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# Widespread subsidence and carbon emissions across Southeast Asian peatlands

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Supporting Information for:

# Widespread Subsidence and Carbon Emissions across Southeast Asian Peatlands

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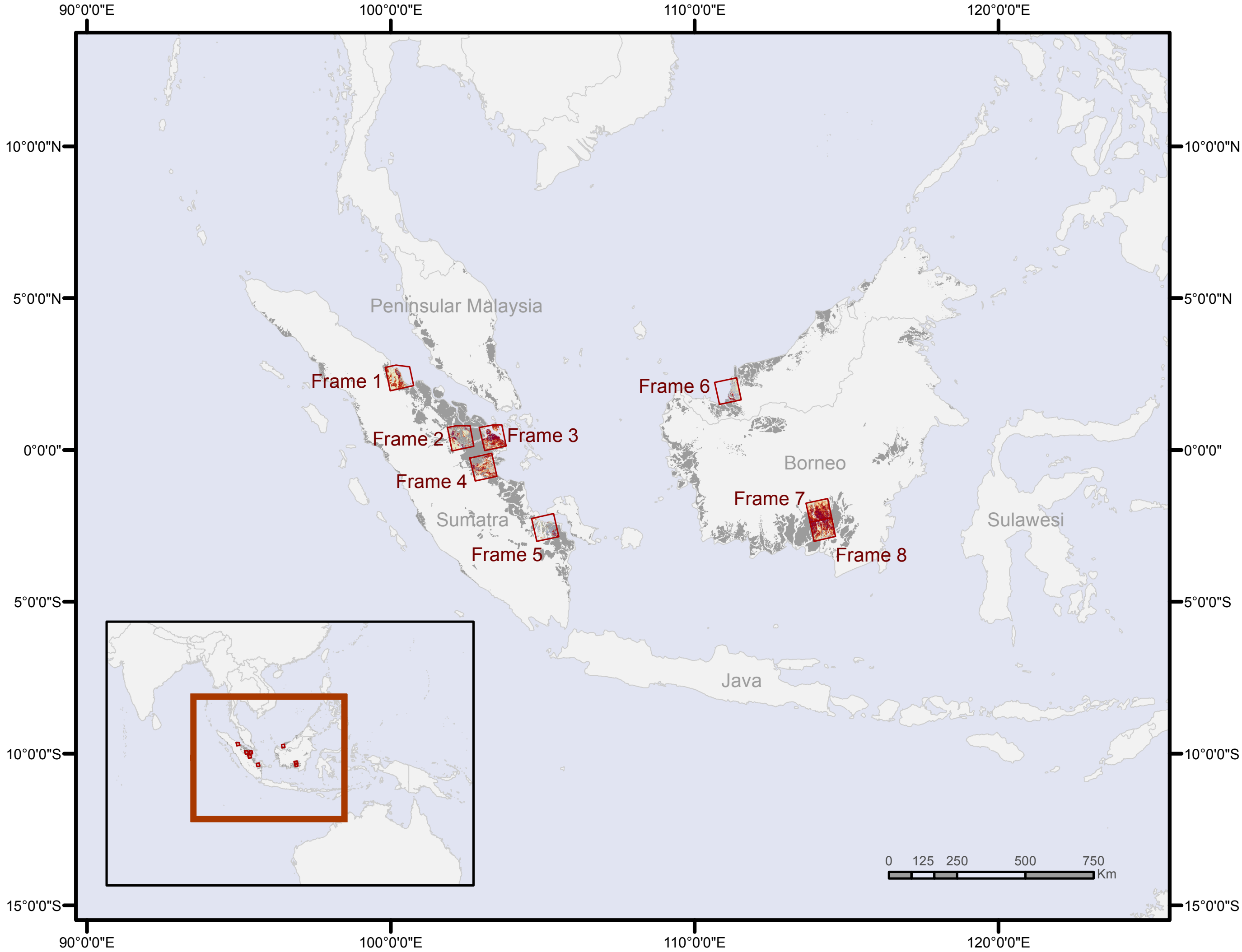


**Figure S1 | Regional Map**. Map showing locations of ALOS frames within insular Southeast Asia and the region as a whole (inset). Grey areas indicate peatland extent.

