Short-term soil drying–rewetting effects on respiration rate and microbial biomass carbon and phosphorus in a 60-year paddy soil

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Abstract

Paddy soils represent the largest anthropogenic wetlands on earth. Soil drying and rewetting that occurs annually inflict significant stress on soil microbial activities in paddy soils. An incubation experiment of 60 years of paddy soil was conducted to simulate the conditions of paddy fields (25 °C and 75% air humidity) during a 16-day incubation time. The effect of drying–rewetting [DRW, with 4 levels: (1) constant soil moisture (CSM), (2) one-stage drought stress (DRW1), (3) two-stage drought stress (DRW2), and (4) three-stage drought stress (DRW3)] and how it evolves over 0, 4, 8, 12, and 16 days after incubation on the concentration of available phosphorus (AP), microbial biomass P (MBP) and microbial biomass C (MBC), and respiration rate (RES) was determined using repeated measures analysis (RMA). The results revealed that an increase in the number of drying–rewetting increases MBC and RES. Compared to CSM, frequent drying and rewetting caused an increase in RES, MBC and MBP by 88%, 38%, and 11%, respectively. Drying–rewetting increased microbial biomass C (MBC) and P (MBP) by 24–38% and 11–54%, respectively, during 8–16 days of incubation. Increasing the number of DRW cycles reduced AP concentration (except in DRW1). The decrease in available phosphorus is due to the increase in the intensity of immobilization under these conditions. Positive correlations were also observed between AP and MBP ($r=0.52$), and between RES and MBC ($r=0.91$). In general, the frequency of moisture in the paddy soil is favorable for increasing microbial activity.

Keywords Bioavailability · Soil moisture · Wetland · Microbial biomass · Incubation

Introduction

Availability of water for agricultural production is gradually becoming a major challenge in the context of climate change (Pandey 2018; Zwane 2019). In many parts

of the world, climate change is altering soil conditions. For example, cycles of harsh drying or freezing of soil affect soil pores systems that eventually impact the availability and forms of plant nutrients. This occurrence is commonly taking place in the soils of arable land (Xu

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et al. 2011; Dao et al. 2016; Chen et al. 2016) like paddy soils (Balaine et al. 2019). Paddy soils represent the largest anthropogenic wetlands in the world that redox potential oscillations due to paddy management control microbial community structure and function, and thus short-term biogeochemical processes (Kögel-Knabner et al. 2010). However, Jones et al. (2019) reported no changes in clay soils, which suggest the presence of high potential micro-site abundance that may improve the preservation of soil functions during dry storage and drought. Chen et al. (2016) showed the presence of a relationship among soil moisture, microbial activity and the availability (bioavailability) of nutrient elements.

The range of microbial biomass carbon is between 4 and 1700 mg kg⁻¹ in paddy soils (Sheng et al. 2013; Wang et al. 2015). Microbial biomass activity increases in continuous flooding conditions, and decomposition of organic matter occurs under constant moisture regime (Nandi 2020). Some studies showed that microbial biomass carbon decreases by 13–70% under wet conditions after drought (Wu and Brookes 2005; Mondini et al. 2002). A previous research on drying–wetting cycles showed the presence of higher microbial activity under wet/dry conditions than under waterlogging conditions (Tian et al. 2013). Other studies showed that drying reduces microbial biomass C (MBC) soon after rewetting, and higher drying intensities accelerate the reduction rate of MBC (Sawada et al. 2019). The decrease in microbial biomass due to drying–rewetting (DRW) stress is attributed to the rapid dehydration of microbial cells. If microorganisms are not swiftly adjusted to sudden changes in water potential, their cell walls can disintegrate leading to cell lysis (Fierer et al. 2003). Biomass that survive soil drying is mainly due to the more adaptable part of the microbial population that can endure drought stress by producing protective compounds such as spores or cysts (Blackwell et al. 2010). A reduction of more than 20% in MBC makes C-saturated conditions for the remaining microbes, because adequate concentrations of labile substrate C are released from the dead MBC. During repeated DRW cycles, since inorganic substrate C supply C, microbial growth rates increase (Sawada et al. 2019). The respiration pulse following DRW events often decreases with increasing numbers of DRW cycles (Mikha et al. 2005), but other studies showed that magnitude of respiration due to rewetting depends on the number of DRW cycles and the number of prior moist days (Shi and Marschner 2014). Chen et al. (2016) reported that rewetting soil caused a rapid increase in respiration rate; and, Orchard and Cook (1983) reported that short period microbial activity increased by up to 40 folds.

