

Supplemental Material for:

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“Public health impacts of the severe haze in Equatorial Asia in September-October 2015: Demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure”

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12 **1. The GEOS-Chem adjoint**

13 We use version 8-02-01 of the GEOS-Chem chemical transport model and its adjoint
14 (Henze *et al* 2007, Kopacz *et al* 2011, Kim *et al* 2015) to quantify the source-receptor
15 relationships relevant for smoke exposure in Equatorial Asia during large haze events. GEOS-
16 Chem is driven by Goddard Earth Observing System (GEOS-5) assimilated meteorological data
17 from the NASA Modeling and Assimilation Office (GMAO) at $0.5^\circ \times 0.67^\circ$ native horizontal
18 resolution with 72 vertical levels. Following Kim *et al* (2015), we use the GEOS-Chem adjoint
19 (v34) to calculate the potential influence of smoke emissions in each $0.5^\circ \times 0.67^\circ$ grid cell for the
20 whole Equatorial Asia model domain [70° - 150° E, 11° S- 55° N] on population-weighted $PM_{2.5}$
21 concentrations in three receptor regions (Indonesia – 250 million people in 2015, Malaysia – 30
22 million people, and Singapore – 4 million people) for each month during July-October based on
23 meteorology for 2006. Population weighting of the mean receptor concentrations was carried out
24 by first weighting the smoke concentration of each grid cell by its fractional population within
25 the receptor area, then taking the average concentration across those grid cells. The resulting
26 sensitivities – i.e., the fractional contribution of each grid cell to smoke exposure at each receptor
27 downwind – are applied to the fire emission inventory, yielding a gridded estimate of the
28 monthly mean smoke-related $PM_{2.5}$ exposure that results from those emissions. We scale the
29 resulting OC-related $PM_{2.5}$ by a factor of 2.1 to account for additional organic matter acquired
30 through atmospheric processing (Turpin and Lim 2001). The fractional contributions to exposure
31 from each grid cell are then summed together to estimate the total population-weighted exposure
32 at each receptor. For this study, we apply the 2006 sensitivities to both the 2006 and 2015
33 emissions. This approach assumes that the smoke transport patterns for these two haze events are
34 similar, which is likely given that they both occurred during similar phases of the ENSO and the
35 IOD, the two major drivers of interannual meteorological variability in Equatorial Asia (Li *et al*
36 2003). Calculation of new adjoint sensitivities would require processing of 2015 GMAO
37 meteorological fields and considerable computational expense, while our streamlined approach
38 allows for near real-time assessment of smoke exposure and attribution to emission sources.

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43 2. Health impact calculations

44 We estimate health impacts from smoke pollution using an approach similar to that in
45 Anenberg *et al* (2012) and two studies quantifying the Global Burden of Disease (Lim *et al*
46 2012, Burnett *et al* 2014). We derive a concentration response relationship (CRF) between
47 relative mortality and PM_{2.5} from the epidemiological literature, modeling health impacts as a
48 1% increase in annual baseline all-cause mortality per 1 µg m⁻³ increase in annual average PM_{2.5}
49 levels when annual average PM_{2.5} concentrations are less than 50 µg m⁻³ (Schwartz *et al* 2008,
50 Anenberg *et al* 2012 and references therein, Lepeule *et al* 2012). Using annual average PM_{2.5}
51 exposure increases the likelihood of capturing the effects of both acute and chronic pollution
52 exposure. In our calculations there were no locations where annual average concentrations
53 exceeded this 50 µg m⁻³ threshold, likely because our estimates reflect population-weighted
54 exposures rather than actual smoke concentrations. Using gridded population data from the
55 Center for International Earth Science Information Network (CIESIN; Columbia University
56 2005) and country-level data on baseline mortality rates and population age structure from the
57 Global Burden of Disease for 2013 (the most recently available year; Lim *et al* 2012, Institute for
58 Health Metrics and Evaluation 2015), we estimate the excess deaths attributable to smoke PM_{2.5}
59 as follows. We first calculate a July-October population-weighted average PM_{2.5} exposure for
60 each receptor country during both 2006 and 2015 (Section S1 above). We next convert these
61 July-October average population-weighted smoke PM_{2.5} exposures to annual average values. We
62 then calculate the total population in each receptor country using the CIESIN population
63 distributions, and apply the baseline mortality rate and age structure information for each country
64 to calculate population over 25 years of age. Finally, we calculate the total mortality attributed to
65 PM_{2.5} from fires in each receptor country *i* using:

66

$$\begin{aligned} \text{Attributable Mortality}[i] &= \text{Baseline Mortality}[i] \times \text{Population}[i] \times \beta \times \text{Population} \\ &\quad - \text{weighted} \Delta \text{PM}_{2.5}[i] \end{aligned}$$

67

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69 where β is the CRF from epidemiological studies, corresponding to the slope of the relationship
70 (1%) between pollutant concentration and mortality, and $\Delta \text{PM}_{2.5}$ is the estimated change in PM_{2.5}

71 from smoke pollution.