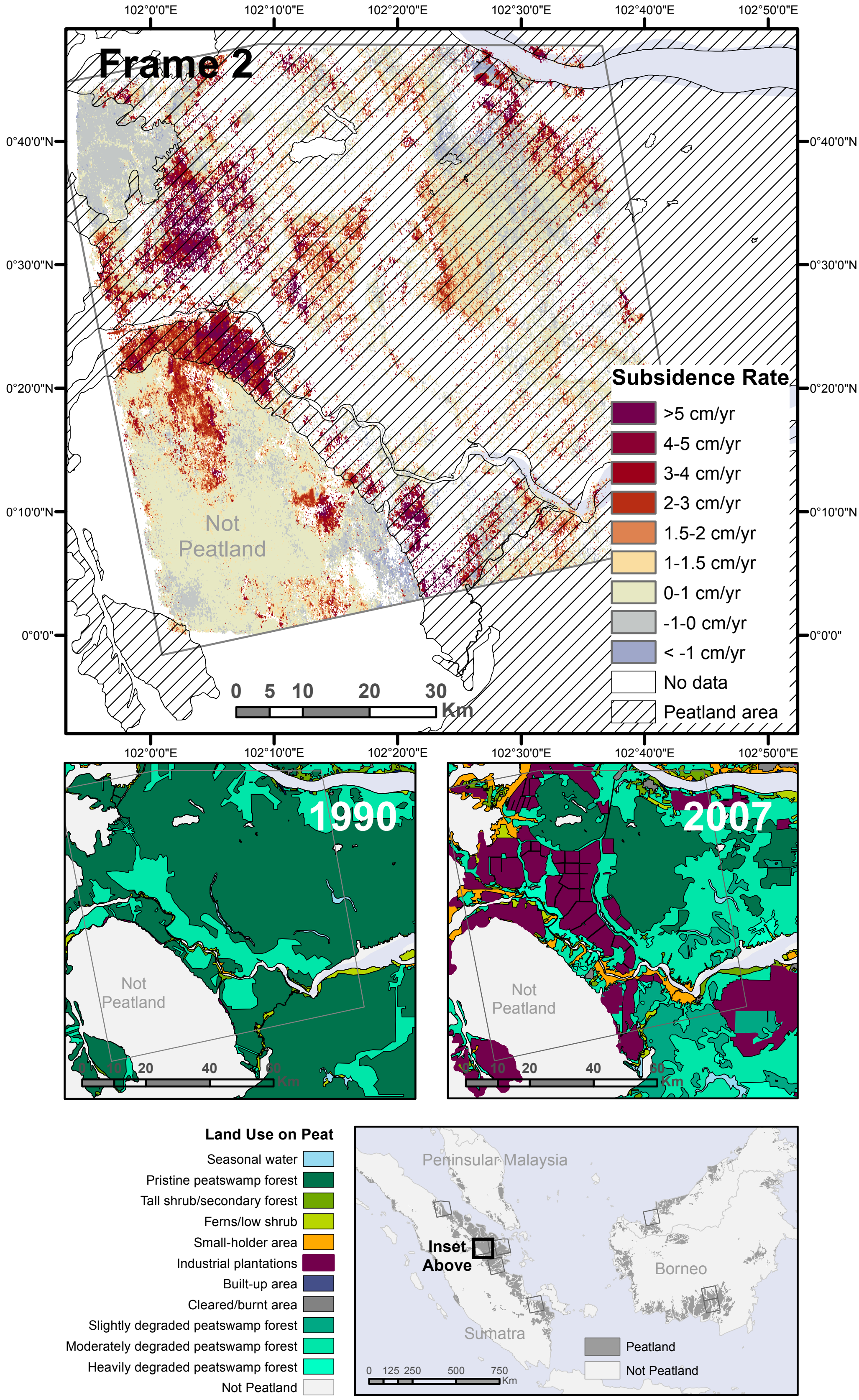


**Figure S2 | Frame 2 Subsidence and Land Use Map.** ALOS Frame 2 mean subsidence rates (top), 1990 land use (left) and 2007 land use (right). Positive values indicate subsidence and negative values indicate uplift.

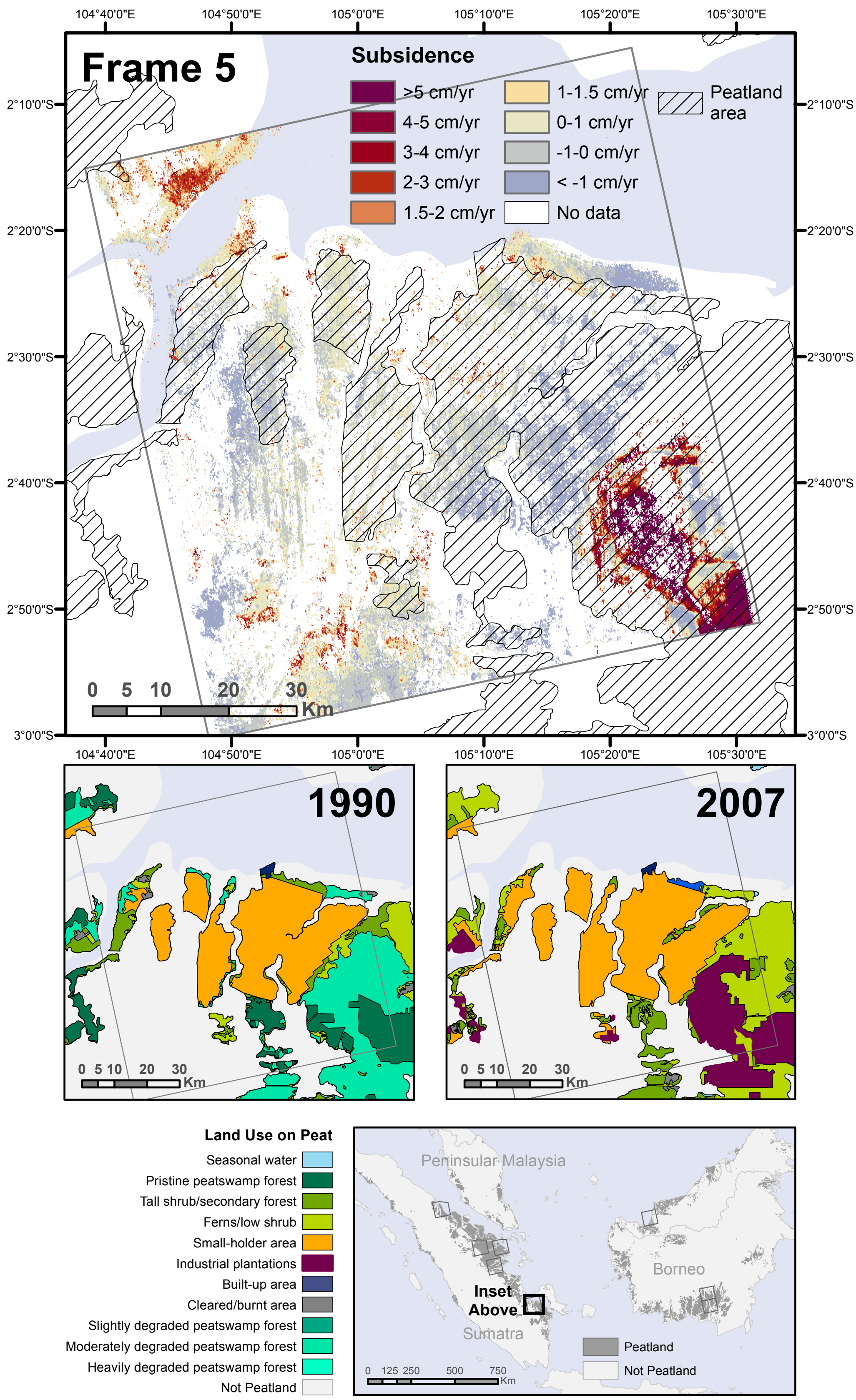


**Figure S3 | Frame 5 Subsidence and Land Use Map.** ALOS Frame 5 mean subsidence rates (top), 1990 land use (left) and 2007 land use (right). Positive values indicate subsidence and negative values indicate uplift.

