Introduction

Globally, nearly two billion people suffer from deficiencies of micronutrients such as iron (Fe) and zinc (Zn) (Black et al., 2008). Such deficiencies cause anemia, cognitive decline, immune compromise and slow/poor growth (Shetty, 2011). Micronutrient deficiencies are therefore important from a public health perspective, and substantial efforts must be made to decrease their prevalence (Shetty, 2011).

Plant-based foods are an important source of micronutrients for human beings, and their micronutrient contents are partially determined by the micronutrient content and availability in the soils on which the foods are grown (Nubé and Voortman, 2011). In areas where the absolute content or bioavailability of certain micronutrients in soils is very low and where, at the same time, local people largely depend on these soils for the production of their foods, human micronutrient deficiencies are bound to occur (Nubé and Voortman, 2011). Therefore, the management of soil micronutrients is fundamental to solving the micronutrient deficiency problem.

On the other hand, trace elements such as Fe, manganese (Mn), copper (Cu) and Zn are increasingly recognized as being essential for achieving higher yields, and much research is being done on the capacity of the soil to provide micronutrients for crop growth (Fageria, 2002). In addition, various studies have indicated that improving the micronutrient supply to crops can result in more vigorous seedlings and lower vulnerability to plant diseases and possibly to drought (Frossard et al., 2000). The status and behaviors of micronutrients in soil may be affected by land use and management practices via changes in general soil characteristics, such as pH, organic matter and macronutrient status (e.g., Abe et al., 2007). However, much less attention has been paid to micronutrients than to macronutrients, and the relationships between micronutrient availability and general soil characteristics have not been well documented (Li et al., 2007).

In the present study, we focus on soil micronutrient availability in the volcanic highlands of Mt. Marapi, West Sumatra, Indonesia, a part of the country where many people suffer from widespread micronutrient deficiencies (Dijkhuizen et al., 2001). Volcanic soil is the major soil resource in the mountainous regions of Indonesia and is often cultivated intensively for the purpose of vegetable production (e.g., Moeskops et al., 2010; 2012; Abe et al., 2018). However, permanent cropping, tight crop rotations and nutrient exports along with the overuse of fertilizers and agrochemicals have accelerated the degradation of ecosystems and soil resources and are increasingly threatening human and environmental health (Rerkasem, 2005; Moeskops et al., 2010; 2012). To establish a sustainable strategy of soil management in the vegetable cropping system in the volcanic soils of the region, it is crucial to assess the impact of the current agricultural systems on soil resources (Abe et al., 2018). The objective of this study, therefore, was to examine the impact of land use and management on the availability of selected micronutrients (Fe, Mn, Cu and Zn) and on the relationship of micronutrient availability with the general soil properties in this region.

Materials and Methods

The study site was located on a foot slope of Mt. Marapi (coordinates: 0°27'S, 100°25'E; elevation: approx. 1200 m a.s.l.; mean slope: 5–15%), an active volcano in West Sumatra, Indonesia. The climate is a tropical rain forest (Af), with a mean air temperature of 23°C and a mean annual rainfall of 2300 mm. This site is widely

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covered by Sil-andic Andosols (IUSS Working Group WRB, 2014) and is used for intensive vegetable (e.g., tomato, chili pepper, onion, carrot, cabbage) cultivation on terraced fields with the frequent use of macronutrient fertilizer (200–300 kg N ha⁻¹ crop⁻¹; 100–150 kg P₂O₅ ha⁻¹ crop⁻¹; and 100–150 kg K₂O ha⁻¹ crop⁻¹) and agrochemicals such as insecticides, fungicides and herbicides (for more details, see Abe et al., 2018). Although the application of chicken manure (5–10 t ha⁻¹ crop⁻¹) is common, the use of micronutrient fertilizer is rare. Each year, 4–6 crops are cultivated in the same field, whereas the fallow period is often restricted to a few weeks only.

