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REVIEW
A Method for High-Quality Citrus Production Using Drip Fertigation and Plastic Sheet Mulching

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Abstract
A novel cultivation method that aims to produce high-quality satsuma mandarin (*Citrus unshiu* Marc.) fruit and other types of citrus fruits was proposed in 2000, in order to meet the market demand for high-quality fruits (i.e., fruits with high sugar content and moderate acidity); this method is called the *marudori* method. The main feature of this method is the combined drip fertigation with conventional plastic sheet mulching, both of which control tree moisture. Tree moisture management is crucial for the production of high-quality citrus, particularly satsuma mandarins. Therefore, proper active moisture control techniques are required in Japan, where precipitation may vary considerably. Sheet mulching is a conventional technique in which trees are subjected to water stress, which increases the sugar content of fruits. Additionally, drip fertigation is a technique for effective watering and fertilizing, but not commonly used in citrus cultivation in Japan. The combination of these techniques allows this method to provide such benefits as improved fruit quality, efficient fertilization, and enhanced growth of young trees, among others. In this review, we describe this method in detail and discuss the challenges encountered during the improvement and enhancement of the marudori method, with the aim of establishing an objective cultivation system integrated with ICT and other scientific techniques.

Discipline: irrigation, drainage and reclamation; horticulture
Additional key words: drip irrigation, fruit quality, marudori method, moisture control, satsuma mandarin

Introduction

1. Importance of tree moisture management in citrus cultivation

Citrus is one of the most important crops in fruit cultivation in Japan. While many different types of citrus fruits are cultivated, satsuma mandarin (*Citrus unshiu* Marc.) has been the predominant fruit cultivated in Japan for many years.

The production of high-quality fruits, including citrus fruits, has become critical in the Japanese fruit market. This is because the demand for high-quality fruits has been growing along with the continuing diversification of consumer needs. Moreover, there has been growing demand for the export of high-quality fruits. High-quality citrus fruits are generally defined as those having a high sugar content and moderate acidity.

The history of tree moisture during the growth stage strongly affects the quality of mature citrus fruits. Water stress during the growth stage of fruit increases both sugar content and acidity. Notably, trees should be maintained under moderate water stress during certain periods in the summer and autumn, e.g., from late August to early December (Yakushiji et al. 1996). In conventional outdoor citrus cultivation, however, tree moisture is roughly controlled with rain-fed or sprinkler irrigation systems. Thus, in order to produce high-quality citrus fruits, tree moisture management techniques are critical.

2. Instability of precipitation in Japan

Japan's annual precipitation falls within the range of 1000 to 2000 mm, or about twice the world average. However, short-term fluctuations in precipitation are considerably large. For example, while there may be 200 days without rainfall, over 100 mm of rain may fall in one day during an average year in Tokyo. There are two climate factors affecting heavy precipitation in Japan. One is the

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rainy season, typically lasting from mid-June to mid-July. The other factor is typhoons that strike repeatedly from August to October. And during the last decade, localized torrential rains have occurred periodically, potentially due to global warming. The precipitation during these heavy rainfall events comprises most of the annual precipitation. Precipitation in summer and autumn is strongly affected by the number of typhoons, which varies widely from year to year; therefore, there is always the risk of drought or excessive tree moisture, which causes difficulties in consistently producing high-quality citrus fruits.

3. Plastic sheet mulching technique

Controlled irrigation can be implemented to avoid the risk of drought. Thus, the national and local governments have promoted the development of sprinkler systems since the 1960s. Today, such systems are installed in many major citrus production areas.

Unlike the possibility of protecting against drought, it is rather difficult to avoid the risks of excessive moisture in open fields. As a technique for preventing rainwater from penetrating the soil, covering the ground surface with plastic sheeting (i.e., sheet mulching) is one of the most widely used techniques due to its effectiveness and simplicity (Iwagaki 1997). In most cases, certain plastic sheeting products, which are water repellent, permeable to vapor, and have high whiteness, are used for sheet mulching. Although sheet mulching is often effective in improving the quality of fruits, it is also associated with some disadvantages. For example, when there are several consecutive hot, dry days, sheet mulching can cause excessive water stress on trees. Moreover, hard labor is required to lay mulch sheets over the ground on a hot summer day.