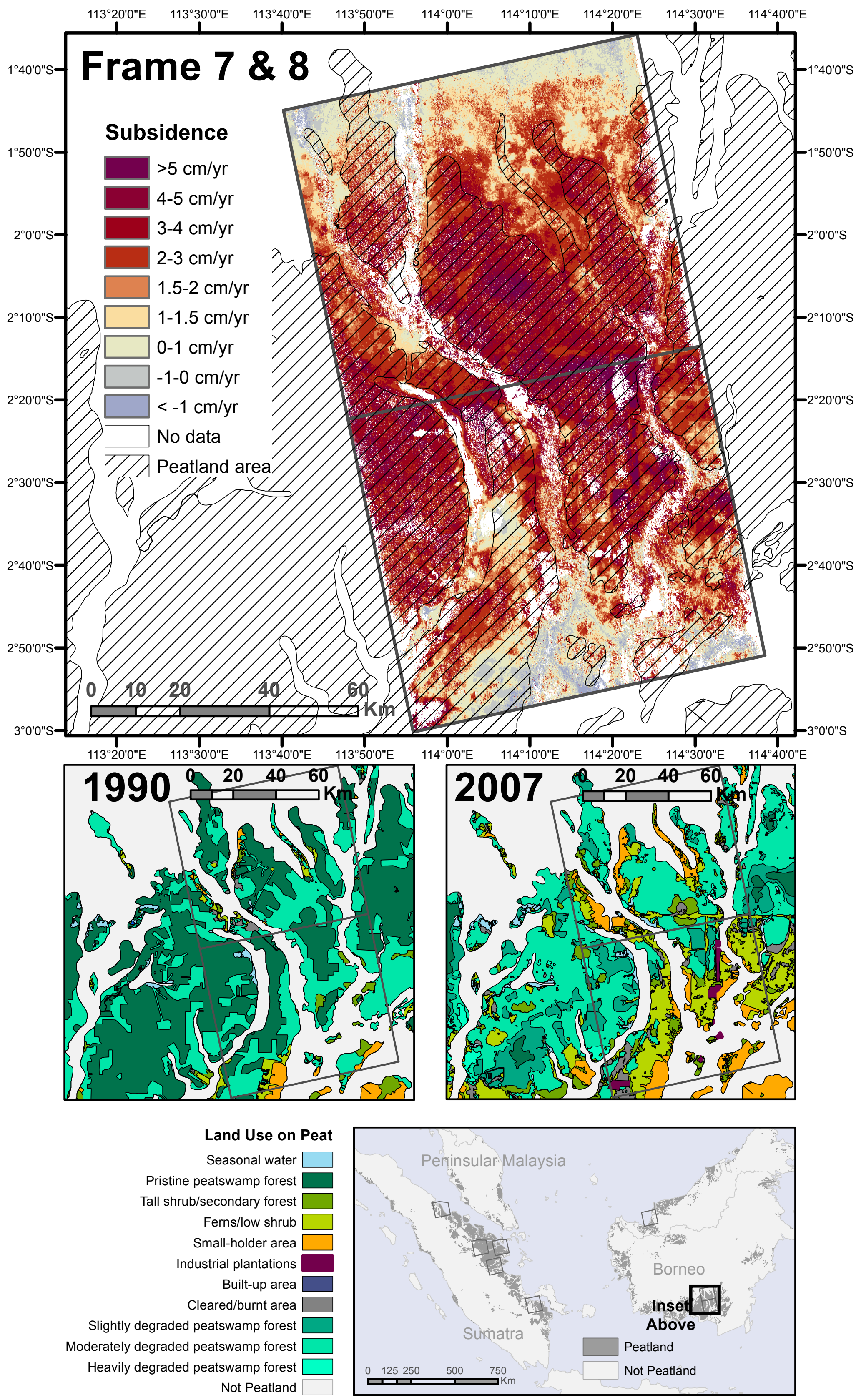


**Figure S4 | Frame 7 and 8 Subsidence and Land Use Map.** ALOS Frame 7 and 8 mean subsidence rates (top), 1990 land use (left) and 2007 land use (right). Positive values indicate subsidence and negative values indicate uplift.

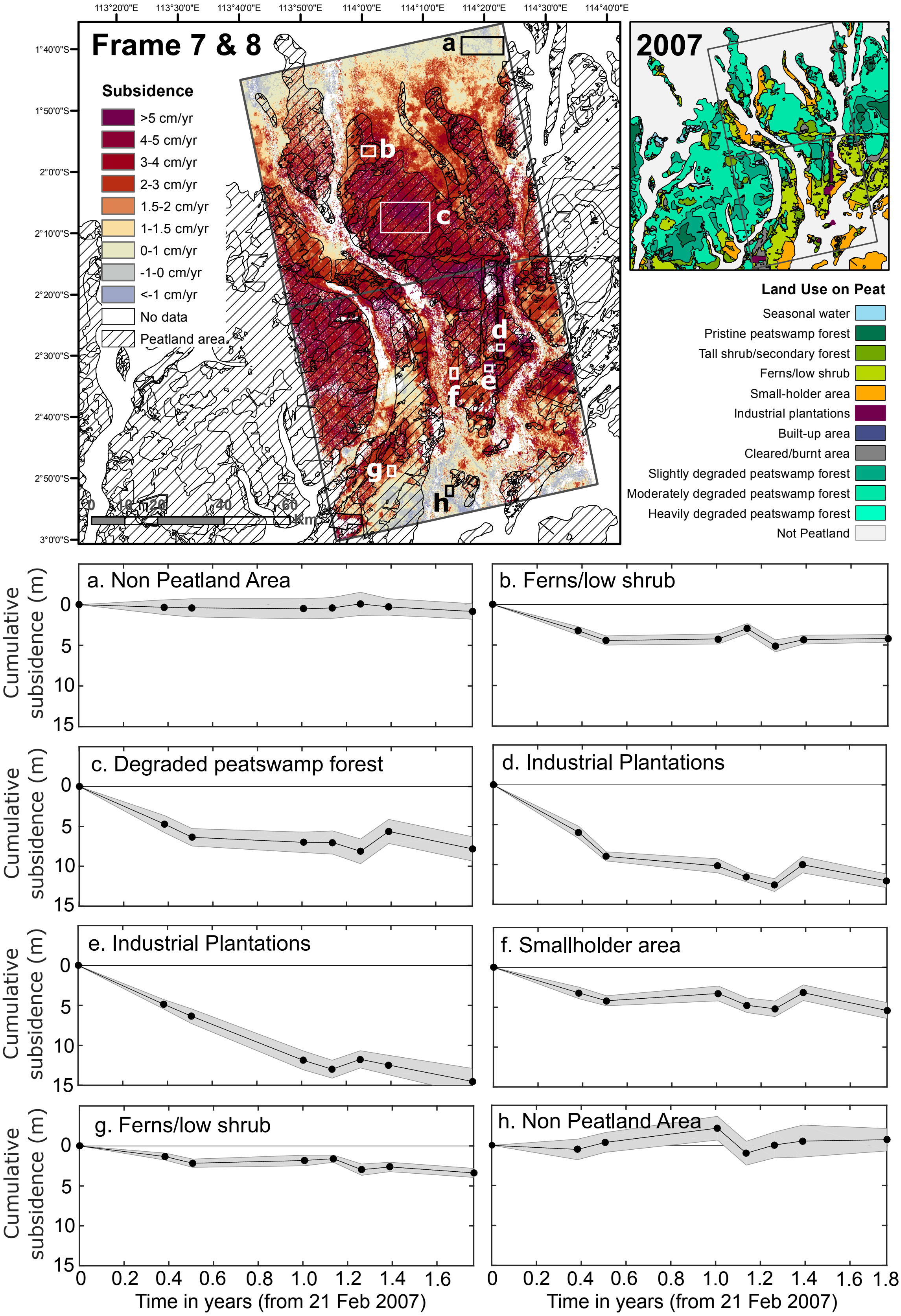


**Figure S5 | Subsidence Time Series from ALOS Frames 7 & 8.** (**a-h**) Time series of cumulative subsidence for different areas and land uses (average of pixels in inset areas; standard deviation in grey) show large spatial variability. Locations are indicated on the subsidence map (upper left; box sizes are approximate). Positive values indicate subsidence and negative values indicate uplift.

