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REVIEW ARTICLE

Adaptation of Wetland Rice to Extreme Weather

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Abstract

Climate change has increased the intensity and the frequency of extreme weather events, particularly strong winds and heavy precipitations. The extreme event is defined as strong wind at speed of 50 km.h^{-1} and rain fall intensity 10 to 20 mm.h^{-1} or more. This condition is detrimental to rice production as this may lead to lodging and flooding, particularly when the extreme weather events occur during the grain filling stage to harvesting, resulting in a significant decrease in yield and grain quality. Simultaneous extreme events and critical rice growth occured more frequently due to increasing cropping seasons within a year in Indonesia. Therefore, it is important to mitigate and develop adaptation strategies in order to sustain rice production. Efforts to adapt to these extreme environmental conditions are mostly based on genetics and agro-ecological approaches. Genetically, rice with strong hills, high aerodynamic and low water retention is desired. Agro-ecological manipulation can be conducted through applying wind breaks, planting arrangement to facilitate better sunlight penetration, managing water level and planting calendar. Availability of weather station in the field is important to improve mitigation and continuous adaptation strategy against the extreme weather events.

Keywords: canopy architecture, climate change, heavy rainfall, lodging, strong wind

Introduction

Rice (*Oryza sativa* L.) is one of the most important crops and is the staple food for most countries in Asia, including Indonesia. The demand for rice every year increases in line with the increase in human population. In Indonesia, annual average rice consumption was 135 kg per capita, and accounted as third largest in the world after Bangladesh and Vietnam (OECD, 2016). However, the carrying capacity of paddy agro ecology to support rice production has limitations such as decreasing land availability, particularly due to conversion to resettlement, decreased soil fertility, and pest and diseases problems (USDA, 2012; BPS, 2013). Simarmata and Joy (2011) reported that more than 70% of rice fields were grown in non-sustainable ways.

The severe weather events have been increasingly experienced by many parts of the world as the temperature rises, including Indonesia. This phenomenon arises among others due to global climate change which then affects the phenomena of periodic atmospheric anomalies such as El Nino and La Nina (Hidayat and Kizu, 2009). In addition to local and regional atmospheric conditions, the physical conditions of the region such as the topography and altitude of places have effects on extreme weather events in Indonesia (Nurlambang et al., 2013). The extreme weather has broad impacts, but in agronomical point of view they are often translated only in the form of high temperatures, droughts and floods. There have been genotypes of rice that are tolerant to these environmental stresses (Yamin and Moentono, 2005; Hairmansis et al., 2012).
Extreme weather is often seen as a more complex phenomenon, which includes high winds and high

rainfall intensity, and in some cases the combination of the two. Along with the increasing incidences of extreme weather it is necessary to continuously improving rice adaptation to support sustainable production (Kodaira, 2014; Trnka et al., 2014), particularly in Indonesia.

Extreme weather according to BMKG (2010) is an abnormal, unusual weather event, which can lead to danger, especially to life and property. According to BNPB (2012), extreme weather is associated with potentially catastrophic disaster, namely tornadoes, tropical cyclones, and whirlwinds; where extreme weather disasters are more referring to tornado events. In Act No. 20 of 2007 on Disaster Mitigation, a tornado is defined as strong sudden cylindrical wind moving around like a spiral with a speed of 40 to 50 km.hr^{-1} in a relatively short period particularly within 3 to 5 minutes.

Only a handful of studies pertaining to strong winds and high rainfall have been done in Indonesia or any other parts of the world, even though its adverse effects are experienced worldwide. Therefore, this review focuses on mapping extreme weather losses in this case the impact of strong winds and high rainfall on rice crops, and efforts that can be done to improve the resilience of rice production in the future.

Extreme Weather: Definition and Scope

Wind is one of the important weather elements which referred to as the movement of air from high pressure areas to low pressure places either vertically or horizontally (Ayoade, 1983; Tjasyono, 2004; Sabaruddin, 2014). Since the vertical wind velocity is relatively small in climatology the wind velocity refers only to the horizontal wind alone.

