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# Impact of Microwave Soil Heating on the Yield and Nutritive Value of Rice Crop

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Received: 30 April 2019; Accepted: 24 June 2019; Published: 27 June 2019



**Abstract:** Microwave (MW) soil heating has been shown to deplete the soil weed seedbank and increase crop productivity. However, the impact of MW soil heating on the nutritive value of crops is unknown. In this study, two field trials were conducted to evaluate the effect of pre-sowing MW soil treatment with a duration of 60 s and an untreated control, which were assigned in a randomized complete block design with five replicates at two locations, on the yield and nitrogen (N) accumulation pattern of rice crops. At Jerilderie site, soil heating at up to 70–75 °C significantly ( $p < 0.09$ ) increased the rice biomass yield by 43.03% compared with rice biomass yield in untreated soils, while at Dookie site no significant increase in biomass yield was detected. Dry matter digestibility (DMD), ash, and N% did not change, whereas the N accumulation in dry biomass was significantly ( $p < 0.09$ ) higher at both sites (8.2% at Dookie and 43.4% at Jerilderie) and N use efficiency (10–40%) increased in response to MW soil treatment. The current study suggests that MW soil treatment can potentially enhance the crop productivity and N accumulation in dry biomass under field conditions. Future research is needed to understand the impact of MW soil heating on the productivity and nutritive value of different fodder crops under field conditions.

**Keywords:** new technology; soil temperature; crop growth; forage quality; sustainable food production

## 1. Introduction

The incorporation of new technologies in the agriculture industry can help in sustaining food production [1]. To this end, pre-sowing microwave (MW) soil heating (i.e., 70–80 °C) has been shown to control weed infestations [2–5], kill the weeds' reproductive parts, and their seeds to a depth of 6 cm [6]. The MW technology was proposed for weed control back in the late 1900s, and the researcher involved in technology development came to the conclusion that large-scale application of MW is impractical [3,7,8]. Later, chemical usage for weed control shifted the weed flora to resistance and farming practitioners moved toward an alternative weed control technology.

Recently, in Australia, a prototype has been developed to apply the MW energy between crop rows to suppress post-emergence weeds (normally at 3–5 leaves stage) and this prototype has also been employed to sterilize soil's weed seed banks before crop sowing. It has four independently controlled 2-kW MW generators, operating at 2.45 GHz [9]. The maximum time required to achieve the target temperature is dependent on the soil conditions, and with this MW weed killer system 60–90 s exposure is enough to achieve the required temperature for soil sterilization. The rapid increase in soil temperature distinguishes MW technology from the numerous thermal technologies and this characteristic of MW technology (i.e., real time heating) has benefitted the technology adaptation for soil sterilization under field conditions.

In addition to weed suppression, MW soil treatment has been shown to increase crop growth and yield, either by reducing weed–crop competition for resources [10], or by altering the availability

of yield-limiting nutrients [11–14]. However, the exact mechanism behind this phenomenon is still unknown. One of the key explanations is that transient heat mediates the mineralization of indigenous organic nitrogen (N) into ammonia ( $\text{HN}_3$ ) [15,16], and is subsequently converted to nitrate ( $\text{NO}_3^-$ ) via nitrification, which could essentially benefit crop growth and development. In addition to soil sterilization, the nutrient uptake and accumulation pattern in response to MW soil treatment is unknown, but may be crucial in order to forecast the value-added benefits of this technology in the agricultural industry.

It has been reported that MW treatment of fodder (to different temperature regimes) can increase the dry matter digestibility (DMD) compared with untreated fodder [17,18]. However, the effect of MW soil treatment on the nutritive value of fodder, under field conditions, is unknown despite it being crucial to understanding how, and to what extent, soil heating can change the productivity and quality of crops. Therefore, the main objective of this study was to evaluate the impact of precropping MW soil treatment on nutritive value and N accumulation of rice crop, under field conditions. For this study, we subsampled rice, (which is an important crop worldwide due to its biomass use as a feed in developing countries) biomass from two trials conducted separately at two different locations to measure whether soil heating has changed the quality characteristics of rice crop or not. Rice biomass data were used from Khan, Brodie, and Gupta [9] for downstream analysis.

