corrections were made for the 1 mM and 0.5 mM runs, accounting for 8% of the total nitrate absorbed. For the 0.1 mM run, instead of manual correction, an automatic nitrate addition strategy was incorporated, in which nitrate extinction was inferred from a reduction in the rate of change of pH. Zero reduction in plant growth rate and leaf chlorophyll content was detected when comparing the 11 mM run with the other runs, indicating optimal hydroponic performance. A novel nitrate control algorithm is presented that uses pH measurement as the sole input. The experimental results and the control algorithm provide encouraging alternatives for reducing nitrogen spillage from soilless agriculture.

Graphical abstract



Keywords: Proton to nitrate ratio; Nitrate concentration control; Nitrogen spillage; Soilless agriculture

Abbreviations

D_R	dosing rate of the acid-nitrate solution used for pH control (B1 in Fig. 2).	mmol-NO_3 day^{-1}
FW	plant fresh mass.	g
n	number of sample points.	#
RDR	relative dosing rate $= \frac{\ln(D_{R,t}) - \ln(D_{R,t+\Delta t})}{\Delta t}$	day^{-1}
RGR	relative growth rate $= \frac{\ln(FW_t) - \ln(FW_{t+\Delta t})}{\Delta t}$	day^{-1}
t	time.	day
α	proton-to-nitrate ratio in the acid-nitrate dosing solution used for pH control (B1 in Fig. 2)	mol mol^{-1}
η	ratio of "proton dosing required for pH homoeostasis" to "nitrate absorbed by the plant"	mol mol^{-1}
∇pH	absolute rate of change of pH with respect to time $\left(\frac{\Delta pH}{\Delta t}\right)$	pH day^{-1}
σ	standard deviation	

1. Introduction

Nitrogen recycling between the atmosphere, biosphere and hydrosphere is intimately connected to all living creatures on earth. Proteins and nucleic acids contain a significant fraction of nitrogen and hence nitrogen is key to life on our planet. Prior to the invention of the Haber-Bosch process, all nitrogen transfer from the atmosphere to the biosphere (nitrogen fixation) was facilitated by prokaryotes, which tightly regulated the influx of bio-available nitrogen (ammonia and nitrates) into the soil (Miles et al., 1992). This changed drastically with the advent of synthetic nitrogen fertilizer, which is produced from atmospheric nitrogen via fossil-fuel combustion. The input of synthetic nitrogen powered the green revolution and contributed directly to the explosion of the human population in the previous century (Erisman et al., 2008). However, this interference with the natural nitrogen cycle had a major influence on Earth's native ecosystems. The resulting environmental impacts range from eutrophication and air pollution to biodiversity loss, climate change and stratospheric ozone depletion (Camargo and Alonso, 2006; Kanter et al., 2020).

Soilless agriculture, such as hydroponics, entails the growth of food crops without the use of soil. In these systems, plant roots are immersed in a liquid solution that contains all the

nutrients required for growth. Hydroponics claims several advantages over conventional agriculture, such as lower water consumption and freedom from soil-borne diseases and pests (Seungjun and Jiyoung, 2015). In particular, the nutrient solution is physically contained and thus nitrogen spillage can be controlled (Kumar and Cho, 2014; Rufi-Salis et al., 2020; Seungjun and Jiyoung, 2015). However, the nutrient solution quickly accumulates salinity and toxic substances due to transpiration (Silberbush and Ben-Asher, 2001). Infinite recycling is thus not possible, and periodic replacement of the nutrient solution is required (Kumar and Cho, 2014). Typically, the spent solution is dumped despite having high nutrient concentrations (Prystay and Lo, 2001). As a result, the release of nitrogen to the environment is intensified (del Amor and Porras, 2009; Kumar and Cho, 2014; Prystay and Lo, 2001). The hydroponic industry is growing rapidly worldwide, especially for producing vegetable greens in a changing world where human nutrition has become topical (Mathias, 2014; Miller et al., 2020). It is imperative that the hydroponic sector does not repeat the mistakes made in the conventional agricultural sector (Castellar et al., 2019; Chen et al., 2008; Delgado, 2002; Eickhout et al., 2006; Kanter et al., 2020). Accordingly, this study aims at reducing nitrogen spillage from hydroponic systems into the environment.

Typical nutrient solutions contain from 12 mM to 15 mM nitrogen (Arnon and Hoagland, 1940; Cooper, 1988; Hewitt, 1996; Steiner, 1984), which is roughly two orders of magnitude higher than the limiting concentration at which symptoms of nitrogen deficiency manifest (Hellgren and Ingestad, 1996; Li et al., 2015; Kuzyakov and Xu, 2013; Le Deunff et al., 2019; Wang and Shen, 2012). As plants consume nitrogen quickly, these high concentrations safeguard against nitrogen depletion and hence deficiency. However, when the nutrient solution is discharged, much more nitrogen is spilled than necessary. Nitrogen concentrations in the discharge solution have been reported in the range of 15 mM to 21 mM (Gagnon et al., 2010; Park et al., 2008; Saxena and Bassi, 2013) which accounts for approximately half of the applied nitrogen (Grewal et al., 2011). The total amount of nitrogen lost is estimated at approximately 1 ton ha^{-1} $year^{-1}$ (del Amor and Porras, 2009).

Numerous authors agree that the disposal of hydroponic wastewater to the environment is a serious issue and that regulations should be put in place to reduce nitrogen release into the environment. Several studies propose a wastewater treatment process after the hydroponic unit (Castellar et al., 2019; Gagnon et al., 2010; Hosseinzadeh et al., 2017; Park et al., 2008; Prystay and Lo, 2001; Rufi-Salis et al., 2020; Saxena and Bassi, 2013). These include separation processes such as filtration or precipitation of nutrients. Others involve the bio-conversion of nutrients such as denitrification units or constructed wetlands. Alternatively, many efforts have been successful at controlling the nitrogen concentration at lower levels during operation, primarily using ion-selective-electrodes (Cho et al., 2018; Kim et al., 2013), resulting in proportionally lower nitrogen discharge. Unfortunately, this strategy is expensive and poses problems such as signal drift and reduced accuracy over time (Bugbee, 2004; Christie, 2014). Other efforts have made use of the electrical conductivity of the nutrient solution to control the total nutrient concentration (Christie, 2014; Domingues et al., 2012). Although cheap and easily implemented, as individual nutrient concentrations are not measured, this approach can lead to nutrient imbalances. Furthermore, the measurement signal is mostly induced by calcium, magnesium and sulphate remaining in solution (Bugbee, 2004; Lenord Melvix and Sridevi, 2014). So rather than risk nitrogen deficiency, excessive nitrogen is still employed (Goins et al., 2004).