The important wind component is its direction and speed (Sabaruddin 2014), and according to Gan and Salim (2014) wind has velocity (kinetic power) and pressure (potential power). Dengel (1956) reported that wind speeds can be classified according to the Beaufort scale as shown in Table 1, where the scale of 7 or more corresponds to fast wind which in extreme cases may lead to violent hurricane with a velocity of >32.6 m.sec^{-1}.

High rain intensity can cause flooding and soaking rice in the field. Although rice is included as an aqueous agroecology crops, submerged crop will

Table 1. The degree of wind velocity by Beaufort scale

Beaufort scale	Class	Characteristics and impacts	Wind speed		
			m.s^{-1}	km.h^{-1}	mile.h^{-1}
0	Calm	No wind, smoke billowing upright	0-0.2	1	1
1	Light Air	The direction of the wind is visible in the direction of smoke, there is no breeze	0.3-1.5	1-5	1-3
2	Light breeze	The wind felt on the face, the leaves lightly rocked	1.6-3.3	6-11	4-7
3	Gentle wind	The leaves and twigs continue to sway	3.4-5.4	12-19	8-12
4	Moderate wind	Dust and paper blowing, twigs and small branches sway	5.5-7.9	20-28	13-18
5	Fresh breeze	Small trees sway, white foam in the sea water	8.0-10.7	29-38	19-24
6	Strong wind	The big branches swayed, the sounds of the electric wire	10.8-13.8	39-49	25-31
7	High wind	The whole tree rocked	13.9-17.1	50-61	32-38
8	Gale	The branches of a broken tree, walking against the wind are quite heavy	17.2-20.7	62-74	39-46
9	Severe gale	The roof of the house is blown and thrown	20.8-24.4	75-88	47-54
10	Strong storm	Trees are uprooted, houses are severely damaged	24.5-28.4	89-102	55-63
11	Violent storm	Storm damage large areas	28.5-32.6	103-117	64-72
12	Hurricane force	Big trees uprooted, houses collapsed	>32.6	>117	>72

Source: Dengel (1956)

have disrupted growth and development, resulting in decreasing production and crop losses. Barry and Chorley (2010) reported that rainfall analysis is related to: 1) the intensity that describes the amount of rain per unit of time (mm.h^{-1}), 2) the frequency that describes the number of rain events per unit of time, 3) distribution describes the area of rainfall, and 4) duration of rain.

Based on the intensity, the degree of rain is divided into five groups: very light rain (< 0.002 mm. min^{-1}), light rain (0.02 to 0.05 mm.min^{-1}), moderate rainfall (0.05 to 0.25 mm.min^{-1}), heavy rain 0.25 to 1.00 mm.min^{-1}), and very heavy rain (>1.00 mm.min^{-1}) (Sosrodarsono and Takeda, 1983; Sabaruddin, 2014) as shown in Table 2.

Regarding the extreme event in rice field, it is concluded as the strong wind at speed of 50 km.h^{-1} and the rain fall intensity 10 to 20 mm.h^{-1} or more. The definition is summarized from field observations and interviews with farmers in Kulon Progro district of Yogyakarta and Central Lombok district of West Nusa Tenggara (Edi Santosa, 2017, unpublished report). Indeed sensitivity of rice hill to strong wind and heavy rain fall might vary among genotypes and culture technique (Sridevi and Chellamuthu, 2015).

Nature of Events and Extreme Weather Simulations

In Situgede Village, Darmaga, Bogor Indonesia, during 2015-2017 it was observed that there was intensive rice planting (three times per year) on about 20 ha of growing area. There were certain rice fields that experienced the impact of extreme weather every season, in others only once a year. Uniquely, three locations were detected where plants in one planting season experienced more than one extreme weather events. The most frequent occurrences were twice, and most were three times in the same place. This mean the crops that have suffered during the first extreme weather condition will get more severely affected on the second and third extreme weather incidence. On the other hand, there were locations that were not affected at all even though the locations were closer to each other. Thus, the nature of extreme weather events is location specific, time-specific and unpredictable.