4. Development of a novel method for satisfactory control of tree moisture

In order to eliminate the disadvantages of sheet mulching, a novel method was proposed in 2000 for using drip irrigation in conjunction with year-round sheet mulching (Morinaga et al. 2004a, 2005, 2010) (Fig. 1). The method is called the *marudori* method, based on the Japanese pronunciation of "mulch" (*maruchi*) and "drip" (*dorippu*). Fertigation is also generally applied in this method. The major advantages of the method are that the utilization of drip irrigation makes it possible to control the moisture of trees rather precisely, the application of fertigation makes fertilization more effective and saves fertilizer, and year-round mulching substantially reduces labor.

In this article, we review the technical aspects and benefits of the marudori method. We also discuss the future challenges associated with application of this method in citrus farming.

Description of the method

1. Hardware

(1) Plastic sheet

The marudori method generally uses the same type of plastic sheeting (Fig. 2) as used in conventional sheet mulching. The sheeting is water repellent to prevent rainwater from penetrating the soil, permeable to vapor to promote drying of the soil, and white in color to enhance the reflection of sunlight, which is thought to promote the coloring of fruit rind.

Different types of sheeting may also be used when moisture in the trees must be high to prevent water stress, as is necessary for cultivating some late-maturing cultivars or using the method for promoting the growth of young trees. Thus, the type of sheeting in these cases should be (i) permeable to water and able to utilize rainwater as well as irrigated water, (ii) impermeable to both water and vapor, and able to retain soil moisture, or (iii) colored other than white and able to absorb solar thermal energy efficiently.

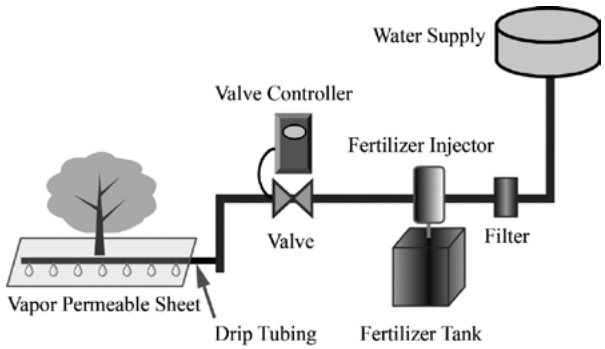

Fig. 1. Schematic of the hardware set required for the marudori method

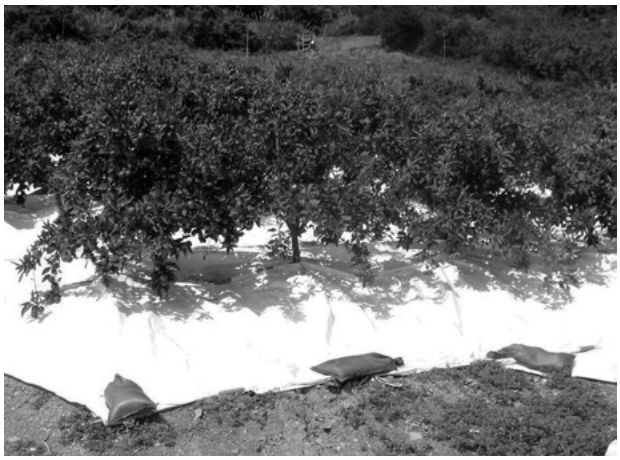

Fig. 2. Plastic sheeting for sheet mulching in a citrus orchard

(2) Drip irrigation devices

Although various types of tubing are available (FAO SAFR 2002a), pressure compensating drip tubing is most widely used in the marudori method. The smooth shape makes this tubing convenient for placement under the mulching sheet, and uniform discharge promotes use of this tubing in orchards located along slopes. Such complementary devices as battery-powered actuator valves, timer controllers for valves, filters to prevent tube clogging, and other devices are also used, similar to the design of common drip irrigation systems (Phocaides 2007).

