The interaction between global climate change and tropical forest ecosystems

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THE INTERACTION BETWEEN GLOBAL CLIMATE CHANGE AND TROPICAL FOREST ECOSYSTEMS

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ABSTRACT

In the last 100 years, the global mean temperature has increased approximately 0.6°C and is predicted to increase approximately 1.1°C to 6.4°C in the end of 21st century. On the other hand, deforestation still continues with the rate of -5.2 million hectares per year. This global climate change phenomenon in physical dimension has been analyzed in detail; yet its effect to the changes of biodiversity particularly in tropical forest ecosystems is still poorly understood. From the literature review, it is clear that there is correlation between global climate change and tropical forest ecosystems. The effect of climate change to forest ecosystems itself includes species range shifts, species extinction risks, biome shifts, and biogeochemical cycling. Furthermore, the deforestation of tropical forest ecosystems also has reverse effects to the global climate change, i.e. is increasing the amount of green house gasses which directly changes the three climatic variables which are the Earth surface temperature, the total precipitation, and the atmospheric moisture convergence.

Keywords: *Global climate change, biodiversity, tropical forest ecosystems*

ABSTRAK

Dalam 100 tahun terakhir, suhu rata-rata global telah naik sekira 0.6°C dan diprediksi akan naik sekira 1.1°C sampai 6.4°C pada akhir abad ke-21. Di sisi lain, laju pengurangan hutan masih berlanjut pada kisarat -5.2 juta hektar per tahun. Fenomena perubahan iklim global ini secara detil telah dibahas dalam dimensi fisiknya tetapi pemahaman tentang pengaruhnya terhadap biodiversitas khususnya di wilayah tropis masih belum banyak diketahui. Dari studi pustaka jelas diketahui bahwa perubahan iklim global memiliki hungungan timbal balik dengan ekosistem hutan tropis. Pengaruhnya sendiri antara perubahan iklim terhadap ekosistem hutan tropis meliputi perpindahan distribusi suatu jenis, risiko kepunahan suatu jenis, perpindahan bioma, dan siklus biogeokimia hutan. Selanjutnya, laju deforestasi yang selama ini terjadi pada ekosistem hutan tropis, diketahui juga memberikan pengaruh pada perubahan iklim global yaitu dengan meningkatkan gas rumah kaca yang secara langsung mempengaruhi tiga variabel iklim yaitu suhu permukaan Bumi, total curah hujan, dan konvergensi kelembapan atmosfer.

Kata kunci: *Perubahan iklim global, biodiversitas, ekosistem hutan tropis*

INTRODUCTION

Global climate change is now a well-known complex phenomenon and is often discussed by a view point of mitigating the effects of anthropogenic emissions of greenhouse gases. [1, 2, 3] Although its physical dimensions have been analyzed in detail [4, 5, 6, 7], the effect of global climate change on biodiversity, particularly in the tropics, are poorly understood.[8] The evidence for biotic responses to global climate change is clear for high latitudes but sparse and controversial for tropical latitudes.[9, 10, 11] For instance, several studies have shown that climate change has an impact on plant distribution in Europe.[12, 13, 14]

The effect of climatic change on tropical forest ecosystems becomes global as well as regional concern because of its impact on tropical forest's high biodiversity and its potential feedback to the carbon, water, and nutrient

Off print request to:Andes Hamuraby Rozak cycles.[15, 16, 17, 18] Tropical forests are kinds of tropical vegetations that have already been facing threats from deforestation, fragmentation and habitat degradation.[19, 20, 21, 22] They are likely to encounter further challenges from the ongoing and impending changes in climate. Although the role of tropical forests as both sinks and sources of carbon has been well recognized [23, 24, 25, 26, 27, 28], less is known about the impact of climate change on tropical biotas.[29, 30, 31, 32]

Tropical forests are among the biologically richest ecosystems on Earth[33, 34, 35, 36], but are being rapidly degraded and destroyed by habitat conversion, wood extraction, hunting, and atmospheric change.[37, 38, 39, 40] These forests are also vulnerable to global warming and other large-scale environmental change[41, 42], but much uncertainty existing about the nature and magnitude of these anthropogenic impacts on the tropical forest organisms.[39, 43]

TROPICAL FOREST ECOSYSTEMS

Tropical forest ecosystems circle the Earth around the equator i.e. between the tropics of Cancer and Capricorn.[35] This includes very diverse types of forests, including rainforests, mangroves, montane forests, dry forests and savanna system[35] and supports a huge number of tree species.[44, 45, 46, 47] Tropical forests cover 7-10% of the global land area, store 40-50% of carbon in terrestrial vegetation and annually process approximately six times as much carbon via photosynthesis and respiration as humans emit from fossil fuel use.[48, 49]

FAO[50] and IPCC[51] reported that the global forest cover is 3,952 million hectares, which is about 30 percent of the world's land area. Furthermore, in 2010, FAO[52] reported that the world's total forest area is estimated to be just over 4 billion hectares, which is about 31 percent of the total land area (Figure 1). Most relevant for the carbon cycle is that between 2000 and 2010, net change of deforestation continued at a rate of -5.2 million hectares per year. This rate is lower than that of -8.3 million hectares per year during the period of 1990-2000. This substantial reduction is due to both a decrease in the deforestation rate and an increase in the area of new forest established through planting or seedling and the natural expansion of existing forests.[52] The largest loss in the period of 2000-2010 is still in Brazil, Australia, and Indonesia (Table 1). Meanwhile, in the period of 2000-2010, the largest annual net gain in forest area is in China, USA, and India (Table 2).