At the study site, the fields were grouped into eight categories according to land use and management practices: crop fields under conventional management with different periods of continuous cultivation, i.e., i) 1–3 years (VC-1; n=4), ii) 6–8 years (VC-2; n=3) and iii) more than 20 years (VC-3; n=3); iv) organic farm (VO; n=5) that made use of livestock manure, a composted mixture of goat dung/urine and green biomass including *Tithonia diversifolia*, but did not use chemical fertilizers nor agrochemicals over the previous 10 years; natural fallow lands with different periods of fallow, i.e., v) 1–3 years (FN-1; n=3), vi) 10 years (FN-2; n=5) and vii) 25 years (FN-3; n=5); and viii) fallow land (FC; n=5) covered by the multipurpose leguminous tree *Calliandra calothyrsus*, which was established about 20 years ago (for more details, see Abe et al., 2018). All of the fields studied were located within a 20-ha area; the distance between the farthest fields is approximately 600 m. All crop fields were cultivated after at least several years of being naturally fallow, while all fallow lands had been cultivated for several years before they were left fallow.

Soil samples were taken at least in triplicate from the topsoil (0–10 cm; in the furrow if there were ridges), air dried, gently ground and passed through a 2-mm mesh sieve for the laboratory analysis. The samples were subjected to general physicochemical analysis according to the routine methods documented by Japanese Society of Soil Science & Plant Nutrition (1997). The analytical results have been reported elsewhere (Abe et al., 2018). In the present study, the availability of micronutrients (Fe, Mn, Cu, and Zn) in the soil samples was assessed by the Mehlich 3 method (Mehlich, 1984). This method is known to be applicable to a wide range of acidic soils and its results often show a good correlation with those obtained by the diethylene triamine pentaacetic acid (DTPA) method and the diluted hydrochloric acid method (Wendt, 1995; Cancela et al., 2002; Elrashidi et al., 2003) which are more widely accepted methods of studying soil micronutrient availability than the Mehlich 3 method. Briefly, 3-g amounts of the fine earth samples were mixed with 30 mL of the Mehlich 3 extractant consisting of 0.015 mol L⁻¹ NH₄F, 0.25 mol L⁻¹ NH₄NO₃, 0.2 mol L⁻¹ CH₃COOH, 0.013 mol L⁻¹ HNO₃ and 0.001 mol L⁻¹ ethylene diamine tetra acetate for 5 min. of reciprocal shaking (Mehlich, 1984). The concentrations of Fe, Mn, Cu, and Zn in the extracts were determined by atomic absorption spectrometry (Z-2300, Hitachi Tech., Co., Tokyo).

Soil parameters were statistically compared among the eight field categories either by Tukey’s or Games–Howell’s test after evaluation of the homogeneity of variances by Levene’s test. Differences in means with \( P<0.05 \) were considered statistically significant. In addition, the correlations between pairs of selected soil properties were calculated using Pearson’s correlation coefficients. All statistical analyses were performed using SPSS software (ver. 24.0.0.0, IBM Co., Chicago, Illinois).