72 Previous estimates of excess deaths from smoke PM_{2.5} pollution for the 1997 event range
73 widely – e.g., 296,000 in Johnston *et al* 2012 and 13,200 in Marlier *et al* 2013. Our estimate of
74 ~100 thousand in 2015 falls between these two extremes. Johnston *et al* (2012) included health
75 impacts on the whole population, including children, and considered all causes of premature
76 mortality, capping exposure above 50 µg m⁻³ in each model grid cell. In contrast, Marlier *et al*
77 (2013) restricted their analysis to cardiovascular mortality in adults and used a different CRF
78 form. In sensitivity analyses Marlier *et al* (2013) found that applying differently shaped CRFs to
79 the same smoke concentrations yielded mortality increases up to four times higher than their
80 reported estimate. Due to the lack of consistent emissions datasets, we cannot directly compare
81 our estimate of excess mortality for 2015 to those reported for 1997. Nonetheless the fine spatial
82 resolution of our approach likely better captures smoke exposure to peak pollution
83 concentrations in populated areas. We also use more recent information about baseline mortality
84 rates and population age structure.

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87 **3. High resolution FRP observations in concessions**

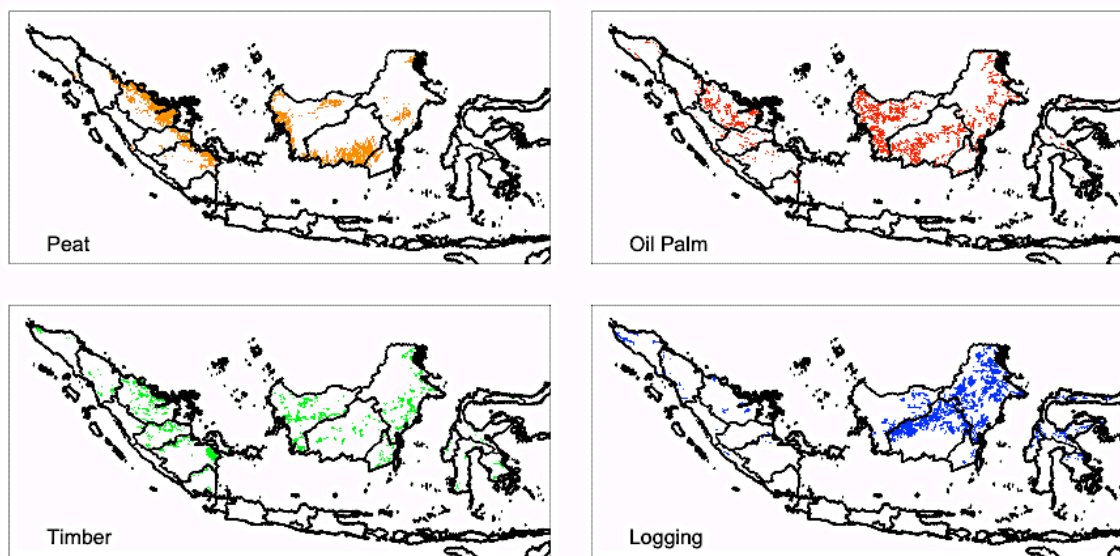
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89 **Table S1.** Average percent contributions of fire radiative power (FRP) on concessions and
 90 peatlands to total FRP observed by MODIS on the Aqua and Terra satellites during July-October
 91 in 2006 and 2015 over Sumatra and Kalimantan. The term “mixed” indicates regions in which
 92 boundaries of oil palm, timber, and/or logging concessions overlap. Estimates of percent
 93 contributions for peat take into account peatland areas both within and outside of concessions.
 94 All values are calculated using FRP Collection 6, and so differ slightly from those reported by
 95 Marlier *et al* (2015), who relied on Collection 5.

96

	Year	Timber %	Oil Palm %	Logging %	Mixed %	Peat %	Total FRP (MW)
Sumatra	2006	26.55	11.33	2.01	0.51	44.47	4.57E+06
	2015	55.07	4.72	1.32	0.44	71.76	6.46E+06
Kalimantan	2006	7.81	32.01	6.57	5.66	32.39	6.59E+06
	2015	9.62	20.06	8.97	3.99	42.85	5.67E+06