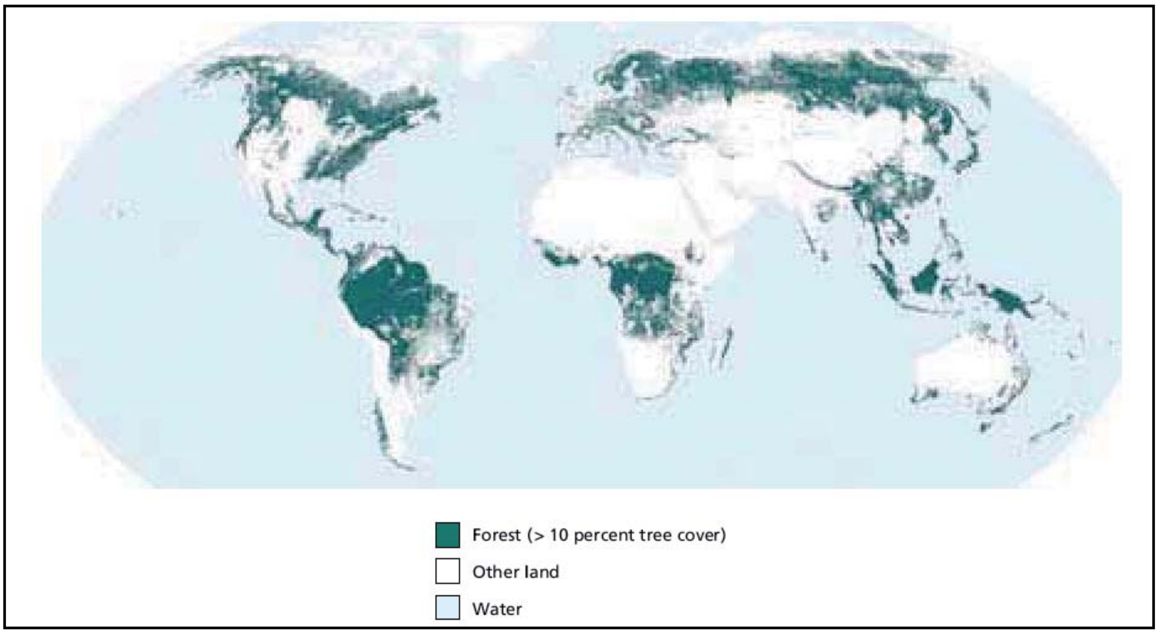

Figure 1. The world's forests area.[52]

Table 1. Five countries with largest annual net loss of forests area, 1990-2010. [52]

Country	Annual change 1990-2000		Country	Annual change 2000-2010	
	1000 ha yr^{-1}	%		1000 ha yr^{-1}	%
Brazil	-2.890	-0.51	Brazil	-2.642	-0.49
Indonesia	-1.914	-1.75	Australia	-562	-0.37
Sudan	-589	-0.80	Indonesia	-498	-0.51
Myanmar	-435	-1.17	Nigeria	-410	-3.67
Nigeria	-410	-2.68	Tanzania	-403	-1.13

Table 2. Five countries with largest annual net gain in forest area, 2000-2010. [52]

Country	Annual change 1990-2000		Country	Annual change 2000-2010	
	1000 ha yr^{-1}	%		1000 ha yr^{-1}	%
China	1.986	1.20	China	2.986	1.57
USA	386	0.13	USA	383	0.13
Spain	317	2.09	India	304	0.46
Viet Nam	236	2.28	Viet Nam	207	1.64
India	145	0.22	Turkey	119	1.11

GLOBAL CLIMATE CHANGE

Climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer.[53, 54, 55] Over the past 100 year, the global average temperature has increased by approximately 0.6°C and is projected to continue to rise at a rapid rate.[56, 57, 58] IPCC[55] was reported the projection of the average surface temperature in six different scenarios (B1, B2, A1B, A1T, A2, and A1FI). The lowest future emissions trajectory scenario (B1) predicted that the surface temperature will increase by 1.8°C (1.1°C to 2.9°C) in 2100, meanwhile, the highest future emissions trajectory scenario (A1FI) predicted that the surface temperature will increase by 4.0°C (2.4°C to 6.4°C) in 2100 (Figure 2). It means that by the end of the 21st century, large portions of the Earth's surface may experience climates not found at present time, and some 20th century climates may disappear.[57]

CLIMATE CHANGE EFFECTS TO FOREST ECOSYSTEMS

Climate is one of the primary constraints on species distributions and ecosystem function and ecologists are faced with the challenge of forecasting species range shifts, extinction risks, biome shifts, altered disturbance regimes, biogeochemical cycling, and other ecological responses to climate change.[59] Simulation study in order to investigate the response of vegetation to global warming and rainfall anomalies has been done by White *et. al.*[60] and found that there are four key changes predicted to cause changes in vegetation area. Those four key changes are:

1) Some areas of tropical evergreen forest in Amazonia were predicted to change to savanna, grassland or even desert by the 2080s, in response to warming of over 7°C and decreasing in rainfall of up to 500mm yr^{-1},
2) Large areas of tropical C4 grassland (e.g. in the Sahel, India and Australia) were lost to desert by the 2080s in response to warming, increasing CO_2 and decreasing rainfall, or superseded by C3 grassland where rainfall increased,
3) Annual precipitation decreases of up to 200mm yr^{-1} resulted in the conversion of large area of temperate forest to grassland or savanna in southern Europe and eastern United States,
4) Needle-leaved boreal forest extended northwards in response to warming, with loss of tundra and southwards in Asia in response to increased precipitation.