This study endeavoured to use pH as the sole input to control the nitrate concentration at lower levels. As pH control is standard protocol in most hydroponic systems, the aim was to

develop a nitrate-control methodology that does not require any additional measurement apparatus or process units. The objectives were to operate at sequentially lower nitrate concentrations down to the lowest possible nitrate concentration at which plant growth and nutrition are conserved.

When nitrate is supplied as the sole nitrogen source, the pH rises, and acid dosing is required for pH homoeostasis. This can be attributed to the release of OH^- ions and the absorption of H^+ ions upon nitrate assimilation (Dijkshoorn, 1962). The theoretical ratio of 1 OH^- ion released per nitrate ion assimilated is typically not reflected in the solution pH since numerous other uptake and exudation effects (such as carboxylic acid exudation) cause pH changes (Dijkshoorn, 1962; Imsande, 1986; Smith and Raven, 1979). The premise of this study is that there may be a relationship between nitrate absorption and the change in pH of solution during crop growth. Given an established relationship, the nitrate absorption rate could be inferred from the change in pH of solution. Nitrate concentration control can then be achieved by feeding nitrate at the same rate. This paper thoroughly investigates the above notion and suggests additional control schemes to compensate automatically for errors in the predicted rates.

2. Experimental

2.1. Overview

To control the nitrate concentration using pH measurements, a relationship between nitrate uptake and the change in pH of solution had to be established. To accomplish this, run 1 was performed under standard hydroponic conditions (detail given in Section 2.2). Nitrate absorption was measured via analysis of liquid samples and the pH was measured online and simultaneously controlled at a set-point by automatic HCl dosing. Analysis of the results yielded a functional relationship between the pH characteristics of the plants (specifically the HCl dosing rates) and nitrate absorbed during growth. Subsequently, a nitrate feed strategy was developed, which feeds nitrate at the same rate at which the plants absorb nitrate, thus achieving nitrate concentration control. This strategy was investigated in runs 2 to 4, in which the nitrate concentration was controlled at various levels. To safeguard against nitrogen depletion, which may result from errors in the predicted nitrate absorption rates, an additional control strategy was incorporated where nitrate extinction was inferred from a reduction in ∇pH (see Nomenclature). Upon nitrate extinction, the controller could immediately supply additional nitrate. The combination of the two control schemes was investigated in run 5.

2.2. Method and planning

Fig. 1 shows four independent flood-and-drain hydroponic systems, each 1.8 L and hosting a single Kale plant (*Brassica oleracea* var. *sabellica*). For each experimental run, all four systems were operated in parallel under the same conditions, analogous to four repeat runs. A total of five runs were conducted, thus 5 × 4 single plant runs.

Fig. 1. Annotated photo of the experimental setup. Four independent hydroponic systems are shown, each hosting a single Kale plant, labelled "plant 1" to "plant 4" from right to left.

In run 1, plants were cultivated in modified Hoagland's solution composed of deionised water with 5 mM KNO_3, 5 mM $Ca(NO_3)_2 \cdot 4H_2O$, 1 mM KH_2PO_4, 2 mM $MgSO_4 \cdot 7H_2O$, 6 mg L^{-1} NaOH, 7.5 mg L^{-1} Fe-EDTA, 0.05 mg L^{-1} Cu-EDTA, 2.9 mg L^{-1} H_3BO_3, 1.8 mg L^{-1} $MnCl_2 \cdot 4H_2O$, 0.2 mg L^{-1} $ZnSO_4 \cdot 7H_2O$ and 0.1 mg L^{-1} $Na_2MoO_4 \cdot 2H_2O$. The solution was replaced regularly to maintain a solution strength >2/3 full Hoagland's solution. The pH was controlled using 1 M HCl. In runs 2 to 5, a nitrogen-free (except for EDTA) solution was used, composed of deionised water with 2 mM K_2SO_4, 4 mM $CaCl_2 \cdot 2H_2O$, 1 mM KH_2PO_4, 2 mM $MgSO_4 \cdot 7H_2O$, 6 mg L^{-1} NaOH, 7.5 mg L^{-1} Fe-EDTA, 0.05 mg L^{-1} Cu-EDTA, 2.9 mg L^{-1} H_3BO_3, 1.8 mg L^{-1} $MnCl_2 \cdot 4H_2O$, 0.2 mg L^{-1} $ZnSO_4 \cdot 7H_2O$ and 0.1 mg L^{-1} $Na_2MoO_4 \cdot 2H_2O$. Subsequently, the desired amount of nitrate was added as KNO_3.

In runs 2, 3, and 4, the nitrate concentration was controlled by controlling the pH with a mixture of 0.3 M HNO_3 and 0.2 M $NaNO_3$ (composition based on the results from run 1), instead of HCl. Small amounts of $NaNO_3$ were added manually during runs 3 and 4 to prevent nitrate depletion. In run 5, no nitrate was added manually; instead, an automatic nitrate addition strategy was incorporated, where nitrate extinction was inferred from a reduction in ∇pH, the logistics of which are outlined in Fig. 3 and explained in more detail in Section 3. The pH was controlled using 0.3 M HNO_3 only (α=1) to allow for a faster depletion rate of nitrate as compared with runs 2 to 4.