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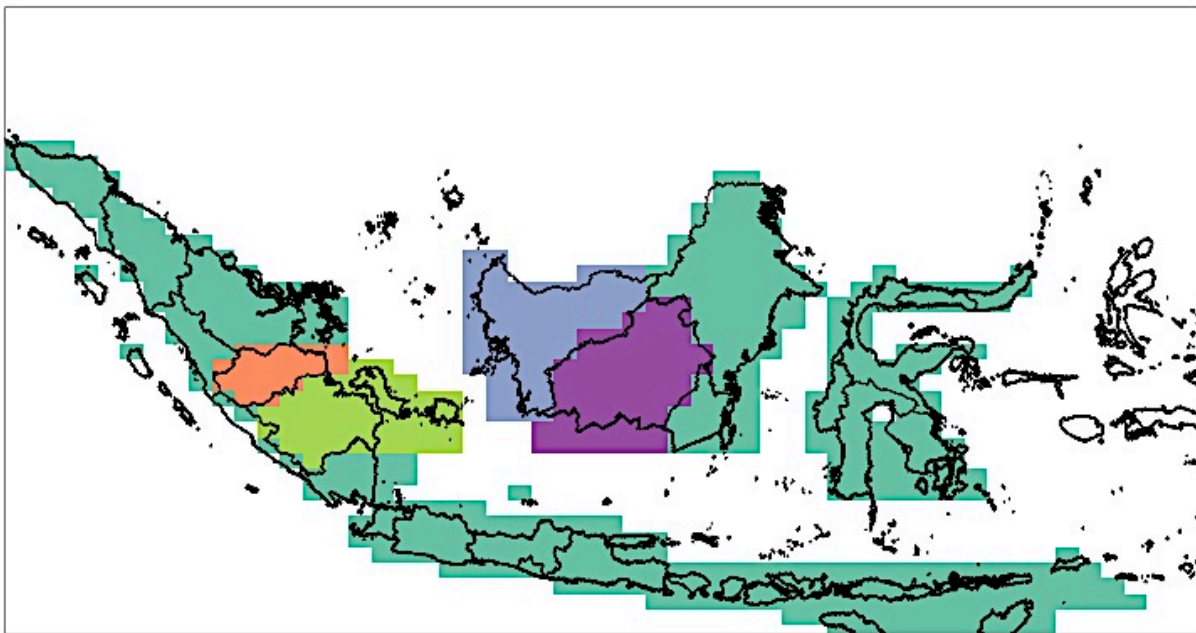
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100 **Figure S1.** Distribution of peatlands and current or planned concession types in Indonesia as of
 101 2010. The top left panel shows the peatland distribution in orange (Wahyunto and Subagjo,
 102 2003,2004). The other three panels show land use distributions from the Global Forest Watch
 103 (World Resources Institute, 2015a,b,c); estimates are based on data provided by the Indonesian

104 Ministry of Forestry. Oil palm concessions are shown in the top right in red, timber in the bottom
105 left in green, and logging in bottom right in blue. Spatial resolution in all panels is 5 x 5 km².