**Results and Discussion**

Selected physicochemical properties of the studied soils which have been reported elsewhere (Abe et al., 2018) are shown in Table 1. In summary, soil acidification, the loss of organic matter and exchangeable bases, and enhanced soil acidity and phosphorus (P) availability were observed in the crop fields, as shown by decreases in soil pH, in the contents of organic carbon (C), total nitrogen (N) and exchangeable calcium (Ca) and magnesium (Mg) and in the phosphate absorption coefficient (PAC), but increases in exchangeable acidity and available (Bray-2) P. The extent of the decreases/ increases in these parameters was associated with the cultivation period. Organic farming had some advantage in terms of the maintenance of soil fertility, as it protected the soil to some extent from the negative impacts listed above. Fallow systems were effective at soil fertility replenishment, as shown by the increases in organic C, total N and exchangeable Ca and Mg, although the soil P fixation capacity recovered, as indicated by the decreased level of available P and increased PAC. The degree of replenishment increased as the length of the fallow period increased. However, the longer fallow periods, especially in fields covered by *C. calothyrsus*, caused soil acidification and increased acidity. These traits were associated with the formation of humus-Al complexes as shown by decreased levels of amorphous aluminosilicate minerals, as indicated by the ammonium oxalate soluble aluminum (Alo) plus half ammonium oxalate soluble Fe (Feo) content, shown as the Alo+1/2Feo content, and by increased humus-complexed Al, as indicated by the ratio...
of sodium pyrophosphate soluble Al (Alp) to Feo, shown as the Alp/Feo ratio. Fig. 1 shows the Fe, Mn, Cu and Zn in the soil samples that were soluble in the Mehlich 3 extractant and thus soluble to be available to the crops (hereafter referred to as M3-Fe, M3-Mn, M3-Cu, and M3-Zn, respectively). The M3-Fe content in all the field categories was found to be around 50 mg kg⁻¹ with moderate variability (coefficient of variation (CoV)=24%) and did not show any significant differences among the field categories. As an exception, FC showed a roughly 30% to 50% higher M3-Fe content than the other field categories, although a significant difference was detected only between FC and VO. The M3-Cu content in the field categories was found to be approximately 2.5 mg kg⁻¹ with low variability (CoV=14%), and thus there were no significant differences between the categories. In contrast, M3-Mn (CoV=68%) and M3-Zn (CoV=60%) showed much higher variability than M3-Fe and M3-Cu. These results suggest that the availability of Fe and Cu in the studied soil was more susceptible to changes in the general soil properties due to changes in land use and management than the availability of Mn and Zn. The soil in FC had the highest M3-Mn content (ca. 20 mg kg⁻¹), roughly two to five times higher than the levels in the other field categories, which was a significant difference. The M3-Mn content did not show any trend of change in relation to land use type and/or period of cultivation/fallow, regardless of its high variability. Meanwhile, the M3-Zn content exhibited a trend: it increased as the length of the cultivation period in the crop field increased but decreased as the length of the fallow period in the naturally fallow land increased. However, a significant difference in the M3-Zn content was detected only between FC and VC-1.

The correlation analysis revealed that there were no significant correlations among the Mehlich-3 extractable micronutrients, except for very weak correlations (R<0.50) between M3-Fe and Mn3 as well as between M3-Mn and M3-Zn (Table 2). The M3-Fe content was negatively correlated with soil pH, base saturation percentage, and the Alp/2Feo content, and was positively correlated with organic C, total N, exchangeable acidity, and the Alp/Al ratio. This result suggests that Fe availability is associated with soil acidity and with the amounts of organic matter and amorphous minerals. The availability of Mn showed the same trend as that of Fe, but was more strongly associated with the amount of organic matter than soil acidity or amorphous minerals. Also, the availability of Zn was associated with soil organic matter. Although the degree of its association with organic matter seems to be similar to that of Fe due to the similar absolute value of its correlation coefficient with organic C, the soil reaction may differently affect their availability; i.e., Fe availability increased with decreasing soil pH but Zn availability did not change. Although the application of organic manure can enhance the availability of the micronutrients except for Cu, through the augmentation of organic matter content (Wei et al., 2006; Li et al., 2007), no effect of goat manure nor of chicken manure was obvious in this study. The current application rate of organic manure (5–10 Mg ha⁻¹ crop⁻¹) appeared to be insufficient to increase the organic matter content in the soil (see Table 1); thus, the application of organic manure...
manures seemed to be ineffective for enhancing the availability of the micronutrients to a significant extent (see Fig. 1). In contrast to M3-Fe, M3-Mn and M3-Zn, the M3-Cu content showed few significant correlations with general soil fertility parameters, which were largely affected by land use and management. The availability of Cu could be associated with other soil characteristics, such as nature of parent materials (Saigusa et al., 1976), which were not examined in this study.

