The challenges of using satellite datasets to assess historical land use change and associated greenhouse gas emissions - a case study of three Indonesian provinces

Supplementary material

# Supplementary figures



Figure SM1 - Schematic overview of LULC change raster calculations



Figure SM2 – Schematic overview of GHG emissions calculation from LULC change.



Figure SM3 – GHG emissions estimates from LULC change data between 2000-2015 in North Sumatra



Figure SM4 – GHG emissions estimates from LULC change data between 2000-2015 in Riau



Figure SM5 – GHG emissions estimates from LULC change data between 2000-2015 in Central Kalimantan

# Supplementary tables

Table SM1 –LULC change periods for the LULC datasets. CRISP 2015 data not used for LULC change analysis

|  |  |  |
| --- | --- | --- |
| **LULC data update** | | |
| **CCI** | **CRISP** | **MoF** |
| 2000 | 2000 | 2000 |
| 2003 |  | 2003 |
| 2006 |  | 2006 |
| 2009 |  | 2009 |
|  | 2010 |  |
| 2011 |  | 2011 |
| 2012 |  | 2012 |
| 2013 |  | 2013 |
| 2015 | *2015* | 2015 |

Table SM2: Carbon stock values for use in calculating aboveground biomass (vegetation) transitions

| **LAND COVER (LC)** | | | | **CARBON STOCK** | |
| --- | --- | --- | --- | --- | --- |
| ***Collective LC class*** | ***CCI LC class*** | ***CRISP LC class*** | ***MoEF CL class*** | ***C stock value***  ***(Mg C ha-1)*** | ***Ref source, notes, comparison with other published average values & ranges*** |
| Primary forest – intact, natural forest with dense canopy | Tree cover, broadleaved, evergreen, closed to open (>15%) | Lowland evergreen forest | Primary dry land forest | 93  121  164  175-200  177  180  195  200  202  225  229  229±62  230  250  250  250  252  254  274±97  300  300-325  390  399 | Harja et al 2011, *Indonesia*  Griscom et al 2009*, Indonesia*  Gibbs & Brown 2007, *tropical Asia*  Brown et al 2003, *the Tropics*  Morel et al 2011, *Malaysia*  Laumonier et al 2010, *Indonesia*  BAPPENAS 2010, *Indonesia*  Toma et al 2005, *Indonesia*  Hoshizaki et al 2004, *Malaysia*  IPCC 2006, *tropical Asia*  Omar 2010, *Malaysia*  Slik et al. 2010, *Borneo*  Rahayu et al 2005, *Indonesia*  Houghton 1999, *the Tropics*  DeFries et al 2002, *the Tropics*  Yamakura et al 1986, *Indonesia*  Prasetyo et al 2000, *Indonesia*  Noordwijk et al 2000, *Indonesia*  Kronseder et al 2012, *Indonesia*  World Agrofor. Centre 2011, *SE Asia*  Murdiyarso & Wasrin 1995, *Indonesia*  Hairiah & Sitompul 2000, *Indonesia*  Proctor et al 1983, *Malaysia* |
|  |  | **Average 233±72** | Agus et al. 2013, 189±42, *SE Asia*  Ziegler et al. 2012, min 40 - max 400, *lowland forests in SE Asia* |