Complex interactions of biotic and abiotic factors determine the magnitude of P concentration changes in the soil. For example, biotic factors including microbial activity

change organic P into inorganic P, and vice versa; and abiotic factors including adsorption and dissolution affect nutrient transfer between non-living pools and soluble forms (Azeez and Averbek 2010). Water management (drying–rewetting) was reported to be effective in these factor changes (Orchard and Cook 1983; Atere et al. 2018), and plays a key role in the availability of phosphorus. Reduced availability of phosphorus in soils results in reduced yield of rice grown in paddy soils (Nishigaki et al. 2019). Singh et al. (2010) showed that microbial biomass phosphorus, compared to nitrogen or biomass carbon is more related to organic matter. Also, organic matter in drying–rewetting land contributes to the maintenance of microbial activity during water shortage (Sun et al. 2017). Therefore, a change in mineralization intensity affects phosphorus availability. In paddy soils, microbial biomass phosphorus is in the range of 2–76 mg kg⁻¹ (Chen and He 2004; Li et al. 2013). Phillips (1998) reported that most soils sorbed phosphate in air-dry, waterlogged, and waterlogged/dried conditions. Some other studies showed that incubation time and drying–rewetting decreases NaHCO₃-extractable P by nearly 25% (Chen et al. 2016). Xu et al. (2011) reported that air drying accelerates changes of no-labile phosphorus forms to labile forms (unstable), and as a result, microbial biomass P (MBP) decreased by 9–29% and recovered to the level before DRW treatment within 7 days; and Chen et al. (2016) reported that drying–rewetting increased MBP 5 times during 21 days and then decreased by 57%. Other studies reported differences in MBC/MBP ratio as a result of changes in soil conditions (Chen et al. 2016; Cleveland and Liptzin 2007; Li et al. 2013). This is an important finding for predicting the future nutritional requirements of phosphorus in the paddy soil as well as the portion of phosphorus available through carbon biomass. Drying–rewetting cycles can influence the decomposition of MBC and their mineralization, which in turn can influence the short-term availability of phosphorus in paddy soils.

Due to the predicted global water shortages and the great need of paddy soils for adequate water (Kumar et al. 2019), this study was conducted to investigate the effect of drying and rewetting sequence on soil MBP, MBC and respiration rate. Few studies have explored the effect of DRW on the short-term mineralization of soil organic matter to revive and stabilize microbial activity (Jones et al. 2019). It is a challenge to find new ways to assess the amount of available phosphorus and carbon under changeable conditions of soil (Soinne et al. 2010; Chen et al. 2016; Jones et al. 2019). Therefore, this study aimed to unlock how the frequency of DRW stress history influences soil MBP and MBC dynamics under paddy field conditions. The objective of the study was determining the changes in MBP, MBC, and NaHCO₃ extractable P under three DRW cycles. Our theory was that DRW had different influences on MBC and MBP, possibly not having a negative effect on MBC and respiration rate,

because the paddy soil has been submerged for 60 years and every year, the added rice plant residues were preserved in the soil, which in turn results the microorganisms to be more resistant to moisture stress.

Materials and methods

Soil sampling, azocompost preparation, and analysis

A composite 60-year paddy soil (ten sample clay soil, Anthrosols; WRB 2015) was collected at a depth of 0–25 cm with a dutch auger (5 cm in diameter) from paddy rice field at the Research Institute of Guilan, in Guilan Province, Iran (longitude: 49 37' 15.94" E and latitude: 37 14' 26.48" N). After the removal of visible plant residues, stones, and soil animals, the soil was mixed thoroughly, air dried, and passed through a 2 mm sieve. The soil samples were adjusted to 70% water-holding capacity (WHC), and then conditioned at 25 °C, 75% air humidity, darkroom, and suitable ventilation for 5 days. Soil moisture was adjusted periodically based on the weight loss.