Seedlings were cultivated in separate systems (aeroponic cloners) and were transplanted to the main experimental setup when they weighed around 10 g, followed by commencement of the respective run. Seedlings were selected randomly in part, with preference given to visually large and healthy plants. Run 1 was conducted for a period of 21 days with solution replacement on days 7, 13, 17 and 19. Runs 2 to 4 were conducted for 13 days with solution replacement on days 5, 9 and 11. Run 5 was conducted for 11 days with solution replacement on day 7. In run 5, an initial nitrate concentration of 5 mM was charged. Nitrate extinction

did not occur until after the solution had been replaced on day 7 with a nitrate concentration of 0.5 mM. A day/night cycle was implemented with 20 h light and 4 h dark in all runs except run 5, where 24 h light was employed to avoid fluctuations in ∇pH. The average relative humidity and temperature in the laboratory was maintained at 36% (σ = 6, n = 570) and 21.6 °C (σ = 1.1, n = 570). In all runs, the nitrate concentration was measured via spectrophotometric analysis of liquid samples. Relative leaf chlorophyll content was measured by dissolving dry leaf material in acetone (2.44 g L^{-1}) and measuring the absorbance at 663 nm. No absolute quantification of chlorophyll content was done, thus only a reduction in chlorophyll content could be detected. Plants were dried at 70 °C for 48 h.

2.3. Apparatus and instruments

A single Arduino Mega 2560™ was used to control the water level, pH, and flood-and-drain mechanism in all four systems. Gravity™ pH probes (HAOSHI™ pH meter Pro) were used for online pH measurements. Generic™ peristaltic pumps (Precision Peristaltic Pump + Intelligent Stepper Controller) were used for dosing. All chemicals/nutrients were purchased from Merck™ (BioXtra©, ≥99.0%). For plant lighting, 4× Mars Hydro™ 400 W blue/red LED lights (Mars II 400 LED Grow Light©) were used. Kale seeds (*Brassica oleracea* var. *sabellica* or Vate's Blue Curled Kale) were purchased from Raw™. The main pumps (responsible for the flood-and-drain mechanism) were purchased from Xylem™ (Flojet Diaphragm Electric Operated Positive Displacement Pump, 3.8 L min^{-1}, 2.5 bar, 12 V DC). For seedling propagation, aeroponic systems (Aeroponic Cloner) purchased from hydroponic.co.za™ were used. Nitrate concentration was measured in a spectrophotometer (Agilent Technologies™, Cary 60 UV–Vis, G6860A) using Merck™ Nitrate Cell Test, DMP 23–225 mg L^{-1} NO_3-N and DMP 0.10–25.0 mg L^{-1} NO_3-N Spectroquant©.

Relative chlorophyll content was determined using pure acetone (99.99%), purchased from Promark Chemicals™.

3. Results and discussion

Plant root exudates consist of numerous chemical species. Some tend to cause a drop in pH (such as carboxylic acids and H^+), while others (such as OH^-) tend to cause a rise in pH (Hosseinzadeh et al., 2017). When nitrate is supplied as the sole nitrogen source, the pH rises. This is due to the release of OH^- ions and the absorption of H^+ ions upon nitrate assimilation, which has a greater basic effect than the sum of the acidic effects (Dijkshoorn, 1962; Imsande, 1986; Smith and Raven, 1979). Thus, the amount of nitrate absorbed may be estimated from the change in pH of the solution. However, this approach depends on several variables such as the change in buffering capacity of the solution resulting from phosphate absorption and the operating pH of the system. To circumvent these problems, nitrate absorption may be better inferred from the proton dosing rate required for pH homoeostasis, which occurs at constant pH and is independent of the solution's buffering capacity. To establish the relationship between nitrate absorption and proton dosing, run 1 was performed.

3.1. Relating nitrate absorption to proton dosing

Run 1 was conducted using standard Hoagland's solution (high nitrate concentration). The results from the 21-day run are given in Fig. 4 in which the proton dosing, nitrate absorption and transpiration rates of the four separate runs are plotted against time. The pH was controlled at an average value of 6.05 (σ = 0.07, n=997). The exponential nature of the plots

suggests that the setup allows for population growth characteristics (Hellgren and Ingestad, 1996; Raistrick, 1999). Fig. 4(c) shows a plot of the HCl dosing rates vs. the nitrate absorption rates using the data from Fig. 4(a) and 4(b), which indicates a constant ratio of proton dosing required for pH homoeostasis and nitrate absorbed by the plant ($\eta \approx 0.49$ mol mol^{-1}). Thus, for every mol of nitrate absorbed, approximately 0.49 mol of protons were dosed to maintain the solution's pH. This relationship provides the means of inferring the nitrate absorption rate from the proton dosing rate.

To control the nitrate concentration, nitrate must be fed at the same rate at which the plants absorb nitrate. Provided that for every mol of nitrate absorbed, 0.49 mol of protons need to be dosed to maintain the solution's pH, the required nitrate feed rate is 1/0.49 of the proton dosing rate. Instead of incorporating a separate nitrate feed system, a simpler technique was employed, where the acid dosing solution (B1 in Fig. 2) was composed of a proton to nitrate ratio of 0.49 ($\alpha=\eta=0.49$). Thus, by controlling the pH with the acid-nitrate dosing solution, the nitrate concentration will be controlled simultaneously. Runs 2, 3 and 4 employed this strategy to control the nitrate concentration at 11 mM, 1 mM and 0.5 mM.

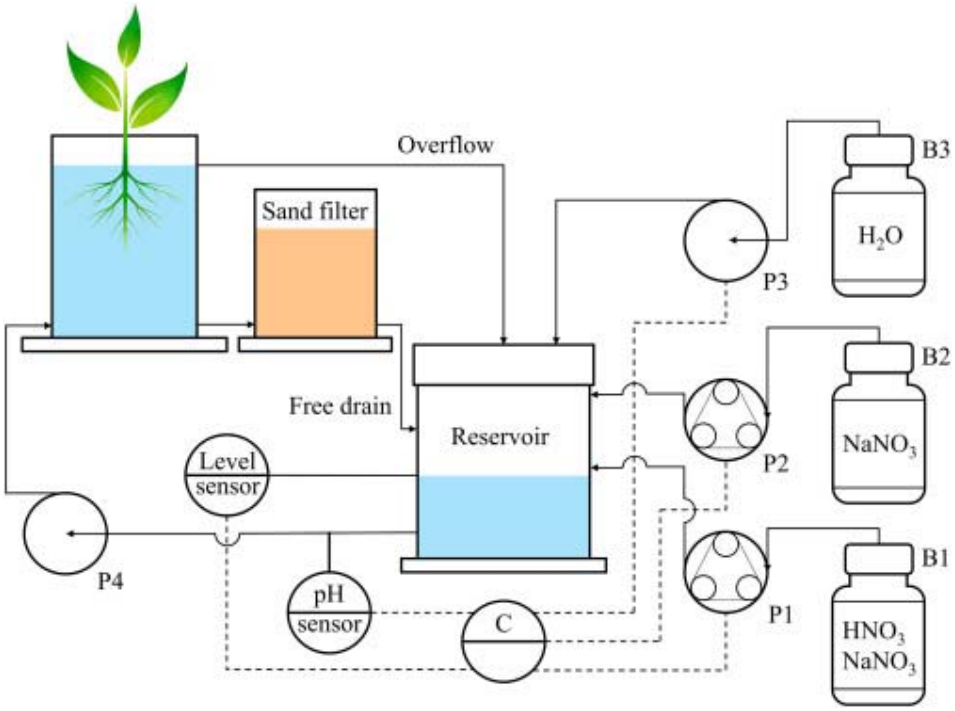


Fig. 2. Simplified process flow and instrumentation diagram of the experimental setup showing major control elements, vessels, and dosing bottles.

