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Effect of soil moisture condition and irrigation regime on bioelectric potential of crops at different growth stages

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Abstract
The objective of this study was to evaluate the effect of soil moisture condition and irrigation regime on the bioelectric potential of crops with different growth stages. The bioelectric potential of broccoli (*Brassica oleracea* var. *italica*) plants at the initial and mid-growth stages was measured under different soil moisture conditions and irrigation regimes using pot experiments. The results indicated that the bioelectric potential varied as a function of the soil moisture, irrigation regime, and stage of crop growth. To more accurately clarify the relationship among the changes in bioelectric potential, soil moisture, and crop growth stage, a wavelet analysis was performed. The results showed that the bioelectric potential changed as a function of both soil moisture and crop growth stage. Further, the dominant frequency band under wet soil condition at the initial growth stage before irrigation had a large wavelet coefficient compared with the results obtained under the other soil moisture conditions. In the mid-growth stage, the dominant frequency bands under wet and intermediate soil conditions were similar before and after irrigation. However, the characteristics of the wavelet conversion chart under dry soil conditions changed after irrigation. The results showed that the growth stage and irrigation regime both affect the crop bioelectric potential. Although clarifying the relationship among the bioelectric potential, soil moisture and crop growth stage was difficult, the wavelet analysis was shown to be effective for evaluating the effect of soil moisture and crop growth stage on the bioelectric potential. The results of the analysis indicated the bioelectric potential could be an important indicator for managing soil moisture and for optimizing irrigation regimes.

Key words: Soil water consumption, water stress, plant electrical signal, wavelet analysis, SPA (Speaking Plant Approach), time series analysis, frequency characteristic, plant responses to environmental stress, irrigation scheduling, water requirement of plant.

Introduction

Plants are sensitive to external stimuli and changes in their environment and plant bioelectric potential can be used to evaluate the extent to which plant physiology is affected by such changes[1-4]. Numerous studies have examined the relationship between the plant bioelectric potential and changes in the surrounding environment. Some researchers [5-8] studied the effect of light on plant bioelectric potentials, and plant responses to air pollution can be evaluated by examining plant bioelectric potentials [9, 10]. The bioelectric potential was affected the gas exchange of plant[11]. The effect of the thermal stress on the electrical signaling of *Aloe vera* was evaluated [12].

Soil moisture condition is one of the most important environmental factors for crop growth and yield. The crop responses to the water stress have been evaluated using the bioelectric potential. The difference of the bioelectric potential in avocado between wet and dry soil conditions was evaluated[13]. The stimuli of the irrigation induced the fluctuation of the bioelectric potential in various fruit trees as documented by several authors[14, 15]. The bioelectric potential changes in non-irrigated and well-watered fruit trees was reported [16]. Irrigation regime induced also the change of the bioelectric potential in grapevines as described [17]. The difference of the crop bioelectric potential between wet and dry soil conditions by volumetric soil moisture content was evaluated in these studies. Managing optimal soil moisture conditions by considering changes in plant bioelectric potential will likely facilitate the optimization of irrigation regimes in agriculture. However, to clarify the effect of the soil moisture condition on the crop bioelectric potential, soil moisture tension should be used as an indicator of soil moisture condition instead of the volumetric soil water content, and the irrigation regimes should be determined considered soil moisture tension because the water stress of crops can be evaluated using the soil moisture retentivity. Additionally as water requirements of crops change with the growth stages, the irrigation regime should be determined with respect to not only the soil moisture condition or water consumption but also the crop growth stages[18−22]. The relationship between the soil moisture condition and the bioelectric potential of crops should be evaluated, considered the irrigation regimes and crop growth stages.