The second constraint faced in extreme weather conditions in the field is the unavailability of weather-data logger. Even if a weather data logger has been installed on the field, in many cases it was not located where the incidence occurred. Vice versa, in the place where there has been an extreme weather events recorded and weather logging device are available, there is no guarantee of incident re-occurring in the next season. The extent of impact due to extreme weather conditions can vary from 1 × 1 m to 50 × 30 m. Thus, installing a weather data logger to capture the phenomenon in real time requires a huge cost. For that reason, the best approach is possibly the use of a simulator although it does not fully describe the real conditions of extreme weather events in the field. The weather simulator can be used to record natural phenomena with good repeatability (Meyer and McCune, 1958). The assembly of a strong wind simulator has actually been done in the form of wind tunnel (Wischmeier and Smith, 1978, Hamed et al., 2002; Cornelis et al., 2004; Sanguesa et al., 2010), although the simulator is primarily intended to look at influences of rainfall and wind to erosion or land properties. Sterling et al. (2003) used a portable wind tunnel (2.7 × 2.7 × 10 m) to conduct a study on lodging of wheat crops. To regulate the rainfall water pumps with nozzles were used with an intensity ranging from 33 to 60 mm.h^{-1}. Strong winds can be simulated using axial or centrifugal fan can be used; the axial type fan has limited speed. Successful simulators have been produced in the Department of Agronomy and Horticulture, Faculty of Agriculture, Bogor Agricultural University, using axial type fan can produce wind speeds > 70 km.h^{-1}. The model simulates the natural state of horizontal wind speed. Wind velocity was measured using an anemometer device in miles or knots per hour or per second with an equivalency of 1 m.s^{-1}, or equivalent to 3.6 km.h^{-1} or 2.24 mile.h^{-1}.

Table 2. The degree of rain based on the amount of the outbreak per specific time

Degree of rain	Rainfall (mm)	
	hours^{-1}	days^{-1}
Very light rain	<1	<5
Light rain	1–5	5–20
Moderate rainfall	5–10	20–50
Heavy rain	10–20	50–100
Very heavy rain	>20	>100

Source: Sosrodarsono dan Takeda (1983)

Losses due to Extreme Weather Condition

Rice grows mainly in aqueous environments, although there are also rice that are grown on dry land. Like any other crops in general rice growth is highly affected by the environment (Table 3). Amongst the environmental factors, excessive rainfall (flood) or drought can potentially cause the great yield losses, but both strong winds and high rainfall directly causes rice plants to collapse on the ground. The lodging of plants may cause a great reduction in yield (Lang et al., 2012), and as reported by Setter et al. (1997) every 2% of the area covered with collapsed rice plants would result in a 1% yield decline. The decrease of grain quality also occurs due to the grain from the lodged plant tend to have a higher water content. In addition, there is also a direct influence in grain calcification and quality as the grains partly lose their color.

Rice crops are most prone to lodging during strong winds and high rainfall at the seed filling phase of until harvest. Lodging generally occurs in the critical phase of the rice growth, i.e., 85 days after planting or from the seed filling period until harvest (Sridevi and Chellamuthu, 2015; Santosa et al., 2016). Vulnerability to lodging may be affected by the genotypes and plant size (Yamin and Moentono, 2005), and unbalanced nitrogen and potassium fertilization (Bhiah et al., 2010). The combination of strong winds and rain aggravates the level of the lumber. Based on field observation in ten rice production centers in Indonesia from 2015 to 2017, lodging was not recorded on rice at their vegetative stage (Edi Santosa, 2017, unpublished report). Lodging conditions affect the quantity and quality of rice yield due to physical damage on leaves where they are stacked on each other, thus reducing the capacity of photosynthesis and broken stem resulting in in the smooth transportation of nutrients to panicle to decrease (Hitaka, 1969) which ultimately may decrease yield up to 30-35% (Biah et al., 2010). In Indonesia, lodging is estimated to cost the rice economy a total of 3.1 trillion rupiahs per year (Santosa et al., 2016). In paddy fields with poor drainage, heavy rain will increase the height of the puddle in the rice fields so lodged rice are more prone to submergence and the grower may incur a much more production loss as compared to those plants that fall on dry grounds. However, the claim has not been widely studied.