**Simple Average of All Measured InSAR Pixels: 2.24 cm/yr**

**Bootstrapped Regression Tree Mean Subsidence: 2.24 ± 0.23 cm/yr** (mean ± standard deviation of the mean)

Bootstrapped mean subsidence using regression tree approach (1000 iterations, 8 frames selected with replacement)

**Frame-Based Cross-Validation: 2.25 ± 0.11 cm/yr** (mean ± standard deviation of the mean)

Removed single frames and applied regression tree to remaining data

| Frame Removed | Predicted Mean Subsidence for Removed Frame | Actual Mean Subsidence for Removed Frame | Absolute Difference | Predicted Regional Subsidence |
|---|---|---|---|---|
| 1 | 2.38 | 1.91 | 0.47 | 2.30 |
| 2 | 2.78 | 1.49 | 1.30 | 2.46 |
| 3 | 2.27 | 2.64 | 0.37 | 2.19 |
| 4 | 1.43 | 1.84 | 0.41 | 2.23 |
| 5 | 2.15 | 0.62 | 1.53 | 2.29 |
| 6 | 2.35 | 1.63 | 0.72 | 2.26 |
| 7 | 2.43 | 3.04 | 0.61 | 2.13 |
| 8 | 2.46 | 2.75 | 0.29 | 2.13 |
| mean: | | | 0.71 | 2.25 ± 0.11 |

**Pixel-Based Cross-Validation: 2.240 ± 0.0007 cm/yr** (mean ± standard deviation of the mean)

Randomly grouped pixels. Removed each group of pixels and applied regression tree to remaining data

| Group of Pixels | Predicted Mean Subsidence for Removed Pixels | Actual Mean Subsidence for Removed Pixels | Absolute Difference | Predicted Regional Subsidence |
|---|---|---|---|---|
| 1 | 2.236 | 2.236 | 0.0006 | 2.240 |
| 2 | 2.235 | 2.236 | 0.0007 | 2.240 |
| 3 | 2.234 | 2.235 | 0.0016 | 2.240 |
| 4 | 2.236 | 2.232 | 0.0040 | 2.241 |
| 5 | 2.236 | 2.241 | 0.0046 | 2.239 |
| 6 | 2.235 | 2.241 | 0.0062 | 2.239 |
| 7 | 2.237 | 2.233 | 0.0034 | 2.241 |
| 8 | 2.237 | 2.230 | 0.0064 | 2.241 |
| mean: | | | 0.0034 | 2.240 ± 0.0007 |

**Table S1 | Cross-Validation and Bootstrapping Results.** Mean regional subsidence calculated using various methods. The mean regional subsidence and standard error of 2.24 ± 0.23 cm/yr used in regional upscaling were based on a frame-based bootstrapping approach to generate 1,000 synthetic datasets and corresponding regression trees (see Methods). Frame-based and pixel-based cross-validation methods compare the predicted mean subsidence generated with individual regression trees to that of the held-out data.

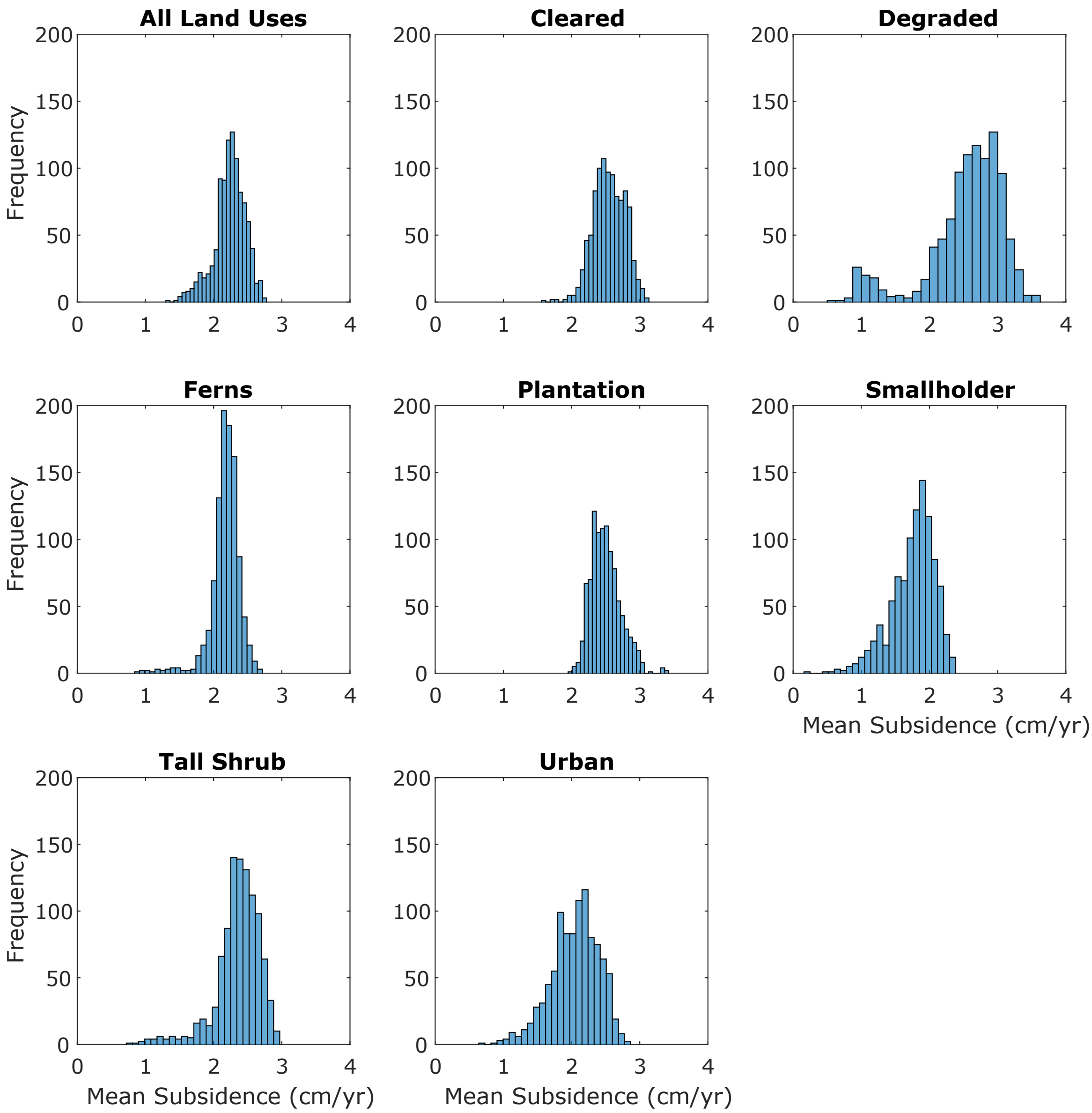


**Figure S6 | Bootstrapping mean subsidence**. Frame-based sampling with replacement used to generate 1,000 synthetic datasets. For each dataset, a regression tree was generated, and the corresponding gridded subsidence and mean subsidence values were calculated. The distribution of the mean across all land uses is shown in the first panel, and for each land use on peat in the other panels. Standard errors used for upscaling and regional emissions factors were calculated as the standard deviation of the distribution of the mean. Positive values indicate subsidence, negative values indicate uplift.