The objective of this study was to evaluate the effect of soil moisture condition and irrigation regime on the bioelectric potential in potted broccoli (*Brassica oleracea* var. *italica*) plants. Crops at the initial and mid-growth stages were subjected to different soil moisture condition and the bioelectric potential was measured before and after irrigation. Three irrigation regimes were determined with respect to the soil moisture tension to measure the bioelectric potential under the different water stress conditions. Some researchers introduced the various mathematical analyses to clarify the characteristics of fluctuation of crop bioelectric potential induced by the environmental changes [23, 24]. The time series analyses are effective to define the characteristic of the fluctuation of the plant bioelectric potential as described in these studies. In this study, a wavelet analysis was performed to clarify the bioelectric potential characteristics under different irrigation regimes.

Materials and Methods

Fig. 1 shows the experimental apparatus used in this study to measure the bioelectric potential. The broccoli plants at 30 and 90 days after planting were potted in individual 1/5000-a Wagner's pots with granite soil. The bioelectric potential was measured every 50 µs using disk electrodes attached to a leaf and stem of individual crops. To clarify the effect of soil moisture on the bioelectric potential of crops in different growth stages, different water management regimes were employed to control soil moisture in the experiment (Table 1).

Fig. 2 shows the soil water retention curve of the granite soil used in pot experiment. Crops were irrigated using tap water when soil moisture reached pF 1.5, pF 2.2 and pF 2.8, respectively. Tensiometers with a pressure gauge (DIK-8333, Daiki, Japan) were placed at the depth of 20 cm in all pots to determine the timing of irrigation as shown in Table 1. As the soil moisture conditions in pF 1.5 and 2.8 represent the field capacity and depletion of soil moisture content for optimum crop growth, respectively, the wet and dry soil conditions were maintained under each treatment. All

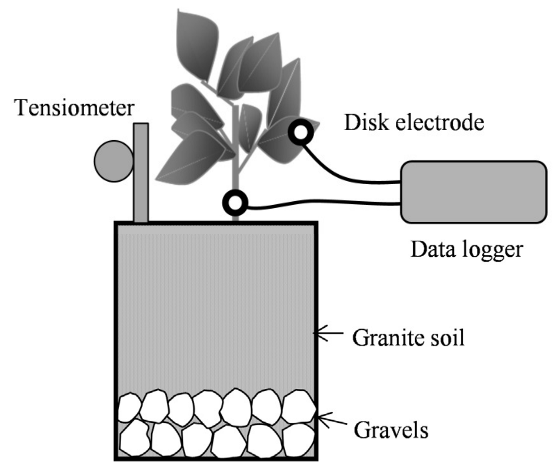

Figure 1. Experimental apparatus used to measure crop bioelectric potential.

Table 1. Water management regime and experimental conditions.

Treatment	Irrigation regime	Soil moisture conditions	Growth stages
1	pF 1.5	Wet	Initial (30 days after planting)
2	pF 2.2	Intermediate	
3	pF 2.8	Dry	
4	pF 1.5	Wet	Mid-growth (90 days after planting)
5	pF 2.2	Intermediate	
6	pF 2.8	Dry	

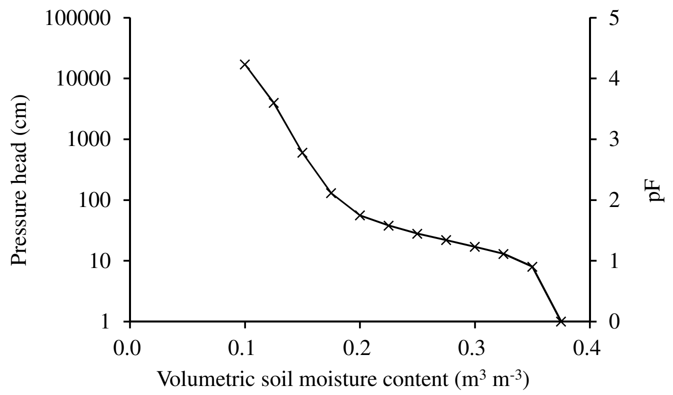

Figure 2. Soil water retention curve of granite soil used in pot experiment.

pots were placed in an artificial climatic chamber (LPH-410S, Nippon Medical & Chemical Instruments Co., Ltd., Japan) to ensure that experiments were conducted under identical conditions. Daytime (i.e. 07:00 am to 17:00) air temperature and humidity conditions were set to 30°C and 60%, respectively. Nighttime air temperature and humidity conditions were 25°C and 65%, respectively.