Rice, like other plants, require air movement in the canopy to support the carbon dioxide (CO_2) needed by plants (Matsubayashi et al., 1963). Rice photosynthesis increases with the increase in wind velocity from 0.75 to 2.25 $cm.sec^{-1}$ (Wadsworth, 1959). But strong winds such as hurricanes or storms that occur in the flowering phase can cause the plant to fall and damage the rice plants (De Datta and Zarate, 1970). Dry wind increases the plant's transpiration rate causing rice leaves to dry (Grist, 1975), increases the proportion of sterile flowers, and hence increases grain sterility (Sridevi and Chellamuthu, 2015). Strong winds can also encourage the spread of bacteria that cause leaf disease (Matsubayashi et al., 1963).

Manipulation of Agroecology

Wind speed, theoretically, can be controlled by building wind breakers around rice plants. Farmers in West Nusa Tenggara, Indonesia, grow *turi* (*Sesbania grandiflora* Pers.) trees in rice terraces not only to allow owls which serves as control for rats to perch on, but also as wind breaker on the field. The actual effectiveness of *turi* as a wind breaker needs to be further investigation as we have recorded several patches of rice fields where rows of rice crops collapsing just around the wind breaker (Edi Santosa,

Table 3. Potential losses of rice crops due to abiotic stress

Abiotic stress	Impact on rice	Potential yield loss	Reference
Temperature	Decrease growth and yield	10% yield loss of the total production for every 1°C increase in temperature	Peng et al., 2004
Rainfall	Drought	Crop failure ('puso') affected production area of up to 44,597 ha per year	Balitbang Kementan, 2011
	Flood	Crop failure affected production area up to 67,275 ha per year	
Strong wind	Lodging	Reduced quality and 1% yield loss for every 2% lodged crops	Setter et al., 1997
Rising sea water surface	Reduced production area and disturbed plant metabolism	50 to 150,000 tonnes per year	Balitbang Kementan, 2011

2017, unpublished report).

Vulnerability to lodging is influenced by the plant architecture (Kono and Takahashi, 1964), plant biometry and leaf orientation (Hayashi et al., 2011; Selino and Jones, 2013; Tadrist et al., 2015). Various studies that need to be conducted include studies on rice morphological characters and plant architecture that is more aerodynamic and hold less rain water. Agro ecologically, the uses of wind breaker, managing appropriate plant spacing and water level, and planting schedule should be considered in order to reduce vulnerability of crops to lodge. In addition, it is necessary to facilitate rice production areas with weather monitoring system in the field to get more accurate environmental data and information.

Manipulation of Genetic Rice Characters

Modern breeding programs have selected for rice cultivars with more rigid stems to be more resistant the crop lodging as well as having high grain yields. The high lodging index of rice plants was primarily attributed to the weak breaking strength of the lower internodes. The longer elongated basal internodes were responsible for higher plant height and a higher lodging index (Zhang et al., 2016). This breeding strategy would make stem breakage at a basal internode relatively uncommon in modern genotypes. Even though plant resistance to lodging is highly affected by the agronomic management practices, plant's resistance to lodging depends on its genetic make up for morphological and anatomical traits in culms, particularly the larger stem diameter (Zhang, et al., 2016) and stronger root systems.

There are three approaches that focus on the morphological character of rice plants that are tolerant to extreme weather conditions. First is the genetic-molecular approach involving the manipulation of genetic morphology of plants to be lodge resistant by inserting dwarf gene *sd-1* (semi dwarf) (Chandler, 1969). Short posture plants can reduce the burden on the top of the plant making them to be more resistant to lodging. Kashiwagi et al. (2006; 2008) have identified the *prl5* to be the resistance genes associated with the strength of the rice stand to withstand lodging.