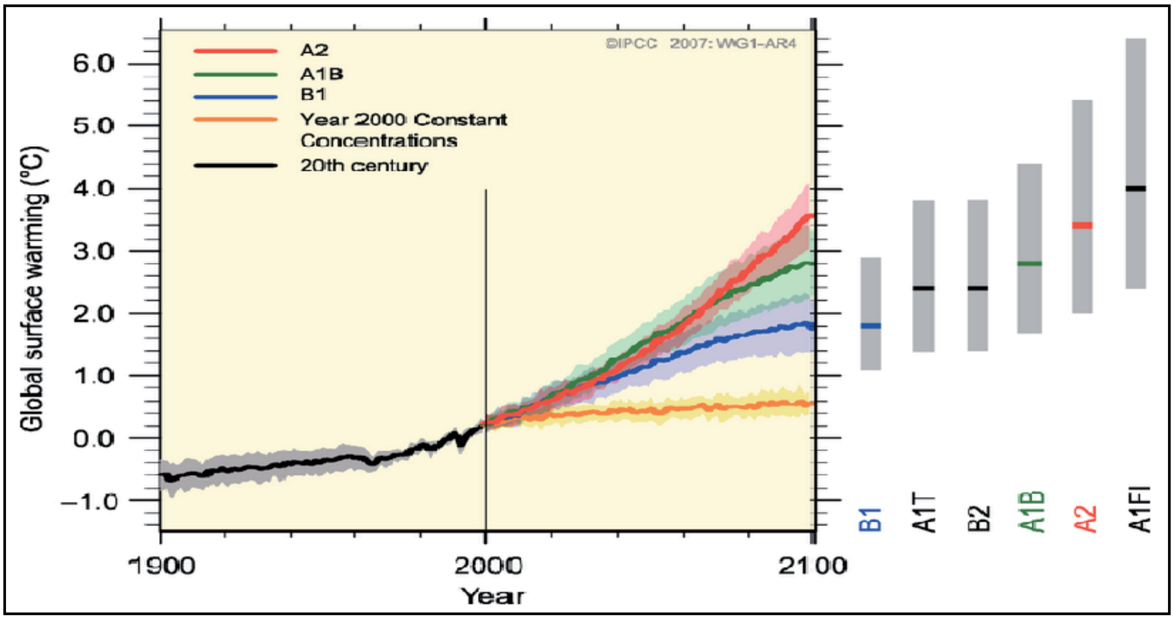

Figure 2. IPCC multi-model averages and assessed ranges for surface warming in six different emissions scenarios.

Another study over tropical forest located in Northern Queensland Australia has been done by Ostendorf *et. al.*[16] Ostendorf *et. al.* evaluate how the spatial arrangement of forest pattern may constrain vegetation change as predicted by spatially static artificial neural network (ANN) model. The ANN model quantifies a most suitable forest type based on the conditional on the transition to the best-suited type. In that model, they evaluate the effect of the 10°C increase of mean annual temperature and the 10% decrease of mean annual precipitation. Depending on the strength of spatial effects included in the models, the predicted future vegetation pattern differs by 1% to 10% of the study area. However, if in addition to spatial constraints ecological constraints are also considered, the predictions may differ by as much as 27% showing a relatively strong dependence of prediction on assumptions about patch-level processes.

Tropical mountain forest ecosystems are also affected by climate change.[61, 62] Foster study[63] tried to explain the negative potential impacts of climate change on tropical mountain cloud forests. Foster[63] argued that the cloud forest will also be affected by climate changes, which particularly cause changes in cloud formation. A number of global climate models suggest a reduction in the level of cloudiness due to the coming of climate changes. One site in particular, i.e. Monteverde - Costa Rica, appears to already be experiencing a reduction in cloud immersion. The coming of climate changes appear very likely to upset the current equilibrium of the cloud forest. He[63] also mentioned that the difficulties for cloud forest species to survive in climate-induced migrations include no remaining location with suitable climate, no pristine location to colonize, migration rates or establishment rates that cannot keep up with climate change rates and new species interactions.

In the species level, species will respond individualistically toward the tropical climate change and vegetation type may expand or contract.[64, 65] The study of Colwell *et. al.*[66] based on species distribution models of plants and insects in Costa Rica showed that about half (53%) of the 1902 species are candidates for lowland biotic attrition, and about half (51%) may be faced with range-shift gaps. Then, the potential for mountain top extinctions is minimal for a 600-m shift in isotherms but begins to appear at about 1000-m range shift. Nevertheless, this species distribution models use several assumptions which are (1) the fundamental climatic niche of each species is fully expressed by current distributions; (2) the effects of climate outweigh any idiosyncratic effects of species interaction, dispersal limitation, demographic patterns, or historical contingency; (3) the change will be too rapid for adaptation to warmer temperatures at lower range limits; and (4) the habitats at the landscape scale are homogenous with regard to microclimate.

FOREST ECOSYSTEMS EFFECTS TO CLIMATE CHANGES

In other perspectives, millions of hectares of forest has been changed into unforested area caused by forest fire, illegal logging/wood extraction, hunting, habitat conversion, and atmospheric change.[37, 38, 39, 40, 67] The deforestation of the areas is affecting the regional climates especially of the increasing of green house gasses.[68, 69] McGuffie *et. al.*[70] describes the impacts of tropical deforestation on regional climates in terms of change have been detected in five regions i.e. Northern Amazon, Southern Amazon, Central Amazon, Southeast Asia, and Africa. For each of these regions, seasonal distributions of three climatic variables are discussed which are the ground (or soil) surface temperature, the total precipitation and the atmospheric moisture convergence. The McGuffie's results[70] showed that precipitation always decreases following tropical deforestation. Although the ground surface temperature increases in Southern Amazon and over Basin as a whole, the Northern Amazon, Southeast Asia and Africa all exhibit decreases in ground temperatures. Then, atmospheric moisture convergence decreases in the Amazon. In contrast, the moisture convergence increased over Southeast Asia and similar effect can be seen in Africa. These changes suggest that regional-scale circulation have been affected by tropical deforestation. Furthermore, it is possible that locations distant from the disturbed tropics may also be affected.

Langman's study[69] also confirmed the effect of deforestation to climate change due to the vegetation fires. Fire emissions contribute to the global budget of greenhouse gases and aerosol particles[71, 72, 73, 74, 75], resulting in direct and indirect modifications of solar irradiation.[76, 77] The change of vegetation covered by fire itself modifies local surface albedo, soil water's holding capacity and surface evaporation, resulting in complex interactions and feedbacks within the climate system. Aerosol particles emitted from vegetation fires modify the atmospheric radiation budget by scattering and absorbing solar radiation. Absorption and scattering of solar radiation by smoke aerosols can also lead to a reduction of cloud cover thereby cooling the surface and heating the atmosphere as it has been observed over the Amazon and the Mediterranean area.[78, 79]

INDONESIA AND GLOBAL CLIMATE CHANGE

Indonesia as an archipelago country in the tropic region is also affected by climate change. Climate change results in making the ocean temperature warmer and in increasing the sea level surface. The temperature and sea level surface are the main drive for *La Nina* and *El Nino*-Northern Oscillation (ENSO) in tropical Pacific Ocean especially around Indonesia.[80] ENSO is one of the main contributor to inter-annual climate variability affecting floods, forest fire and drought in the tropical area.[81, 82] Several studies show that ENSO in Indonesia affects canopy tree recruitment[83], mast fuiting[84], rainfall intensity[85], tree species composition and diversity[86], tree survival and mortality[87, 82], forest biomass[88], and also rice production.[89]

Initial indication of forest fire and/or drought caused by ENSO could be identified by the number of hotspot which is detected within a certain area.[90, 91] During the period of 2004-2011 (Table 3.a), the highest number of hotspot in Indonesia occured on 2006 (146,264 hotspots) and the lowest number of hotspot occured on 2010 (9,880 hotspots). In the year of 2008 (Figure 3.b), the number of hotspots increased significantly from July to September with the highest hotspot occured in September. Compared to the data from Meteorological Station in Bandung, Indonesia[92], the shortest rainfall and longest dry period occured in 2006/2007 (160 rainfall days and 200 dry days). These finding indicates that the highest number of hotspot occured in dry season (Figure 3.b) and there might be a positive correlation between the number of hotspot (Figure 3.a) and the duration of dry season (Figure 3.c) and maximum temperature (Figure 3.d) in Indonesia.

