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学位論文全文に代わる要約
Extended Summary in Lieu of Dissertation

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学位論文題目：
Title of Dissertation

Identifying and modeling the dynamic response of the plant growth to root zone temperature in hydroponic chili pepper cultivation using neural networks
(ニューラルネットワークを用いた唐辛子水耕栽培における液温に対する植物成長反応の同定とモデル化)

学位論文要約：
Dissertation Summary

Introduction

There has been growing interest in adopting hydroponic systems for crop production worldwide. In combination with protected agriculture such as greenhouses and plant factories, about 3.5% of the worldwide area has adopted hydroponic systems for crop production (Sambo et al., 2019). As a soilless technology, the benefits of adopting a hydroponic system for growing plants are flexibility and accuracy in controlling the root zone environment. Among the root zone environmental factors, temperature is one of the most important factors that influence plant growth and development (He, 2016). It has been reported that the mechanisms of nutrient and water absorption processes within the roots are mainly regulated by root zone temperature (RZT) (Gosselin and Trudel, 1983; Ingram et al., 2015; Mortensen, 1982). Therefore, RZT has been widely used as the determining factor for promoting plant growth in hydroponic systems. A better understanding of optimal RZT in hydroponic cultivation could lead to the improvement of plant growth.

Studies on environmental control technology for plant production systems (Hashimoto, 1989; Morimoto and Hashimoto, 2009; Morimoto et al., 1985, 1996) suggest that the optimal plant conditions during cultivation vary between growth stages. This is because the physiological status of the plant is changing and is remarkably affected by changes in environmental factors. This typical control approach is known as a “speaking plant approach” (SPA). In order to control the growth of plants using the RZT, a dynamic model of the process is necessary. By constructing a dynamic model of the process, the optimal control strategy of RZT in hydroponic systems can be determined. However, it is difficult to develop a dynamic model of the eco-physiological process of a plant conduct successfully using mathematical modeling. This is because most of the eco-physiological processes of plants have strong non-linearity, time delay, and time-varying parameters, which can be characterized as a complex system with uncertain parameters (Carson et al., 2006; Morimoto and Hashimoto, 2000; Morimoto et al., 1985; Whittaker and Thieme, 1990; Yin and Laar, 2005). One useful approach to identifying a black box system is artificial neural networks (ANNs) (Isermann et al., 1997). ANNs are an information-processing approach inspired by the biological neural system. Artificial neural networks can identify a complex system without requiring prior knowledge of the relationships among the parameters within the system by learning from its input–output signals (Hinton, 1992; Rumelhart et al., 2013; Sablani et al., 2006). With these capabilities, artificial neural networks are useful in handling uncertainties and non-linear relationships (Isermann et al., 1997).

The present study is an attempt to apply an artificial neural network to model the dynamic responses of plant growth as affected by change in the RZT in hydroponic chili pepper plants. The dynamic model proposed here was developed using system identification based on artificial neural networks in a single input–single output (SISO) system. The model estimates the output variable of dynamic response in plant growth using the input variable of RZT.

Materials and method

Chili pepper's seeds (*Capsicum annum* L. 'Takanotsume Togarashi'; Takii Seed Ltd., Japan) were germinated for 14 days. Then, the seedlings were transplanted into the measurement system after 35 days from sowing. In this study, the experiments were conducted in a growth chamber (2.5×2.5×2.0m; NK System, Nippon Medical & Chemical Instruments Co., Ltd., Japan) where the environment factors were controlled.