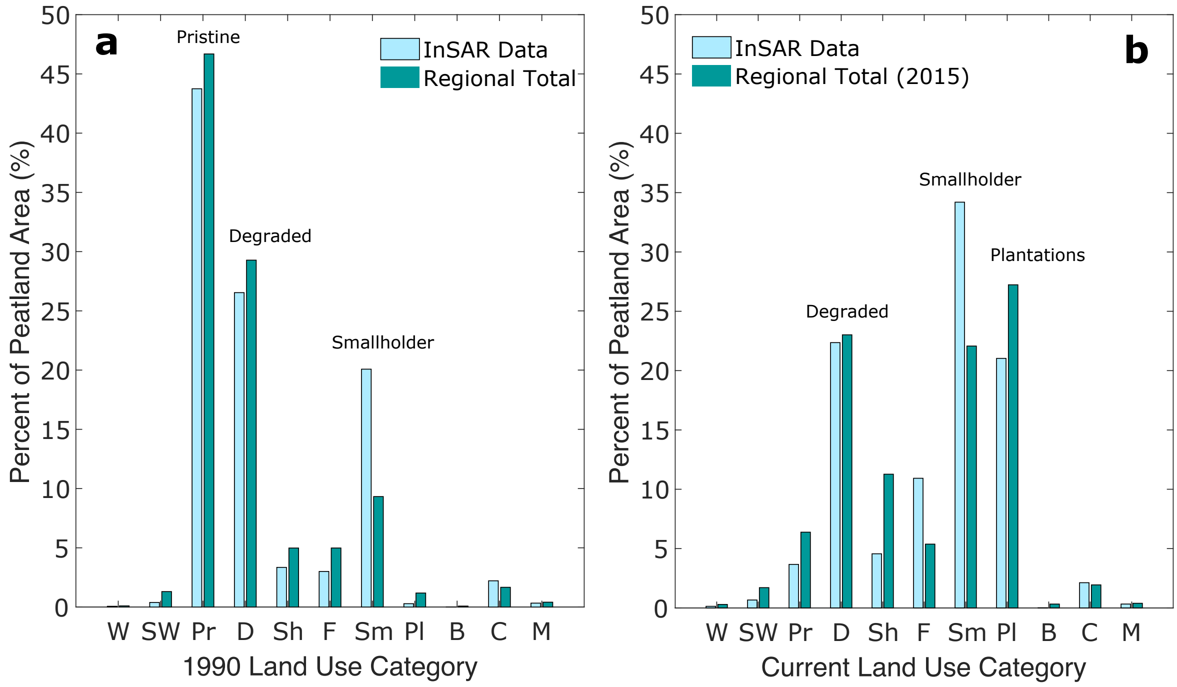


**Figure S7 | InSAR coverage of peatland area by land use classifications as a percentage of total peatland area vs. regional distribution for 1990 and current land use**. (**a**) Land use in 1990; (**b**) Present land use, defined as land use in 2007 for InSAR data, and land use in 2015 for regional upscaling. The area covered by the InSAR data is broadly similar to the region as a whole. The regression tree upscaling approach is used to account for differences in the distribution. Land use classifications on peat from left to right: W: water, SW: seasonal water, Pr: pristine peatswamp forest, D: degraded peatswamp forest, Sh: smallholder area, Pl: industrial plantations, B: built-up area, C: cleared/burnt area, M: mangrove.

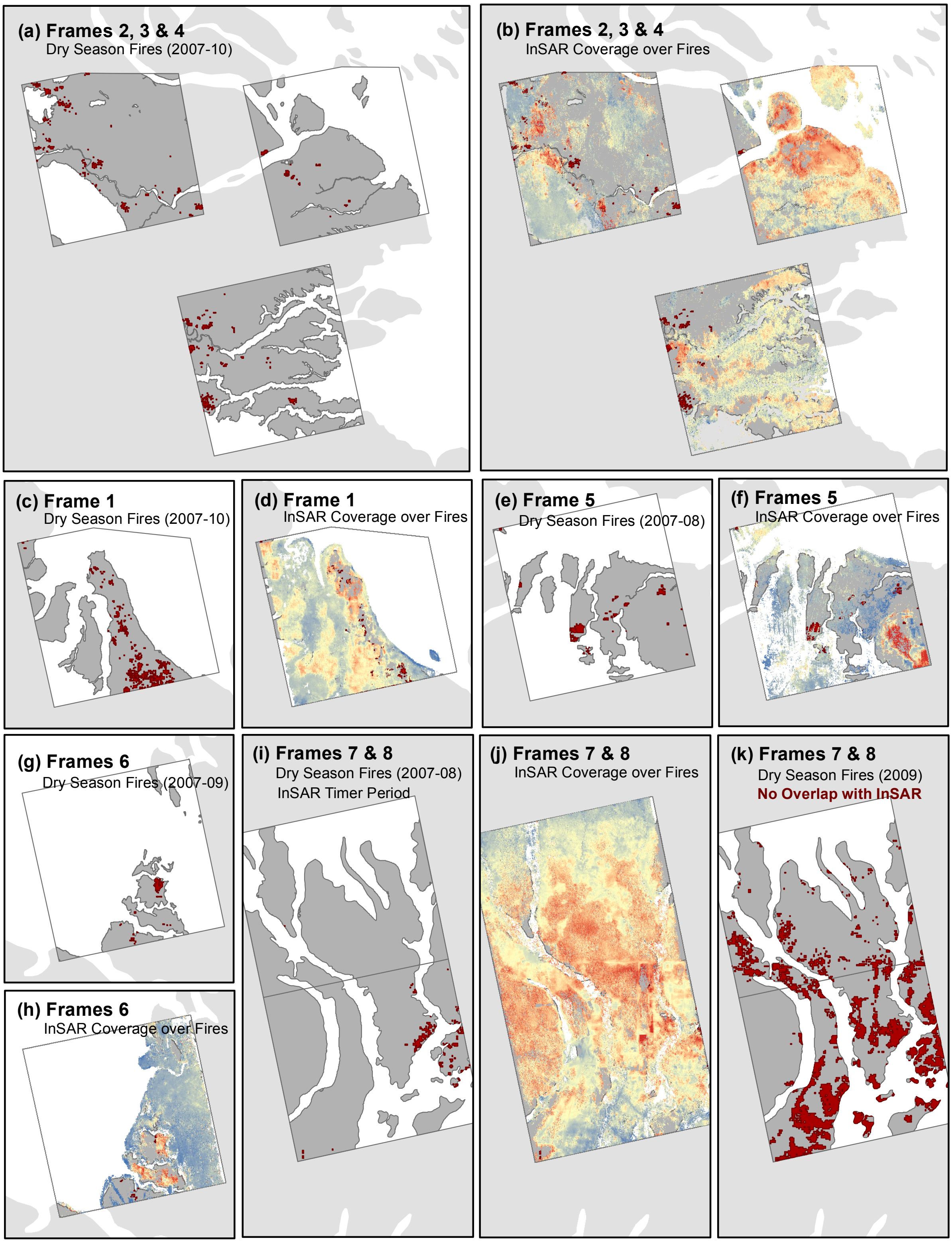


**Figure S8 | Distribution of Fire and InSAR Coverage.** **(a-j)** Left panels: Burned areas (red) on peatlands (dark grey) in each ALOS frame for the duration of the time series, aggregated from the Collection 6 MODIS Burned Area Products (MCD64monthly) for all dry seasons (June-October). Right panels: InSAR deformation, highlighting the areas with ground deformation data (areas maintaining coherence) for comparison with the fire extents. InSAR time series covered primarily very low fire years. (**k**) Fires in Central Kalimantan shown for comparison. This period does not overlap with the InSAR time series. Please note that within the frames, dark grey indicates peatland area, and white indicates non-peatland area. Outside the ALOS frames, light grey indicates land and white indicates water.