## 2. Material and Methods

Two field trials were conducted between October 2016 and April 2017 in a randomized complete block design, with five replications, at two different locations: Dookie, Victoria (36.395° S, 145.703° E) and Jerilderie, New South Wales (35.36° S, 145.75° E). According to Australian soil classification, Dookie experimental site soil is classified as a Yellow Subnatric-Dystrophic Sodosol (medium clay) and Jerilderie site soil is classified as Grey Vertosol (heavy clay) [19]. Soil properties of both experimental sites are given in Table 1. Further, the details of the experiments are given in Khan, Brodie, and Gupta [9]. Briefly, an experimental MW weed killer has been designed to eradicate the weeds between crop rows and for preemergence soil treatment. However, in this study, two-treatment durations of zero (untreated control) and 60 s were assigned in a randomized complete block design, with five replicates, at both study locations. The selection of 60 s treatment duration was based on the findings of the previous field trials by Khan, et al. [20], where a treatment duration of 120 s with a MW source of 0.7 kW (i.e., low energy) was used.

**Table 1.** Physio-chemical properties of soils of two different locations. Note: This table is adapted from a previously published study, see Khan, Brodie, and Gupta [9].

Soil Properties	Locations		Units
	Dookie, Victoria	Jerilderie, New South Wales	
pH (1:5 H <sub>2</sub> O)	5.6	7.0	-
Organic Carbon	1.2	0.77	%
Nitrate-Nitrogen	3.6	<0.55	mg kg <sup>-1</sup>
Ammonium-Nitrogen	3.2	10	mg kg <sup>-1</sup>
Phosphorus (Colwell)	15	55	mg kg <sup>-1</sup>
Electrical Conductivity	0.7	0.6	dS m <sup>-1</sup>
Cation Exchange Capacity	5.21	21.8	cmol (+) kg <sup>-1</sup>
Available Potassium	200	340	mg kg <sup>-1</sup>
Calcium/Magnesium Ratio	2.5	0.76	-
Zinc	4.7	0.47	mg kg <sup>-1</sup>
Sodium % of Cations	8.3	8.6	%

At both locations, after MW soil treatments, the plots remained undisturbed for a few hours (4 h) to allow the soil to cool until it reached equilibrium temperature, after which the rice variety YRM70 was sown with a small seed plotter at a seeding rate of 80 kg ha<sup>-1</sup> with a row-to-row distance of 25 cm. Diammonia phosphate was applied at the time of sowing at the rate of 80 kg ha<sup>-1</sup>. Three split doses of N were applied during the growing period of rice (i.e., at three different crop stages: 3–5 leaf stage,

maximum tillering and panicle initiation according to the standard agronomic practices of rice growing in Australia), using urea, at the total rate of 125 kg N ha<sup>-1</sup>. Irrigation for rice growing at both locations was scheduled as per the recommendation of the Ricegrower Association of Australia. Immediately after sowing, a two-water flush was given and field drained quickly in order to maintain the seed imbibition process for germination and emergence. After germination, irrigation was categorised into three phases: (1) Maintenance of shallow water depth (i.e., 3–5 cm) from the 3–4 leaves stage to maximum tiller establishment; (2) permanent water depth was maintained from panicle initiation (i.e., 10–15 cm depth) to flowering (i.e., 20–30 cm depth); and (3) water drainage started at grain filling but maintained 3–4 cm until harvesting [21].

At maximum physiological maturity, the rice crop at both locations was harvested, and two quadrats (0.25 m<sup>2</sup>) were taken from the whole plot area at both locations, to avoid edge effects, for biomass yield assessment, after drying in an oven for 24 h at 65 °C. The N concentration in the rice dry biomass (straw + grain) was measured using the micro-Kjeldhal procedure (VELP Scientifica s.r.l., Usmate, Italy). The N use efficiency (NUE) was calculated as previously described by Cassman, Peng, Olk, Ladha, Reichardt, Dobermann, and Singh [22], according to them this is actually a partial factor productivity of N. Although this is a generic term in nutrient-response studies, however, it gives a good indicator of the amount of all the nutrient (N in this study) resources for crop productivity.