3.2. Controlling pH and nitrate concentration simultaneously using a single dosing reservoir

It was observed in trial experiments (not reported) that an α value of 0.5 mol mol^{-1} resulted in slow accumulation of nitrate in solution, whereas an α value of 0.6 resulted in slow depletion of nitrate. Inevitable variation in η, due to genetics or changes in plant growth stage, or variation in α due to error in composing the acid dosing solution (B1 in Fig. 2), will result in either accumulation or depletion of nitrate in solution. Thus, conceding that α will not equal η exactly, an α value of 0.6 mol mol^{-1} (allowing for slow depletion of nitrate in solution) was

employed in runs 2, 3 and 4. Nitrate depletion was prevented by small manual additions of $NaNO_3$ in runs 3 and 4.

Fig. 5 (a) to (c) gives the nitrate concentrations (marked as triangles with magnitudes on the left vertical axis) for runs 2 to 4, respectively. Vertical dotted lines indicate the times at which the solution was replaced. A common/bulk dosing solution (B1 in Fig. 2) was used in all three runs. Thus, variation in the rate of nitrate depletion in solution is due to variation in η, as α remained constant. Relatively constant nitrate concentration profiles are observed. For run 2, with an initial nitrate concentration of 11.5 mM, no additional nitrate was added manually. A slight decrease in nitrate concentration can be observed between solution replacements, indicating that the choice of α is larger than the plant's η value. In runs 3 and 4, additional nitrate was added manually to correct for the gradual decrease in concentration. Manually added amounts are plotted as bars in Fig. 5 with magnitudes on the right vertical axis. Given the manual additions as well as the quantified automatic dosages of acid and nitrate, the total nitrate consumed could be calculated. It was found that manual dosing accounted for 8% ($\sigma=4$, $n=8$) of the total nitrate addition. The calculated η values varied between 0.52 and 0.57, with an average value of 0.55 for the eight plants.

Given that the same dosing solution was used during runs 2 to 4, from Fig. 5 it can be seen that η varied between plants. For example, in run 3, the plant cultivated in system 2 (plant 2) had the lowest η value (as more nitrate had to be added manually), whereas in run 4, plant 1 had the lowest η value. Thus, it is clear that η varies slightly between plants, which may be due to genetic differences in nutrient uptake characteristics.

Fig. 6 (a), (b) and (c) provide the proton-nitrate dosing rates (D_R) for runs 2 to 4 where the natural logarithm is used to linearise the growth curves. The linear trends resulting from the logarithmic plots indicate exponential growth characteristics, as observed in run 1. It can be shown from the population growth equation that the slopes of the fitted lines equal the relative dosing rates (*RDR*) (Hellgren and Ingestad, 1996; Raistrick, 1999). Practically identical relative dosing rates are observed, which are in agreement with the relative growth rates (*RGR*) given in Fig. 6(d). Thus, it is evident that no reduction in growth rate occurred with decreasing nitrate concentration. To the contrary, there appears to be a slight increase in the growth parameters.

Fig. 6(d) compares the average growth parameters (*RGR* and *RDR*) of the three runs reported in Fig. 6(a) to (c). It is evident that the relative growth rates (*RGR*) are higher than the relative dosing rates (*RDR*), which indicates that less nitrogen per plant mass is absorbed with increasing plant size. This can be attributed to a decreasing η value with plant size (fewer protons need to be dosed to maintain the pH at the same nitrate absorption rate). However, no further evidence of this has been found in the data. Instead, it is assumed that the nitrogen content in the plants decreases with plant size, which is corroborated by Le Bot et al. (1998).

3.3. Automatic prevention of nitrate depletion using a second dosing reservoir

For run 5, nitrate addition was fully automated (no manual addition). In addition to the nitrate-control strategy used in runs 2 to 4, where the nitrate concentration was controlled by controlling the pH with a mixture of acid and nitrate (such that $\alpha \approx \eta$), a second dosing pump (P2 in Fig. 2) and a dosing solution containing $NaNO_3$ only (B2 in Fig. 2) was installed, the purpose of which was to dose automatically the extra required nitrate which previously had to be added manually in runs 3 and 4 to prevent nitrate depletion.

