SPATIAL DISTRIBUTION OF SOME CHEMICAL CHARACTERISTICS OF AN ACID SULFATE SOIL–AFFECTED BRACKISHWATER PONDS IN THE COASTAL AREA OF LUWU REGENCY SOUTH SULAWESI PROVINCE

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ABSTRACT

Spatial distribution of brackishwater pond soil has important role in the system of bio-environment including brackishwater pond environment. This research was aimed to determine the spatial distribution of some chemical characteristics of an acid sulfate soil–affected brackishwater pond in coastal area of Luwu Regency South Sulawesi Province, Indonesia. ALOS AVNIR-2 images (acquisition 16 May 2008, 16 October 2008, 17 September 2009) were integrated with Indonesian Topographic maps to obtain base map. Sampling soil points were determined by simple random sampling in 104 points for two different soil depths i.e. 0-0.2 m and 0.5-0.7 m. A total of 18 soil chemical characteristics was measured in the field and analyzed in the laboratory. Geostatistic using kriging method in the ArcGIS 9.3 software was used to interpolate the data. The results of this study indicated that in general pond soil chemical characteristics in Luwu Regency could be categorized with high variability or relatively heterogenic with the value of variation coefficient more than 36%. The soil characteristics that explain acidity had shown similar pattern in spatial distribution as well as other soil characteristics with soil nutrient. The high value of pH and low value of PO_4 were generally found in the northern part of Luwu Regency, including East Lamasi, East Walenrang, Bua, and Ponrang Subdistricts. It is recommended that soil management in brackishwater ponds of Luwu Regency could be based on soil chemical characteristics so its could improve the production through minimizing the input, increasing carrying capacity, and avoiding environmental degradation.

KEYWORDS: spatial analysis, soil, brackishwater pond, coastal area, Luwu Regency

INTRODUCTION

Ministry of Marine Affairs and Fisheries of the Republic of Indonesia has programs focused on minapolitan, industrialization, and blue economic to increase fisheries production, especially aquaculture production. Aquaculture is currently implemented in Indonesia including marine culture, brackishwater pond, freshwater pond, paddy fields, and inland open waters. Potency land for brackishwater ponds reached 2,963,717 ha with the utilization only about 682,857 ha; and the production of 1,737,260 tonnes (MMAF, 2011).

Until 2008, the gross area of brackishwater ponds in the east coast of South Sulawesi Province reached 50,131 ha (Anonymous, 2009).

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Brackishwater ponds are distributed in East Luwu, North Luwu, Luwu, Wajo, Bone, and Sinjai Regencies as well as in Palopo City with the area of 11,397; 6,367; 6,889; 12,000; 11,633; 714; and 1,131 ha; respectively. Brackishwater ponds in Luwu Regency mainly used to produce tiger shrimp (*Penaeus monodon*), speckled shrimp (*Metapenaeus monoceros*), whiteleg shrimp (*Litopenaeus vannamei*), seaweed (*Gracilaria verrucosa*), milkfish (*Chanos chanos*), and other fish such as tilapia (*Oreochromis niloticus*).

One of the environmental factors that affect brackishwater ponds productivity is soil quality. Soil quality is a major factor of production in aquaculture because it can affect water quality, biological, and engineering processes of brackishwater ponds (Sammut, 1999). Therefore, generally, soil quality has to be considered in land suitability evaluation for brackishwater ponds (Treece, 2000; Salam *et al.*, 2003; Giap *et al.*, 2005; Karthik *et al.*, 2005; Mustafa *et al.*, 2011). One type of soil which is common in brackishwater ponds of coastal area in Indonesia, including Luwu Regency is acid sulfate soil (Mustafa, 2007). Acid sulfate soil is the common name given to soil or sediment containing iron sulfides or pyrite (Dent, 1986; Sammut & Lines-Kelly, 2000; Lin *et al.*, 2004; Schaetzl & Anderson, 2005). Chemical characteristics of the soil need much more attention than physical and biological characteristics of the soil and a lot of acid sulfate soil chemical characteristics which is a typical characteristic of the acid sulfate soil.

Spatial distribution of soil types is controlled by a set of environmental factors such as climate, organisms, parent material, and topography as well as time and space (Barthold *et al.*, 2013); in which changes in the environmental factors will change the spatial distribution of soil types. Identification of the spatial distribution of soil characteristics has an important role in many bio-environmental systems (Zuo *et al.*, 2008; Dong *et al.*, 2009; Akbarzadeh & Taghizadeh-Mehrjardi, 2010; Zare-Mehrjardi *et al.*, 2010; Yu *et al.*, 2011). Knowledge of spatial variability on soil characteristics and soil intercharacteristic relationship is important for the evaluation of soil management practices (Huang *et al.*, 2001; Saadi & Athanasopoulos-Zekkos, 2013), and increases the sustainability of land cover/land use (Liu *et al.*, 2006). Variability is one of the essential characteristics of the soil quality and the same ecosystem soil quality may show noticeable spatial varia-

tions (Robinson & Metternicht, 2006). These variations are mainly arise from the factors and processes of pedogenesis and land cover/land use (Tuzinsky, 1990; Ersahin, 2003; Martin *et al.*, 2011; Beguería *et al.*, 2013) as well as land management practices (Pan Gozalez *et al.*, 2000; Anuar *et al.*, 2008). With classical statistics that take into account the data of land as free data, the implementation often produces unrealistic results (Zare-Mehrjardi *et al.*, 2010). In addition, contrary to the assumption that when used classical statistics is that the soil characteristics on a landscape are not distributed randomly (not just random variability but also not correlated to the spatial location) (Essington, 2004). Natural soil characteristics can vary continuously in time and space, and for such conditions is very difficult if it is possible to measure the quality of the soil at any point in the field (Madyaka, 2008). Spatial variation in soil characteristics are so complex that no description can be resolved, so the prediction is certain or uncertain (Aberegg *et al.*, 2009). Geostatistics can be used to characterize and quantify the spatial variability of soil characteristics, rationally interpolate, and estimate or predict the difference of the interpolated values (Lin *et al.*, 2001; Essington, 2004). Therefore, geostatistical method was applied in this study to better understand the spatial distribution of some chemical characteristics of acid sulfate soils in coastal area of Luwu Regency South Sulawesi Province. Results of this study could be used as a basic for determining soil management.