Given the marked variability observed in the original bioelectric potentials, a wavelet analysis was performed to clarify the relationship between the bioelectric potential and the different soil moisture conditions. The wavelet analysis is effective to display the scale-dependent structure of a signal which varies with time [5]. The wavelet coefficient ω can be described as follows:

$$\omega_k^{(j)} = 2^{j/2} \int_{-\infty}^{\infty} f(t)\overline{\phi\left(2^{-j}t - k\right)}dt \qquad (1)$$

where f is the data function, ϕ is the mother wavelet function, j is the level, and k is the position (or time).

Results and Discussion

Relationship among bioelectric potential, soil moisture, and growth stage: Figs 3-6 show the temporal changes in the bioelectric potential measured in each experimental pot. The figures show that the bioelectric potential changed frequently and markedly. In the crops at the initial growth stage, the ranges of these fluctuations were small and the periodicities were relatively distinct, compared with the data obtained from crops at the mid-growth stage. In crops at the initial growth stage, the ranges of the fluctuations in bioelectric potential under wet soil conditions (Figs 3a and 4a) were wider than those observed for the other irrigation treatments. The range of the bioelectric potential under the wet soil condition in crop at the initial growth stage decreased after irrigation. The fluctuations in the bioelectric potential under intermediate and dry soil conditions were not affected by the irrigation regime as shown in Figs 3b, 3c, 4b and 4c. As shown in Figs 5a and 6a, in mid-growth stage crops, the differences in the range and periodicity of the fluctuations in bioelectric potential were not marked before or after irrigation under the wet soil condition. The similar result was obtained under the dry soil condition as shown in Figs 5c and 6c. However, under the intermediate soil conditions shown in Figs 5b and 6b, the range of bioelectric potential fluctuations before irrigation was more apparent before irrigation compared to after irrigation.