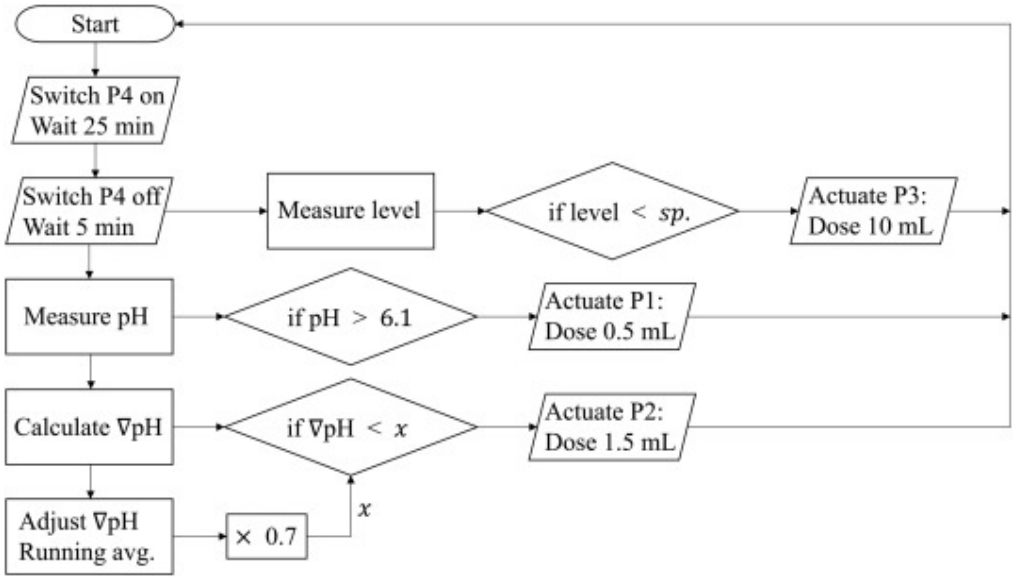


Fig. 3. Sequential function chart of the control algorithm responsible for the flood-and-drain mechanism (switching P4 on and off), liquid level control (first horizontal branch), pH control (second branch) and nitrate extinction prevention (bottom branch). "*sp*." corresponds to a set-point of 1.8 L.

It was noted in trial experiments that ∇pH decreased as the nitrate concentration approached zero. This can most likely be attributed to a reduction in the nitrate assimilation rate when nitrate concentrations are critically low. Thus, nitrate extinction may be inferred from a reduction in ∇pH, which upon detection, can actuate the second dosing pump P2, as outlined in Fig. 3. The extra nitrate will then only be added upon extinction of nitrate in the solution. Provided that the nitrate concentrations are not critically low for any significant period, this strategy should satisfy the plant's nitrogen demands while maintaining low nitrogen concentrations. The results from the last 4 days of the run are given in Fig. 7 (no nitrate extinction occurred prior to this), which shows how ∇pH decreases when nitrate becomes extinct. This is conveyed by plotting the nitrate concentrations together with the relative ∇pH measurements. The relative ∇pH measurements are the ratios of the instantaneous ∇pH measurements to the running average of the ∇pH measurements (average over the past 6 h). As described in Fig. 3, the controller doses additional nitrate when this ratio falls below 0.7, indicating a 70% reduction in ∇pH. Consistent dosing occurring approximately every 6 h is observed, which suggests that the strategy works well to provide the extra required nitrogen which previously had to be added manually in runs 3 and 4. Furthermore, a favourably fast response is observed where an increase in ∇pH (recovery) is apparent immediately after dosing. As shown in Fig. 7, the nitrate concentrations varied between 0 and 0.2 mM, which is two orders of magnitude lower than the standard protocol.

In Fig. 8, the average *RGR* and *RDR* values for run 5 are given in the top right-hand box. For comparison, the average *RGR* and *RDR* values for runs 2 to 4 (total of 12 plants) are given in the top left-hand box. Similar growth rates are observed between run 5 and runs 2 to 4, considering that the plants in run 5 received 20% more light (no night cycle to prevent fluctuations in ∇pH). The root mass fraction and relative chlorophyll content for each of the four runs are plotted as bars, with relative chlorophyll content on the left vertical axis and root mass fraction on the right vertical axis. A slight increase in root mass fraction and leaf chlorophyll content with decreasing nitrate concentration is observed.

