Dynamic optimization of watering for maximizing the sugar content and size of Satsuma mandarin using intelligent approaches

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Abstract: Larger size and higher sugar content fruits are desired for fruit production. However, these factors compete with each other. For example, water stress (smaller watering) causes an increase in sugar content but a decrease in fruit size. Therefore, there exists an optimal watering operation for their maximization. In this study, an optimal watering scheduling that maximize both of the sugar content and the diameter of Satsuma mandarins grown in the field was investigated using neural networks and genetic algorithms. The monthly data of the fruit responses and climate factors were measured for identification from August to November, 1996-2009. Dynamic changes in the sugar content and diameter of the Satsuma mandarins, as affected by the rainfall (watering), sunshine duration and air temperature, were first identified using neural networks, and then an optimal watering scheduling (rainfall management) that maximizes the sugar content and size of the Satsuma mandarins was determined through simulation of the identified neural-network model using genetic algorithms. The optimal value obtained here was a combination of the marked increase in watering during the fruit-developmental stage (August and September) and a significant decrease in watering during the fruit-maturing stage (October and November). From the model simulation, a marked increase in watering during the former stage induced an active developmental growth of the fruit, and a significant decrease in watering during the latter stage induced an increase in the sugar content. Drip irrigation is commonly used for increasing the watering whereas plastic-film mulching is used for reducing it.

Keywords: Dynamic optimization, fruit quality, climatic factors, sugar content, fruit size, neural networks, genetic algorithms

1. INTRODUCTION

Satsuma mandarin is one of the most important crops in Japan, and is preferred by many consumers for its soft texture and sweet taste. Ehime Prefecture, which is located in the southeastern area of Japan, is known as its major production region.

The Satsuma mandarin fruit is usually ranked by the sweetness, which is usually estimated from the value of sugar content (Brix%) in Japan. The fruit is also evaluated by the size (diameter). In general, larger size and higher sugar content fruits are desired for fruit production. Based on these findings, we chose two types of fruit responses, sugar content and size, as the controlled outputs for optimization. As for the control input, there are many environmental factors such as rainfall, sunshine duration, air temperature and son on. Here, we selected rainfall (watering) for the control input because it is only controllable for the field cultivation.

It is well known that two types of fruit responses (sugar content and size) compete with each other. For example, water stress (smaller watering) causes an increase in sugar content but a decrease in fruit size. Therefore, there exists an optimal value of watering for their maximization. The optimal value should be obtained using an optimization technique. Here, intelligent approaches are used for obtaining an optimal solution.

Intelligent approaches have emerged as promising techniques for dealing well with complex systems in biological production systems. Biological control processes are usually characterized by complexity and uncertainty. An intelligent control technique combining neural networks with genetic algorithms has been developed for the optimization of complex systems such as cultivation and storage processes (Morimoto et al. 1995, 1996, 1997 and 2003). Neural networks are able to identify nonlinear characteristics of a system with their own learning capability (Chen et al. 1990). Genetic algorithms have a high ability to search for a global optimal value of a complex objective function, using genetic operations such as crossover and mutation (Goldberg 1989).

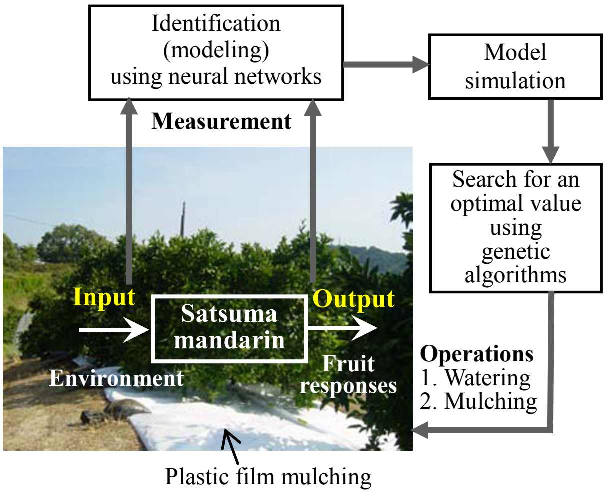

Fig. 1. Schematic diagram of an intelligent control system for optimizing the watering of Satsuma mandarins grown in the field.