MATERIALS AND METHODS

The research was conducted in July 2010 in Luwu Regency South Sulawesi Province, Indonesia. Research sites were distributed in 11 coastal subdistricts, namely: East Lamasi, East Walenrang, Bua, Ponrang, South Ponrang, Kamanre, North Belopa, Belopa, Suli, Larompong, and South Larompong (Figure 1). The research was initiated in the form of discussions with staff of Marine and Fisheries Office of Luwu Regency in Belopa in order to obtain general information about brackishwater ponds in coastal area of Luwu.

Data Collection

Primary Data

Soil chemical characteristics were the primary data used in this study. Points of measurement and soil sampling were randomly
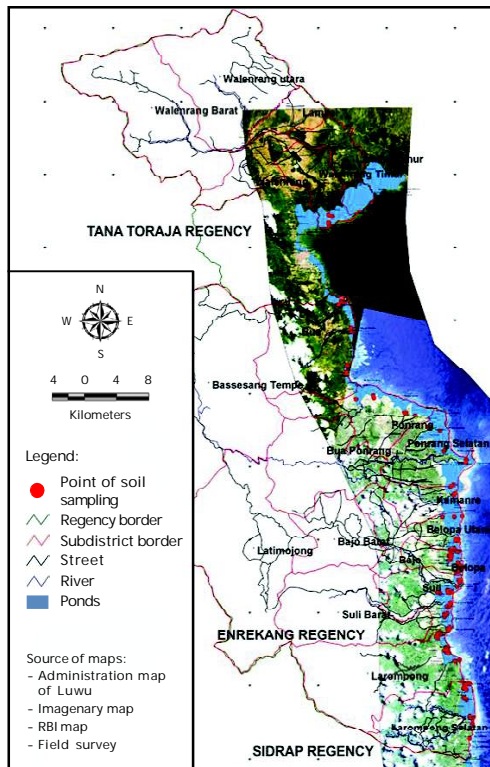
Figure 1. Points of soil sampling in brackish-water ponds of Luwu Regency South Sulawesi Province

determined at 104 measurement points, and soil sampling following the instructions from Hazelton & Murphy (2009). Soil quality variables directly measured in the field were pH_F (soil pH measured in the field) with a pH-meter (Ahern & Rayment, 1998); pH_{FOX} (soil pH was measured in the field after oxidized with hydrogen peroxide (H_2O_2) 30%) with pH-meter (Ahern & Rayment, 1998); and redox potential with redox-meter. Soil samples were taken at two soil depths from the soil surface, i.e. 0.0-0.2 m and 0.5-0.7 m. For analyzing other soil quality variables, soil sample was immediately collected in plastic bag and then stored in a cool box containing ice; because the soil samples were classified as acid sulfate soil. Left over fresh herbs, pebbles, shells, other debris, and garbage were taken out manually by hand. Soil samples were oven-dried at 80°C-85°C for 48 hours (Ahern & Blunde, 1998). Once dried, pulverized soil samples were ground on porcelain mortar and sieved with sieve having 2.0 mm and 5.0 mm mesh size and then analyzed

in the Soil Laboratory of Research Institute for Coastal Aquaculture (RICA) in Maros, South Sulawesi Province. Soil quality analyzed in the laboratory include pH_{KCl} (pH of KCl extract) (McElnea & Ahern, 2004a), pH_{OX} (McElnea & Ahern, 2004b), S_P (sulfur peroxide) (McElnea & Ahern, 2004c), S_{KCl} (sulfur is extracted by KCl) (McElnea & Ahern, 2004d), S_{POS} ($S_P - S_{KCl}$) (Ahern & McElnea, 2004), TPA (Titratable Peroxide Acidity or previously known as Total Potential Acidity) (McElnea & Ahern, 2004b), TAA (Titratable Actual Acidity or previously known as Total Actual Acidity) (McElnea & Ahern, 2004a), TSA (Titratable Sulfidic Acidity or previously known as Total Sulfidic Acidity) (TPA - TAA) (McElnea & Ahern, 2004b), pyrite (Ahern *et al.*, 1998a; 1998b), organic carbon by Walkley and Black method (Sulaiman *et al.*, 2005), total N by Kjedhal method (Sulaiman *et al.*, 2005), PO_4 by Bray 1 or Olsen method (depending on soil pH) (Sulaiman *et al.*, 2005), Fe and Al with a spectrophotometer (Menon, 1973).

Secondary Data

Secondary data were collected by searching various reports, literatures, research on the results of various related agencies, satellite imagery, and maps. ALOS (Advanced Land Observing Satellite) AVNIR-2 (The Advanced Visible and Near Infrared Radiometer type 2) acquired on 16 May 2008 (2 scenes), 16 October 2008 (1 scene), and 17 September 2009 (1 scene) were used in this study. Indonesia Topographic maps of 1:50,000 scale were collected from Indonesian Geospatial Agency such as sheets number 2113-14 (Masamba Sheet), 2113-12 (Amassangan Sheet), 2113-11 (Palopo Sheet), 2112-44 (Padangsappa Sheet), 2112-42 (Belopa Sheet), and 2112-14 (Larompong Sheet), and map of Luwu Administration.

Data Analysis

Maps of land cover/land use classification were acquired from the image of ALOS AVNIR-2 by using ER Mapper 7.1. The ALOS AVNIR-2 images were integrated with Indonesia Topographic maps in order to obtain the base map. Other spatial information derived from primary and secondary data were also integrated with the map of land cover/land use. Data of variable soil characteristics from the same soil depth were analyzed by classical statistical methods to obtain minimum, maximum, average, standard deviation, coefficient of varia-

tion, curtosis, and skewness based on the instructions from Sokal & Rohlf (1981). Kriging method (Mulla & McBratney, 1999; Essington, 2004; Lin, 2008; Saadi & Athanasopoulos-Zekkos, 2013) in ArcGIS 9.3 software was used in the interpolation of the existing soil data at 0-0.2 m soil depth.

RESULTS AND DISCUSSION

Soil types found in brackishwater ponds of Luwu Regency were dominated by acid sulfate soil and acid sulfate soil associated with peat soils. Based on soil taxonomy (Soil Survey Staff, 2001), soil in the coastal area of Luwu is classified as sulfaquent, hydraquent, and sulfihemits for great groups. Sulfaquentis characterized by aquents that has sulfidic materials or pyrite up to 0.5 m from soil surface and is included as potential acid sulfate soil. Hydraquent is characterized by a depth of 1.0 m from the soil surface and has sulfidic materials or sulfiric layer at a depth of 0 to 0.15 m or more and in addition it has pH of 3.5-4.0. Hydraquent and sulfaquent classified into entisol while in Soil Classification System of Soil Research Centre they are classified into

Alluvium. Acid sulfate soil is not only found in mineral soil, but also in organic soil, including acid sulfate soil. In Luwu Regency was classified as sulfihemits. Sulfihemits is characterized by the presence of sulfidic materials up to 1.0 m of the surface that does not oxidize and does not have a sulfuric horizon at a depth of 0.5 m from the surface and is also classified as potentially acid sulfate soil. In the category of Major Soil Group, sulfihemits is histosol or in Soil Classification System of Soil Research Centre it is classified into organosol.