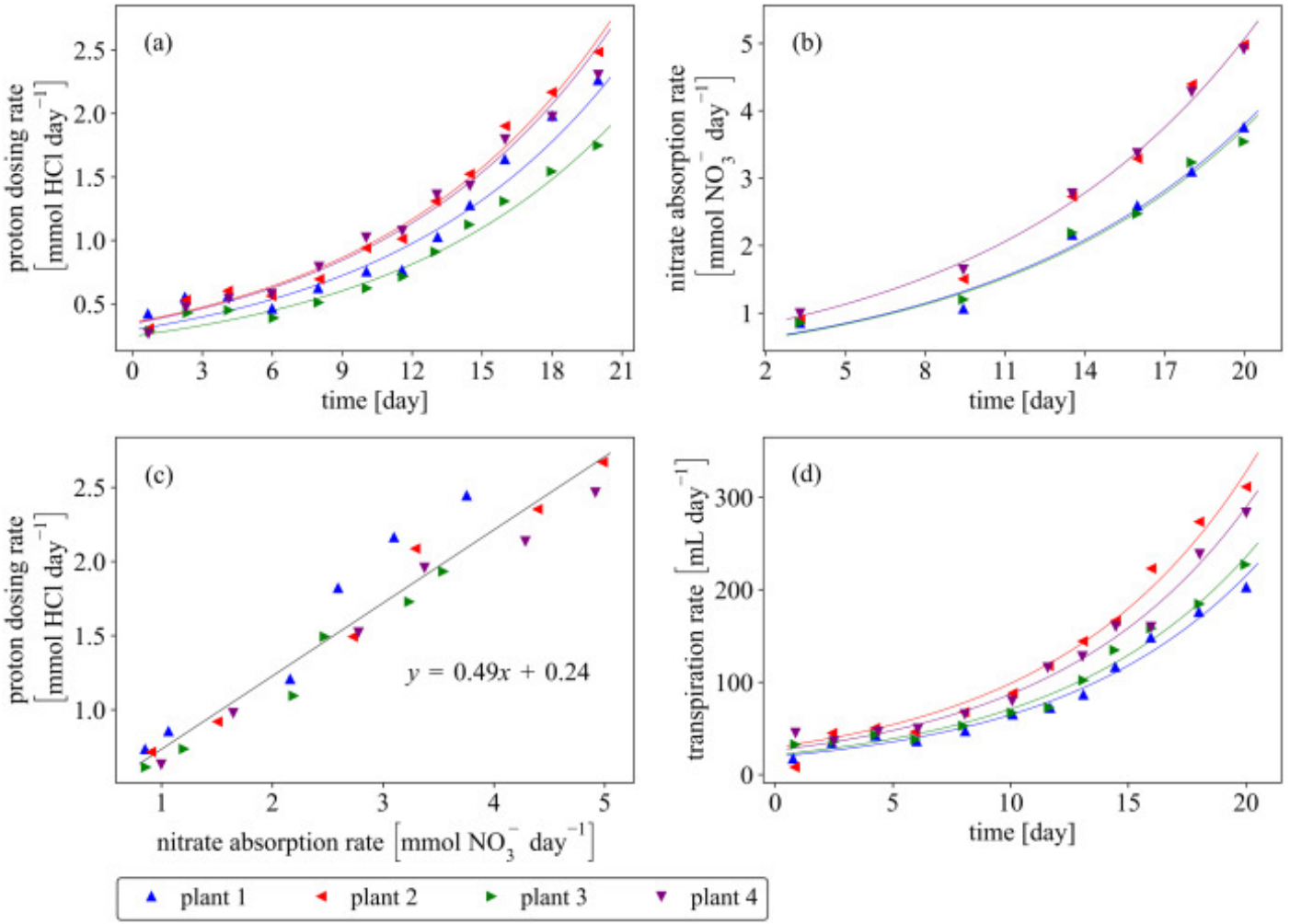


Fig. 4. Results from run 1 using Hoagland's solution with frequent replacement (average nitrate concentration of 12 mM). The pH was controlled at an average value of 6.05 (σ= 0.07, n= 997). HCl dosing rates (a), nitrate absorption rates (b) and transpiration rates (d) all exhibit an exponential increase. Subplot (c) relates proton dosing to nitrate absorption where a fitted value of η= 0.49 is obtained.

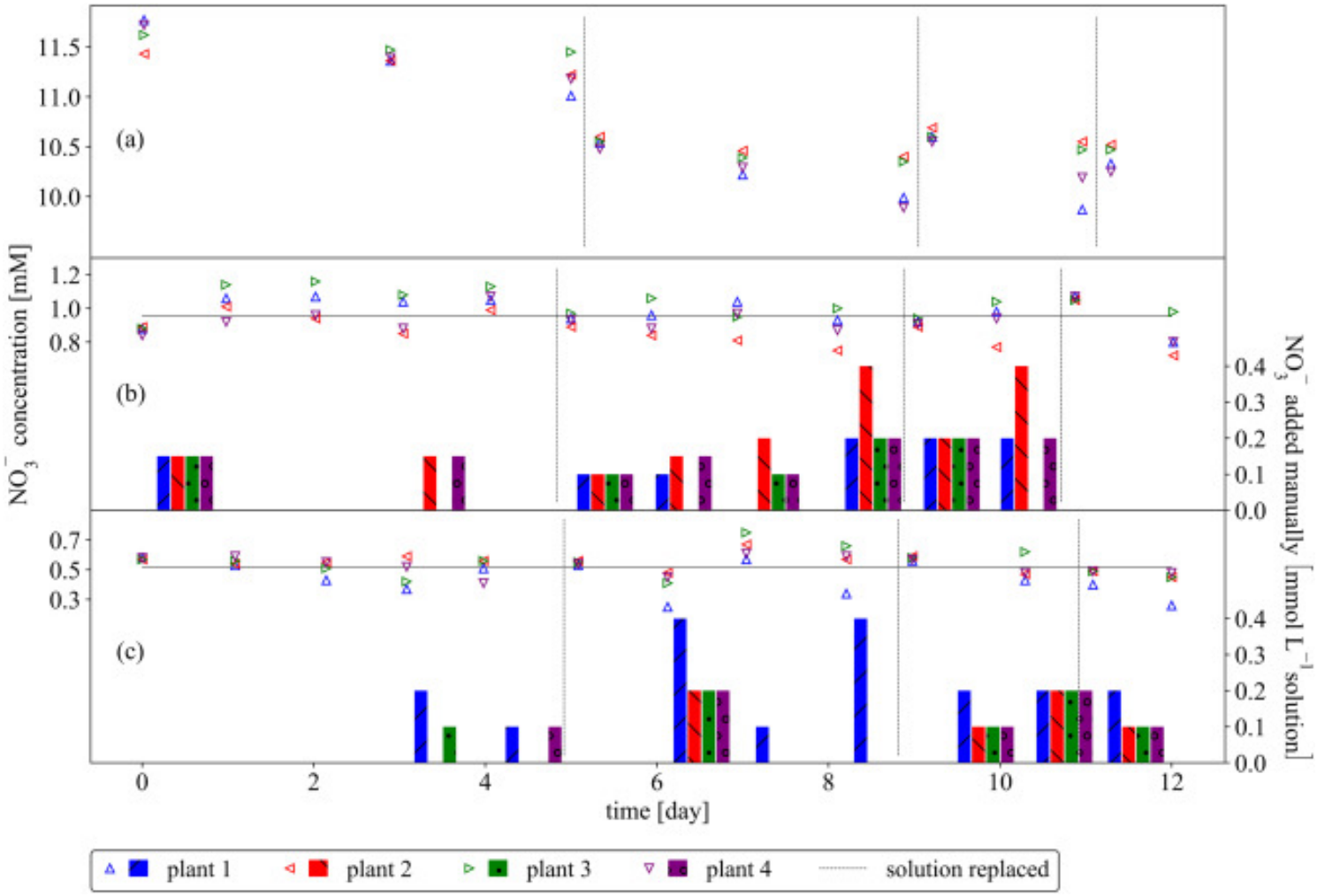


Fig. 5. Results from runs 2 to 4. Nitrate controlled at approximately 1 and 0.5 mM for runs 3 and 4, respectively. All runs used the same dosing solution composed of 0.3 M HNO_3 and 0.2 M $NaNO_3$ (α= 0.6 mol mol^{-1}). For runs 3 and 4 manual corrections were made with $NaNO_3$ as indicated by bar plots in (b) and (c). Vertical dotted lines indicate solution replacement.