| ALOS Frame | 2007 Peatland Burned (%) | 2008 Peatland Burned (%) | 2009 Peatland Burned (%) | 2010 Peatland Burned (%) |
|---|---|---|---|---|
| 1 | 0.75 | 0.12 | **5.15** | 0.40 |
| 2 | 0.14 | 0.17 | 1.20 | 0.03 |
| 3 | 0.00 | 0.08 | 0.31 | 0.04 |
| 4 | 0.00 | 0.35 | 1.08 | 0.00 |
| 5 | 0.71 | 1.30 | **13.63** | 0.00 |
| 6 | 2.37 | 0.00 | 0.37 | 0.00 |
| 7 | 0.01 | 0.00 | **8.03** | 0.00 |
| 8 | 1.36 | 0.02 | **23.82** | 0.00 |

**Table S2 | Percentage of Peatland Area Burned.** Dry season (June-October) burned area as a fraction of peatland area in each ALOS frame calculated from the Collection 6 MODIS Burned Area Products (MCD64monthly). Red numbers indicate years in which > 5% of peatland area burned. Grey shading indicates years which are not covered by the InSAR time series, as individual frames have a different time series duration. Our InSAR measurements are dominated by very low fire years.

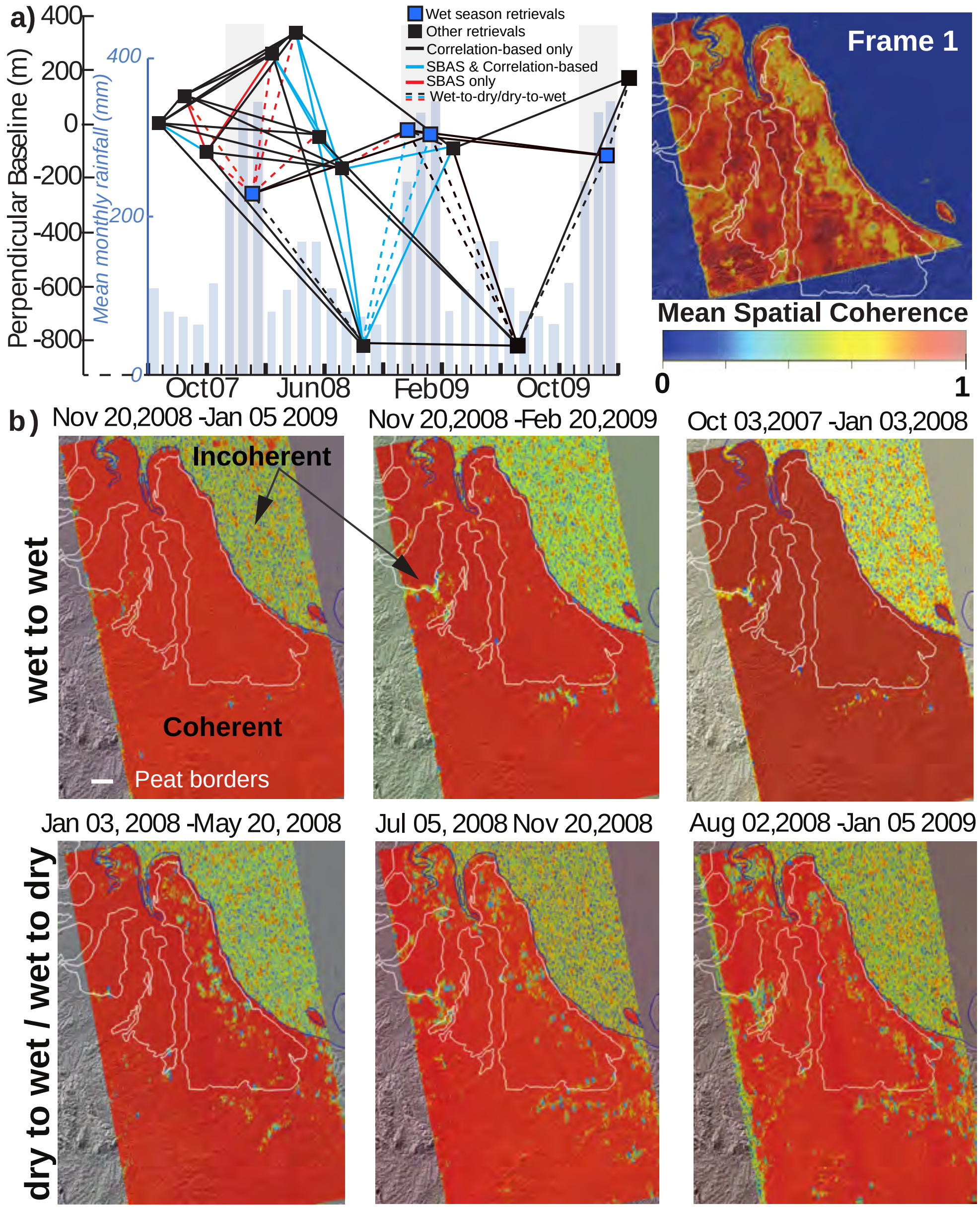


**Figure S9 | Decorrelation resulting from changes in soil moisture is most likely between wet-to-dry and dry-to-wet transitions**. (**a**) Perpendicular baselines versus temporal baselines plot for Frame 1. The shaded grey area highlights the wet season (November to January). Blue bars indicate monthly mean precipitation values from 2008 (repeated annually) as a seasonal reference. Each square represents a SAR acquisition. Dashed lines highlight interferograms from wet to dry seasons. The small baseline approach (SBAS; using temporal baselines of 180 days or less) relies on many such cross-season interferograms, while the correlation-based method relies on a limited number of cross-season interferograms. Red lines indicate interferograms used only in the SBAS method; blue lines indicate interferograms used in both the SBAS and correlation-based methods; black lines indicate interferograms used only in the correlation-based method. Right: mean spatial coherence map used for masking the mean velocity maps (areas with coherence <0.7 are masked), white contours highlight the peatland extent. There is no direct correlation between the mean spatial coherence and the peat extent. (**b**) Coherence of interferograms in wet-to-wet season (top row) and across seasons (wet-to-dry or dry-to-wet, bottom row). Lower coherence areas observed in cross-seasons interferograms (likely due to soil moisture changes) correspond to areas with lower average spatial coherence, which are masked in the final mean velocity maps.