The decreased availability of micronutrients in croplands has been reported elsewhere (e.g., Wei et al., 2006; Abe et al., 2007; Li et al., 2007). This primarily results from the removal of micronutrients by crop harvesting and is often seen in sandy soils and/or in soils with neutral/alkaline reactions, as in these soils the availability of the micronutrients is inherently limited (e.g., Wei et al., 2006; Abe et al., 2007; Li et al., 2007). However, in our study, the availability of micronutrients was not decreased to a significant degree because of the inherently high micronutrient availability in the studied soils. Andosols often have acidic reactions and high organic matter content (Dahlgren et al., 2004), both of which enhance the solubility of the micronutrients (Vitosh et al., 1994; Wei et al., 2006; Li et al., 2007). In fact, these micronutrient levels were much higher than the critical levels, i.e., Fe=4.8 mg kg⁻¹; Mn=4.0 mg kg⁻¹; Cu=0.3–1.5 mg kg⁻¹; Zn=1.0–2.0 mg kg⁻¹ (Havlín and Soltanpour, 1981; Makarim and Cox, 1983; Martens and Lindsay, 1990, Sims and Johnson, 1991). Therefore, crop micronutrient deficiencies are unlikely at the study site. On the other hand, the chance that these micronutrients may be present at toxic levels for crop production become a concern if soil acidification reaches below pH=5.0 (Vitosh et al., 1994). Among these micronutrients, Mn toxicity is of particular concern because cabbages and tomatoes, which are cultivated widely at the study site, are sensitive to excess Mn (Li et al., 2007). However, no apparent symptoms of Mn toxicity were observed in vegetables at the study site during the field survey. Moreover, the soil micronutrient levels at the study site were lower than toxic levels, i.e., Fe=100–500 mg kg⁻¹; Mn=220 mg kg⁻¹; Cu=7 mg kg⁻¹; Zn=160 mg kg⁻¹ (USEPA, 2003, 2007a, 2007b, 2007c). These results indicate that soil micronutrient toxicities are also unlikely at the study site. Yet, acidity constraints in volcanic soils, especially Alu-andic Andosols as seen in the Calliandra fallow land at the study site (Abe et al., 2018), which often have high humus-complexed Al and exchangeable acidity contents, are mainly derived form Al toxicity (Dahlgren et al., 2004; IUSS Working Group WRB, 2014). There-

Table 2. Correlation coefficients of Mehlich 3 extractable micronutrients with selected soil properties at the study site.

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Fe</th>
<th>Mn</th>
<th>Cu</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meylich Fe</td>
<td>1.00*</td>
<td>0.40*</td>
<td>0.25</td>
<td>0.19</td>
</tr>
<tr>
<td>Meylich Mn</td>
<td>0.40*</td>
<td>1.00*</td>
<td>0.01</td>
<td>0.48***</td>
</tr>
<tr>
<td>Meylich Cu</td>
<td>0.25</td>
<td>0.01</td>
<td>1.00</td>
<td>0.26</td>
</tr>
<tr>
<td>Meylich Zn</td>
<td>0.19</td>
<td>0.48***</td>
<td>0.26</td>
<td>1.00</td>
</tr>
<tr>
<td>pH(H₂O)</td>
<td>-0.42*</td>
<td>-0.45**</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>Exch. Acidity</td>
<td>0.74***</td>
<td>0.42*</td>
<td>0.10</td>
<td>-0.17</td>
</tr>
<tr>
<td>Organic C</td>
<td>0.52**</td>
<td>0.81***</td>
<td>-0.03</td>
<td>0.55***</td>
</tr>
<tr>
<td>Total N</td>
<td>0.55***</td>
<td>0.82***</td>
<td>0.06</td>
<td>0.53***</td>
</tr>
<tr>
<td>Exch. Ca</td>
<td>0.07</td>
<td>0.46*</td>
<td>-0.08</td>
<td>0.65***</td>
</tr>
<tr>
<td>Exch. Mg</td>
<td>0.22</td>
<td>0.58**</td>
<td>0.00</td>
<td>0.67***</td>
</tr>
<tr>
<td>Exch. K</td>
<td>-0.13</td>
<td>-0.11</td>
<td>0.20</td>
<td>0.27</td>
</tr>
<tr>
<td>Exch. Na</td>
<td>0.47**</td>
<td>0.43*</td>
<td>0.06</td>
<td>0.21</td>
</tr>
<tr>
<td>ECEC</td>
<td>0.13</td>
<td>0.51**</td>
<td>-0.05</td>
<td>0.67***</td>
</tr>
<tr>
<td>BS</td>
<td>-0.56***</td>
<td>-0.02</td>
<td>-0.05</td>
<td>0.42*</td>
</tr>
<tr>
<td>Avail. P</td>
<td>0.09</td>
<td>-0.22</td>
<td>0.10</td>
<td>0.17</td>
</tr>
<tr>
<td>PAC</td>
<td>-0.29</td>
<td>-0.02</td>
<td>-0.13</td>
<td>-0.28</td>
</tr>
<tr>
<td>Sio</td>
<td>-0.63***</td>
<td>-0.56***</td>
<td>0.14</td>
<td>-0.34</td>
</tr>
<tr>
<td>Alp/Alo</td>
<td>0.63***</td>
<td>0.71***</td>
<td>-0.10</td>
<td>0.37***</td>
</tr>
<tr>
<td>Alp+1/2Feo</td>
<td>-0.60***</td>
<td>-0.57***</td>
<td>0.16</td>
<td>-0.36***</td>
</tr>
</tbody>
</table>