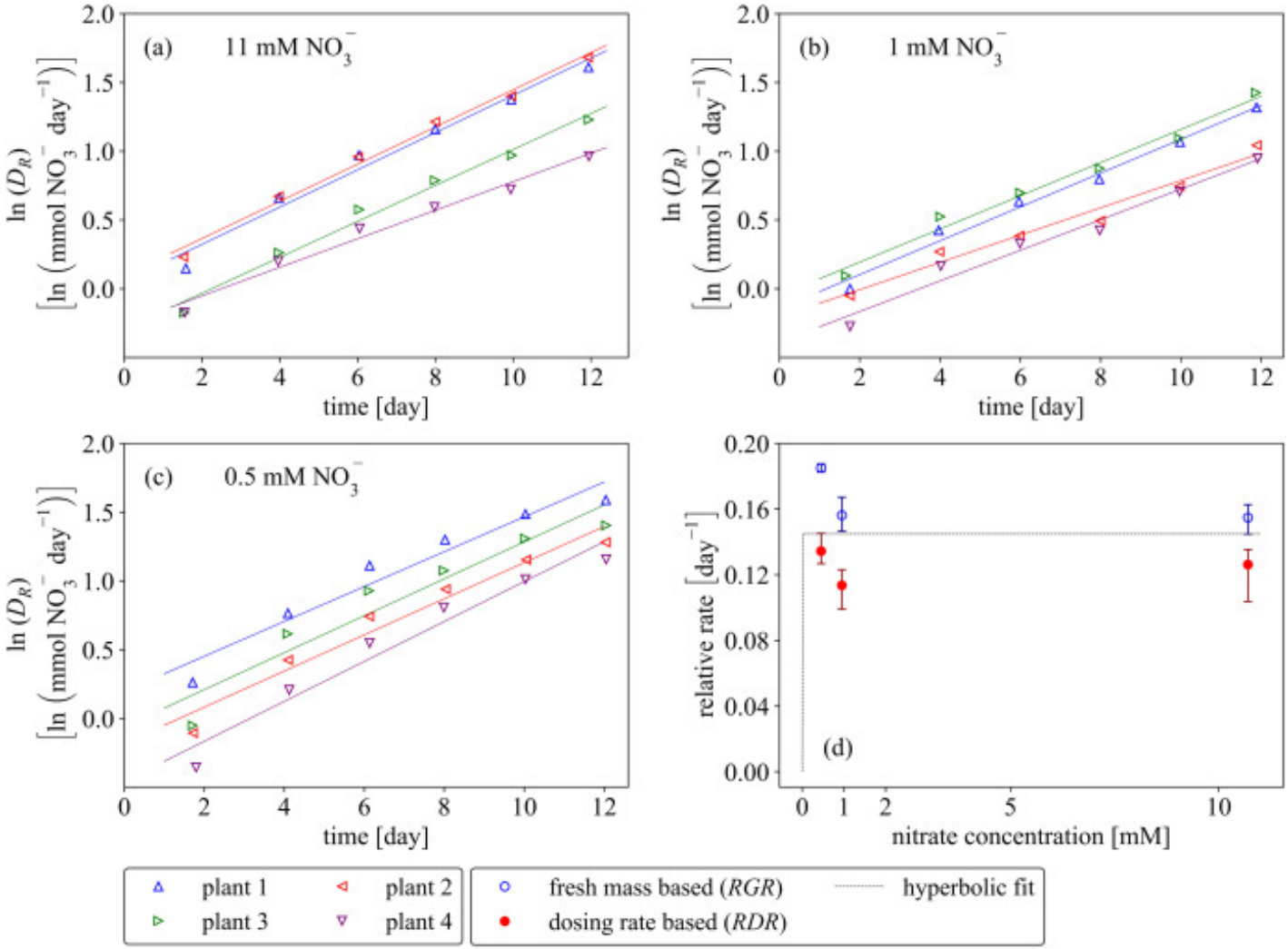


Fig. 6. Subplots (a), (b) and (c) provide logarithmic plots of the dosing rates (D_R) for runs 2 to 4. The slopes of the fitted lines equal the *RDR* values. Subplot (d) gives *RDR* and *RGR* as a function of the nitrate operating concentration. Error bars span the data range (min. ↔ max.) of the four plants.