The azocompost used in the experiment is a mixture of organic matter including azola, cow manure, and rice husk, respectively, with a ratio of 1:2:3 (volumes/volumes/volumes) with the initial moisture content of the mixed mass set at 70% moisture and with complete aerobic ventilation during a 6-week storage (Razavipour et al. 2018). The samples were oven dried at 40 °C for 5 days. Then, after powdering to pass through 1 mm sieve, subsamples were collected for chemical and physical analysis from both materials and the following analyses were conducted on the soil and azocompost samples. Soil electrical conductivity (EC) (1:5) and azocompost (1:10) (Rhoades 1996), soil reaction (pH) (1:5) and azocompost (1:10) (Thomas 1996), soil texture (Gee and Bauder 1986), soil organic carbon (Nelson and Sommers 1996), azocompost organic carbon (Wang et al. 2012), total nitrogen (Bremner 1996), azocompost phosphorus (Watson and Isaac 1990), MBP was determined using the fumigation–extraction method (Brookes et al. 1982), and soil available phosphorus (Olsen et al. 1954; Kuo 1996).

Incubation experiment

Before the drying–rewetting (DRW) experiment, the pre-incubated soil was amended with chemical and organic fertilizer similar to crop residue incorporation (the best condition and N fertilization practices in paddy rice field at the Research Institute of Iran in Guilan Province, Iran). The general fertilizer recommendation for rice was 120, 100 and 100 kg ha⁻¹ of nitrogen, phosphorus, and potassium, respectively. Phosphorus and potassium were

added from triple superphosphate and potassium sulphate. According to the regional recommendation and moderate consumption for maximum yield of rice, 5 ton ha⁻¹ azocompost (passed through 2 mm sieve) was applied in a 25 cm depth. The amended soil was thoroughly mixed. To reduce the use of chemical fertilizers, the nitrogen sources used were 20 kg ha⁻¹ urea and 100 kg ha⁻¹ azocompost. After organic and chemical fertilizer application, PVC pots (diameter 10 cm and height 10 cm) were incubated for 7 days under 25 °C temperature and 75% relative humidity to reach equilibrium. Each portion of moist soil (equivalent to 250 g oven-dried soil) was weighed into 500 mL PVC pots and then placed in an incubator 250 mL deionized water.

Figure 1 shows the DRW experimental design and sampling times. The following four treatments were applied (three replications per treatment) and incubation conditions (temperature of 25 °C and 75% relative humidity) and it was irrigated daily: (1) constant soil moisture as control (CSM), in which the soil moisture was held constant at 100% WHC by daily watering at 25 °C; (2) DRW1, in which a single 2-day drying events was operated on day 12 after incubation; (3) DRW2, in which two cycles of 2-day drying events were operated on days 8 and 12 after incubation; and (4) DRW3, in which three cycles of 2-day drying events were operated on days 4, 8, and 12 after incubation. The DR cycles were performed with 2 days of air-drying of the soil, thinly spreading it on a plastic sheet at room temperature [moisture content after drying 10% (7.4%)], crushing and passing through a 2 mm sieve, and then doing a quick water-logging to 100% WHC by spraying de-ionized water on the soil. Available P (AP), microbial biomass P (MBP), microbial biomass C (MBC), and respiration rate were measured at 0, 4, 8, 12, and 16 days after the start of incubation. AP in dried soil were measured at 6, 10, and 14 days after the start of incubation.

AP, MBP, and MBC were measured as follows. AP was obtained by the Olsen method (Olsen et al. 1954; Kuo 1996); MBP was determined using the fumigation–extraction method (Brookes et al. 1982); and to measure MBC, the soil samples were fumigated with chloroform (Sparling and West 1988). The organic carbon in the filtrate was determined and converted to biomass-C. $K_{EC} = 0.38$ (converts the organic C-flush to microbial C) (Shibahara and Inubushi 1995). Soil samples were incubated in a closed vessel at 25 ± 0.5 °C.