Based on the coefficient of curtosis, most of the data on the chemical characteristics of brackishwater ponds soil of Luwu Regency were distributed relatively platykurtic (flat) with coefficient of curtosis less than 3, both in 0-0.2 m soil depth (Table 1) and 0.5-0.7 m soil depth (Table 2). Tables 1 and 2 also showed that most data of soil characteristics in Luwu Regency were skewed to the right with skewness coefficient less than 2, and in general data of soil characteristics has also indicated positive skewness. This indicates that data in each soil characteristics of brackishwater pond in Luwu Regency have relatively equal distri-

Table 1. Chemical characteristics of brackishwater ponds soil in 0-0.2 m soil depth in coastal area of Luwu Regency South Sulawesi Province (n=104)

Variables	Minimum	Maximum	Average	Standard deviation	Coefficient of variation	Curtosis	Skewness
Redox potential (mV)	-518	349	-272.3	110,458	40,558	8,918	1,962
pH_F	5.31	8.26	6.89	0.376	5,454	3,346	-0.351
pH_{FOX}	1.22	6.01	2.41	1,266	52,524	1,080	1,522
$pH_F - pH_{FOX}$	0.99	6.15	4.48	1,246	27,803	0.940	-1,421
pH_{KCl}	1.28	7.75	5.56	1,359	24,451	0.550	-1,051
pH_{OX}	0.90	6.79	2.25	0.875	38,802	7,008	2,088
S_{KCl} (%)	0.07	1.85	0.54	0.411	76,340	1,526	1,459
S_P (%)	0.35	4.64	2.07	1,044	50,368	-0.445	0.401
S_{POS} (%)	0.13	3.56	1.54	0.797	51,928	-0.601	0.210
TPA (mole H^+/tonne)	0.00	3,453.00	556.73	594,623	106,807	5,429	2,093
TAA (mole H^+/tonne)	0.00	223.00	6.57	24,936	379,692	56,754	6,981
TSA (mole H^+/tonne)	0.00	3,418.00	550.16	582,900	105,951	5,588	2,100
Pyrite (%)	0.00	15.26	2.46	2,602	105,951	5,588	2,100
Total N (%)	0.04	1.63	0.44	0.304	69,821	4,065	1,898
PO_4 (ppm)	2.77	113.57	20.65	16,475	79,793	9,854	2,580
Organic matter (%)	1.17	27.87	8.70	6,496	74,636	0.955	1,250
Fe (mg/L)	114.00	5,085.00	3,765.77	1,465.670	38,921	0.675	-1,423
Al (mg/L)	0.01	777.00	348.46	126,411	36,277	1,845	0.065

Table 2. Chemical characteristics of brackishwater ponds soil in 0.5–0.7 m soil depth in coastal area of Luwu Regency South Sulawesi Province (n=104)

Variables	Minimum	Maximum	Average	Standard deviation	Coefficient of variation	Curtosis	Skewness
Redox potential (mV)	-445	387	-289.8	107.50	37,101	14,171	2,806
pH_F	6.23	7.65	6.76	0.263	3,889	0.464	0.507
pH_{FOX}	0.95	4.34	1.72	0.476	27,622	9,725	2,523
$pH_F - pH_{FOX}$	2.09	6.33	5.04	0.545	10,806	8,412	-1,937
pH_{KCl}	1.49	7.63	4.26	1,641	38,547	-1,162	0.173
pH_{OX}	0.92	6.98	1.77	0.749	42,241	25,005	4,276
S_{KCl} (%)	0.12	2.52	0.76	0.500	66,113	0.540	1,080
S_P (%)	0.42	4.85	2.65	0.936	35,325	-0.321	0.152
S_{POS} (%)	0.02	3.67	1.89	0.689	36,444	0.035	-0.304
TPA (mole H^+/tonne)	6.50	2,999.50	826.77	554,459	67,063	1,904	1,251
TAA (mole H^+/tonne)	0.00	120.00	19.54	26,693	136,619	2,944	1,776
TSA (mole H^+/tonne)	6.50	2,905.50	807.23	538,645	66,727	1,973	1,275
Pyrite (%)	0.03	12.97	3.60	2,405	66,727	1,973	1,275
Total N (%)	0.12	1.25	0.43	0.259	60,497	1,926	1,459
PO_4 (ppm)	0.01	81.05	19.40	13,875	71,526	4,899	1,832
Organic matter (%)	1.04	28.60	10.31	6,432	62,362	0.798	1,143
Fe (mg/L)	211.50	4,976.00	4,296.81	705,319	16,415	12,001	-3,044
Al (mg/L)	120.00	1,026.50	387.97	140,761	36,281	2,959	1,195

bution. Tabi & Ogunkunle (2007) obtained a positive value of skewness for P-available, Mg, and K soil in 0-0.15 m soil depth in Nigeria.

Coefficient of variation of soil brackishwater ponds in Luwu Regency varies from the lowest in pH_F (5.454%) and the highest in TAA (379.692%) for 0-0.2 m soil depth (Table 1), while the lowest value of the coefficient of variation is also in pH_F (3.889%) and the highest in TAA (136.619%) for 0.5-0.7 m soil depth (Table 2). Similar results were reported for brackishwater ponds in Pangkep Regency South Sulawesi Province (Rachmansyah & Mustafa, 2011). Goh *et al.* (1998) also reported that coefficient of variation of soil characteristics in Sabah (Malaysia) can exceed 100% on the same soil series. Beguería *et al.* (2013) reported that coefficient of variation of soil characteristics exceeds 77%. Coefficient of variation of soil characteristics are of great value, and only reflect conditions at specific locations (Saadi & Athanasopoulos-Zekkos, 2013). Based on the classification established by Essington (2004), variable classified as having small variability or relatively homogeneous was pH_F; variables classified as having moderate variability were

pH_F-pH_{FOX} and pH_{KCl}, while other soil quality variables relatively have high variability or relatively heterogeneous for 0-0.2 m soil depth. In 0.5-0.7 m soil depth, variables which have relatively small variability or relatively homogeneous were pH_F and pH_F-pH_{FOX}, variables classified as having moderate variability were S_P and Fe, while other soil quality variables have relatively high variability or relatively heterogeneous. This indicate that general soil characteristics of brackishwater ponds in Luwu Regency relatively have high variability or relatively heterogeneous. Essington (2004) stated that soil characteristics have relatively high variability due to location on the landscape and soil depth difference. High variability of soil characteristics in the same soil series has also been reported in Malay Peninsular by Law & Tan (1977). It also has been reported that the characteristics of brackishwater ponds soil in Indonesia are similar to those in Pekalongan City Central Java Province (Asaad & Mustafa, 2011) and Pangkep Regency South Sulawesi Province (Rachmansyah & Mustafa, 2011) which have relatively high variability or relatively heterogeneous. Vertical spatial distribu-

tion of brackishwater ponds soil in Luwu Regency, can be seen in Tables 1 and 2, while spatial horizontally distribution is shown in Figures 2-7.