$$\text{NUE} = \frac{Y}{N_r} \quad (1)$$

$$\text{NUE} = \frac{Y_0 + \Delta Y}{N_r} \quad (2)$$

$$\text{NUE} = \frac{Y_0}{N_r} + \frac{\Delta Y}{N_r} \quad (3)$$

where Y = crop yield (we used total above ground biomass yield), N<sub>r</sub> = applied N (i.e., 125 kg N ha<sup>-1</sup> in this study), Y<sub>0</sub>/N<sub>r</sub> = yield without N application (i.e., indigenous N supply for crop yield), and ΔY/N<sub>r</sub> = change in crop yield with N application (often called as agronomic efficiency).

Therefore, we used ΔY/N<sub>r</sub> to measure the change in crop biomass yield with applied N (i.e., NUE) in response to MW soil treatment at both study locations.

According to Australian Fodder Industry Association (AFIA; Method-1.7R), the *in vitro* pepsin-cellulase digestion procedure is conducted through the following steps: 0.25 g of a sample digested for 24 h at 40 °C with 15 mL acidified pepsin (3.0 g pepsin: 0.3% w/v in 0.125 M hydrochloric acid solution), then further heated to 80 °C, and digested with thermostable alpha-amylase. Immediately after digestion, the samples were incubated at 40 °C with a buffered cellulase solution (12.5 g cellulase: 1 L of 20.4 g sodium acetate, and 8.7 mL acetic acid), followed by pH adjustment to 4.6. The disappearance of dry matter or organic matter were determined, based on samples of known *in vivo* digestibility.

All measures were analysed through a one-way ANOVA using GenStat (Version: 16th Edition; VSN Int. Ltd.). The statistical significance was declared when *p* < 0.05, and a least significant difference (l.s.d) test was used to compare the treatment means. The NUE presented as mean ± standard deviation.

### 3. Results and Discussions

Pre-sowing MW soil treatment increased the dry biomass yield of rice crops (*p* < 0.09; Table 2) with an overall increase in biomass of ~7 t ha<sup>-1</sup> compared with the untreated control plots at Jerilderie site, while at Dookie the dry biomass yield did not significantly increase in response to MW soil treatment (*p* > 0.05, Table 2). The DMD, ash, and N did not change in response to MW soil treatment (*p* > 0.15; Table 2) at either location. Despite that, N accumulation in rice dry biomass significantly increased due to MW soil treatment (*p* < 0.08; Table 2) and maximum N accumulation was detected at Jerilderie (43.4%) than at Dookie (8.17%). Overall, MW soil heating improved NUE by 10.37% at Dookie and 42.4% at Jerilderie compared with the untreated control treatment.

**Table 2.** Influence of pre-sowing microwave soil treatment on the yield and quality components of rice crop. Numbers with different letters represent significant difference between treatment at 5% probability level. l.s.d = least significant difference, “–” represents value not calculated. Note: Total N applied in this study was about 125 kg ha<sup>-1</sup> at both study locations.

Observations	Dookie			Jerilderie			l.s.d	p-Value
	Microwave Treated	Untreated Control	Percentage Change	Microwave Treated	Untreated Control	Percentage Change		
Dry Biomass Weight (t ha <sup>-1</sup> )	13.73 a	12.44 a	20.7%	23.60 a	16.50 b	43.03%	7.1	0.09
Dry Matter Digestibility (%)	36.6 a	39.3 a	–	41.8 a	35.3 a	–	10.04	0.56
Ash (%)	7.05 a	5.84 a	–	8.08 a	8.17 a	–	1.5	0.27
Nitrogen (%)	1.5 a	1.5 a	–	1.4 a	1.4 a	–	0.28	0.72
Nitrogen Accumulation in Dry Biomass (kg ha <sup>-1</sup> )	204.89 a	189.41 b	8.17%	332.43 a	231.68 b	43.4%	99.0	0.09
Nitrogen Use Efficiency (kg biomass kg N <sup>-1</sup> )	109.83 ± 36.8	99.51 ± 38	10.37%	188 ± 33.5	132 ± 34	42.4%	–	–

The primary purpose of MW soil treatment is to reduce the germination capacity of soil weed seed banks in no-till agriculture systems. In addition to weed control, MW soil treatment increases the crop growth and yield. Furthermore, understanding the impact of soil heating on the nutritive value of crop is essential to accept the broad-spectrum activity of this new weed management technology. Therefore, the main objective of this study was to understand the influence of MW soil heating on the nutritive value of rice crop. Soil heating for short intervals increased the dry biomass yield of rice crop. These findings are consistent with previous studies [20,23,24].