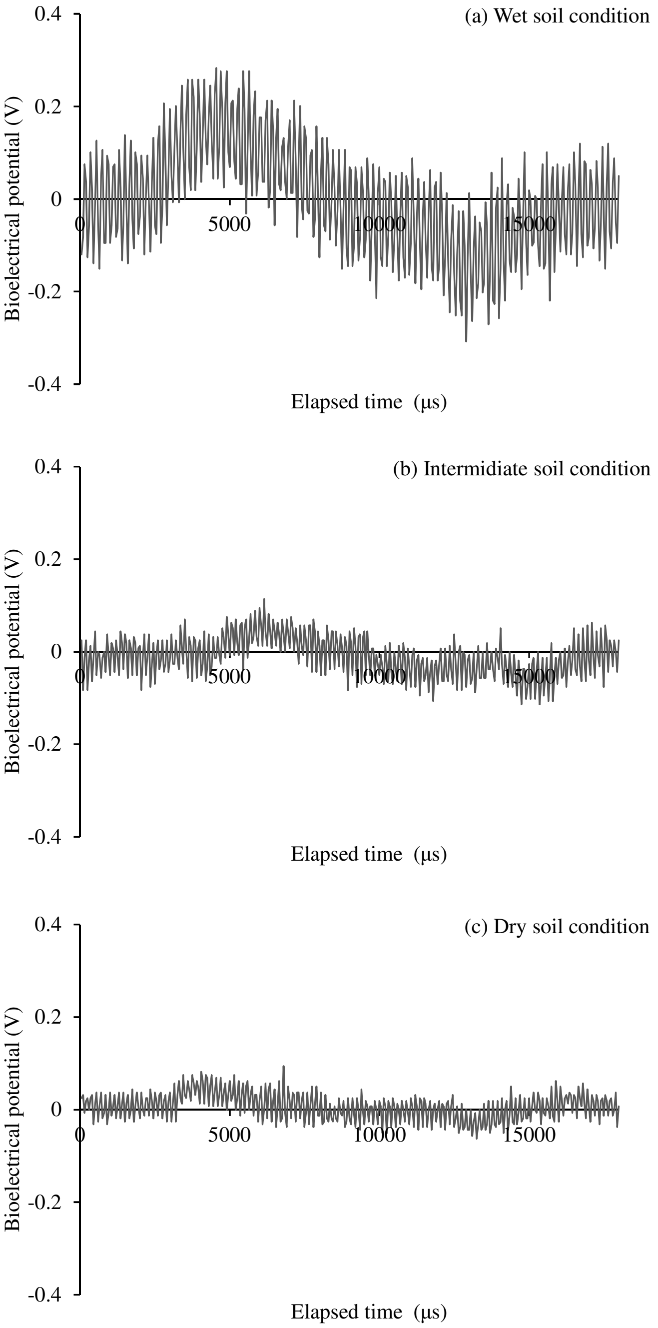

Figure 3. Temporal changes in bioelectric potential in crops at the initial growth stage before irrigation.

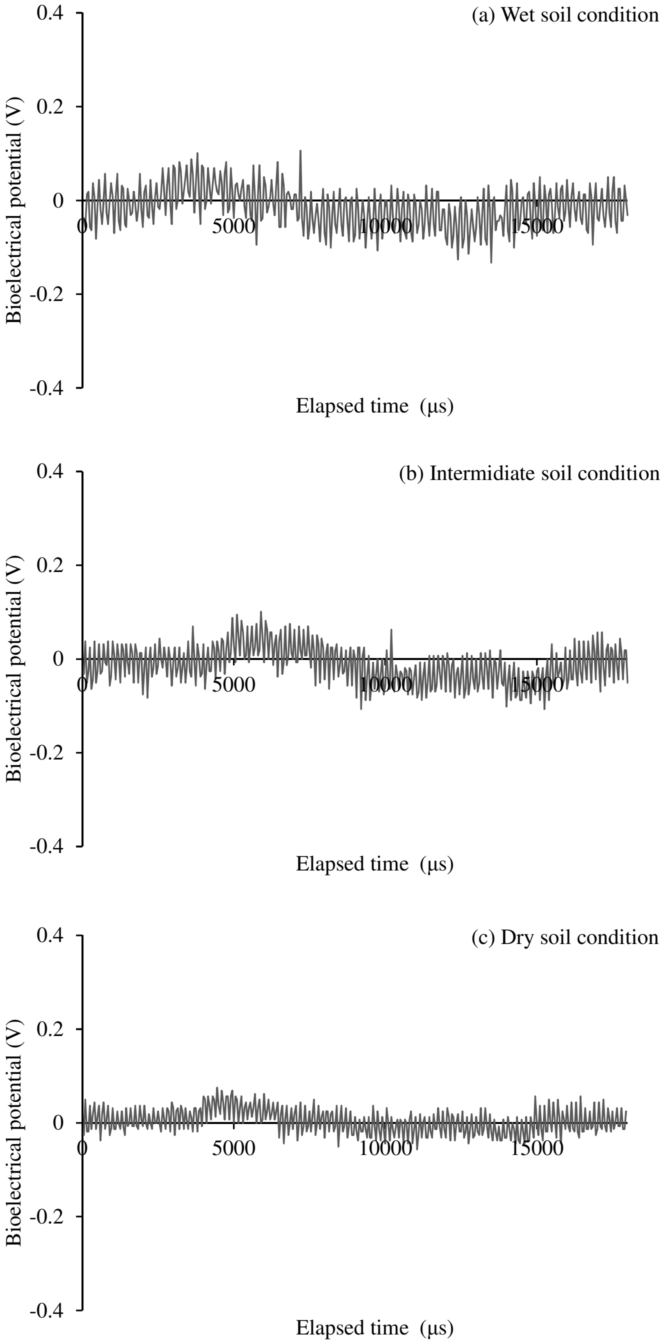

Figure 4. Temporal changes in bioelectric potential in crops at the initial growth stage after irrigation.