In the term of carbon sequestration and emission in Indonesia which are closely related to the global climate change[93, 94], Finlayson[95] reported that the carbon density dynamics clearly show the consistent decline of carbon stock and Indonesia has become a net emitter of the greenhouse gas. Indonesia's total net emissions were estimated at 9.23 gigatonne of CO_2 equivalent with a rate of 0.68 gigatonne per year (Table 3). Interesting result shows that during the 1990-2000 period, Indonesia's emission rate was equivalent with 0.79 gigatonne of CO_2 per year. In more recent period (2000-2005), the rate was lower (slowed down to 0.47 per year), compared to 0.68 per year during the previous period (1990-2005).

CONCLUSION

It is clear that there is interaction between global climate change and tropical forest ecosystems. The effect itself, in terms of the effect of climate change to tropical forest, includes species range shifts, extinction risks, biome shifts, and biogeochemical cycling. Furthermore, the change of tropical ecosystems, as a result of deforestation, has a reverse effect to the regional climate change which is increasing the green house gasses and directly affect the three climatic variables

Table 3. Aboveground carbon-stock dynamics in Indonesia 1990, 2000, 2005

Periods	1990-2000	2000-2005	1990-2005
Total gross emission (Gt CO_2e)	7.93	2.35	10.27
Total sequestration (Gt CO_2e)	0.93	1.10	1.04
Total net emission (Gt CO_2e)	6.99	1.25	9.23
Gross emission rate (Gt CO_2e/year)	0.79	0.47	0.68

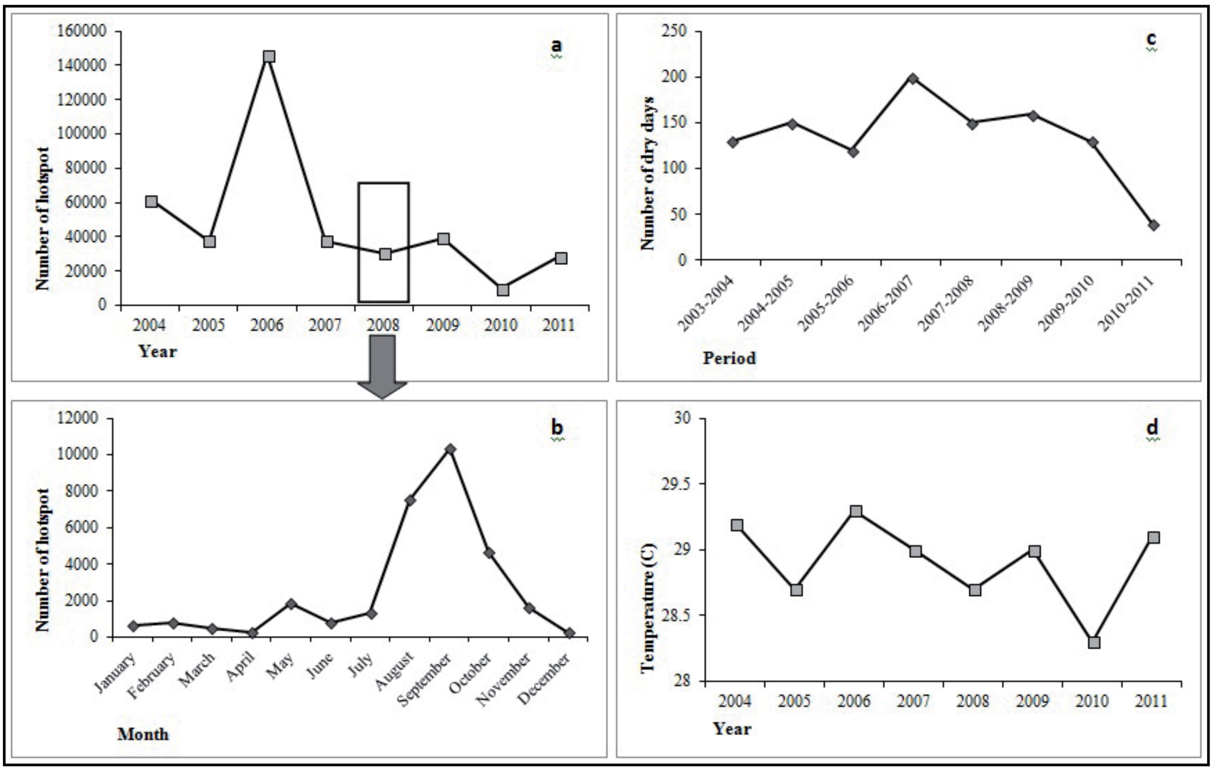

Figure 3. The number of hotspot during the period of 2004-2011 in Indonesia (a); the number of hotspot in 2008 in Indonesia (b); the number of dry days during the period of 2003-2011 from Bandung Meteorogical Station (c); and the maximum temperature during the period of 2004-2011 from Bandung Meteorogical Station.

which are the Earth surface temperature, the total precipitation and the atmospheric moisture convergence including increasing the aerosol particle in the air.

REFERENCES

[1] Dyurgerov, M.B. and M.F. Meier. (2000). "Twentieth century climate change: evidence from small glaciers".*Proceedings of the National Academy of Sciences,* 97 (4), pp. 1406-1411.

[2] Taylor, D. (2010). "Biomass burning, humans and climate change in Southeast Asia". *Biodiversity and Conservation,* 19 (4): pp. 1025-1042. DOI: 10.1007/s10531-009-9756-6.