Statistical analysis

Repeated measurement analysis (RMA) of a completely randomized design with 4 drying–rewetting cycle (DRW) treatments (CSM, DRW1, DRW2, and DRW3) and 3 replications was conducted to determine the effect of DRW and how it evolves over days after incubation on AP, MBP, RES,

Fig. 1 Schematic figure of the drying–wetting cycles (DR) and sampling days (*). CSM (soil moisture constant). One drought cycle (DRW1) (on 12th day). Two drought cycles (DRW2) (on 8th and 12th days). Three drought cycles (DRW3) (on 4th, 8th, and 12th days) (revised cycles of Chen et al. 2016)

and MBC. RMA, which is an advanced statistical method appropriate for response measurements done on the same experimental unit repeatedly, using the most appropriate covariance structure (Unstructured for all four response variables) was conducted, because the response values were measured repeatedly on 0, 4, 8, 12 and 16 days after the beginning of incubation. The analysis was completed using the Mixed Procedure of SAS (SAS 2014) software. Since the interaction between DRW and day was significant for all four response variables, multiple means comparison was completed to compare the 20 treatment combinations of DRW and day using the lsmeans statement of the Mixed Procedure. Letter groupings were generated at the 5% level of significance using Tukey's multiple range test. The significance of the effect of DRW on MBC to MBP ratio was determined at 16 days after incubation. The effect of Drying of the soil stress treatments (DRW1, DRW2, and DRW3) at day 14, and the effect of day (6, 10, and 14 days after drying stress) in DRW3 on AP concentration changes 2 days after drying of the soil ($\mu\text{g g}^{-1}$ soil) stress was also determined. The validity of model assumptions on the error terms (constant variance and normal distribution) were verified by examining the residuals as described in Montgomery (2020). The relationships between AP and MBP as well as between RES and MBC were measured using Pearson's correlation coefficient.

Results

Chemical and physical properties of soil and azocompost

Some soil properties including textural components were sand 12%, silt 30%, and clay 58%. Electrical conductivity of soil (EC) (1:5) was $241 \pm 21 \mu\text{mho cm}^{-1}$, and azocompost EC (1:10) was $7.7 \pm 0.24 \mu\text{mho cm}^{-1}$, soil reaction (pH) (1:5) was 7.365 ± 0.035 , and azocompost pH (1:10) was 7.01 ± 0.014 , organic carbon content of soil and azocompost were $2 \pm 0\%$ and $65.39 \pm 0.89\%$, respectively, the percentage of total N was $0.15 \pm 0.004\%$ and azocompost was $2.815 \pm 0.035\%$, soil available P was $13.4 \pm 0.56 \text{ mg kg}^{-1}$, and soil total P and azocompost were $546 \pm 12 \text{ mg kg}^{-1}$ and $0.68 \pm 0\%$, respectively.

Analysis of variance (ANOVA) results

Repeated measures analysis revealed that the interaction effect of drying–rewetting cycle (DRW) and days after incubation (day) on AP, MBP, RES, and MBC is highly significant ($P < 0.01$). The main effect of DRW on MBC to MBP ratio at 16 days after incubation was also highly significant ($P < 0.01$). As a result, multiple means comparison of the 20 combinations of DRW and day was conducted for all four response variables and the results are shown in Figs. 2, 3, 4, and 5. Multiple means comparison of the four DRW treatments was conducted for MBC to MBP ratio and the results are shown in Fig. 6.

Fig. 2 Interaction effect of drying–rewetting cycle (DR) and days after incubation on available P ($\mu\text{g g}^{-1}$ soil). Means sharing the same letter are not significantly different

Fig. 3 Interaction effect of drying–rewetting cycle (DR) and days after incubation on microbial biomass P ($\mu\text{g g}^{-1}$ soil). Means sharing the same letter are not significantly different

Fig. 4 Interaction effect of drying–rewetting cycle (DR) and days after incubation on respiration rate ($\text{mg C-CO}_2 \text{ kg}^{-1} \text{ soil day}^{-1}$). Means sharing the same letter are not significantly different