Characteristics of bioelectric potential variation: Figs 7- 10 show wavelet conversion charts obtained for variations in bioelectric potential before and after irrigation. The wavelet coefficients were estimated using Eq. (1) and the data shown in Figs 3-6.

Fig. 7 shows the wavelet conversion chart for the bioelectric potentials in initial growth stage crops before irrigation. This figure shows that the dominant frequency band changed with soil moisture. For example, the dominant frequency band under the wet soil conditions shown in Fig.7a has a distinctive characteristic compared with those obtained for the intermediate and dry soil conditions shown in Fig. 7b-c and the magnitude of the wavelet coefficient is large compared to that obtained for other soil moisture conditions. Fig. 8 shows the wavelet conversion chart for the bioelectric potential of crops at the initial growth stage after irrigation. The figure shows that the characteristics of the wavelet conversion chart changed as a function of irrigation regime and the obtained data were not remarkable compared with the results obtained before the irrigation shown in Fig. 7.

Fig. 9 shows the wavelet conversion chart obtained for crops at the mid-growth stage before irrigation. Although the magnitude of the wavelet coefficient differed between Fig. 9a and b, the dominant frequency bands under the wet and intermediate soil conditions were similar. Compared with these soil moisture conditions (Fig.9a -b), the wavelet conversion chart obtained using the data for the dry soil conditions (Fig. 9c) has the characteristic of the low frequency band. Fig. 10 shows the wavelet conversion chart obtained for crops at the mid-growth stage after irrigation. Fig. 10a-b shows that the dominant frequency bands under wet

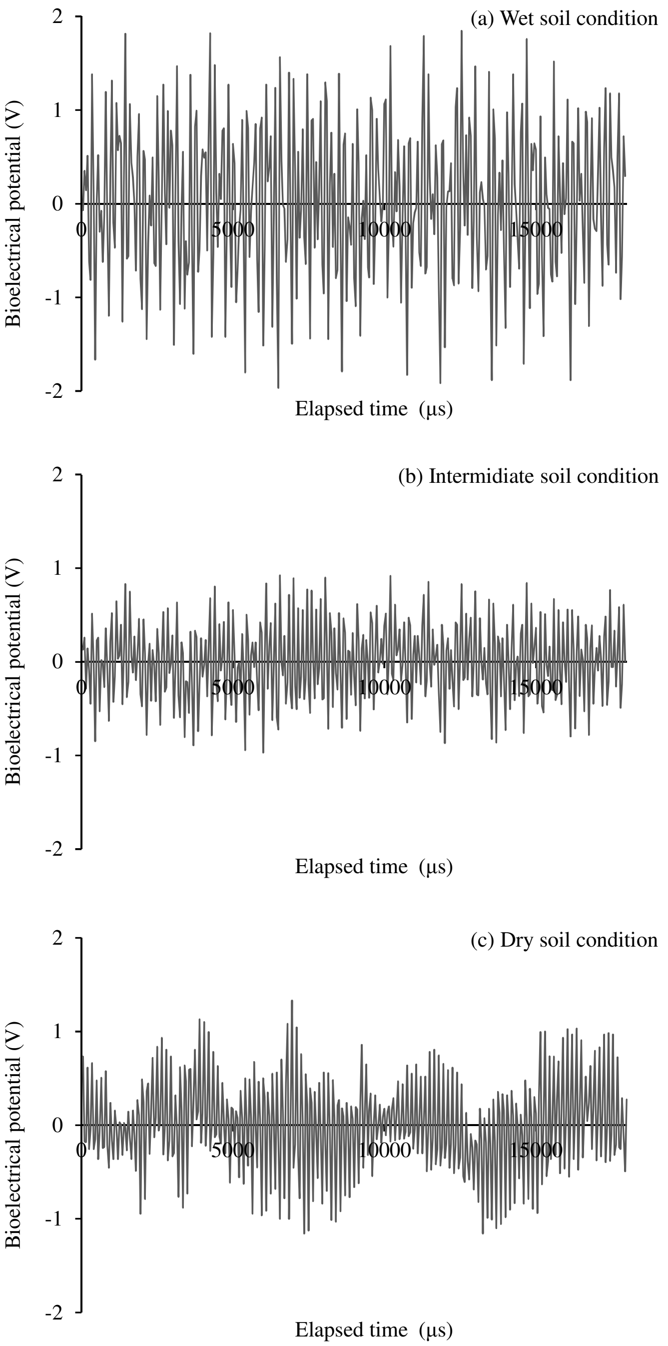

Figure 5. Temporal changes in bioelectric potential in crops at the mid-growth stage before irrigation.