Many growers encounter difficulty in the design of drip irrigation lines, given the level of skill required. To address this drawback, one of the authors has developed design support software for distribution to the public (NARO). This software indicates the calculated values and adequacy of pressure at any laterals using the given topography and equipment data. We will provide information about ordering this software to any interested individuals.

(3) Fertilizer injector

Fertigation is a technique of injecting fertilizer along the irrigation lines and commonly applied in the marudori method. For the fertilizer injector, the water-driven piston pump (FAO SAFR 2002b) is commonly used and very precise for injecting fertilizer. The venturi type is less precise, but also costs less and offers an alternative when cost is a major factor in applying the marudori method.

(4) Water supply

In the marudori method, there are several ways of arranging the water supply; however, using this method could prove challenging without an available and appropriate water supply. The most convenient water supply is a pipe under a certain pressure, from which water can be guided directly into the drip tubing. In many cases, the water supply may be a source of free-surface water, such as a pond, stream, well, or concrete cistern.

Pressure must be applied to the water when the water supply lacks sufficient pressure (i.e., 0.3-0.9 MPa in many cases). A relatively small pump connected directly to the drip tubing would be adequate for an orchard located on flat ground or a gentle slope. A head tank and a solar driven pump would be convenient for remote orchards on slopes (Shimazaki et al. 2014).

2. Watering and fertilizing

(1) Basic scenario

Watering and fertilizing with the marudori method during the cultivation of satsuma mandarin in southwestern Japan, where most satsuma mandarin production areas are located, are generally carried out according to following schedule. About 1 mm of water is applied about once every two days for the purpose of supplementing water and fertilizing in the spring and early summer. Small amounts of water are applied frequently to maintain moderate water stress over trees and raise the sugar content of fruits in the summer. Slightly more water is then applied to reduce the acidity of fruits in the autumn. Water with fertilizer is applied to recover the nutritional state of the trees after harvest until water absorption of the roots becomes very low due to the low temperature. Watering is then done as needed to prevent the trees from drying out excessively in the winter (Morinaga et al. 2004a).

(2) Small frequent watering in summer and autumn

Tree moisture control in the summer and autumn is critical for producing high-quality satsuma mandarin fruit. During this period, moderate water stress must be maintained over the trees; therefore, watering is done by applying less water at higher frequencies, such as once a day, as compared to the watering amount and frequency required for other methods. The appropriate amount of water for a single watering and frequency should be determined according to the moisture status of the trees. However, such moisture status is not easy to evaluate, even for skilled growers or with the aid of specialized sensing devices. Several studies published by our research group have focused on the development of an algorithm for watering control (Hoshi et al. 2011) and an approach to scheduling watering based on evapotranspiration (Nesumi et al. 2014).

(3) Dependence on farmers' skill

Each tree in an orchard will respond differently to changes in soil moisture conditions. In addition, not all trees will exhibit detectable changes with slight variations in tree moisture. Therefore, optimizing the irrigation regime for satsuma mandarins in summer and autumn may be difficult. Such a skill would involve comprehensive decision-making abilities based on prior experiences and insights, as well as scientific knowledge. Thus, the development of an objective method for tree moisture management is critical.

Benefits of using the marudori method

1. Merits of drip irrigation

Because drip irrigation is an important element of the marudori method, the merits of drip irrigation also apply to the marudori method. These merits include the efficient application of water and fertilizer, reduced leaching, lower requirement for water energy, a smaller source of energy (e.g., dry cell battery) for automated watering, uniform distribution of water, and improved soil moisture control.