Redox potential describes the condition of the soil which is oxidized or reduced. Redox potential is a quantitative measurement results to inform a diagnostic index of the level of anaerobic or anoxic soil (Patrick & Delaune, 1977). Table 1 shows that the redox potential of the soil in 0-0.2 m soil depth was higher than in 0.5-0.7 m soil depth. It can be caused by the drying of brackishwater pond bottom which is usually done by farmers at the time preparation of brackishwater pond, in which the surface of brackishwater ponds soil becomes dry, so that the soil redox potential was higher than the soil beneath the surface. In general, brackishwater ponds soil in Luwu Regency was classified under reduced conditions. This was as a result of soil sampling conducted in brackishwater while in the process of both shrimp and milkfish culture in monoculture or polyculture between milkfish and seaweed and polyculture among milkfish, tilapia, and seaweed, so brackishwater ponds are in waterlogged conditions.

All forms of pH measured in this research (pH_F, pH_{FOX}, pH_{KCI}, pH_{OX}) were showed higher value in the depth of 0-0.2 m soil depth than in 0.5-0.7 m soil depth. This was as a result of natural leaching process in a relatively long period of time, causing compounds of soil acidity was decreased on the soil surface. In addition, soil management practices such as the use of lime by farmers is leading to high pH_F in the surface soil. Pond farmers in brackishwater ponds in Luwu Regency applied agricultural lime up to 250 kg/ha with an average of 104 kg/ha (Mustafa & Sammut, 2010). Applying lime on soil surface can only give real effect in soil depth of 0.05 m (Conyers *et al.*, 2003). On the other hand, liming in dyke of brackishwater ponds-affected acid sulfate soil can reach a depth of 0.4 m, as a result of the fracture in dyke so that lime can give real effect to such depths (Mustafa, 2007). At a depth of 0-0.2 m soil appeared that the relatively low pH found in the northern part of Luwu Regency, include East Lamasi, East Walenrang, Bua, and Ponrang Subdistricts (Figures 2 and 3).

pH_F-pH_{FOX} value is often used as one of the variable quality of the soil to determine the potential acidity of the soil. The values of pH_F-pH_{FOX} were ranged between 0.99 and 6.15 (av-

erage 4.48) at a depth of 0-0.2 m and between 2.09 and 6.33 (average 5.04) at a depth of 0.5-0.7 m. It was clear that soil in brackishwater ponds of Luwu was classified as acid sulfate soil. On acid sulfate soil, pH_F-pH_{FOX} can exceed the value of 5 (Mustafa & Rachmansyah, 2008). It was also clarified the previous description that the degree of acidity in the soil surface was lower than the soil at a depth of 0.5-0.7 m. Figure 2 shows that there have a value of pH_F-pH_{FOX} fairly low in brackishwater pond of Luwu which was located in the northern part. Relative spatial distribution similar to pH_F-pH_{FOX} was the spatial distribution of pH_{OX}, but in areas high value of pH_F-pH_{FOX} the other wise low pH_{OX}. pH_{OX} is the pH of the soil that has been dried and then oxidized with H_2O_2 30% (McElnea & Ahern, 2004b), that describes all potential existing in the soil acidity.

Spatial distribution of organic matter content also has shown the same pattern with pH_F-pH_{FOX}. This suggests that the potential for soil acidity in brackishwater ponds of Luwu, apart from pyrite was also derived from organic matter. High organic matter content was derived from mangrove forest conversion to brackishwater ponds. Fallen leave is the largest contributor of organic matter in sediments of mangrove forests (Koch, 2005). Decomposition of organic matter can produce humic acids that lead to lower soil pH. Another possibility of the high acidity of the soil from mangrove forest because of the high tannin content of *Rhizophora* sp., *Bruguiera* sp., *Ceriopstagal*, *Xylocarpus granatum*, and *Nypa fruticans* which can cause more acid soil (Mustafa, 2007). Thus, land cover/land use such as the mangrove forest may be the cause of the variation of soil organic matter content. Spatial distribution of organic matter content depends on land cover/land use, and more specifically different between forest land and land used for agricultural cultivation (Martin *et al.*, 2011). It has been reported that land cover/land use in coastal area of Luwu are mangrove forest, brackishwater pond, paddy fields, shrub, dry forests, uni irrigated fields, and settlements. Land cover/land use is one factor that causes the variation of soil characteristics (Ersahin, 2003).