Secondly, the morphological approach in order to increase the strength of the plant. Lodging has been correlated with stem strength which includes dry weight of stem, stem diameter, and stem wall rigidity (Zhang et al., 2014a, Zhang et al., 2016). However, the stem morphology is also influenced by environmental factors and cultivation techniques, especially the level of nitrogen fertilizer application (Zhang et al., 2014a). Li et al. (2011) reported that stem diameter, thickness of the stem wall and dry weight of the lower internodes were significantly correlated with the physical strength of rice crops, whereas the shorter genotypes and stronger lower internodes tended to be resistant to lodging. Other characters associated with the vulnerability to lodge are the panicle weight, the weight of the top three leaves, and the height of the plant (Zhang et al., 2013). Good plant architecture affects how the crops withstand lodging even though the plant has large number of seeds per panicle such as rice cultivar "Habataki" (up to 300 seed per panicle; Ookawa et al., 2010).

Strong culms are influenced by physiological factors such as sugar, starch, cellulose, and lignin content (Zhang et al., 2014b). Resistance to lodging is associated with the ability of plants to reactivate carbohydrates during seed filling and the delay of senescence (Kashiwagi et al., 2006). The decrease in lignin content is often associated with reduced tendency to lodge. *Gold hull and internode2* (*gh2*) is the gene responsible for lignin deficiency (Zhang et al., 2006). The decrease in lignin content is compensated by increased cellulose and hemicellulose in the culm, resulting in increased resistance to break (Ookawa et al., 2014). Physiologically damaged plants have disrupted water transport and nutrients (Duwayri et al., 2000; Kashiwagi et al., 2005). Biochemical studies related to lodging has not been widely explored.

The magnitude of production losses in the lodging varies greatly and is determined by other factors such as the presence of water in paddy fields, plant age, losses of grain in the field, and pest attack. Even though the impacts of extreme weather are already evident in the field, more evaluation should be conducted on the impacts of the strong wind and high rain intensity and the mitigation in the field.

Conclusion

Rice crops are vulnerable to extreme weather conditions particularly of strong winds and high rain intensity in the tropics. These conditions can cause lodging of the crop and can cause the crops totally submerged in wetlands. Strong winds with a speed of 50 $km.h^{-1}$ accompanied by 10 to 20 $mm.h^{-1}$ rainfall are considered extreme weather constraints which can be detrimental to rice growth and production. The adaptation efforts to the have a sustainable rice production primarily rests on agro ecological and genetic manipulations.

References

Ayoade, J.O. (1983). "Introduction to Climatology for the Tropics". John Willey and Son. New York.

Balitbang Kementan [Badan Penelitian dan Pengembangan Pertanian Kementerian Pertanian]. (2011). "General Guideline on Adaptation of Climate Change in Agriculture Sector". Indonesian Agency for Agriculture Research and Development, Ministry of Agriculture Republic of Indonesia. 67pp. Jakarta.

Barry, R.G., and Chorley R.J. (2010). "Atmosphere, Weather, and Climate". 9th edition. London.

Bhiah, K.M., Guppy, C., Lockwood, P., and Jessop, R. (2010). Effect of potassium on rice lodging under high Nitrogen nutrition *In* "Soil Solution for a Changing World", Brisbane, Australia. 19th World Congress of Soil Science.

BMKG [Badan Meteorologi Klimatologi dan Geofisika]. (2010). "Standard Operational Procedure Implementation of Early Warning, Reporting and Information Dissemination". Peraturan BMKG No.009 Tahun 2010. Agency of Meteology Climatology and Geophysics, Republic of Indonesia. Jakarta.

BNPB [Badan Nasional Penanggulangan Bencana]. (2012). "General Guideline for Disaster Risk Evaluation". Peraturan BNPB No. 02 Tahun 2012. National Agency for Disaster Management, Republic of Indonesia, Jakarta.