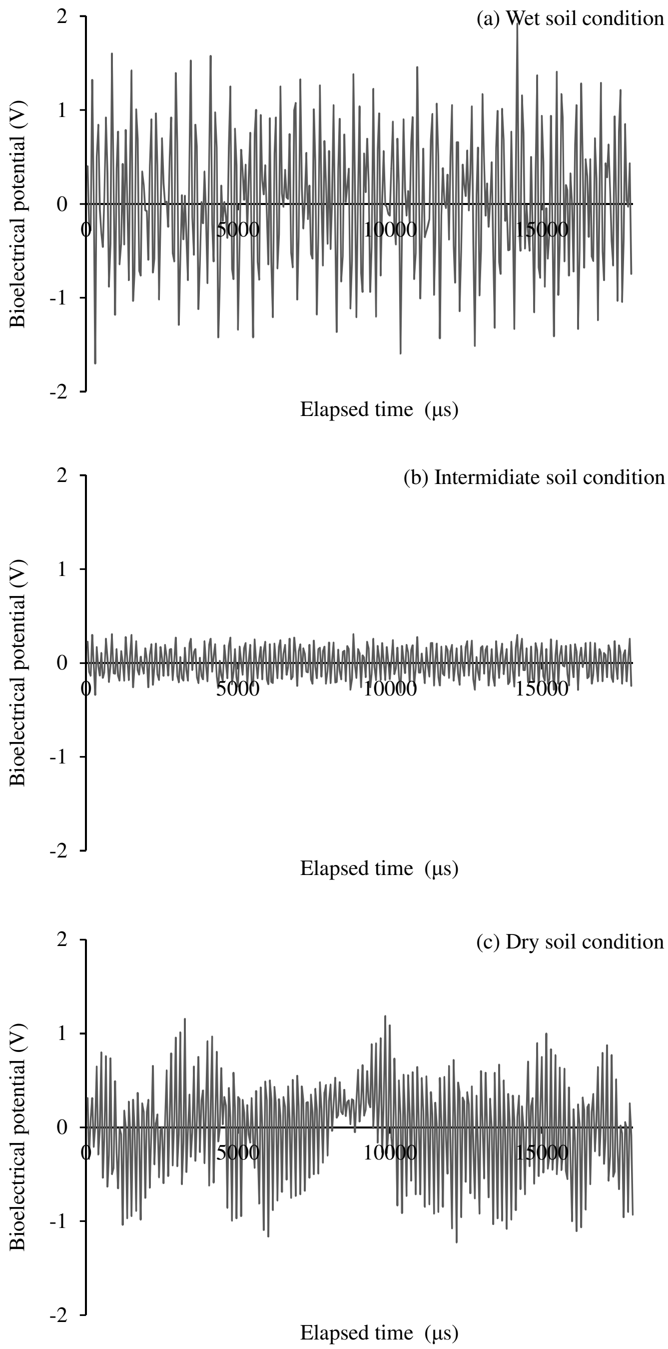

Figure 6. Temporal changes in bioelectric potential in crops at the mid-growth stage after irrigation.

and intermediate soil conditions are similar. However, the characteristics of the dominant frequency bands differed from the results shown in Fig. 9a-b. The dominant frequency band under the wet soil conditions shown in Fig. 10c was small, and the characteristics of the wavelet conversion chart differed from those measured before irrigation (Fig.9c).