Results of other variables that describe the measurement of soil acidity were S_{KCI}, S_P, S_{POS}, TPA, and TSA, and the variables showed the same relative spatial distribution of soil acidity with variables that have been previously de-
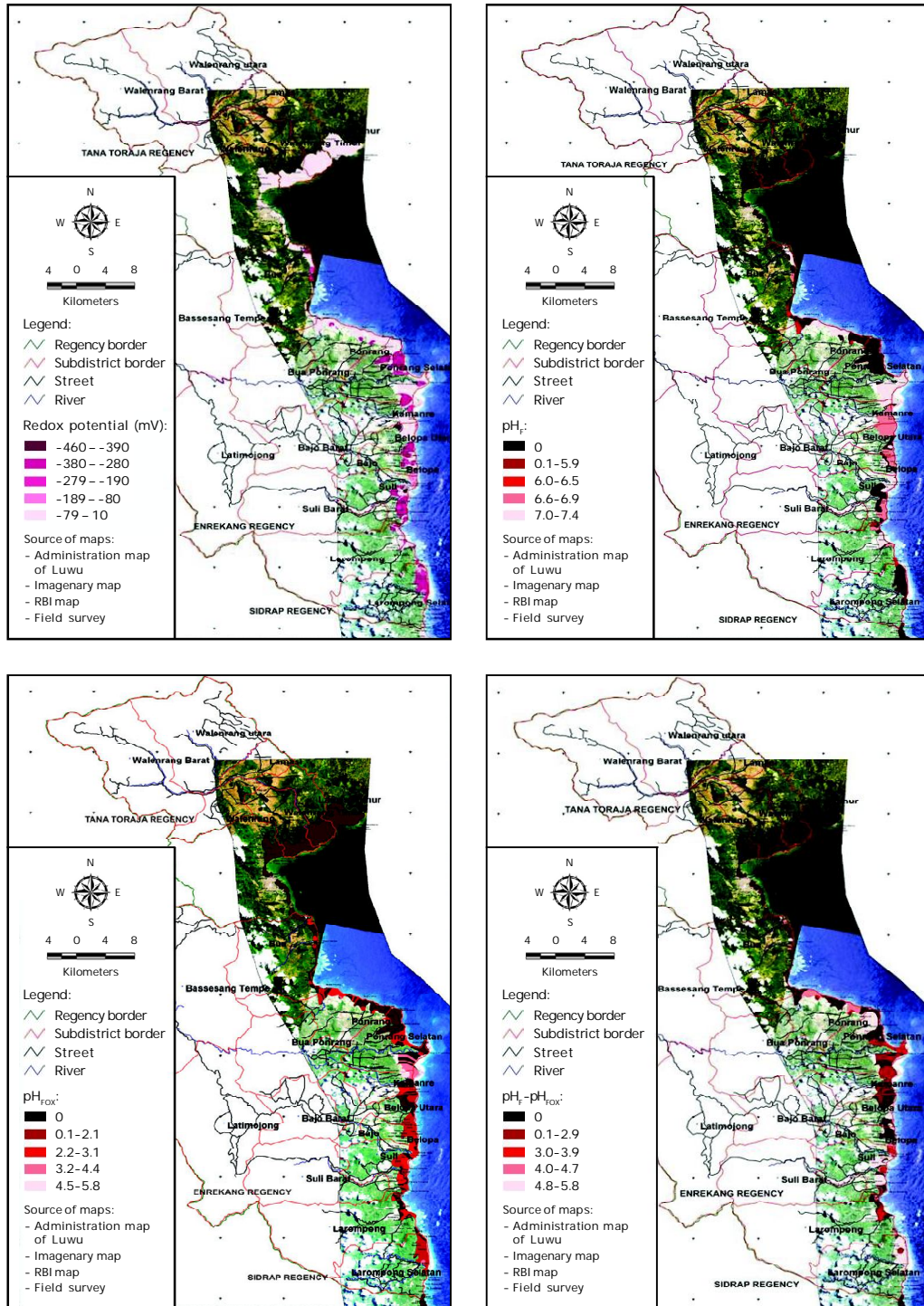
Figure 2. Spatial distribution map of redox potential (top left), pH_F (top right), pH_{FOX} (bottom left), and pH_F-pH_{FOX} (bottom right) of brackishwater ponds soil in 0-0.2 m soil depth in coastal area of Luwu Regency South Sulawesi Province
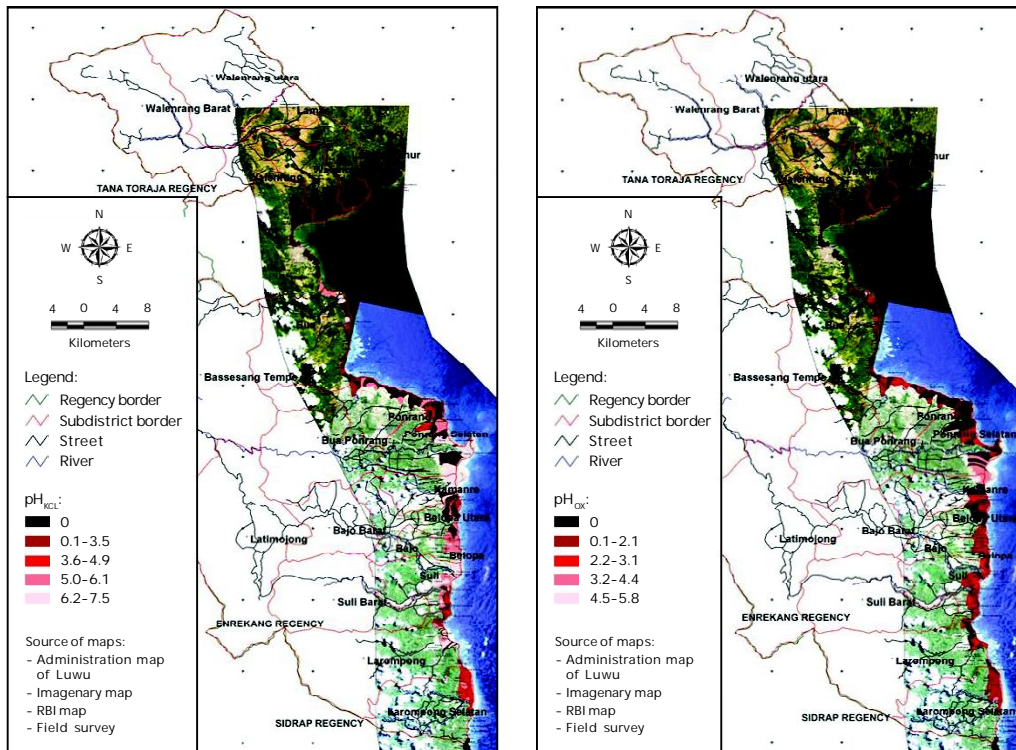
Figure 3. Spatial distribution map of pH_{KCl} (left) and pH_{OX} (right) of brackishwater ponds soil in 0-0.2 m of depth in coastal area of Luwu Regency South Sulawesi Province

scribed, namely pH_{OX}. Figures 4 and 5 show that the value S_{KCl}, S_P, S_{POS}, TPA, and TSA were found on soil surface of brackishwater ponds mainly located in the northern part of Luwu Regency, namely: in East Lamasi, East Walenrang, Bua, and Ponrang Subdistricts. McElnea *et al.* (2002a; 2002b) stated that the acid sulfate soil, especially organic matter content is low, then the TSA correlates well with S_{POS}. TSA also has a linear relationship with the content of pyrite on acid sulfate soil (Rachmansyah & Mustafa, 2011). Variables that describe the quality of the soil acidity were generally lower concentration at a depth of 0-0.2 m than 0.5-0.7 m. It has been reported by Mustafa (2007) that S_{POS} pond bottom soil decreased from 2.1300% to 1.8587% or 0.2713% reduced after the pond bottom soil remediated three times for 72 days.