The effect of drying–rewetting on AP and MBP

The multiple means comparison results shown in Fig. 2, revealed that the amount of AP was affected by the drying–rewetting cycles in different ways. Increasing the number of DRW cycles reduced AP concentration (except DRW1). Although the effects of DRW on microbial and available P were significant, these do not follow a specific trend to differentiate between the treatments. In the CSM treatment, the effect of waterlogging on available P initially increased, then decreased until reaching a constant level (Fig. 2). During the first 4 days, AP increased from 16.32 to 21.76 (33%) $\mu\text{g g}^{-1}$ soil in all four (CSM, DRW1, DRW2,

and DRW3) treatments (Fig. 1). At the end of the incubation period, 17% reduction in AP concentration was observed in the waterlogging constant moisture. In the DRW1 treatment, there was no significant change in AP after 8 days of incubation (Fig. 1). On day 16, the AP concentration of DRW1 treatment was significantly higher than that of CSM (by 40%), that of DRW2 (by 88%), and that of DRW3 (by 112%). In DRW2, we observed a 36% and 9% reduction in AP between the 8th and the 12th days of incubation and between the 12th and the 16th days of incubation, respectively. After two stresses (DRW3), AP concentration reduced by 64% from its peak on day 12 (Fig. 2).

Fig. 5 Interaction effect of drying–rewetting cycle (DR) and days after incubation on microbial biomass C ($\mu\text{g g}^{-1}$ soil). Means sharing the same letter are not significantly different

Fig. 6 Plot of mean MBC to MBP ratio at 16 days after incubation obtained from the four drying–rewetting cycle (DR) levels. Means sharing the same letter are not significantly different

As shown in Fig. 3, waterlogging increased MBP concentration initially (on day 4), and then fluctuated depending on the treatment. During the first 4 days, MBP increased by 286% in all four treatments. Between 4 and 8 days of waterlogging, MBP decreased significantly from 9.376 to 0.646 $\mu\text{g g}^{-1}$ soil in CSM, DRW1, and DRW2 treatments, but stayed the same in the DRW3 treatment. Between 8 and 12 days, MBP increased significantly in CSM and DRW1 treatments, but decreased significantly in the DRW2 treatment (Fig. 3). While MBP stayed the same in CSM treatment between 12 and 16 days of incubation, it increased in DRW1 and DRW2 treatments, but decreased in DRW3 treatment (Fig. 3). On day 16, the mean MBP of DRW1 and DRW3

were higher than that of the control treatment (CSM) by 54% and 11%, respectively.

The effect of drying–rewetting on RES and MBC

Multiple means comparison results of respiration rate (RES) and microbial biomass carbon (MBC) are shown in Figs. 4 and 5, respectively. All in all, increasing the number of DRW cycles increased RES and MBC concentration. RES decreased from 567 to 498 C-Co₂ kg⁻¹ soil day⁻¹ in all four treatments; then started to increase on day 4, day 8, and day 12 in DRW1, DRW2, and DRW3 treatments, respectively (Fig. 4). RES continuously

decreased in CSM treatment. There was no significant difference in the respiration rate of DRW1, DRW2, and DRW3 on 16 days of incubation; however, compared to that of CSM, the most frequent drying and rewetting (DRW3) treatment increased RES by 88%.

The MBC results shown in Fig. 5 are somewhat similar to those of RES (Fig. 4). In CSM treatment, MBC decreased by 21% during the 16 days of incubation (Fig. 5). On day 16, the mean MBC concentration in DRW1, DRW2 and DRW3 was higher than that of the control treatment (CSM) by 25%, 24%, and 38%, respectively. On day 12, MBC concentrations of DRW2 and DRW3 treatments were higher than that of CSM by 25% and 27%, respectively. Specifically, frequent drying and rewetting increased RES, MBC and MBP by 88%, 38%, and 11%, respectively. During 8–16 days of incubation, DRW increased microbial biomass C (MBC) and P (MBP) by 24–38% and 11–54%, respectively.