|  | Tree cover, flooded, fresh or brackish water | Peatswamp forest | Primary swamp forest | 90  90±54  113±9  196  200  250 | Harja et al. 2011, *Indonesia*  Murdiyarso et al. 2010, *Indonesia*  Toriyama et al 2014, *Indonesia*  MoF 2008, *Indonesia*  World Agrofor. Cent. 2011, *Indonesia*  Murdiyarso & Wasrin 1995, *Indonesia* |
|  | |  |  | **Average 157±68** | Agus et al. 2013, 162±51, *SE Asia* |
|  | Tree cover, flooded, saline water | Mangrove | Primary mangrove forest | 12-104-143  65  85  86  135  160  170  200 | Murdiyarso et al. 2009, *Indonesia*  Murdiyarso & Wasrin 1995, *Indonesia*  Harja et al. 2011, *Indonesia*  IPCC 2013, *the wet Tropics*  Putz & Chan 1986, *Malaysia*  Donato et al. 2011, *Asia*  Komiyama et al 2008, *Indonesia*  World Agrofor. Cent. 2011, *Indonesia* |
|  |  |  |  | **Average 116±56** | Agus et al. 2013, 148±43, *SE Asia* |
| Secondary forest – disturbed forest with evidence of logging |  |  | Secondary dry land forest | 43-60  55-132  74  87  92±25  93  124-194  134  150-250  170  180  203 | Pinard & Putz 1996, *Malaysia*  Morel et al 2011, *Malaysia*  Harja et al 2011, *Indonesia*  Henson 2005, *Malaysia*  Carlson et al. 2013, *Indonesia*  Palm et al 1999, *the Tropics*  Carlson et al. 2012, *Indonesia*  Omar et al 2010, *Malaysia*  World Agrofor. Cent. 2011, *Indonesia*  MoF 2008, *Indonesia*  IPCC 2006, *tropical Asia*  Rahayu et al. 2006, *Indonesia* |
|  |  |  |  | **Average 128±53** | Agus et al. 2013, 104±59, *SE Asia*  Ziegler et al. 2012, min 30 - max 210, *logged forests in SE Asia* |
|  |  |  | Secondary swamp forest | 33-64  72±43  78  85±24  114±49  120  125-156  155 | Morel et al 2011, *Malaysia*  Carlson et al. 2013, *Indonesia*  Harja et al 2011, *Indonesia*  Hergoualc’h & Verchot 2011, *SE Asia*  Kronseder et al 2012, *Indonesia*  World Agrofor. Cent. 2011, *Indonesia*  Waldes & Page 2001, *Indonesia*  MoF 2008, *Indonesia* |
|  |  |  |  | **Average 102±37** | Agus et al. 2013, 84±42, *SE Asia* |
|  |  |  | Secondary mangrove forest | 77  100  105  120 | Harja et al. 2011, *Indonesia*  World Agrofor. Cent. 2011, *Indonesia*  Ong et al 1982, *Malaysia*  Komiyama et al 2008, *Indonesia* |
|  |  |  |  | **Average 101±15** | Agus et al. 2013, 101±15, *SE Asia* |
| Cropland | Cropland, irrigated or post-flooding | Large scale oil palm plantations | Plantations | *Oil palm plantations* | |
|  |  |  |  | 23  26  30  31  31  35-55  36  36  37  38-42  40  60 | Corley & Tinker 2003, *Malaysia*  Morel et al 2011, *Malaysia*  Germer & Sauerborn 2008, *the tropics*  World Agrofor. Cent. 2011, *Indonesia*  Sitompul & Hairiah 2000, Indonesia  Syahrinudin 2005, Indonesia  Henson 2005, *Malaysia*  Palm et al 2004, *the Tropics*  Dewi et al. 2009, *Indonesia*  Khasanah et al. 2015, *Indonesia*  van Noordwijk et al 2010, *Indonesia*  Rogi 2002, Indonesia |
|  |  |  |  | **Average 37±10** | Agus et al 2013, 36±11ǂ, *SE Asia*  Ziegler et al 2012, min 17- max 69, *SE Asia* |