[3] Liu, Y., J. Stanturf, and S. Goodrick. (2010). "Trends in global wildfire potential in a changing climate" *Forest Ecology and Management,* 259, pp. 685-697. DOI: 10.1016/j.foreco.2009.09.002

[4] Fung, I.Y., S.C. Doney, K. Lindsay,and J. John. (2005). "Evolution of carbon sinks in a changing climate". *Proceedings of the National Academy of Sciences,* 102 (32), pp. 11201-11206. DOI: 10.1073/pnas.0504949102

[5] Hijman, R.J., S.E. Cameron, J.L. Parra, P.G. Jones, and A. Jarvis. (2005). "Very high resolution interpolated climate surfaces for global land areas". *International Journal of Climatology,* 25, pp.1965-1978. DOI: 10.1002/joc.1276.

[6] He, F. and S.P. Hubbel. (2011). "Extinction and climate change". *Nature,* 473, pp. 368-371. DOI: 10.1038/nature10858.

[7] Skinner, L. (2012). "A long view on climate sensitivity". *Science,* 337, pp. 917-919. DOI: 10.1126/science.1224011.

[8] Meynecke, J-O. (2004). ''Effects of global climate change on geographic distributions of vertebrates in North Queensland". *Ecological Modelling,* 174, pp. 347-357. DOI: 10.1016/j.ecolmodel.2003.07.012.

[9] Thuiller, W., S. Lavorel, M.B. Araujo, M.T. Sykes, and I.C. Prentice. (2005). ''Climate change threats to plant diversity in Europe". *Proceedings of the National Academy of Sciences,* 102 (23), pp. 8245-8250. DOI: 10.1073/pnas.0409902102.

[10] Wright, S.J. (2005). ''Tropical forests in a changing environment". *Trends in Ecology and Evolution,* 20 (10), pp. 553-560. DOI: 10.1016/j.tree.2005.07.009.

[11] Woodward, F.I. and C.K. Kelly. (2008). "Responses of global plant diversity capacity to changes in carbon dioxide concentration and climate". *Ecology Letters,* 11, pp. 1229-1237. DOI: 10.1111/j.1461-0248.2008.01240.x.

[12] Walther, G.-R. (2003).''Plants in a warmer world". *Perspectives in Plant Ecology, Evolution and Systematics,* 6 (3), pp. 169-185. DOI: 10.1078/1433-8319-00076.

[13] Pompe, S., J. Hanspach, F. Badeck, S. Klotz, W. Thuiller, and I. Kuhn, (2008). ''Climate and land use change impacts on plant distributions in Germany". *Biology Letters,* 4, pp. 564-567. DOI: 10.1098/rsbl.2008.0231.

[14] Randin, C.F., R. Engler, S. Normand, M. Zappa, N.E. Zimmermann, P.B. Pearman, P. Vittoz, W. Thuiller, and A. Guisan. (2009). "Climate change and plant distribution: local models predict high-elevation persistence". *Global Change Biology,* 15, pp. 1557-1569. DOI: 10.1111/j.1365-2486.2008.01766.x.

[15] Malhi, Y., D.D. Baldocchi, and P.G. Jarvis. (1999).''The carbon balance of tropical, temperate and boreal forests". *Plant, Cell and Environment,* 22, pp. 715-740.

[16] Ostendorf, B., D.W. Hilbert, and M.S. Hopkins. (2001). ''The effect of climate change on tropical rainforest vegetation pattern". *Ecological Modelling,* 145, pp. 211-224. DOI: 10.1016/S0304-3800(01)00392-1.

[17] Scholze, M., W. Knorr, N.W. Arnell, and I.C. Prentice. (2006). "A climate-change risk analysis for world ecosystems". *Proceedings of the National Academy of Sciences,* 103 (35), pp. 13116-13120. DOI: 10.1073/pnas.0601816103.

[18] Carilla, J. and H.R. Grau. (2010). "150 years of tree establishment, land use and climate change in montane grasslands, Northwest Argentina". *Biotropica,* 41 (1), pp. 49-58. DOI: 10.1111/j.1744-7429.2009.00565.x.

[19] Curran, L.M., S.N. Trigg, A.K. McDonald, D. Astiani, Y.M. Hardiono, P. Siregar, I. Chaniago, and E. Kasischke. (2004). "Lowland forest loss in protected areas of Indonesian Borneo". *Science,* 303, pp. 1000-1003. DOI: 10.1126/science.1091714.

[20] Cannon, C.H., M. Summers, J.R. Harting, and P.J.A. Kessler. (2007). "Developing conservation priorities based on forest type, condition, and threats in a poorly known ecoregion: Sulawesi, Indonesia". *Biotropica,* 39 (6), pp. 747-759. DOI: 10.1111/j.1744-7429.2007.00323.x.

[21] Laurance, W.F. (2007). “Forest destruction in tropical Asia”. *Current Science,* 93 (11), pp. 1544-1550.

[22] Giam, X., C.J.A Bradshaw, H.T.W. Tan, N.S. and Sodhi. (2010). ”Future habitat loss and the conservation of plant biodiversity”. *Biological Conservation,* 143, pp. 1594-1602. DOI: 10.1016/j.biocon.2010.04.019.

[23] Detwiller, R.P. and C.A.S. Hall. (1988). ”Tropical forests and the global carbon cycle”. *Science,* 239, pp. 42-47.

[24] Brown, S., L.R. Iverson, A. Prasad, and D. Liu. (1993). ”Geographical distributions of carbon biomass and soils of tropical Asian forests”. *Geocarto International,* 4, pp. 45-59.

[25] DeFries, R.S., R.A. Houghton, M.C. Hansen, C.B. Field, D. Skole, and J. Townshend. (2002). “Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s”. *Proceedings of the National Academy of Sciences,* 99 (22), pp. 14256-14261. DOI: 10.1073/pnas.182560099.

[26] Saatchi, S.S., N.L. Harris, S. Brown, M. Lefsky, E.T.A. Mitchard, W. Salas, B.R. Zutta, W. Buermann, S.L. Lewis, S. Hagen, S. Petrova, L. White, M. Silman, and A. Morel. (2011). “Benchmark map of forest carbon stocks in tropical regions across three continents”. *Proceedings of the National Academy of Sciences,* 108 (24), pp. 9899-9904. DOI: 10.1073/pnas.1019576108.

[27] Sloan, S. and J. Pelletier. (2012). ”How accurately may we project tropical forest-cover change? A validation of a forward-looking baseline for REDD”. *Global Environmental Change,* 22, pp. 440-453. DOI: 10.1016/j.gloenvcha.2012.02.001.