The increase in N accumulation in dry biomass potentially reveals that a transient heat treatment might have changed the indigenous N source for crop productivity and accumulation. In general, soil heating at up to 70–100 °C has been reported to change the soil's indigenous N supply for plant productivity [15,25]. In addition, a recent study reported that MW soil heating has the potential to increase the indigenous soil N for plant uptake [14]. This agrees with the results of this study. The MW soil treatment increased the NUE in this study (Table 2). According to Cassman, Peng, Olk, Ladha, Reichardt, Dobermann, and Singh [22], NUE includes the indigenous N contribution for yield increase. Therefore, this portion of plant available N might have increased the N accumulation in dry biomass in this study, which potentially reveals the heating effect on the soil fertility for crop productivity. Thermal denaturation of soil organic compound can help in nurturing and/or shaping the microbial communities after soil heating [25,26], and those microbial communities (particularly soil bacterial taxa) accelerate the availability of yield changing nutrients [27]. Furthermore, the partitioning of N into crop dry biomass can be evaluated by labelling the soil N pool with isotopic N, and then checking in crop biomass whether it has come from indigenous or applied sources. In this study, N accumulation in dry biomass was considered as an indicator that MW soil heating can potentially increase the quality of crops. This implies that crop productivity and higher nutritive value can be acquired with MW soil heating as an additional benefit of this technology in the agricultural systems.

In this instance, a recent study reported that MW (915 MHz; different power × duration) soil treatment increased the dissolved organic carbon (+1.6-fold compared with the control), inorganic phosphorus (+1.2-fold compared with the control), and nitrate content in soil [27]. In addition, they grew the pregerminated seeds of *Medicago truncatula* Gaertn. in MW treated soil and found that its dry biomass accumulation significantly increased due to soil heating (75–80 °C), compared with the untreated control soils. It can be postulated that MW soil treatment has the potential to increase the soil nutrient availability for crop productivity; however, it is important to note that increases in dissolved organic carbon and N do not necessarily increase the soil fertility. It can cause the degradation of the soil's organic carbon and N pool, as it can increase the excessive uptake by crop plants and can accelerate the nitrate leaching, which has a serious environmental concern arising from agricultural inputs. Therefore, it is advisable to apply an appropriate dose, maybe a half amount, of fertilisers in the MW-treated soils to avoid nutrient depletion. Overall, these results suggest that MW soil treatment can increase the nutrient output of crops; however, the treatment modification of MW soil heating intensities needs further investigation to evaluate the nutrient availability and uptake in different forage crops under field conditions.

#### 4. Conclusions

The current study suggests that MW soil treatment can potentially enhance the crop productivity and N accumulation in dry biomass under field conditions. Future research is needed to understand the impact of MW soil heating on the productivity and nutritive value of different fodder crops under field conditions.

**Author Contributions:** Conceptualization, G.B. and M.J.K.; methodology, M.J.K., R.J. and W.L.; validation, G.B. and L.C.; formal analysis, M.J.K.; investigation, G.B. and L.C.; writing—original draft preparation, M.J.K.; writing—review and editing, G.B. and L.C.

**Funding:** This research was funded by Agrifutures Australia, grant number PRJ-008765. The forage nutritive value analysis was supported by Dr. Long Cheng Start-up fund from the Faculty of Veterinary and Agricultural Sciences, The University of Melbourne, Australia.

**Acknowledgments:** We thank to SunRice for trial site at Jerilderie.

**Conflicts of Interest:** The authors declare no conflict of interest.

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