Pyrite (FeS_2) is the main characteristic of acid sulfate soil. Relatively low content of pyrite was found in the northern part of Luwu Regency: East Lamasi, East Walenrang, Bua, and Ponrang Subdistrict (Figure 5). Factors that in-

fluence the formation of pyrite are the amount of organic matter, sediment temperature, supply SO_4 and bicarbonate, anaerobic atmosphere, and content of Fe (Dent, 1986). The low content of pyrite in the north of Luwu was caused by lower organic matter content (Figure 6). Organic matter is a source of carbon for the bacteria in the formation of pyrite. Ersahin (2003) stated that variations of soil characteristics in addition to the result of the factors and processes of land use, as well as a result of the factors or pedogenesis processes.

Western and northern parts Luwu consist of Lamasi volcanic. Existence at the height elevation of Lamasi volcanic can determine the characteristics of sedimentary material that is based on the source rock. Volcanic rocks of Lamasi transported through the river and deposited in the coastal area. The upper of Lamasi River consists of a Lamasi volcanic. Lava light gray color containing pyrite has been found by Ratman & Atmawinata (1993) in Lamasi volcanic. Breccia in Lamasi volcanic, in some places formed hydrothermally altered pyrite, gold,
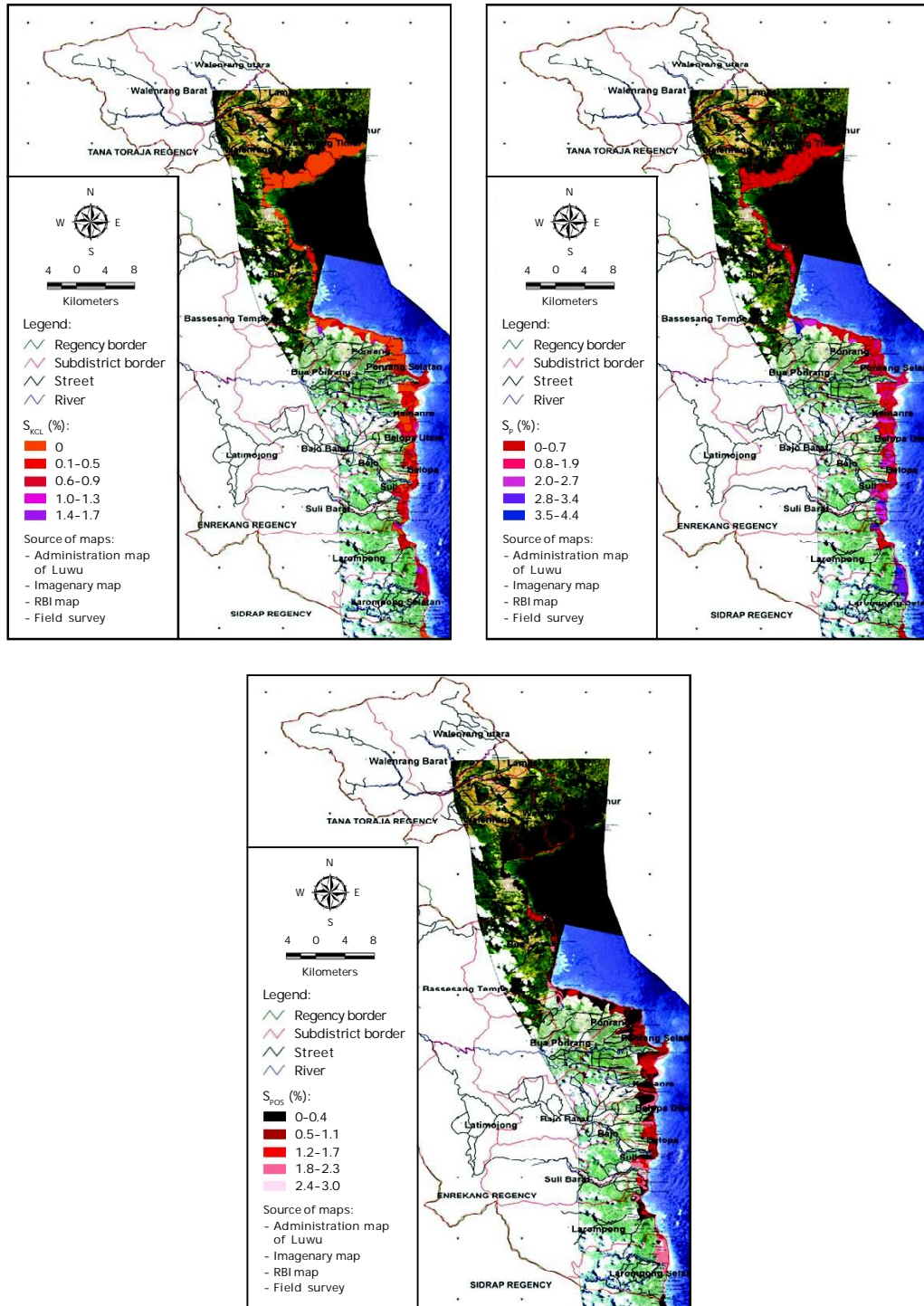
Figure 4.   Spatial distribution map of S_{KCl} (top left), S_P (top right) and S_{POS} (bottom) of brackishwater ponds soil in 0-0.2 m of depth in coastal area of Luwu Regency South Sulawesi Province
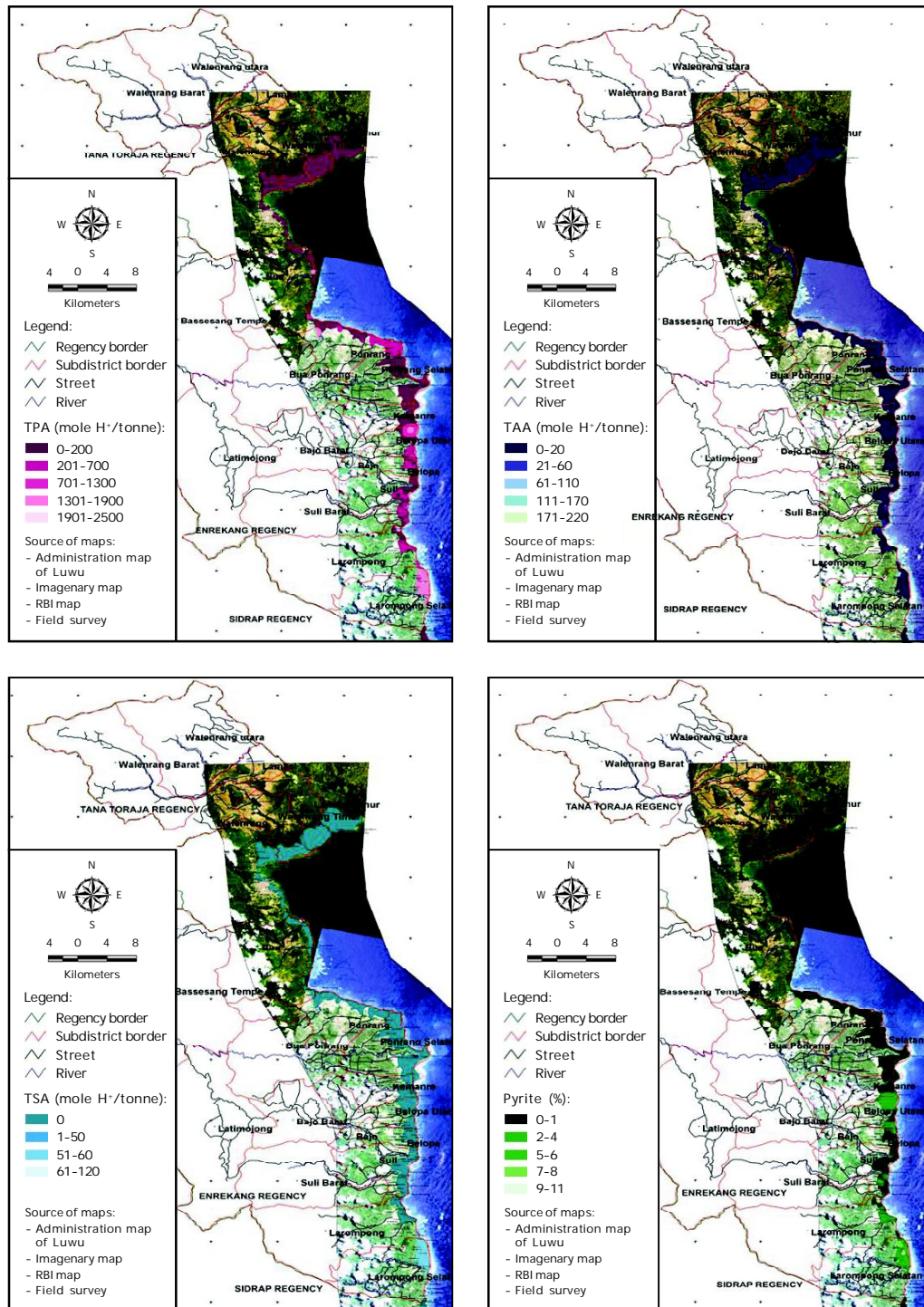
Figure 5.   Spatial distribution map of TPA (top left), TAA (top right), TSA (bottom left), and pyrite (bottom right) of brackishwater ponds soil in 0-0.2 m of depth in coastal area of Luwu Regency South Sulawesi Province
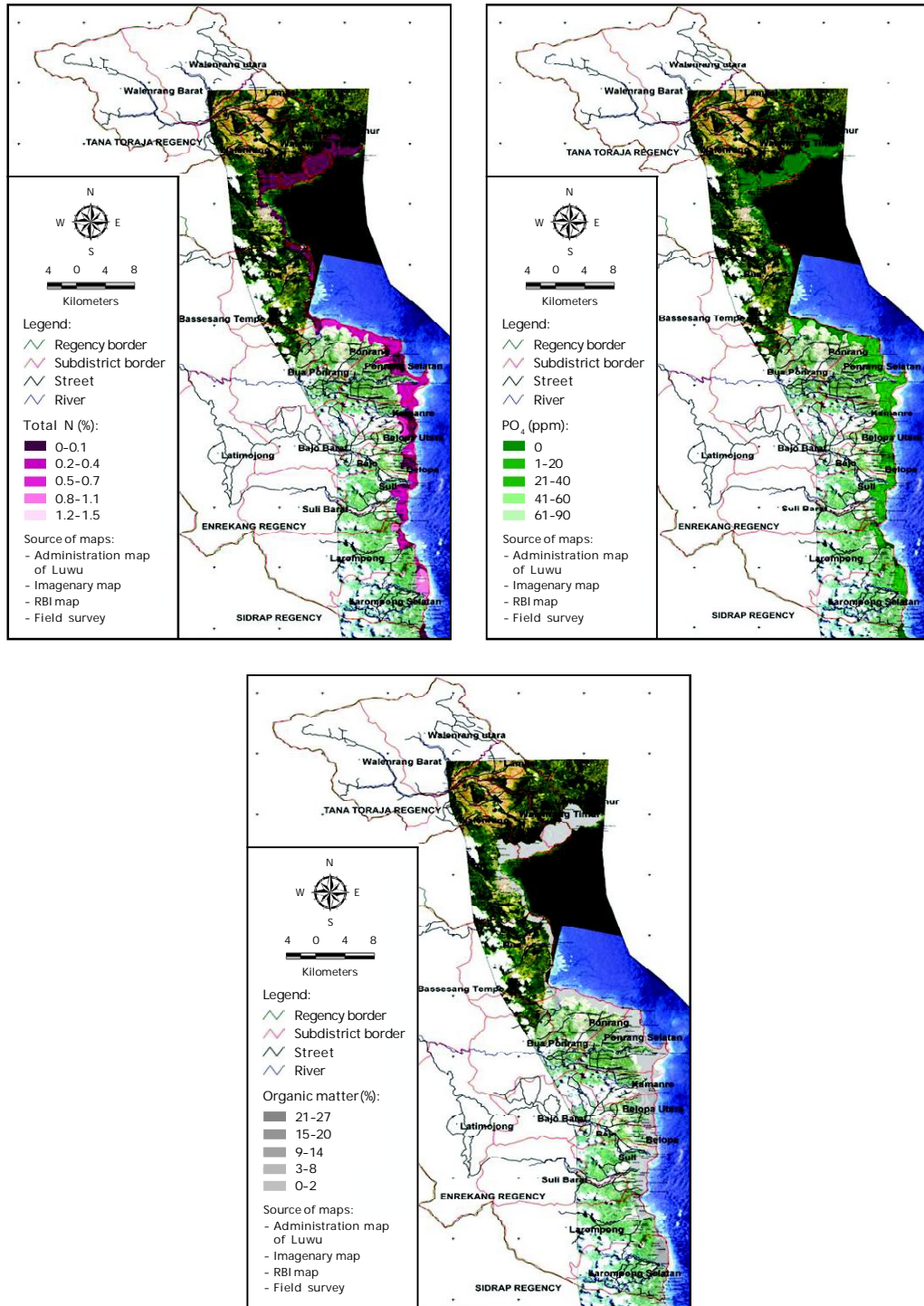
Figure 6. Spatial distribution map of total N (top left), PO$_4$ (top right) and organic matter (bottom) of brackishwater ponds soil in 0–0.2 m of depth in coastal area of Luwu Regency South Sulawesi Province