[28] Zarin, D.J. (2012). ”Carbon from tropical deforestation”. *Science,* 336, pp. 1518-1519. DOI: 10.1126/science.1223251.

[29] Bawa, K.S. and A. Markham. (1995). ”Climate change and tropical forest”. *Trends in Ecology and Evolution,* 10 (9), pp. 348-349.

[30] Fearnside, P.M. (2004). ”Are climate change impacts already affecting tropical forest biomass?” *Global Environmental Change,* 14, pp. 299-302. DOI: 10.1016/j.gloenvcha.2004.02.001.

[31] Brodie, J., E. Post, and W.F. Laurance. (2012). ”Climate change and tropical biodiversity: a new focus”. *Trends in Ecology and Evolution,* 27 (3), pp. 145-150. DOI: 10.1016/j.tree.2011.09.008.

[32] Corlett, R.T. (2012). ”Climate change in the tropics: the end of the world as we know it?” *Biological Conservation,* 151, pp. 22-25. DOI: 10.1016/j.biocon.2011.11.027.

[33] Myers, N. (1988). ”Tropical forests: much more than stocks of wood”. *Journal of Tropical Ecology,* 4 (2), pp. 209-221.

[34] Plotkin, J.B., M.D. Potts, D.W. Yu, S. Bunyavejchewin, R. Condit, R. Foster, S. Hubbel, J. LaFrankie, N. Manokaran, H.S. Lee, R. Sukumar, M.A. Nowak, and P.S. Ashton. (2000). ”Predicting species diversity in tropical forests”. *Proceedings of the National Academy of Sciences,* 97 (20), pp. 10850-10854.

[35] Lewis, S.L. (2006). ”Tropical forests and the changing earth system”. *Philosophical Transaction of the Royal Society B: Biological Sciences,* 361, pp. 195-210. DOI: 10.1098/rstb.2005.1711.

[36] Corlett, R.T. (2011). ”Impacts of warming on tropical lowland rainforests”. *Trends in Ecology and Evolution,* 26 (11), pp. 606-613. DOI: 10.1016/j.tree.2011.06.015.

[37] Myers, N., R.A. Mittermeier, C.G. Mittermeier, G.A.B. da Fonseca, and J. Kent. (2000). ”Biodiversity hotspots for conservation priorities”. *Nature,* 403, pp. 853-858.

[38] Laumonier, Y., Y. Uryu, M. Stuwe, A. Budiman, B. Setiabudi, and O. Hadian. (2010). “Eco-floristic sectors and deforestation threats in Sumatra: identifying new conservation area network priorities for ecosystem-based land use planning”. *Biodiversity and Conservation,* 19 (4), pp. 1153-1174. DOI: 10.1007/s10531-010-9784-2.

[39] Wright, S.J. (2010). “The future of tropical forests”. *Annals of the New York Academy of Sciences,* 1195, pp. 1-27. DOI: 10.1111/j.1749-6632.2010.05455.x.

[40] Margono, B.A., S. Turubanova, I. Zhuravleva, P. Potapov, A. Tyukavina, A. Baccini, S. Goetz, and M.C. Hansen. (2012). ”Mapping and monitoring deforestation and forest degradation in Sumatra (Indonesia) using Landsat time series data sets from 1990 to 2010”. *Environmental Research Letters,* 7: 034010, p. 16. DOI: 10.1088/1748-9326/7/3/034010.

[41] Scholes, R.J. and N. van Breemen. (1997). The effects of global change on tropical ecosystems. *Geoderma,* 79, pp. 9-24.

[42] Phillips, O.L., Y. Malhi, B. Vinceti, T. Baker, S.L. Lewis, N. Higuchi, W.F. Laurance, P.N. Vargas, R.V. Martinez, S. Laurance, L.V. Ferreira, M. Stern, S. Brown, and L. Grace. (2002). “Changes in growth of tropical forests: evaluat-

ing potential biases". *Ecological Applications,* 12 (2), pp. 576-587.

[43] Laurance, W.F., D.C. Useche, L.P. Shoo, S.K. Herzog, M. Kessler, F. Escobar, G. Brehm, J.C. Axmacher, I-C, Chen, L.A. Gamez, P. Hietz, K. Fiedler, T. Pyrcz, J. Wolf, C.L. Merkord, C. Cardelus, A.R. Marshall, C. Ah-Peng, G.H. Aplet, M.D.C. Arizmendi, W.J. Baker, J. Barone, C.A. Bruhl, R.W. Bussmann, D. Cicuzza, G. Eilu, M.E. Favila, A. Hemp, C. Hemp, J. Homeier, J. Hurtado, J. Jankowski, G. Kattan, J. Kluge, T. Kromer, D.C. Lees, M. Lehnert, J.T. Longino, J. Lovett, P.H. Martin, B.D. Patterson, R.G. Pearson, K.S.-H Peh, B. Richardson, M. Richardson, M.J. Samways, F. Sanbeta, T.B. Smith, T.M.A. Utteridge, J.E. Watkins, R. Wilson, S.E. Williams, and C.D. Thomas. (2011). ''Global warming, elevation ranges and the vulnerability of tropical biota". *Biological Conservation,* 144, pp. 548-557. DOI: 10.1016/j.biocon.2010.10.010.

[44] Phillips, O.L., P. Hall, A.H. Gentry, S.A. Sawyer, and R. Vasquez. (1994). "Dynamics and species richness of tropical rain forests". *Proceedings of the National Academy of Sciences,* 91, pp. 2805-2809.

[45] Burslem, D.F.R.P., N.C. Garwood, and S.C. Thomas, S.C. (2001). "Tropical forest diversity – the plot thickens". *Science,* 291 (5504), pp. 606-607. DOI: 10.1126/science.1055873.

[46] Molino, J.-F. and D. Sabatier. (2001). "Tree diversity in tropical rain forests: a validation of the intermediate disturbance hypothesis". *Science,* 294, pp. 1702-1704. DOI: 10.1126/science.1060284.

[47] Gibson, L., T.M. Lee, L.P. Koh, B.W. Brook, T.A. Gardner, J. Barlow, C.A. Peres, C.J.A. Bradshaw, W.F. Laurance, T.E. Lovejoy, and N.S. Sodhi. (2011). ''Primary forests are irreplaceable for sustaining tropical biodiversity". *Nature,* 478, pp. 378-383. DOI: 10.1038/nature10425.