Figure 6 shows the mean MBC to MBP ratios obtained from the four treatments at 16 days of incubation. These means ranged from 88 to 154. The most negative effect on MBC and positive effect on MBP (the lowest ratio) was observed in DRW1 treatment. Comparing this result with the results shown in Figs. 2, 3 and 5, it can be concluded that slower increase in microbial biomass carbon is associated with faster increase in microbial biomass phosphorus and the amount of available phosphorus concentration. The highest mean MBC to MBP ratio was obtained from DRW2, and the lowest was obtained from DRW1 treatment. DRW2 and DRW3 treatments had significantly higher MBC to MBP ratio than CSM and DRW1 treatments (Fig. 6).

AP concentration changes 2 days after drying of the soil

On the 14th day, the mean AP concentrations obtained from DRW1, DRW2, and DRW3 were 12.76, 10.86, and 16.04 $\mu\text{g g}^{-1}$ soil, respectively. The mean AP concentrations obtained from DRW2 and DRW3 on the 10th day were 6.76 and 3.34 $\mu\text{g g}^{-1}$ soil, respectively. The mean AP concentration in DRW3 on the 6th, 10th and 14th days were 11.98, 3.34, and 16.04 $\mu\text{g g}^{-1}$ soil, respectively. The highest increase in phosphorus concentration in DRW3 (380%) occurred between 10 and 14 days. Comparison of these (dry soil) AP means with those shown in Fig. 2 (wet soil) reveals that soil has more available phosphorus under wet condition than in dry condition. In addition, drying the soil over a 2-day interval drastically changes the available phosphorus concentration.

Correlation analysis

Pearson's correlation coefficient (r) between available phosphorus and microbial biomass phosphorus was 0.52 ($P < 0.05$), and the correlation coefficient between respiration rate and microbial biomass carbon was 0.91 ($P < 0.01$). This strong positive correlation between respiration rate and microbial biomass carbon indicates that much of the microbial respiration is due to the microbial biomass carbon.

Discussion

There is limited information in the literature regarding the effects of changing the physical state of the soil, such as drying and wetting, on chemical concentration of phosphorus and biological indices (Fierer et al. 2003; Xu et al. 2011). Dao et al. (2016) showed that most microbial activities considered were affected by different drying–rewetting and elemental changes due to it. Soils with high organic matter (like this paddy soil that has 2% OC), the effects of drying and rewetting has a greater impact on P concentration (Xu et al. 2011; Gao et al. 2016). Past studies showed the short-term effects of alternate DRW on soil processes. Most of these studies have shown that, compared to the control treatment, a rapid rewetting of dry soil yields a 1–4-day increase in C and N mineralization (Scheu and Parkinson 1994). The novelty of the present study is that it showed mineralization of phosphorus increases by a 2-day air drying of soil (Fig. 2). In this 60-year paddy soil, the first 4 days were considered as the time of mineralization of P. The results of this study showed a positive relationship between AP and MBP and RES and MBC.

Briefly, our results showed that increasing the number of DRW cycle increases microbial biomass carbon and microbial respiration rate. Long-term waterlogging along with the return of rice organic residues to paddy soils preserves soil carbon and improves soil properties and microbial community biodiversity in rice paddy soil (Chen et al. 2012). Therefore, in these conditions, moisture stress is not affected by the short-term drying stress. Also, our results are consistent with the results of Butterly et al. (2011) and Venterink et al. (2002), but not with those of Sun et al. (2018), Chen et al. (2016), and Khan et al. (2019). Soil respiration and biomass activity are enhanced by drying–rewetting cycles, because dead microorganisms release intra-cellular osmolytes due to the change in water pressure, fracture of soil aggregates, and uncoupling of enzymatic activity from cellular respiration (Moyano et al. 2013). Repeated DRW cycles cause an increase in the microbial growth rates, because substrate C gets supplied from non-biomass organic C (Sawada et al. 2019). Perhaps, it is partly related to the increase in mineralization or extractability of non-microbial soil organic

matter; or the influence of drought that might decrease with increasing frequency of DRW events because of microbial adaptation to DRW (Chen et al. 2016). Increasing the number of DRW cycles reduced AP concentration (except in DRW1). Singh et al. (2010) stated that DRW affects the rate of release of P from stable forms to more available forms. Based on the results of increasing MBP, it can be concluded that much of the released phosphorus is consumed by microbial activity and as a result, AP decreased. Some researchers showed that microbial immobilization controls P availability for plants, which seems plausible that immobilisation increases along with mineralization (Walbridge 1991; Venterink et al. 2002). Soil drying process can increase iron and aluminium hydroxide and decrease the saturation of the soil phosphorus (Laakso et al. 2016) that results in a decrease in AP concentration.