|  |  |  |  | *Rubber plantations* | |
|  |  |  |  | 31  36  46-89  97 | World Agroforest. Cent. 2011, *Indonesia*  Prasetyo et al 2000, *Indonesia*  Palm et al. 1999, *the Tropics*  Lasco & Puhlin 2004, *SE Asia* |
|  |  |  |  | **Average 60±31** | Agus et al. 2013, 58±28, *SE Asia*  Ziegler et al. 2012, min 25 - max 143, *SE Asia* |
|  |  |  |  | *Timber plantations (monocultures, e.g. Acacia, Eucalyptus)* | |
|  |  |  | HTI (hutan temanan industri) | 21±2  29  35  37  38  60-70 | Hergoualc’h & Verchot 2011, *SE Asia*  Morel et al 2011, *Malaysia*  Matsumura et al 2008, *Malaysia*  Palm et al 1999, *the Tropics*  Nurwahyudi & Tarigan 2001*, Indonesia*  World Agroforest. Cent. 2011, *Indonesia* |
|  |  |  |  | **Average 41±17** | Agus et al. 2013, 44±14, *SE Asia* |
|  |  |  | Rice land | *Rice fields* | |
|  |  |  |  | 2  5  5 | Palm et al 1999, *the Tropics*  Hergoualc’h & Verchot 2011, *SE Asia*  Rahayu et al. 2005, *Indonesia* |
|  |  |  |  | **Average 4±2** | Agus et al. 2013, 2±0, *SE Asia* |
| Agroforestry (mixed tree crops) | Mosaic cropland | Lowland mosaic |  | 38-73  71±131  77 | Rahayu et al 2005, *Indonesia*  Carlson et al. 2013, *Indonesia*  World Agroforest. Cent. 2011, *Indonesia* |
|  |  |  |  | **Average 65±18** | Agus et al. 2013, 54±24, *SE Asia*  Ziegler et al 2012, min 15 - max 100, *SE Asia* |
| Scrub – small trees and woody shrubs, early stage forest regrowth | Shrubland evergreen; sparse vegetation (tree, shrub, herbaceous cover) | Lowland open | Scrubland (on mineral soils) | 24  27  29  30  35  42 | Hashimotio et al 2000, *Indonesia*  World Agroforest. Cent., *Indonesia*  Jepsen 2006, *Malaysia*  Isotomo et al 2006, *Indonesia*  IPCC 2006, *the Tropics*  Halenda 1989, *Malaysia* |
|  |  |  |  | **Average 31±6** | Agus et al. 2013, 30±3, *SE Asia* |
|  |  |  | Swamp scrubland (on peat soils) | 10-25  18  29  30  35 | Hoscilo et al. 2011, *Indonesia*  World Agroforesty Cent. 2001, *Indonesia*  Jepsen 2006, *Malaysia*  Isotomo et al. 2006, *Indonesia*  IPCC 2006, *the Tropics* |
|  |  |  |  | **Average 25±9** | Agus et al. 2013, 28±6, *SE Asia* |
| Settlements | Urban areas | Urban | Housing | 4  10 | World Agroforest. Cent., *Indonesia*  BAPPENAS 2010, *Indonesia\**  (\*assumes 1/3 of land is tree crops & agriculture) |
|  |  |  |  | **Average 7±3** | Agus et al. 2013, 7±3, *SE Asia* |
| Grassland –  dry soils |  |  | Savannah | 2  4 | World Agroforest. Cent. 2011, *Indonesia*  Rahayu et al 2005, *Indonesia* |
|  |  |  |  | **Average 3±1** | Agus et al. 2013, 3±1, *SE Asia* |
| Bare land |  |  | Bare land | **0** | Value recommend by Agus et al. (2013): C stock is mostly in the form of necromass (i.e. plant litter). |
| Water bodies | Water bodies | Water | Bodies of water, fish pond | **0** | Assumed |