[48] Malhi, Y. and J. Grace. (2000). ''Tropical forests and atmospheric carbon dioxide". *Trends in Ecology and Evolution,* 15 (8), pp. 332-337.

[49] Lewis, S.L., G. Lopez-Gonzalez, B. Sonke, K. Affum-Baffoe, T.R. Baker, L.O. Ojo, O.L. Phillips, J.M. Reitsma, L.White, J.A. Comiskey, K. Djuikouo K., C.E.N. Ewango, T.R. Feldpausch, A.C. Hamilton, M. Gloor, T. Hart, A. Hladik, J. Lloyd, J.C. Lovett, J.-R. Makana, Y. Malhi, F.M. Mbago, H.J. Ndangalasi, J. Peacock, K.S.-H. Peh, D. Sheil, T. Sunderland, M.D. Swaine, J. Taplin, D. Taylor, S.C. Thomas, R. Votere, and H. Woll. (2009). ''Increasing carbon storage in intact African tropical forests". *Nature,* 457, pp. 1003-1006. DOI: 10.1038/nature07771.

[50] FAO. (2006). ''*Global forest resources assessment 2005: progress towards sustainable forest management*". FAO Forestry Paper. 147, pp. 350.

[51] IPCC. (2007a). *Climate change 2007: mitigation of climate change (contributions of working group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change).* in Metz, B. *et. al.* (eds.). Cambridge: Cambridge University Press.

[52] FAO. (2010). *Global Forest Resources Assessment 2010*. FAO Forestry Paper 163, p. 378.

[53] Smith, J.B. (1997). "Setting priorities for adapting to climate change". *Global Environmental Change,* 7 (3), pp. 251-264.

[54] Karl, T.R. and K.E. Trenberth. (2003). "Modern global climate change". *Science,* 302, pp. 1719-1723. DOI: 10.1126/science.1090228.

[55] IPCC, (2007b). *Climate change 2007: the physical science basis (contributions of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change).* in Solomon, S. *et. al.* (eds.). Cambridge: Cambridge University Press.

[56] Crowley, T.J. (2000). "Causes of climate change over the past 1000 years". *Science,* 289, pp. 270-277. DOI: 10.1126/science.289.5477.270.

[57] Root, T.L., J.T. Price, K.R. Hall, S.H. Schneider, C. Rosenzweig, and J.A. Pounds. (2003). ''Fingerprints of global warming on wild animals and plants". *Nature,* 42, pp. 57-60. DOI: 10.1038/nature01333.

[58] Schlesinger, W.H. (2006). "Global change ecology". *Trends in Ecology and Evolution,* 21 (6), pp. 348-351. DOI: 10.1016/j.tree.2006.03.004.

[59] Williams, J.W., S.T. Jackson, and J.E. Kutzbach. (2007). ''Projected distributions of novel and disappearing climates by 2100 AD". *Proceedings of the National Academy of Sciences,* 104 (14), pp. 5738-5742. DOI: 10.1073/pnas.0606292104.

[60] White, A., M.G.R. Cannell, and A.D. Friend. (1999). ''Climate change impacts on ecosystems and the terrestrial carbon sink: a new assessment". *Global Environmental Change,* 9, pp. S21-S30.

[61] Pounds, J.A., M.P.L. Fogden, and J.H. Campbell. (1999). "Biological response to climate change on a tropical mountain". *Nature,* 398, pp. 611-615.

[62] Still, C.J., P.N. Foster, and S.H. Schneider. (1999). "Simulating the effects of climate change on tropical montane cloud forests". *Nature,* 398, pp. 608-610.

[63] Foster, P. (2001). ''The potential negative impacts of global climate change on tropical montane cloud forests". *Earth-Science Reviews,* 55, pp. 73-106.

[64] Malhi, Y. and J. Wright. (2004). "Spatial patterns and recent trends in the climate of tropical rainforest regions". *Philosophical Transaction of the Royal Society B: Biological Sciences,* 359, pp. 311-329. DOI: 10.1098/rstb.2003.1433.

[65] Mayle, F.E., D.J. Beerling, W.D. Gosling, and M.B. Bush. (2004). ''Responses of Amazonian ecosystems to climatic and atmospheric carbon dioxide changes since last glacial maximum". *Philosophical Transaction of the Royal Society B: Biological Sciences,* 359, pp. 499-514. DOI: 10.1098/rstb.2003.1434.

[66] Colwell, R.K., G. Brehm, C.L. Cardelus, A.C. Gilman, and J.T. Longino. (2008). "Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics". *Science,* 322: pp. 258-261. DOI: 10.1126/science.1162547.

[67] Flannigan, M.D., B.J. Stocks, and B.M. Wotton. (2000). ''Climate change and forest fires". *The Science of the Total Environment,* 262, pp. 221-229.

[68] Van der Werf, G.R., J. Dempewolf, S.N. Trigg, J.T. Randerson, P.S. Kasibhatla, L. Giglio, D. Murdiyarso, W. Peters, D.C. Morton, G.J. Collatz, A.J. Dolman, and R.S. DeFries. (2008). ''Climate regulation of fire emissions and deforestation in equatorial Asia". *Proceedings of the National Academy of Sciences,* 105 (51), pp. 20350-20355. DOI: 10.1073/pnas.0803375105.

[69] Langman, B., B. Duncan, C. Textor, J. Trentmann, and G.R. van der Werf. (2009). ''Vegetation fire emissions and their impact on air pollution and climate". *Atmospheric Environment,* 43, pp. 107-116. DOI: 10.1016/j.atmosenv.2008.09.047.

[70] McGuffie, K., A. Henderson-Sellers, H. Zhang, T.B. Durbidge, and A.J. Pitman. (1995). ''Global climate sensitivity to tropical deforestation". *Global and Planetary Change,* 10, pp. 97-128.

[71] Ward, D.E. and C.C. Hardy. (1991). "Smoke emissions from wild land fires". *Environment International,* 17, pp. 117-134.

[72] Cofer III, W.R., J.S. Levine, E.L. Winstead, B.J. Stocks, D.R. Cahoon, and J.P. Pinto. (1993). "Trace gas emissions from tropical biomass fires: Yucatan Peninsula, Mexico". *Atmospheric Environment,* 27A (12), pp. 1903-1907.