Number of entry=33.

Abbreviations: ECEC=effective cation exchange capacity; BS=base saturation percentage; Feo, Alo=ammonium oxalate extractable Fe, Al; Si=Feo, Alp=pyrophosphate extractable Fe, Al; PAC=phosphate absorption coefficient.

***, ** and * indicate significance at P<0.001, <0.01 and <0.05, respectively.

Fig. 1. Mehlich 3 extractable micronutrient contents according to the field categories at the study site. Different letters indicate significant differences at P<0.05 among the field categories; ns denotes insignificant difference. Abbreviations: VC-1=1–3 year old crop field; VC-2=6–8 year old crop field; VC-3=>20 year old crop field; VO=10 year old organic farm; FN-1=1–3 year old natural fallow land; FN-2=10 year old natural fallow land; FN-3=25 year old natural fallow land; FC=20 year old Calliandra fallow land.
fore, liming would be the most effective way to combat micronutrient toxicity as well as Al toxicity. In particular, liming is desirable in FC when it is opened for recultivation, as the soils in FC had the lowest pH values and the highest contents of exchangeable acidity and Mehlich 3 extractable micronutrients. This was the case despite the fact that most soil samples examined in the present study had pH values higher than 5.0 and exchangeable acidities lower than 2 cmol, kg⁻¹, a threshold value that may cause acidity problems in some acidity-prone edible plants in Andosols (Dahlgren et al., 2004).

On the other hand, it has been reported elsewhere that a high level of available P reduces the availability of micronutrients due to their possible precipitation as metal phosphates (Wei et al., 2006; Li et al., 2007). However, the field categories were found to contain M3-Zn at levels that could be ranked as follows: VC-3>VC-2>VC-1. This is the same order as that for the available P, although there were no significant differences between these three croplands. Moreover, the M3-Zn content exhibited no significant correlation with either available P content or PAC. These contradictory results may be attributed to the high P-fixation capacity of Andosols.

In conclusion, the deficiencies of soil micronutrients (Fe, Mn, Cu and Zn) are not likely to constrain vegetable production at the study site even after 20 consecutive years of cultivation because of the inherently high availability of the micronutrients due to the low pH and high level of organic matter in the soil. In contrast, soil acidification that proceeds under conventional crop management and in Calliandra-covered fallow fields increases the solubility of the micronutrients and may result in toxic levels of the micronutrients as well as Al. Therefore, liming would be a desirable approach to eliminate the risk of these toxicities.

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References