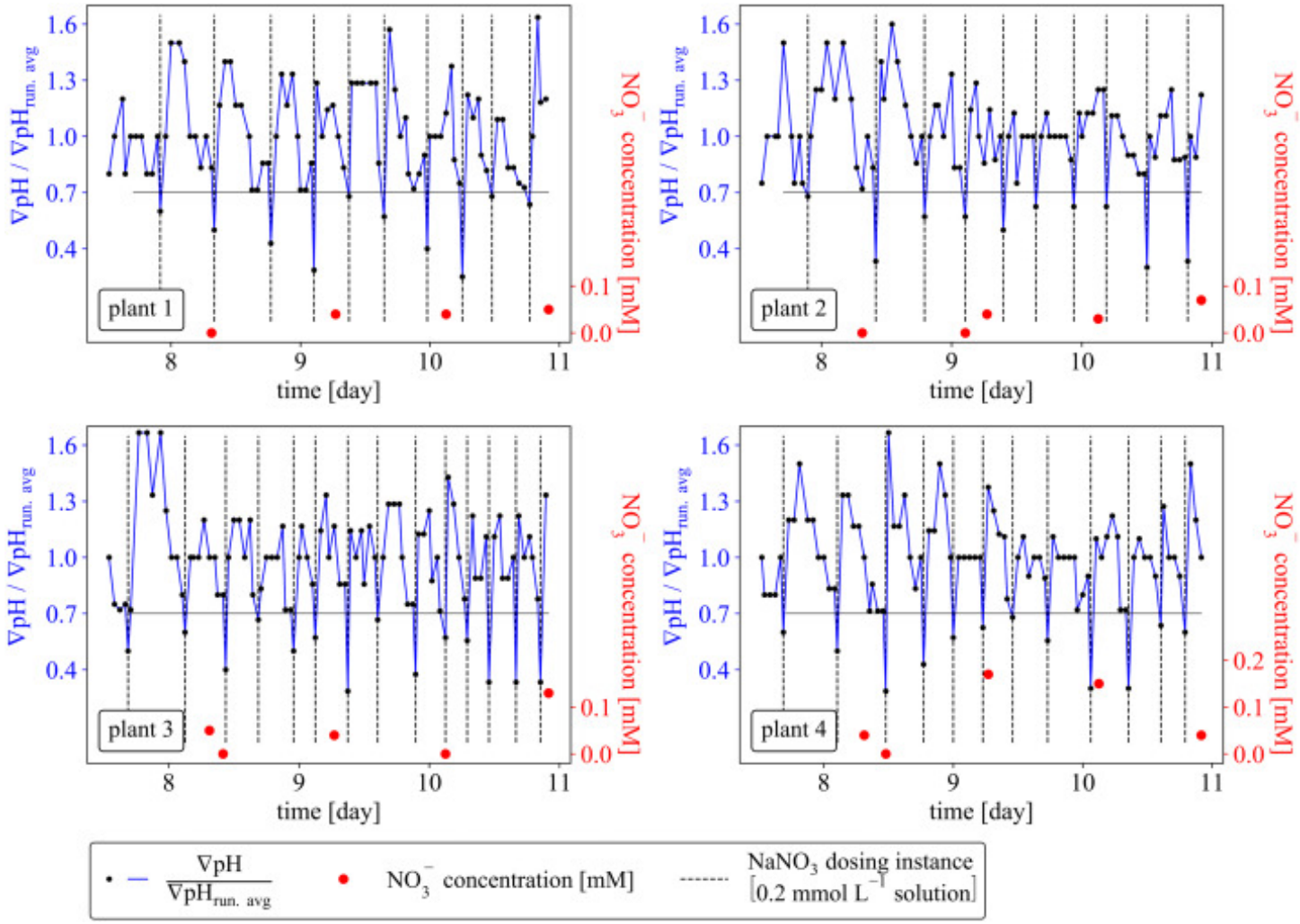


Fig. 7. Results from run 5. Shown are profiles of ∇pH divided by the running average of ∇pH. As described in Fig. 3, $NaNO_3$ dosing (from B2 in Fig. 2) occurs when there is a 70% reduction in ∇pH, whereupon 0.2 mmol $NaNO_3$ L^{-1} solution is dosed. Also shown, are the measured nitrate concentrations in solution.

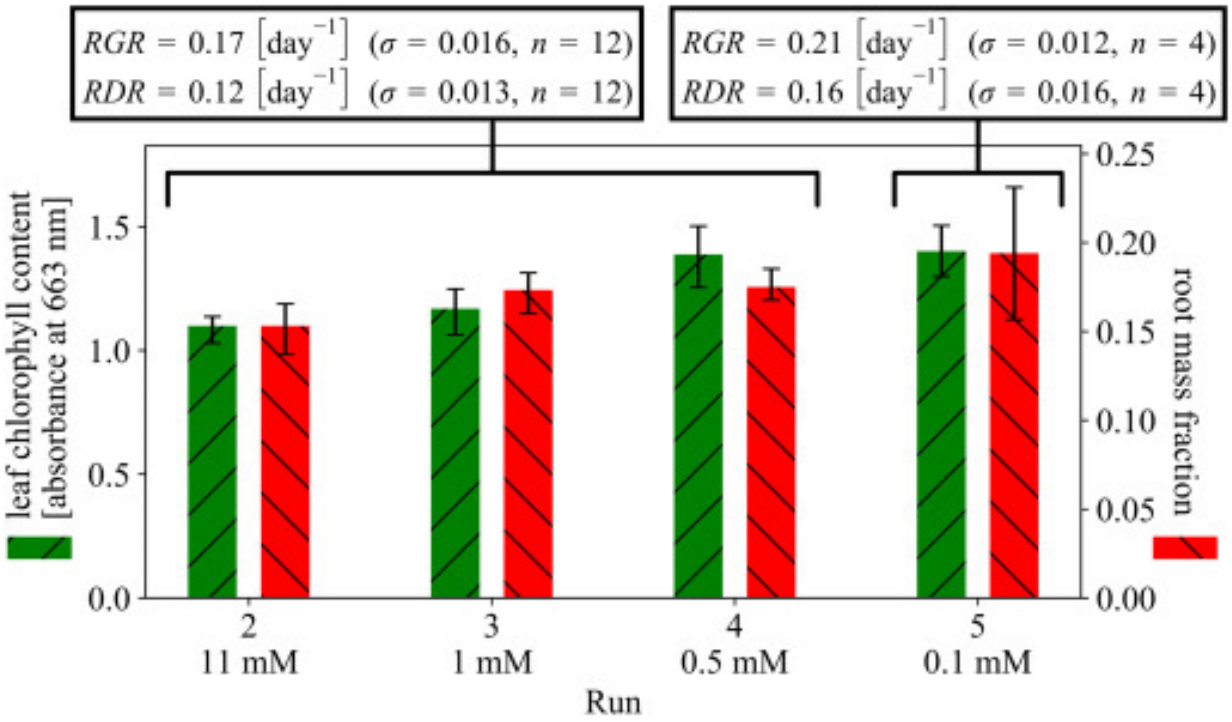


Fig. 8. Comparison of leaf chlorophyll content and root mass fraction of runs 2 to 5. Also shown are average values of the growth parameters *RGR* and *RDR* for runs 2 to 4, which are compared against the growth parameters for run 5 (20% more light was received) in two separate annotations. Error bars span the data range (min. ↔ max.) of the four plants.

The results provide clear evidence that plant growth is not sacrificed when operating at the nitrate concentrations investigated. The results also give a preliminary indication that plant nutrition was not affected. Regarding nitrogen spillage to the environment, the results are very promising since the effluent from the hydroponic unit contains a nitrate level two orders of magnitude lower than in conventional operation. The soilless agricultural industry may thus keep the benefits of regular solution replacements while reducing nitrogen spillage by two orders of magnitude. This implies that the load of nitrates dumped into the environment, and hence the consequences of nitrogen pollution as stated in Section 1, can be reduced proportionally without sacrificing crop growth and nutrition.

4. Conclusions

It was shown that the nitrate concentration in a hydroponic system can be controlled at much lower levels compared with the standard protocol using pH as the sole measured variable, without sacrificing plant health or growth rate. This was accomplished by selecting an α value slightly higher than the plant's η value, which allows for a slow depletion rate of nitrate in solution. As depletion ultimately results in extinction, an automatic nitrate-addition strategy was included where nitrate extinction was inferred from a reduction in the rate of change of pH. This combination was successful at maintaining nitrate concentrations below 0.2 mM without sacrificing plant health or growth rate. A cheap and simple control strategy was developed to reduce nitrogen spillage to the environment.

From an environmental perspective, the suggested control strategy has the potential to reduce nitrate pollution from soilless agriculture by two orders of magnitude. The fast-growing soilless agriculture sector has the potential to become a noteworthy contributor to nutrient spillage into waterways, and circumventing design strategies are required to reduce environmental harm. The control scheme presented here can easily be incorporated into commercial hydroponic farms where pH measurement and control are standard procedures and thus it provides an achievable strategy for reducing nitrogen pollution.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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