[73] Miranda, A.I., M. Coutinho, and C. Borrego. (1994). "Forest fire emissions in Portugal: a contribution to global warming?" *Environmental Pollution,* 83, pp. 121-123.

[74] Barlow, J., L. Parry, T.A. Gardner, J. Ferreira, L.E.O.C. Aragao, R. Carmenta, E. Berenguer, I.C.G. Vieira, C. Souza, and M.A. Cochrane, M.A. (2012). "The critical importance of considering fire in REDD+ programs". *Biological Conservation,* 154, pp. 1-8. DOI: 10.1016/j.biocon.2012.03.034.

[75] De Vasconcelos, S.S., P.M. Fearnside, P.M.L.A. Graca, E.M. Nogueira, L.C. de Oliveira, and E.O. Figueiredo. (2013). "Forest fires in southwestern Brazilian Amazonia: estimates of area and potential carbon emissions". *Forest Ecology and Management,* 291, pp. 199-208. DOI: 10.1016/j.foreco.2012.11.044.

[76] Erlykin, A.D., T. Sloan, and A.W. Wolfendale. (2010). "Correlations of clouds, cosmic rays and solar radiation over the Earth". *Journal of Atmospheric and Solar-Terrestrial Physics,* 72, pp. 151-156. DOI: 10.1016/j.astp.2009.11.002.

[77] Erlykin, A.D., T. Sloan, and A.W. Wolfendale. (2010). "Clouds, solar irradiance and mean surface temperature over the last century". *Journal of Atmospheric and Solar-Terrestrial Physics,* 72, pp. 425-434. DOI: 10.1016/j.astp.2009.12.013.

[78] Koren, I., Y.J. Kaufman, L.A. Remer, and J.V. Martins. (2004). "Measurement of the effect of Amazon smoke on inhibition of cloud formation". *Science,* 303, pp. 1342-1345. DOI: 10.1126/science.1089424.

[79] Koren, I., J.V. Martins, L.A. Remer, and H. Afargan. (2008). "Smoke invigoration versus inhibition of clouds over the Amazon".

Science, 321, pp. 946-949. DOI: 10.1126/science.1159185.

[80] Parameswaran, K., S.K. Nair, and K. Rajeev. (2004). "Impact of Indonesian forest fires during the 1997 El Nino on the aerosol distribution over the Indian Ocean". *Advances in Space Research,* 33, pp. 1098-1103. DOI: 10.1016/S0273-1177(03)00736-1.

[81] Annas, S., T. Kanai, and S. Koyama. (2007). "Assessing daily tropical rainfall variations using a neuro-fuzzy classification model". *Ecological Informatics,* 2, pp. 159-166. DOI: 10.1016/j.ecoinf.2007.04.001.

[82] Cerda, I.G., F. Lloret, J.E. Ruiz, and J.H. Vandermeer. (2012). "Tree mortality following ENSO-associated fires and drought in lowland rain forests of Eastern Nicaragua". *Forest Ecology and Management,* 265, pp. 248-257. DOI: 10.1016/j.foreco.2011.10.034.

[83] Curran, L.M., I. Caniago, G.D. Paoli, D. Astianti, M. Kusneti, M. Leighton, C.E. Nirarita, H. and Haeruman. (1999). "Impact of El Nino and logging on canopy tree recruitment in Borneo". *Science,* 286, pp. 2184-2188.

[84] Wich, S.A. and C.P. van Schaik. (2000). "The impact of El Nino on mast fruiting in Sumatra and elsewhere in Malesia". *Journal of Tropical Ecology,* 16(4), pp. 563-577.

[85] Herawati, H. and H. Santoso. (2011). ''Tropical forest susceptibility to and risk of fire under climate change: a review of fire nature, policy and institutions in Indonesia". *Forest Policy and Economics,* 13, pp. 227-233. DOI: 10.1016/j.forpol.2011.02.006.

[86] Slik, J.W.F. (2004). "El Nino droughts and their effects on tree species composition and diversity in tropical rain forests". *Oecologia,* 141, pp. 114-120. DOI: 10.1007/s00442-004-1635-y.

[87] Van Nieuwstadt, M.G.L. and D. Sheil. (2005). "Drought, fire and tree survival in a Borneo rain forest, East Kalimantan, Indonesia". *Journal of Ecology,* 93, pp. 191-201. DOI: 10.1111/j.1365-2745.2004.00954.x.

[88] Rolim, S.G., R.M. Jesus, H.E.M. Nascimento, H.T.Z. do Couto, and J.O. Chambers. (2005). "Biomass change in an Atlantic tropical moist forest: the ENSO effect in permanent sample plots over 22-year period". *Oecologia,* 142, pp. 238-246. DOI: 10.1007/s00442-004-1717-x.

[89] Naylor, R.L., D.S. Battisti, D.J. Vimont, W.P. Falcon, and M.B. Burke (2007). "Assessing risks of climate variability and climate change for Indonesian rice agriculture". *Proceedings of the National Academy of Sciences,* 104 (19), pp. 7752-7757. DOI: 10.1073/pnas.0701825104.

[90] Ministry of Forestry,.(2009). *Forestry Statistics of Indonesia 2008*. Ministry of Forestry, Republic of Indonesia. Available online at www.dephut.go.id.

[91] Ministry of Forestry. (2012). *Forestry Statistics of Indonesia 2011*. Ministry of Forestry, Republic of Indonesia. Available online at www.dephut.go.id.

[92] BMKG. (2012). *Information book of climate change and air quality in Indonesia* [*Buku informasi perubahan iklim dan kualitas udara di Indonesia*]. Badan Meteorologi, Klimatologi, dan Geofisika.

[93] Luo, Y. (2007). "Terrestrial carbon-cycle feedback to climate change". *Annual Review of Ecology, Evolution and Systematics,* 38, pp. 683-712. DOI: 10.1146/annurev.ecolsys.38.091206.095808.

[94] Bridgham, S.D., J. Pastor, B. Dewey, J.F. Weltzin, and K. Updegraff. (2008). "Rapid carbon response of peatlands to climate change". *Ecology,* 89 (11), pp. 3041-3048. DOI: 10.1890/08-0279.1.

[95] Finlayson, R. (2011). "Mapping a greenhouse gas hotspot: Indonesia's forest losses and greenhouse gas emissions have finally been mapped". Available online at http://www.worldagroforestrycentre.org/sites/default/files/Indonesia_land_cover_maps_story.pdf.