BPS [Badan Pusat Statistik]. (2013). "Agricultural Land Conversion". http://www.bps.go.id. [March 1, 2017].

Chandler, J.R.F. (1969). Plant morphology and stand geometry in relation to nitrogen. *In* "Physiological Aspect of Crop Yield" (J.D. Eastin, F.A. Haskins, C.Y. Sullivan, and C.H.M. Bavel, eds.), pp. 265–285. American Society of Agronomy, Madison, Wisconsin.

Cornelis, W.M., Erpul, G., and Gabriels, D. (2004). The ICE Wind tunnel for wind and water interaction research *In* "Wind and Rain Interaction in Erosion" (S.M. Visser, and W.M. Cornelis eds.), pp. 59–68. Tropical Resource Management Papers. Wageningen University and Research Centre, Wageningen, The Netherlands.

De Datta, S.K., and Zarate, A.C. (1970). Environmental conditions affecting growth characteristics, nitrogen response and grain yield of tropical rice. *Biometeorology* **4**, 71–89.

Dengel, G.O.F. (1956). "Fundamental on Climate". Wolters JB. Jakarta-Groningen.

Duwayri, M., Tran, D.V., and Nguyen, V.N. (2000). *Reflection on Yield Gaps in Rice Production: How to Narrow the Gaps*. www.fao.org/DOCREP/003/X6905E [March 1, 2017].

Gan, C.J., and Salim, S.M. (2014). Numerical analysis of fluid-structure interaction between wind flow and trees *In* "Proceedings of the World Congress on Engineering 2014 Vol. II", pp. 1218-1223, London, U.K

Grist, D.H. (1975). "Rice". Longman Group Ltd. London.

Hairmansis, A., Supartono, B., Kustianto, Suwarno, and Pane, H. (2012). Breeding and genotype development of new rice type tolerant to flooding Inpara 4 and Inpara 5 for area vulnerable to flooding. *Jurnal Litbang Pertanian* **31**, 1–7.

Hamed, Y., Albergel, J., Pépin, Y., Asseline, J., Nasri, S., and Zante, P. (2002). Comparison between rainfall simulator erosion and observed reservoir sedimentation in an erosion-sensitive semi-arid catchment. *Catena* **50**, 1–16.

Hayashi, K., Tatuno, M., Nagabayashi, H., Hasimoto, H., and Tada, T. (2011). Fluid forces acting on a tree. Journal of *Japan Society Civil Engineers* **67**, 569-580. DOI:10.2208/jscejam.67.I_569.

Hidayat, R., and Kizu, S. (2009). Influence of the medden-julian oscillation on Indonesian rainfall variability in Austral summer. *International Journal of Climatology* **10**.

Hitaka, H. (1969). Studies on lodging of rice plant. *Japan Agricultural Research* **4**, 1–6.

Islam, M.S., Peng, S., Visperes, R.M., Ereful, N., Bhuiya, M.S.U., and Julfiquar, A.W. (2007). Lodging-related morphological trait of hybrid rice in a tropical irrigated ecosystem. *Field Crop Research* **101**, 240–248.

Kashiwagi, T., Sasaki, H., and Ishimaru, K. (2005). Factor responsible for decreasing sturdiness of the lower part in lodging of rice (*Oryza sativa* L.). *Plant Production Science* **8**, 166–172.

Kashiwagi, T., Togawa, E., Hirotsu, N., and Ishimaru, K. (2008). Improvement of lodging resistance with

QTLs for stem diameter in rice (*Oryza sativa* L.). *Theoretical and Applied Genetics* **117**, 749-757.

Kashiwagi, T., Madoka, Y., Hirotsu, N., and Ishimaru, K. (2006). Locus prl5 improves lodging resistence of rice by delaying senescense and increasing carbohydrate reaccumulation. *Plant Physiology and Biochemistry* **44**, 152–157.