Conclusions

To evaluate the effect of soil moisture on the crop bioelectric potential, pot experiments were conducted in broccoli plants at the initial and mid-growth stages under different soil moisture conditions. The results indicated that the bioelectric potential varied as a function of the soil moisture, irrigation regime, and stage of crop growth. Given the marked variations that existed in the original bioelectric potential data, a wavelet analysis was employed to clarify the changes in bioelectric potential in response to differences in soil moisture and crop growth stage. The results showed that the dominant frequency band changed in response to soil moisture and crop growth stages. For example, the dominant frequency band under wet soil conditions at the initial growth stage before irrigation was distinctive compared with those obtained for the intermediate and dry soil conditions and the magnitude of the wavelet coefficient was large compared with that obtained for the other soil moisture conditions. After irrigation, the wavelet conversion chart obtained for the initial growth stage of crops revealed that the dominant bioelectric potential frequency

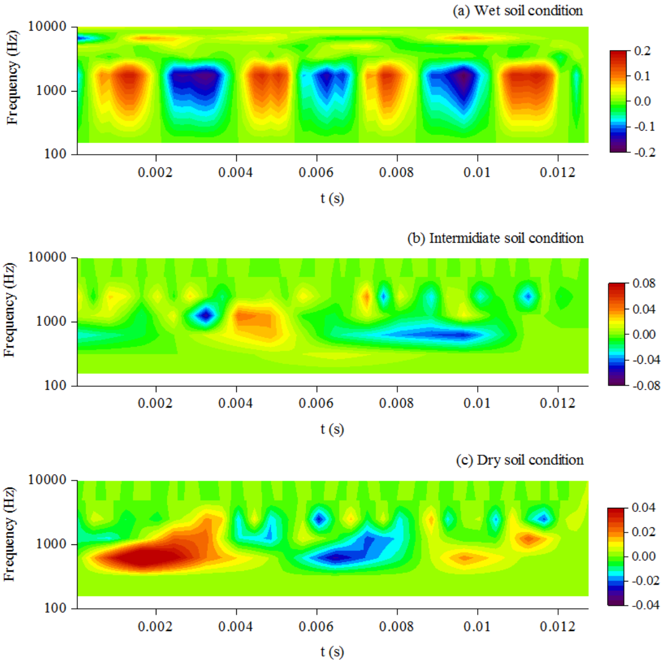

Figure 7. Wavelet conversion chart for the bioelectric potential in crops at the initial growth stage before irrigation.

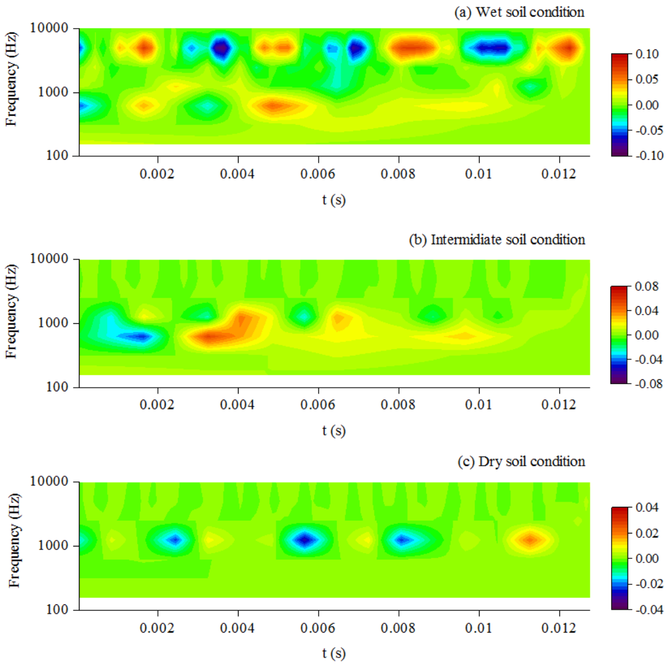

Figure 8. Wavelet conversion chart for the bioelectric potential in crops at the initial growth stage after irrigation.