2. High-quality fruits

The most important benefit of this method is the production of satsuma mandarin fruit with a high sugar content—the most crucial factor affecting the quality of fruits (Fig. 3). Another very important factor is moderate and balanced acidity. Appropriate watering in autumn prevents

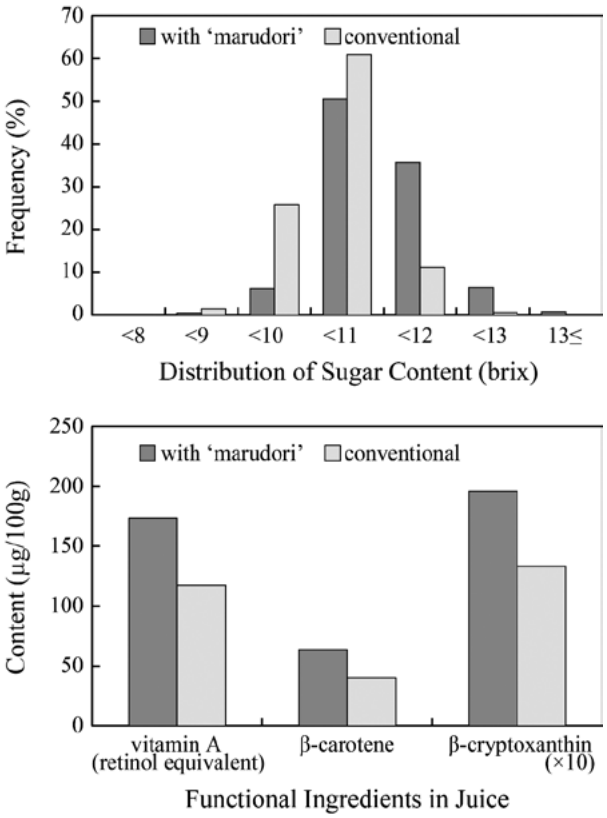

Fig. 3. Effects of the marudori method on fruit quality (Morinaga et al. 2004b)

excessive acidity, which is often caused by strong water stress (Morinaga et al. 2004b, Kriston-Vizi et al. 2008, Shimazaki et al. 2013). In addition, the content of functional ingredients, such as beta-cryptoxanthin or beta-carotene, tends to be proportional to the sugar content (Morinaga et al. 2004b) (Fig. 3). Late-maturing cultivars are also affected by tree moisture control, though many of these types of trees require sufficient water rather than water stress during the summer and autumn. The growers of all citrus cultivars would therefore benefit from application of this method, so as to achieve improved fruit quality.

The production of high-quality fruits would result in increased fruit sales. Many citrus growers sell their products through fixed fruit sorting centers that are generally managed by agricultural cooperatives. These co-ops determine producer prices according to the wholesale price of fruits. Satsuma mandarins cultivated with the marudori method and of sufficiently high quality are generally priced considerably higher than fruits cultivated using conventional methods. For example, Saito et al. (2009) showed that producer prices of marudori-cultivated fruits are about double that of fruits cultivated using conventional methods.

We and some other researchers have reported the effects of applying the marudori method on late-maturing citrus, as described below. Well-controlled moderate water stress in the summer would result in fruits with higher sugar content in 'Setomi', 'Harehime' and 'Shiranui' cultivars (Iwasaki 2011, 2012). Additionally, adequate watering in autumn would result in sufficient reductions in acidity. Moreover, cultivating lemon with a sufficient amount of watering in summer would result in increased production (Akasaka et al. 2012).

3. High-efficiency fertilization

Most citrus growers apply solid fertilizer in conventional cultivation. In contrast, the marudori method utilizes liquid fertilizer applied through drip tubing in a process called fertigation. Because the application of fertilizer can be strictly controlled to not exceed the absorption rate of roots, fertilizer can be absorbed promptly and efficiently. In field experiments using satsuma mandarin trees on lysimeters, Kusaba et al. (2006a) found that leached nitrogen represents a small portion of the applied nitrogen for which the annual amount is equal to the amount absorbed by trees cultivated traditionally (Table 1). Thus, the efficiency of fertilizer is very high in fertigation, resulting in many benefits, as described below.

Interestingly, Kusaba et al. (2004) found that satsuma mandarin trees cultivated with the marudori method have more fibrous roots than trees cultivated with conventional methods. In addition, the fibrous roots have high respiratory activity (Table 2). These observations may be explained by the maintenance of appropriate tree moisture levels in addition to fertigation.