Tabel 1. Environmental factors set points inside growth chamber during experiment

Environmental factors	Unit	Environmental set points Day	Environmental set points Night
Photoperiod	h	12	12
Photosynthetic active radiation	μmol m^{-2} s^{-1} PPFD	270	0
Air temperature	°C	25±1	20±1
Humidity	% RH	55±5	70±5

In this study, a total of 15 chili pepper plants were used and grown in a deep floating technique (DFT) hydroponic system, with the nutrient solution controlled at 2.3±0.2 dS m^{-1}, and the dissolved oxygen (DO) level was maintained with the application of a bubble generator. Figure 2 shows the nutrient solution control system consisting of a cooling and a heating mechanism to control the RZT. Five different RZT regimes, in the range of 15-37 °C, were randomly implemented to the plants in order to obtain adequate information about the dynamic response of plant growth to RZT. The plant growth responses to RZT were approximated by measuring the fresh weight of the plant using an automatic non-destructive plant weight measurement system based on a load cell (CZL635, 0.05% precision; Phidgets Inc., Canada), as shown in Figure 2. However, because the roots were in the nutrient solution, the measured weight only represented the fresh weight of the plant shoots (Hu et al., 2018).

A nonlinear autoregressive network with exogenous input (NARX) (Siegelmann et al., 1997) network architecture were evaluated to identify the dynamic responses of plant growth as affected by RZT. The architecture was chosen due to their advantages in identifying a nonlinear time-series system and for their effective use in a control system (Mohd and Aziz, 2016). A single-input, being the RZT $T(k)$ and single-output, being the responses of plant growth $WR(k)$ – (SISO), were used for identification (k: sampling time). The architecture of the network is shown in Figure 3(a). The responses of plant growth were approximated using a neural networks model from the input of the present value of RZT $T(k)$, historical data of RZT $T(k - dt)$ and the historical data of the response of plant growth $WR(k)$. For evaluating the accuracy of the identified neural network model, the data for identification were divided into three independent datasets, being a training, a validation, and a test dataset. The data split was important to provide an unbiased and robust evaluation of the final model (Kuhn and Johnson, 2013). The performance of the identified model was measured using root mean squared error (*RMSE*), and the coefficient of determination (R^2). A program based on the Matlab® Deep Learning Toolbox™ R2019a (MathWorks® Inc.) was created to build the model.

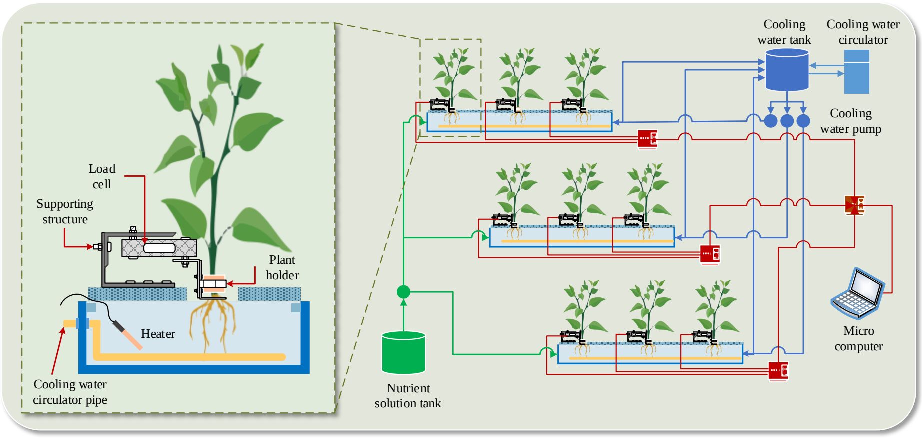

Figure 1. Root zone temperature control system and plant growth measuring system using a load cell sensor