Kementan [Kementerian Pertanian]. (2016). “Rice Cultivation using Jajar Legowo Super”. 58pp. Indonesian Agency for Agriculture Research and Development, Ministry of Agriculture Republic of Indonesia. Jakarta.

Kodaira, H. (2014). Responding to climate change and expectations for research. *Paddy and Water Environment* **12**, S211-S212. DOI: 10.1007/s10333-014-0421-7

Kono, M., and Takahashi, J. (1964). The effect of wind force with reference to lodging of paddy rice. *Soil Science and Plant Nutrition* **10**, 20–27. DOI: 10.1080/00380768.1964.10431141.

Kuroda, E., Ookawa, T., and Ishihra, K. (1989). Analysis on different of dry matter production between rice cultivar with different hight in relation to gas diffusion inside stand. *Journal of Crop Science* **58**, 374–382.

Lang, Y., Yang, X., Wang, M., and Zhu, Q. (2012). Effects of lodging at different filling stages on rice yield and grain quality. *Rice Science* **19**, 315-319.

Li, J., Zhang, H.C., Gong, J.L., Chang, Y., Dai, Q.G., Huo, Z.Y., Xu, K., and Wei, H.Y. (2011). Effect of different planting methods on the culm lodging resistance of super rice. *Journal of Integrative Agriculture* **44**, 2234–2243.

Matsubayashi, M., Ito, R., Takase, T., Nomoto, T., and Yamada, N. (1963). “Theory and Practice of Growing Rice”. 502 pp. Fuji Publishing Co. Ltd. Tokyo.

Meyer, L.D., and McCune, DL. (1958). Rainfall simulator for runoff plots. *Journal of Agricultural Engineering* **10**, 1085–1089.

Nurlambang, T., Kusratmoko, E., Ludiro, D., Harmantyo, D., Halide, H., Sobirin, Rahmawati, F., Rahaningtyas, N.S., Rustanto, A., Zakir, A., et al. (2013). Management of extreme weather disaster in Indonesia. *In* “Prosiding Seminar Nasional Riset Kebencanaan”, pp 8, Mataram, Indonesia.

Ookawa, T., Hobo, T., Yano, M., Murata, K., Ando, T., Miura, H., Asano, K., Ochiai, Y., Nishitani, R., Ebitani, T., et al. (2010). New approach for rice improvement using a pleiotropic QTL gene for lodging resistance and yield. *Nature Communications* **1**. DOI: 10.1038/ncomms1132.

Ookawa, T., Inoue, K., Matsuoka, M., Ebitani, T., Takarada, T., Yamamoto, T., Ueda, T., Yokoyama, T., Sugiyama, C., and Nakaba, S. (2014). Increased lodging resistance in long-culm, low-lignin gh2 rice for improved feed and bioenergy production. Research Gate Scientific Reports 4, 6567. DOI: 10.1038/srep06567.

Ookawa, T. and Ishihara, K. (1992). Varietal difference of physical characteristics of the culm related to lodging resistance in paddy rice. *Japan Journal of Crop Science* **61**, 419–429.

Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Centeno, G.S., Khush, G.S., and Cassman, K.G. (2004). Rice yields decline with higher night temperature from global warming *In* Proceeding of the National Academy of Science **101**, 9971–9975.

Rejekiningrum, P. (2013). Optimation model of rice surplus to determine national food security level *In* Prosiding Seminar Nasional Matematika, Sains, dan Teknologi **4**, A62–A75.

Sabaruddin L. (2014). “Agroklimatologi: Aspek-aspek Klimatik untuk Sistem Budidaya Tanaman”. Alfabeta Bandung.

Sanguesa, C., Arumi, J., Pizarro, R., and Link, O. (2010). A rainfall simulator for the in situ study of superficial runoff and soil erosion. *Chilean Journal of Agricultural Research* **70**, 178–182.

Santosa, E., Dulbari, Agusta, H., Guntoro, D., and Zaman, S. (2016). Phenomenon of lodging and its implication on improvement of rice adaptive to extreme weather in Indonesia. *In* “Prosiding Strategi Pemuliaan dalam Mengantisipasi Perubahan Iklim Global”, pp. 45–53. Pekanbaru-Riau, Indonesia. Seminar Nasional Perhimpunan Ilmu Pemuliaan Indonesia.