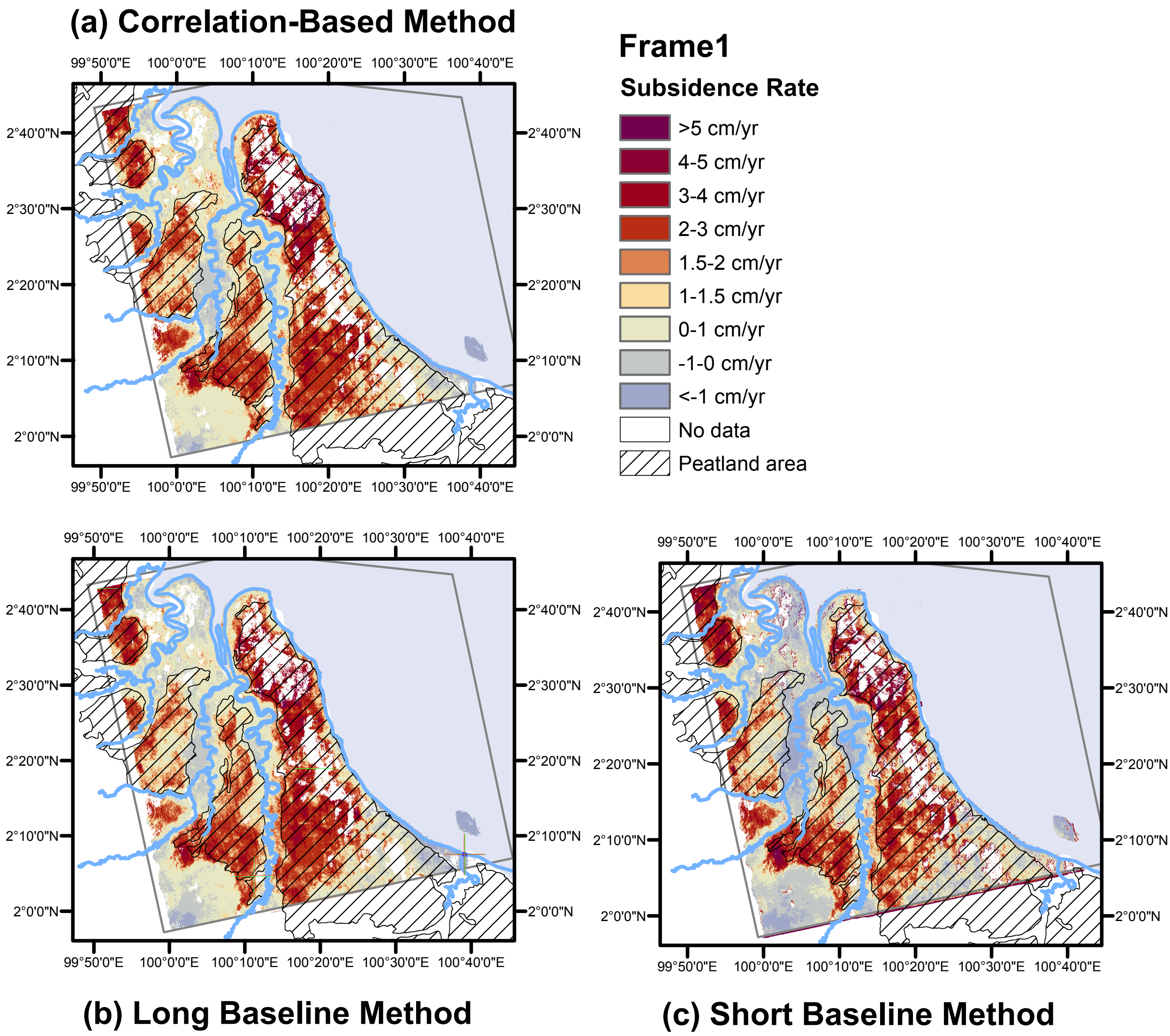


**Figure S10 | Comparison of correlation-based mean velocity maps with alternative short and long baseline methods (Frame 1).** (**a**) Mean velocity map derived using a correlation-based method. This method was used for all our analyses (map reproduced from Figure 1a). (**b**) Mean velocity map derived using a long baseline method, designed to eliminate soil moisture effects. The subsidence rates derived from this method are nearly identical to the correlation-based method we use. (**c**) Mean velocity map derived from SBAS short baseline method. The SBAS mean velocity map is more likely to be affected by soil moisture effects than the long baseline or correlation-based mean velocity maps. However, in most areas differences between this method and the correlation-based method are within the uncertainties. Areas with larger differences do not spatially correlate with peatland areas, suggesting weak soil moisture changes.