Table SM3: Emission factors for below ground carbon stocks (soil/peat)

| **LAND COVER (LC)** | | | | **SOIL EMISSIONS FROM LAND CONVERSION** | |
| --- | --- | --- | --- | --- | --- |
| ***Collective LC class*** | ***CCI LC class*** | ***CRISP LC class*** | ***MoEF CL class*** | ***Soil organic matter carbon emission factor***  ***(Mg C ha-1 yr-1)*** | ***Ref source, notes*** |
| Primary forest – intact, natural forest with dense canopy | Tree cover, broadleaved, evergreen, closed to open (>15%) | Lowland evergreen forest | Primary dry land forest | 0 | Khasanah et al. 2015, *Indonesia* |
|  |  |
|  | Tree cover, flooded, fresh or brackish water | Peat swamp forest | Primary swamp forest | 0 | IPCC 2013, *the Tropics* |
| Secondary forest – disturbed forest with evidence of logging |  |  | Secondary dry land forest | 0 | Khasanah et al. 2015, *Indonesia* |
|  |  |  | Secondary swamp forest | 7.9 | Hooijer et al. 2014, *Indonesia* |
| Cropland | Cropland, irrigated or post-flooding | Large scale oil palm plantations | Plantations | *Oil palm plantations on mineral soils* | |
|  |  |  |  | 0 | Khasanah et al. 2015, *Indonesia* |
|  |  |  |  | *Oil palm plantations on organic (peat) soils* | |
|  |  |  |  | 11\*\* | IPCC 2013, *the Tropics* |
|  |  |  |  | *Rubber plantations on mineral soils* | |
|  |  |  |  | 0 | Khasanah et al. 2015, *Indonesia* |
|  |  |  |  | *Rubber plantations on organic (peat) soils* | |
|  |  |  |  | 15\*\* | IPCC 2013, *the Tropics* |
|  |  |  |  | *Timber plantations (e.g. Acacia for pulpwood) on mineral soils* | |
|  |  |  | HTI | 0 | Khasanah et al. 2015, *Indonesia* |
|  |  |  |  | *Timber plantations (e.g. Acacia for pulpwood) on organic (peat) soils* | |
|  |  |  |  | 20\*\* | IPCC 2013, *the Tropics* |
|  |  | Lowland mosaic – check | Dry rice land +/- mixed scrub; rice land | *Rice fields on mineral soils* | |
|  |  |  |  | 0 | Khasanah et al. 2015, *Indonesia* |
|  |  |  |  | *Rice fields on organic (peat) soils* | |
|  |  |  |  | 9.4\*\* | IPCC 2013, *the Tropics* |
| Agroforestry (mixed tree crops) | Mosaic cropland | Lowland mosaic |  | *Agroforestry on mineral soils* | |
|  |  |  |  | 0 | Khasanah et al. 2015, *Indonesia* |
|  |  |  |  | *Agroforestry on organic (peat) soils* | |
|  |  |  |  | 15\*\* | IPCC 2013, *the Tropics* |
|  |  |  |  | *Mosaic cropland (smallholder farming) on organic (peat) soils* | |
|  |  |  |  | 14\*\* | IPCC 2013, *the Tropics* |
| Scrub – small trees and woody shrubs | Shrubland evergreen; sparse vegetation (tree, shrub, herbaceous cover) | Lowland open | Scrubland (on mineral soils) | 0 | Khasanah et al. 2015, *Indonesia* |
|  |  |  | Swamp scrubland (peat soils) | 4.5 | Hooijer et al. 2014 |
| Settlements | Urban areas | Urban | Housing | *Urban areas on mineral soils* | |
|  |  |  |  | 0 | Khasanah et al. 2015, *Indonesia* |
|  |  |  |  | *Urban areas on peat soils* | |
|  |  |  |  | 9.6\*\* | Miettinen et al. 2017, *SE Asia* (derived from IPCC 2013) |
| Grassland – dry mineral soils |  |  | Savannah | 0 | Khasanah et al. 2015, *Indonesia* |
| Bare land |  |  | Bare land | *Bare land on mineral soils* | |
|  |  |  |  | 0 | Khasanah et al. 2015, *Indonesia* |
|  |  |  |  | *Bare land on organic (peat) soils* | |
|  |  |  |  | 11, 15, 20\*\* (apply appropriate plantation EF) | IPCC, 2013 |
| Water bodies | Water bodies | Water | Bodies of water | 0 | Assumed |

Table SM4– GoF scores of all AOIs and LULC map combinations for the year 2000, with analysis direction indicated with -> (left Original, right Reference) and <- (right Original, left Reference). Highest GoF score per AOI indicated in bold.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **CRISP <-> CCI** | | **MoF <-> CCI** | | **MoF <-> CRISP** | |
| **CRISP -> CCI** | **CRISP <- CCI** | **MoF -> CCI** | **MoF <- CCI** | **MoF -> CRISP** | **MoF <- CRISP** |
| North Sumatra | 0.378 | **0.508** | 0.394 | 0.394 | 0.499 | 0.369 |
| Riau | 0.318 | **0.433** | 0.308 | 0.270 | 0.395 | 0.249 |
| Central Kalimantan | 0.281 | 0.386 | 0.318 | 0.278 | **0.407** | 0.254 |

Table SM5 – GoF scores of all AOIs and LULC map combinations for the year 2015, with analysis direction indicated with -> (left Original, right Reference) and <- (right Original, left Reference). Highest GoF score per AOI indicated in bold.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **CRISP <-> CCI** | | **MoF <-> CCI** | | **MoF <-> CRISP** | |
| **CRISP -> CCI** | **CRISP <- CCI** | **MoF -> CCI** | **MoF <- CCI** | **MoF -> CRISP** | **MoF <- CRISP** |
| North Sumatra | 0.475 | 0.557 | 0.467 | 0.401 | **0.575** | 0.419 |
| Riau | 0.399 | **0.465** | 0.356 | 0.267 | 0.448 | 0.285 |
| Central Kalimantan | 0.295 | 0.494 | 0.328 | 0.287 | **0.525** | 0.272 |

Table SM6 – Overview of LULC Change estimated from CCI, CRISP and MoF for the three AOIs between 2000 and 2015