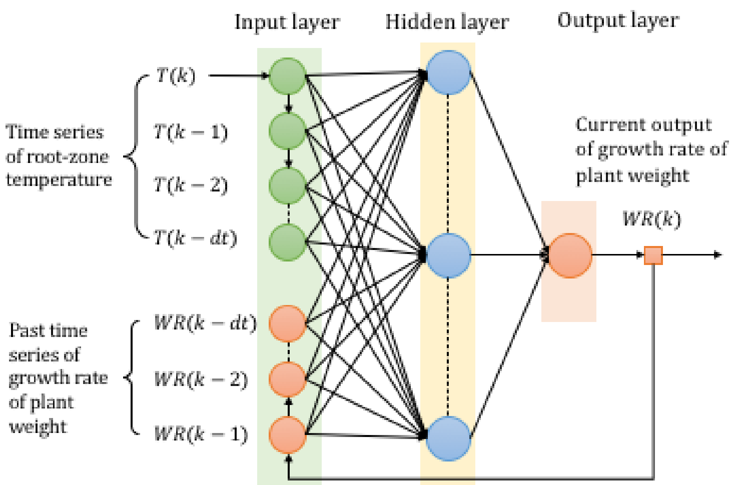

Figure 2. Nonlinear autoregressive with exogenous input (NARX) neural network structure with three layers, one input time series of the root zone temperature (RZT), one output time series of the growth rate of plant weight, and a time-delay neural network for identifying a dynamic model.

Findings and discussion

The dynamic responses of plant growth as affected by changes in the RZT were examined using an automatic plant weight measurement system based on a load cell, as shown in Figure 3(a). Since plant tissue is composed mostly of water, the fresh weight of a plant is very sensitive to changes in environmental conditions. For this reason, in order to examine the fundamental eco-physiological behavior of the response of plant growth to RZT, experiments were conducted in a strictly controlled environment using a growth chamber, where light intensity, temperature, and relative humidity were controlled precisely. As the environmental conditions inside the growth chamber were maintained constant, it can be assumed that the responses of plant growth were affected by the changes in RZT.

Then, an artificial neural network was used to construct a dynamic model of the responses of plant growth as affected by changes in the RZT in hydroponic cultivation. Based on the examination, it was found that the NARX networks presented in this study were useful in identifying the complex process of the dynamic response of plant growth as affected by changes in the RZT over 45 days of cultivation (Figure 3(b)). The NARX networks were shown to be capable of performing long-term dependency prediction, as also showed by (Menezes and Barreto, 2008; Siegelmann et al., 1997). In Figure 4(a), the model also successfully performed step response simulation, which is typically conducted in control studies to estimate the basic properties of a dynamic system (Isermann and

Münchhof, 2011). This suggests that dynamic optimization can potentially be applied to the system in order to maximize plant growth. Moreover, from the simulation, estimation of the static relationship between the response of plant growth and RZT can also be generated (Figure 4(b)). The static relationship was determined as having strong nonlinearity with an upside-down parabolic curve peaking in the range of 24 to 26°C, which is consistent with previous studies on the relationship of plant growth and RZT (Díaz-Pérez, 2010; Gosselin and Trudel, 1986). This suggests that a reliable computational model can be useful to predict the dynamic behavior of plant growth as affected by RZT. Identification of the dynamic responses of plant growth as affected by RZT, which was conducted in this study, may be useful for a better understanding of plant growth control in plant production systems.