Selino, A., and Jones, M.D. (2013). Large and small eddies matter: Animating trees in wind using coarse fluid simulation and synthetic turbulence. *Computer Graphics Forum* **32**, 75–84. DOI: 10.1111/j.1467-8659.2012.03232.x

Setter, T., Laureles, E., and Mazaredo, A. (1997). Lodging reduce yield of rice by self-shading and reduction in canopy photosynthesis. *Field Crops Research* **49**, 95–106.

Simarmata, T., and Joy, B. (2011). Technology rice land recovery and sustainable increase rice productivity based on straw compost and biodecomposer in Indonesia. *In* "Proceeding Seminar teknologi pemulihan kesehatan lahan sawah dan peningkatan produktivitas padi", pp 16. Lampung, Indonesia.

Sosrodarsono, S., and Takeda, K. (1983). "Hidrology for Irrigation". Pradnya Paramita, Jakarta.

Sridevi, V., and Chellamuthu, V. (2015). Impact of weather on rice, a review. International *Journal of Applied and Research* **1**, 825-831.

Sterling, M., Baker, C.J., Berry, P.M., and Wade, A. (2003). An experimental investigation of the lodging of wheat. *Agricultural and Forest Meteorology* **119**, 149–165.

Tadrist, L., Julio, K., Saudreau, M., and de Langre, E. (2015). Leaf flutter by torsional galloping: experiments and model. *Journal of Fluids and Structures* **56**, 1–10. DOI: 10.1016/j.jfluidstructs.2015.04.001.

Tjasyono, B.H.K. (2004). "Climatology". 2nd edition. Institut Teknologi Bandung. Bandung, Indonesia.

Trnka, M., Rötter, R.P., Ruiz-Ramos, M., Kersebaum, K.C., Olesen, J.E., Žalud, Z., and Semenov, M.A. (2014). Adverse weather conditions for European wheat production will become more frequent with climate change. *Nature Climate Change* **4**, 637-643.

USDA [United States Department of Agriculture]. (2012). I*ndonesia: Stagnating Rice Production Ensures Continued Need for Imports. www.pecad.fas.usda.gov /highlights* /2012/ 03 /Indonesia_rice.

Wadsworth, R.M. (1959). On optimum wind speed for the plant growth. *Annual Botany* **23**, 195–199.

Wischmeier, W.H., and Smith, D.D. (1978). "Predicting Rainfall Erosion Losses, a Guide to Conservation Planning". Agriculture Handbook No 537. US Department of Agriculture, Washington DC, USA.

Yamin, M., and Moentono, M.D. (2005). Selection several rice variety for strong culm and high lodging resistant. *Ilmu Pertanian* **12**, 94-102.

Zhang, W., Li, G., Song, Y., Zhang, W., Yang, C., Wang, S., and Ding, Y. (2013). Lodging resistance of super hibrid rice Ylingyou 2 in two ecological regions. *Acta Agronomica Sinica* **39**, 682–692.

Zhang, W., Li, G., Song, Y., Liu, Z., Yang, C., Tang, S., Zheng, C., Wang, S., and Ding, Y. (2014a). Lodging resistance characteristics of high-yield rice populations. *Field Crops Research* **161**, 64–74.

Zhang, W., Li, G., Yang, Y., Li, Q., Zhang, Z., Liu, J., Wang, S., Tang, S., and Ding, Y. (2014b). Effect of nitrogen application rate and ratio on lodging resistance of super rice with different genotype. *Journal of Integrative Agriculture* **13**, 63–72.

Zhang, W., Wu, L., and Wang, S. (2016). Lodging resistance of Japonica rice (*Oryza Sativa* L.): morphological and anatomical traits due to top-dressing Nitrogen application rates. *Rice* **27**, 31-35.