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | CCI | | | MoF | | | CRISP | | |
| ha | % peat | ha | | % peat | ha | | % peat |
| **North Sumatra** | | | | | | | | | |
| 2000-2003 | 25,901 | 20.9 | 8,050 | | 4.3 | 508,381 | | 7.8 |
| 2003-2006 | 37,661 | 28.5 | 34,724 | | 29.9 |
| 2006-2009 | 55,106 | 19.8 | 638,860 | | 6.4 |
| 2009-2011 | 31,964 | 18.1 | 61,406 | | 9.0 |  | |  |
| 2011-2012 | 30,565 | 11.2 | 53,095 | | 6.1 |  | |  |
| 2012-2013 | 26,239 | 5.4 | 22,930 | | 18.7 |  | |  |
| 2013-2015 | 54,826 | 5.7 | 130,253 | | 10.2 |  | |  |
| *average 2000-2009/2010* | *39,556* | *23.1* | *227,211* | | *13.5* | *508,381* | | *7.8* |
| *average 2000-2015* | *37,466* | *15.7* | *135,617* | | *12.1* |  | |  |
|  | | | | | | | | | |
| **Riau** | | | | | | | | | |
| 2000-2003 | 97,048 | 45.0 | 150,228 | | 58.4 | 803,360 | | 46.8 |
| 2003-2006 | 157,049 | 51.7 | 353,083 | | 60.2 |
| 2006-2009 | 141,662 | 49.1 | 376,841 | | 58.6 |
| 2009-2011 | 117,938 | 56.8 | 262,590 | | 72.7 |  | |  |
| 2011-2012 | 90,888 | 57.5 | 326,130 | | 71.8 |  | |  |
| 2012-2013 | 52,621 | 55.0 | 1,118,233 | | 31.7 |  | |  |
| 2013-2015 | 63,003 | 63.4 | 508,996 | | 49.8 |  | |  |
| *average 2000-2009/2010* | *131,920* | *48.6* | *293,384* | | *59.1* | *803,360* | | *46.8* |
| *average 2000-2015* | *102,887* | *54.1* | *442,300* | | *57.6* |  | |  |
|  | | | | | | | | | |
| **Central Kalimantan** | | | | | | | | | |
| 2000-2003 | 83,163 | 38.9 | 103,631 | | 33.7 | 911,095 | | 21.5 |
| 2003-2006 | 74,028 | 24.4 | 388,471 | | 19.3 |
| 2006-2009 | 149,672 | 27.2 | 222,781 | | 29.8 |
| 2009-2011 | 78,931 | 27.8 | 139,834 | | 13.4 |  | |  |
| 2011-2012 | 50,239 | 30.0 | 59,815 | | 2.4 |  | |  |
| 2012-2013 | 36,892 | 30.6 | 109,720 | | 23.9 |  | |  |
| 2013-2015 | 65,128 | 25.0 | 1,237,019 | | 23.0 |  | |  |
| *average 2000-2009/2010* | *102,288* | *30.1* | *238,294* | | *27.6* | *911,095* | | *21.5* |
| *average 2000-2015* | *76,865* | *29.1* | *323,039* | | *20.8* |  | |  |

Table SM7 – GHG emissions for CRISP and MoF data, based on carbon stock at maturity for palm oil. Percentages are proportions of baseline emissions estimates, see Tables 4 and 5

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Emissions per year (Mg C yr-1)** | | | | | | |
| **North Sumatra** | | | | | | |
|  | CRISP (2000-2010) | | MoF (2000-2011) | | MoF (2011-2015) | |
| Mineral | 3,544,872 | *72%* | 871,984 | *77%* | 4,036,280 | *117%* |
| Peat | 3,320,671 | *96%* | 1,651,461 | *91%* | 857,838 | *101%* |
| *Total* | *5,656,438* | *67%* | *2,523,446* | *86%* | *4,894,117* | *114%* |
|  | | | | | | |
| **Riau** | | | | | | |
|  | CRISP (2000-2010) | | MoF (2000-2011) | | MoF (2011-2015) | |
| Mineral | 9,892,785 | 84% | 4,676,420 | 97% | 4,671,123 | *75%* |
| Peat | 28,058,789 | 96% | 22,905,655 | 99% | 15,443,351 | *93%* |
| *Total* | 37,951,574 | 92% | *27,582,075* | 99% | 20,114,473 | *88%* |
|  | | | | | | |
| **Central Kalimantan** | | | | | | |
|  | CRISP (2000-2010) | | MoF (2000-2011) | | MoF (2011-2015) | |
| Mineral | 13,094,148 | *89%* | 7,229,204 | *87%* | 8,277,973 | *80%* |
| Peat | 10,984,926 | *94%* | 4,997,529 | *97%* | 10,472,336 | *96%* |
| *Total* | 24,079,074 | *91%* | 12,226,733 | *91%* | 18,750,309 | *88%* |

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