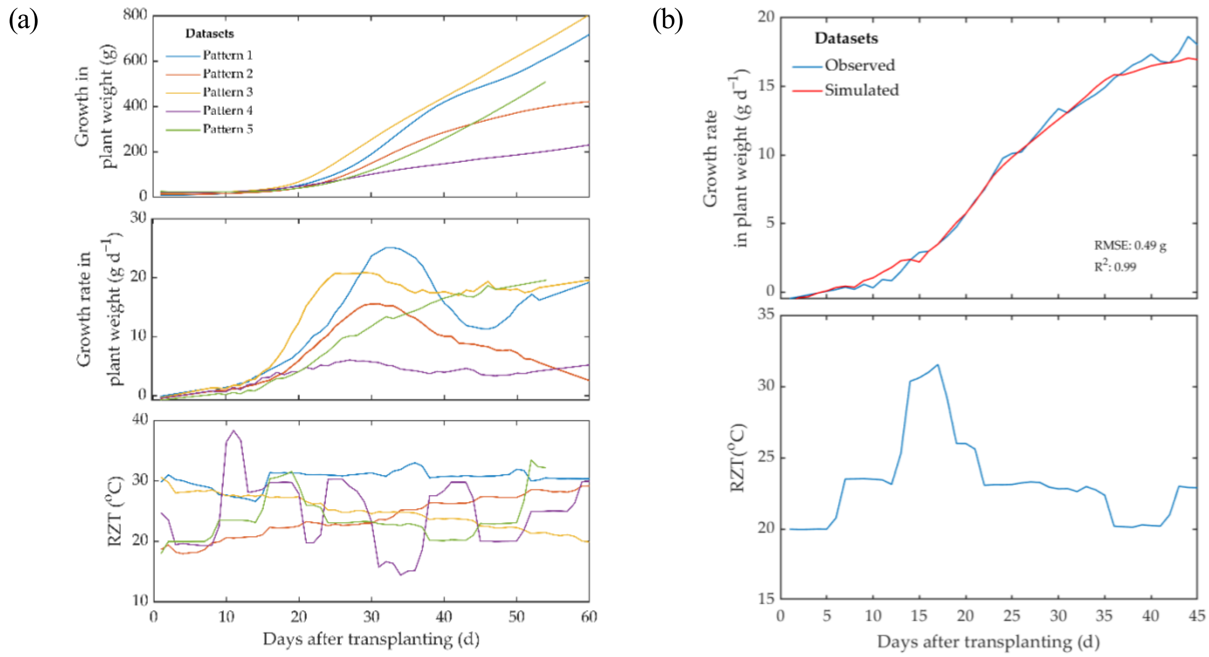

Figure 3. (a) Typical daily change in plant weight, the growth rate of plant weight, and RZT in hydroponic pepper cultivation; (b) Comparison of the estimated response calculated by the developed neural network model and the observed growth rate of plant weight.

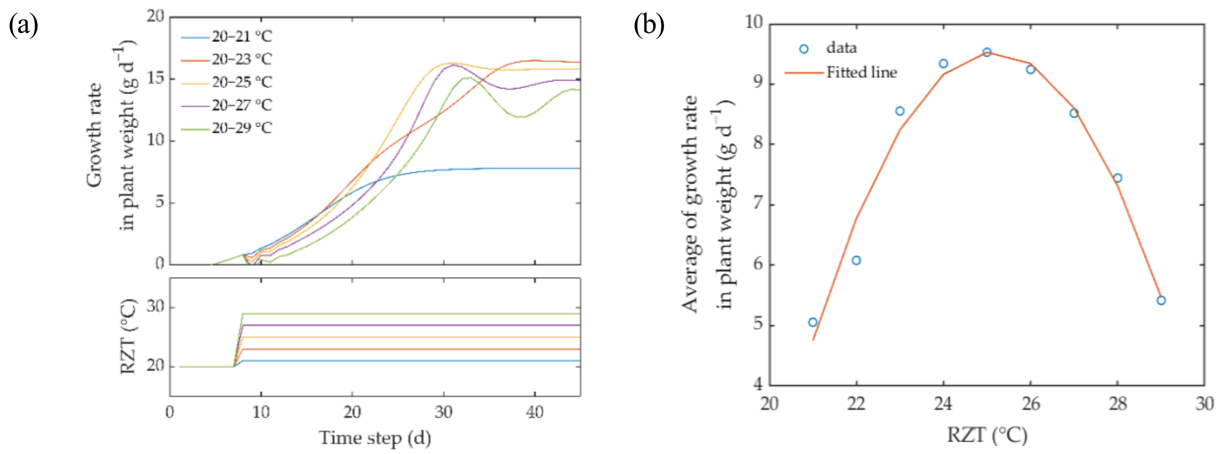

Figure 4. (a) Estimated step response of the growth rate of plant weight to stepped RZT input, obtained via simulation; (b) The estimated static relationship between the growth rate of plant weight and RZT, obtained via simulation.