bands were different from those obtained before irrigation but the characteristics of the wavelet conversion chart did not differ markedly from the results obtained before irrigation. In the mid-growth stage crops, the dominant frequency bands under wet and intermediate soil conditions had similar characteristics before and after irrigation. However, the characteristics of the wavelet conversion chart for dry soil conditions was changed with the irrigation and differed from those obtained for the wet and intermediate soil conditions. These results indicate that the crop growth stage and the irrigation regime both affect the crop

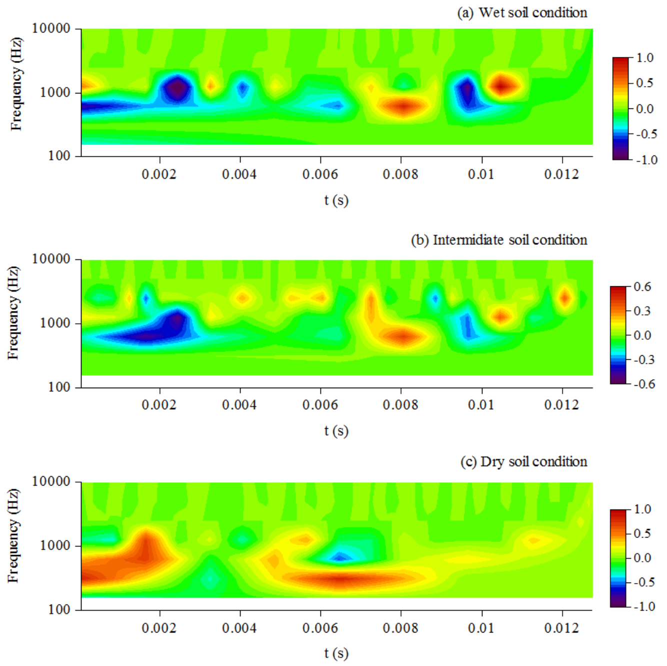

Figure 9. Wavelet conversion chart for the bioelectric potential in crops at the mid-growth stage before irrigation.

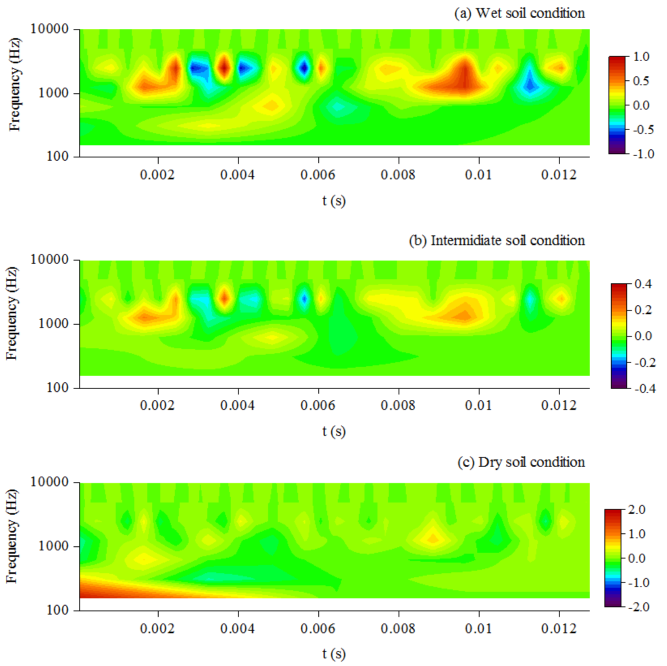

Figure 10. Wavelet conversion chart for the bioelectric potential in crops at the mid-growth stage after irrigation.

bioelectric potential. Although clarifying the relationship among the bioelectric potential, soil moisture and crop growth stage was difficult, the wavelet analysis was shown to be effective for evaluating the effect of soil moisture and crop growth stage on the bioelectric potential. Crops reactions of different growth stages to changes in soil moisture can thus be evaluated using the bioelectric potential. The results of the analysis indicated the bioelectric potential could be an important indicator for managing soil moisture and for optimizing irrigation regimes. Future research will be extended to other crops and soil moisture conditions.

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