The present work applied an intelligent control technique combining neural networks with genetic algorithms to obtain the optimal watering schedule for maximizing the sugar content and the size of the Satsuma mandarin grown in the field through simulation of the identified model. The control input is watering, including rainfall, and the controlled outputs are the sugar content and the size of the fruit.

2. MATERIALS AND METHODS

2.1 Plant materials and measuring instruments

Satsuma mandarin trees (*Citrus unshu* Marc. cv. Okitsuwase) cultivated on south-facing and sunny mountain slopes were used for this experiment. The changes of the fruit responses and climatic factors with time were measured monthly from August to November, from 1996 to 2004. Flowering occurs in early May, fruit enlargement from June to November, and maturation from August to November. The period from August to November corresponds to both the development and maturing stages of the Satsuma mandarin grown in Japan.

Figure 1 shows a schematic diagram of an intelligent control system for optimizing the watering of the Satsuma mandarin trees. An intelligent control technique combined with neural networks and genetic algorithms was used for solving this optimization problem (Morimoto et al. 1995, 1996 and 2003). The system consists of (1) the measurement of both fruit responses (sugar content and fruit size) and climatic (environmental) factors (rainfall, sunshine duration and temperature), (2) identification (modeling) of fruit responses as affected by climatic factors using neural networks, (3) model simulation, and (4) the search for an optimal environment that maximize an objective function using genetic algorithms. The amount of watering (rainfall) can be controlled by two methods, irrigation (watering) and plastic-film mulching. In this study, the irrigation system was used for supplying water when the rainfall was low, and the plastic-film mulching was used for reducing water infiltration into the soil when rainfall was high. The sugar content (Brix %) was measured using a refraction saccharimeter (Atago, ATC-20E), and the fruit size was determined using a ruler. 20 fruit samples were obtained to measure the sugar content and fruit size at each time point.

2.2 Optimization problem

In general, fruit quality is determined from many factors such as sugar content, acidity, firmness, size and so on. Here, since most consumers prefer a sweeter tasting fruit, we supposed that the fruit quality increases with the sugar content. It is also supposed that the commodity value of the fruit increases with the size. From these findings, the aim for optimization is to maximize the sugar content and the size of Satsuma mandarin at the last time point of the maturing stage.

However, it is well known that these two fruit responses compete with each other. For example, water stress (smaller watering) causes an increase in sugar content but a decrease in fruit size in many kinds of plants. Therefore, there exists an optimal watering operation that maximizes both the sugar content and the size of the fruit.

Let $y_1(k)$ and $y_2(k)$ (k=1, 2, ..., N) be time series of the sugar content and the size (diameter) of the fruit, respectively. Let $u_1(k)$, $u_2(k)$ and $u_3(k)$ be time series of rainfall, sunshine duration and temperature, respectively. Here, a three input ($u_1(k)$, $u_2(k)$ and $u_3(k)$) - two output ($y_1(k)$ and $y_2(k)$) model is built.

For optimization, on the other hand, only the optimal value of watering $u_1(k)$ will be obtained because only it is controllable. As for other two input variables (u_2 and u_3), they were fixed to the same data (time-series) during the search for an optimal value. Therefore, an objective function is expressed by $F(u_1)$ and it is given by the summation of the sugar content $y_1(N)$ and the fruit diameter $y_2(N)$ at their last time points, N.

$$F(u_1) = a \cdot y_1(N) + b \cdot y_2(N) + c \qquad (1)$$

where a and b are coefficients (weights) for the sugar content and fruit size, respectively. c is a constant value (here c=0).

For realizing optimization, the control process was divided into 4 steps because the data was measured over 4 months. Therefore, the optimization problem here is to determine the 4-step set points of watering (rainfall, u_1) that maximize the objective function $F(u_1)$. Here, only the watering u_1 is optimized because it is controllable.

$$\text{maximize } F(u_1) \qquad (2)$$
$$\text{subject to } 10 \le u_1(k) \le 300 \text{ mm},$$