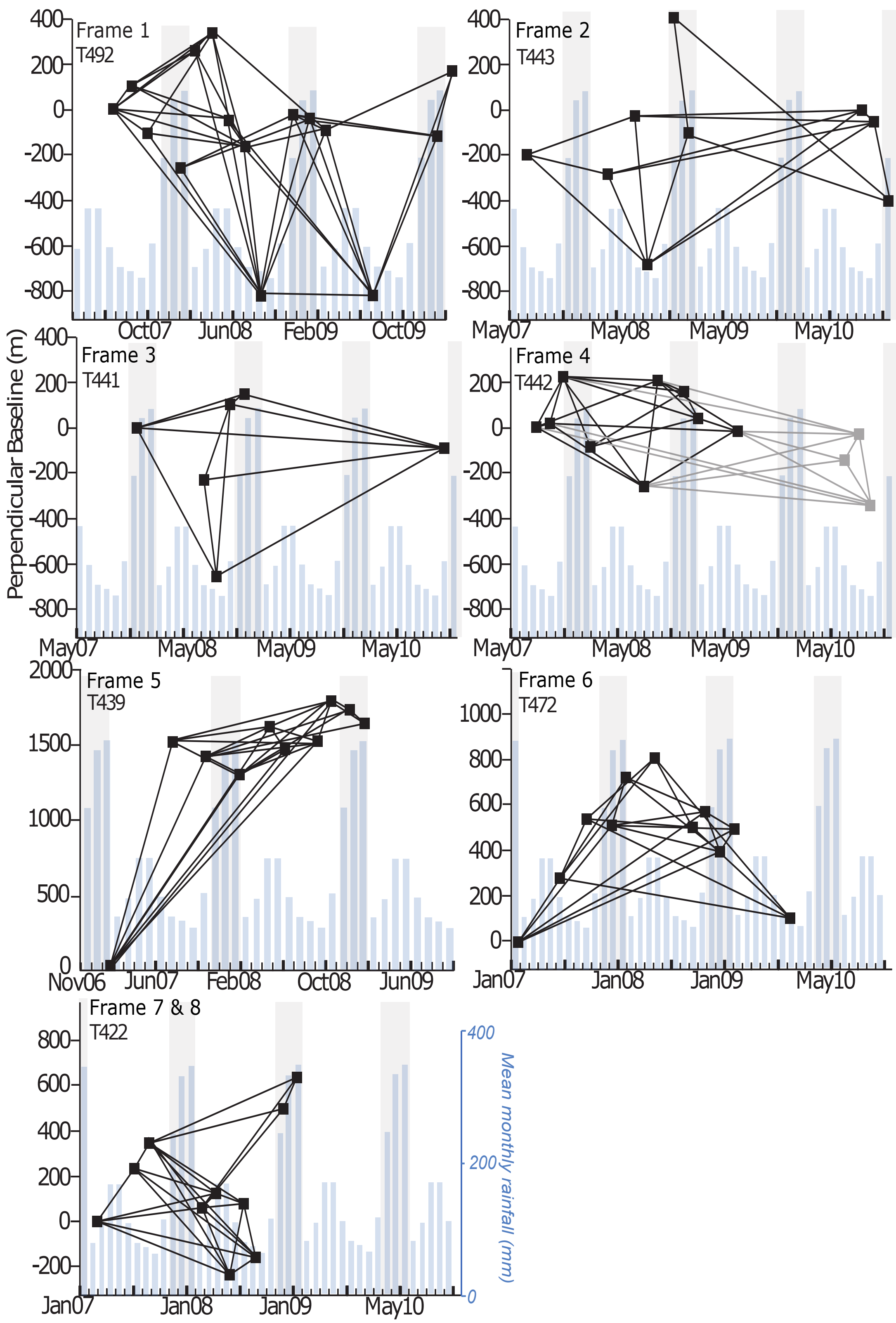


**Figure S11 | Perpendicular baselines versus temporal baselines**. Perpendicular and temporal baselines for the 8 ALOS frames (correlation-based method). The shaded grey area highlights the wet season. Blue bars indicate monthly mean precipitation values from 2008 (repeated annually) as a seasonal reference (axis on the bottom panel). The grey SAR acquisitions and interferograms for Frame 4 (T442) indicate data that were removed from our correlation-based approach due to the long time gap (see table ED1).

| Land Use in 2007 | Frame | Mean | SD | Pixels |
|---|---|---|---|---|
| Not Peat | 1 | -0.79 | 0.54 | 1667 |
| Not Peat | 2 | 0.67 | 0.48 | 10199 |
| Not Peat | 3 | 0.61 | 1.15 | 3110 |
| Not Peat | 4 | 0.86 | 1.28 | 429 |
| Not Peat | 5 | 0.01 | 1.07 | 7529 |
| Not Peat | 6 | -0.04 | 1.22 | 13207 |
| Not Peat | 7 | 0.31 | 0.63 | 1933 |
| Pristine Peatswamp Forest | 2 | 0.76 | 1.06 | 72302 |
| Tall Shrub/ Secondary Forest | 1 | 2.20 | 1.20 | 2676 |
| Tall Shrub/ Secondary Forest | 2 | 1.40 | 1.73 | 4497 |
| Tall Shrub/ Secondary Forest | 3 | 1.45 | 1.49 | 4615 |
| Tall Shrub/ Secondary Forest | 4 | 2.26 | 1.33 | 461 |
| Tall Shrub/ Secondary Forest | 5 | -0.86 | 1.47 | 2320 |
| Tall Shrub/ Secondary Forest | 6 | 2.20 | 2.85 | 5053 |
| Tall Shrub/ Secondary Forest | 7 | 3.12 | 1.14 | 38437 |
| Tall Shrub/ Secondary Forest | 8 | 2.70 | 1.48 | 31872 |
| Ferns/ Low Shrub | 1 | 2.48 | 1.12 | 17145 |
| Ferns/ Low Shrub | 2 | 2.42 | 2.09 | 5993 |
| Ferns/ Low Shrub | 3 | 1.96 | 1.51 | 6285 |
| Ferns/ Low Shrub | 4 | 2.51 | 1.07 | 1670 |
| Ferns/ Low Shrub | 5 | 0.54 | 2.35 | 14006 |
| Ferns/ Low Shrub | 6 | 2.76 | 2.23 | 2402 |
| Ferns/ Low Shrub | 7 | 2.80 | 0.88 | 38600 |
| Ferns/ Low Shrub | 8 | 2.17 | 1.29 | 129290 |
| Smallholder Area | 1 | 1.53 | 1.07 | 79443 |
| Smallholder Area | 2 | 1.25 | 1.45 | 18601 |
| Smallholder Area | 3 | 2.70 | 1.62 | 143484 |
| Smallholder Area | 4 | 1.84 | 1.23 | 267019 |
| Smallholder Area | 5 | -0.58 | 1.17 | 72419 |
| Smallholder Area | 6 | 0.57 | 2.03 | 4839 |
| Smallholder Area | 7 | 2.14 | 0.69 | 41922 |
| Smallholder Area | 8 | 1.71 | 1.53 | 46430 |
| Built-up area | 1 | 1.06 | 0.21 | 143 |
| Built-up area | 7 | 0.74 | 0.22 | 25 |
| Cleared/ Burnt Area | 1 | 3.22 | 0.91 | 6036 |
| Cleared/ Burnt Area | 2 | 1.46 | 2.30 | 3220 |
| Cleared/ Burnt Area | 3 | 2.79 | 1.93 | 1958 |
| Cleared/ Burnt Area | 4 | 3.79 | 1.62 | 737 |
| Cleared/ Burnt Area | 5 | 2.09 | 1.50 | 612 |
| Cleared/ Burnt Area | 6 | 3.73 | 2.31 | 297 |
| Cleared/ Burnt Area | 7 | 3.08 | 1.01 | 7750 |
| Cleared/ Burnt Area | 8 | 2.76 | 1.44 | 21273 |
| Degraded Peatswamp Forest | 1 | 2.18 | 1.40 | 6700 |
| Degraded Peatswamp Forest | 2 | 1.09 | 1.54 | 72968 |
| Degraded Peatswamp Forest | 3 | 2.30 | 1.75 | 8830 |
| Degraded Peatswamp Forest | 4 | 0.74 | 1.62 | 13197 |
| Degraded Peatswamp Forest | 6 | 0.34 | 2.59 | 13618 |
| Degraded Peatswamp Forest | 7 | 3.26 | 1.27 | 192665 |
| Degraded Peatswamp Forest | 8 | 3.62 | 1.18 | 132820 |
| Industrial Plantations | 1 | 2.00 | 0.92 | 125839 |
| Industrial Plantations | 2 | 2.84 | 2.05 | 59579 |
| Industrial Plantations | 3 | 2.66 | 1.44 | 170062 |
| Industrial Plantations | 4 | 3.05 | 1.48 | 11076 |
| Industrial Plantations | 5 | 3.87 | 3.09 | 27899 |
| Industrial Plantations | 6 | 3.08 | 1.93 | 11521 |
| Industrial Plantations | 8 | 3.74 | 1.56 | 8635 |

**Table S3 | Subsidence by Land Use and ALOS Frame**. Mean subsidence rate, standard deviation, and number of InSAR pixels for each 2007 land use category, within each ALOS frame (see Figure ED2). Non-peatland areas include pixels >15km from the edge of the peat to exclude transition zones between peatland and mineral soils.