According to these previous works, the marudori method promotes the growth of trees; therefore, introducing this method for replanting orchards has been shown to yield fruit-bearing trees within three rather than five years, for example (Tanada & Nesumi 2014). And because the roots absorb most of the fertilizer as mentioned above, the environmental impact remains low. Furthermore, the annual usage of fertilizer can be substantially reduced as mulching prevents the growth of weeds, which may interfere with tree nutrition, while fertigation further promotes efficient fertilization.

Application of the method in Japan

In 2006, Kusaba et al. (2007) conducted a questionnaire survey to evaluate the area of satsuma mandarin orchards cultivated using the marudori method or drip irrigation. This survey revealed that drip irrigation was used throughout an area of 430 ha, including 260 ha cultivated using sheet mulching along with drip irrigation. According to a survey conducted by the Ministry of Agriculture, Forestry and Fisheries in 2006, satsuma mandarin orchards in Japan accounted for a total area of 53,500 ha. Therefore,

Table 1. Runoff rate of nitrogen in fertilizer for the marudori method (satsuma mandarin) (modified from Kusaba et al. 2006a)

Date	Applied nitrogen (g N/4 trees)	Runoff nitrogen (%)	
		NO_3-N	T-N
Apr 16, 2004 to Nov 4, 2004	276	1.6	1.8
Nov 5, 2004 to Apr 13, 2005	64	3.8	5.8
Entire crop year, 2004	340	2.0	2.6

Table 2. State of fibrous roots in the marudori method (satsuma mandarin) (Kusaba et al. 2004)

Location	Root length (cm/g FW)	Respiratory activity in November (μmol O_2/g DW/h)
Just under emitter	367	31.5
Separate from emitter	234	26.6
Control (conventional)	255	17.2

the marudori method had been adopted in about 0.5% of orchards in Japan as of 2006. It is believed that the prevalence of this method has been increasing; however, more current numbers are not available at this time.

Future challenges

1. Management of watering and fertilizing

As mentioned above, tree moisture management is an important and challenging issue in the cultivation of citrus fruits. In addition, nutrition management is also critical. The understanding of these features by particularly skilled growers cannot be achieved by other growers because the knowledge is mostly tacit and the technique mostly implicit. Moreover, the precise control of watering and fertilizing is difficult using conventional methods. Therefore, the development of explicit techniques based on explicit knowledge could enable growers to develop a practical understanding, and more sophisticated techniques to control tree moisture and tree nutrition could foster the development of such understanding. Many studies are focused on transforming the tacit knowledge and skills of growers into explicit knowledge (Hoshi 2007, Hoshi 2011, Kusaba et al. 2006b, Nesumi et al. 2014), and these studies generally aim to develop tree moisture and nutrition management methods for high-quality fruit production.

2. Application of information and communications technology (ICT)

Once objective moisture and nutrition management methods based on sufficient explicit knowledge become available, ICT may prove useful in developing more appropriate management systems to promote better decision-making and device operation than could be achieved by skilled growers alone. Moreover, ICT may also offer applications in monitoring devices, sensing fields, and supporting economic decision-making, among others.

The application of ICT can be expected to proceed at an accelerated rate. Indeed, the Japanese government is currently promoting the introduction of ICT to agriculture in order to realize so-called “aggressive agriculture,” thus motivating researchers and engineers to utilize ICT.

3. Technique for arrangement of water supply

In Japan, many citrus orchards have no irrigation facilities installed; however, the marudori method requires a water supply having sufficient pressure. Hence, the lack of an appropriate water supply often poses an obstacle that must be overcome when using the marudori method. Therefore, the development and application of various techniques may improve water availability, including the reuse of rainwater and conservation of water quality.

4. Reducing costs associated with the marudori method

Finally, the most important challenge facing growers is how to lower the costs of the marudori method (Saito et al. 2009). The introduction of various types of hardware inevitably increases the start-up costs associated with implementing the method. Given the rather small market

for fertigation devices in Japan, the prices of devices are relatively high, with few alternatives available when selecting devices. Thus, despite the importance of reducing costs, this situation remains a major obstacle and highlights the need for the development or discovery of devices or techniques contributing to cost reduction.

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