and silver deposits (Simandjuntak *et al.*, 1991 *in* Ernowo & Pardiarto, 2011). According to Ratman & Atmawinata (1993), breccia from Lamasi volcanic containing quartz with sulfide minerals (mainly pyrite) and copper. Tuff in Lamasi volcanic also containing pyrite and copper (Ratman & Atmawinata, 1993). However, pyrite from Lamasi volcanic was not associated with pyrite present in acid sulfate soil in coastal area. High content of soil organic matter was found in the southern of Luwu Regency. Soil in the southern part of Luwu can also be classified as peat soil because organic matter content higher than 20%. Peat soil is soil that contains organic material more than 20% (when the soil is not containing clay) or more than 30% (when the soil is containing clay more than or equal to 60%) (Soil Survey Staff, 2001).

Spatial distribution of nutrient content of brackishwater pond soil in Luwu is shown in Figures 6 and 7. It illustrated that the organic matter content, total N, Fe, and Al have a relatively similar distribution pattern. Organic mat-

ter, instead as a carbon source, also a source of nitrogen (Boyd, 2008), that was having a great influence on the chemical and physical soil fertility (Chen *et al.*, 2011). According to Abuduwaili *et al.* (2012), Choudhury *et al.* (2013), and Zhang *et al.* (2013), the distribution of nutrient content of soil in natural systems is mainly influenced by topography, climate, and biological activity of natural soil fertility. High content of Fe and Al in the area of high organic matter content as a result of the low pH in the area that causes the solubility of both the toxic elements are high. The content of Al in acid sulfate soil increases at lower pH, i.e. pH 4.0-4.5 (Dent, 1986). In addition, the content of Al in acid sulfate soil associated with pyrite oxidation. The atmosphere is very acid accelerate alumino-silicate mineral weathering due to the destruction of 2:2 layer type minerals (such as montmorillonite) into a 1:1 type minerals (kaolinite) to liberate and more dissolving Al (Pons, 1973). Contents of Fe and Al were higher in the subdistricts of North Belopa, Belopa, Suli, Larompong, and South
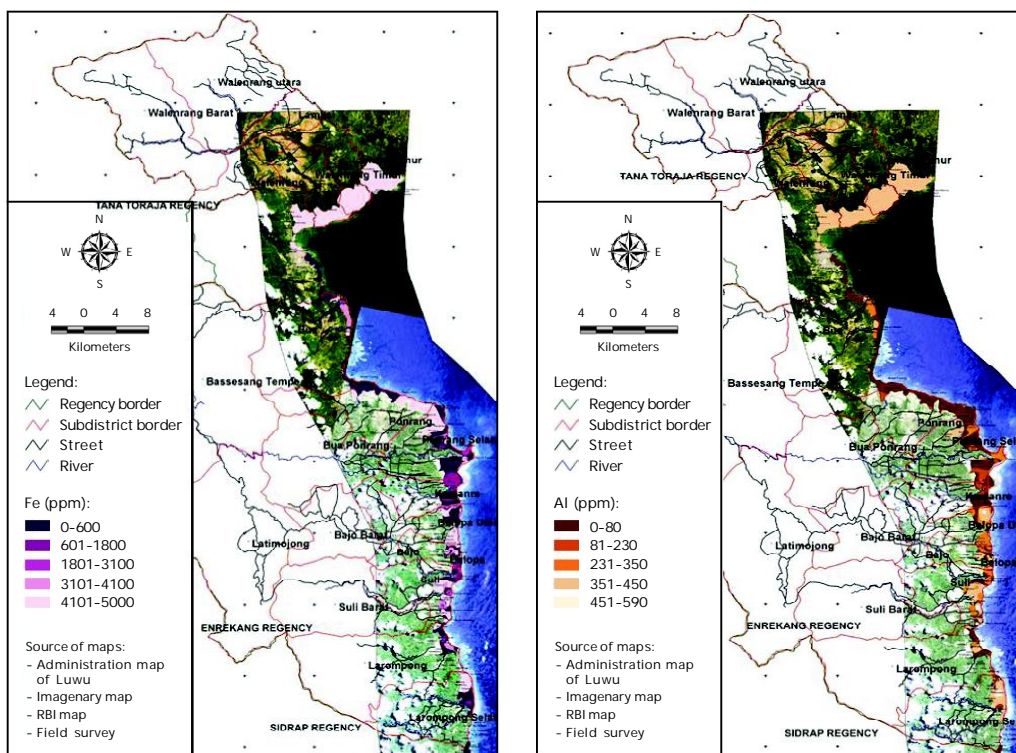

Figure 7. Spatial distribution map of iron (left) and aluminium (right) of brackishwater ponds soil in 0-0.2 m of depth in coastal area of Luwu Regency South Sulawesi Province

Larompong, those can cause relatively lower content of PO_4 (phosphate). This was as a result of Fe and Al soil that can cause PO_4 become unavailable. At low soil pH, PO_4 bound strongly by Fe and Al in the form of insoluble $FePO_4$ or $AlPO_4$ (Mustafa & Sammut, 2007; Moriarty, 2010). Figures 5 and 6 show that the low PO_4 content found in area that contain high Fe and Al.

CONCLUSIONS AND RECOMMENDATIONS

Brackishwater pond soil in coastal area of Luwu Regency South Sulawesi Province, Indonesia was acid sulfate soil and acid sulfate soil associated with peat soils. In general, soil chemical characteristics of brackishwater pond has a high variability or relatively heterogeneous with coefficient of variation in excess of 36%. Chemical characteristics of the soil that indicates oil acidity has a spatial distribution pattern relatively similar. More over the chemical characteristics of the soil that indicate nutrient content of the soil also has a relatively similar spatial distribution pattern. A low degree of soil acidity and conversely a high content of PO_4 generally found in East Lamasi, East Walenrang, Bua, and Ponrang Subdistricts. It is recommended that soil management in brackishwater ponds of Luwu Regency could be based on soil chemical characteristics which could improve the production through minimizing the input, increasing carrying capacity, and avoiding environmental degradation.

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