Reported soil MBC/MBP ratio values are very variable, ranging from < 5 to > 400 (Cleveland et al. 2004; Chen et al. 2016). The range of mean MBC/MBP ratios in our study was between 88 and 154. This close range may be associated with P bioavailability (Zhao et al. 2009). The highest available phosphorus concentration was obtained under the conditions of DRW1, which resulted in the lowest MBC/MBP ratio. Drying and rewetting, being similar to weathering, may have caused the release of phosphorus from stable to available forms. Soil drying releases considerable amounts of phosphorus to water compared to the equivalent moist soil (Turner et al. 2002). This may have happened in DRW1 condition. This is plausible because of the depletion of available carbon or the development of microbes being compatible with water stress (Chen et al. 2016). Our results demonstrate the presence of differences in available phosphorus content in dry and water-logging soil conditions (Xu et al. 2011), which leads us to recommend measuring available phosphorus in natural soil under water-logging conditions. Our results showed that available phosphorus (under wet condition) is positively correlated with microbial biomass P in paddy soil. Turner and Haygarth (2001) also showed the presence of a positive correlation between the amount of soil microbial biomass P and available phosphorus after DRW cycle. They also showed that available phosphorus is released from the microbial biomass. Most studies focused on unstable sources of phosphorus or phosphorus solubility in water and sodium bicarbonate extract (Sardans and Peñuelas 2004; Khan et al. 2019). Soils may act as sources or sinks of volatile organic compounds (VOCs), and many of the formed VOCs are produced by a microorganism. These compounds can release available phosphorus in soil environment (Insam and Seewald 2010). In our study, frequent drying–rewetting increased RES, MBC, and MBP, which caused more phosphorus to be absorbed by soil microorganisms. As a result, it reduced the availability of phosphorus. Whereas the first moisture stress (DRW1) increased the

microbial biomass of phosphorus and available phosphorus. Drought-tolerant microorganisms increased with increasing water stress.

Conclusion

In this 60-year paddy soil, the first 4 days were considered as the time of mineralization of P. The results of this study showed a positive relationship between AP and MBP and between RES and MBC. To be close to the natural conditions of the soil, we recommend that phosphorus measurements in soil waterlogging conditions be conducted in wet soil conditions. Frequent drying and rewetting increased the volatility of microbial biomass phosphorus and available phosphorus in paddy soils in DRW1 treatment. DRW3 treatments reduced AP and increased microbial biomass P after three stages of drought stress. Therefore, the present study demonstrated that moderate (one stress) soil drying during drying–rewetting events could improve the mineralization of P, and that increasing DRW numbers were responsible for the increase in MBC and respiration rate observed during drying–rewetting events. Possible reasons may be that these paddy soil has been under constant waterlogging for 60 years and it is exposed to alternating moisture every year during the non-growing season of rice and obtained organic compounds every year by rice residues. Therefore, microbial activities are adapted to the present conditions and increase their activity even under drought conditions. The results of this research are suitable for paddy soil that are being influenced by drying and rewetting. It is recommended to make measurements of microbial biomass and available P at shorter intervals. A significant correlation exists between soil moisture, microbial activity, and bioavailability of phosphorus which plays an important role in water and nutrient management. In general, the frequency of moisture in the paddy soil is favorable for increasing microbial activity.

Author contributions SBN conceived and carried out the project, collected the data and contributed to the preparation of the manuscript; HMH supervised the project and designed the experiment; HE and TR provided advice to the research and contributed to data collection; BAL contributed to the data collection; and TA conducted the statistical analysis of the data, and contributed to the preparation of the final version of the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical statement This article does not contain any studies with human participants or animals performed by any of the authors.

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