106 **4. Province masks**

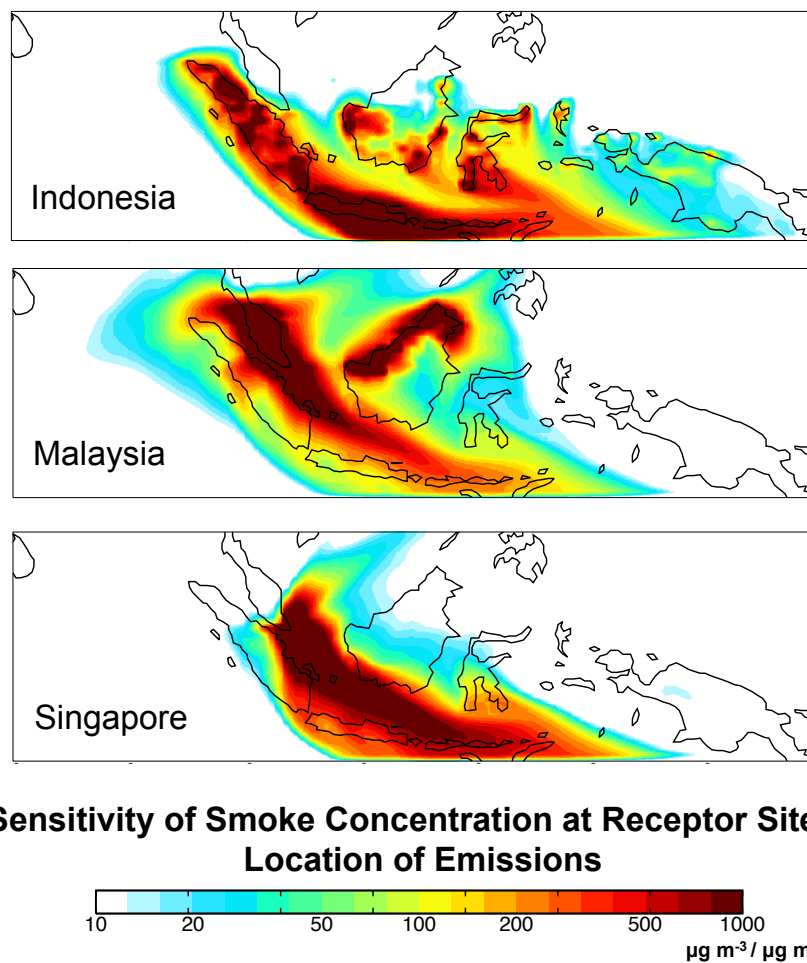
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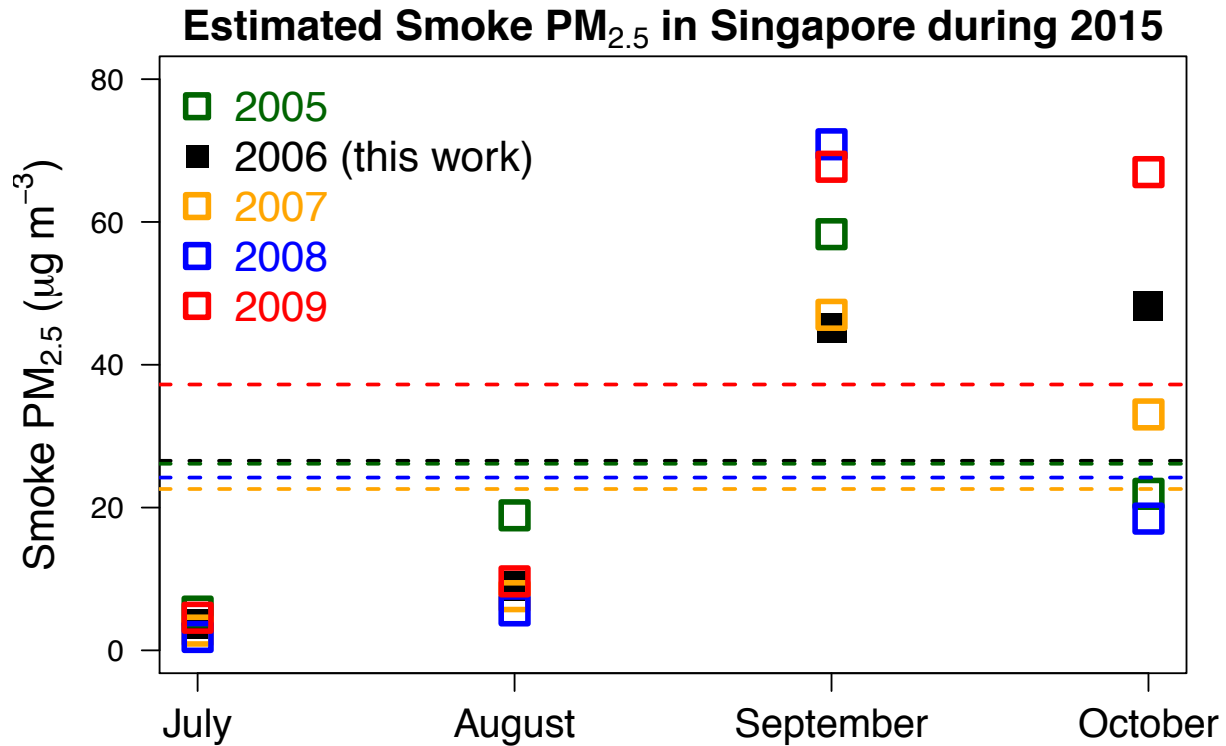
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109 **Figure S2.** Province masks at $0.5 \times 0.67^\circ$ resolution used in this analysis. Jambi is shown in
110 coral, West Kalimantan in blue, and Central Kalimantan in purple. South Sumatra and Bangka-
111 Belitung are combined and shown in green. Other provinces are shown in teal.

112 5. Adjoint sensitivities
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116 **Figure S3.** GEOS-Chem adjoint sensitivities simulated for September-October 2006 of
117 population-weighted $\text{PM}_{2.5}$ in each receptor region to smoke emissions in gridboxes across the
118 domain. The top panel shows the sensitivities for Indonesia; the middle panel, Malaysia; and the
119 bottom panel, Singapore. These sensitivities are for hydrophobic organic carbon (OC)
120 specifically, but spatial patterns are similar for hydrophilic OC as well as for BC.
121



122
 123 **Figure S4.** Monthly mean smoke exposure at Singapore estimated using 2015 GFAS emissions
 124 scaled by 50% and a suite of adjoint sensitivities for 2005-2009. The exposures used in this
 125 work, estimated with the 2006 sensitivities, are shown in black filled squares. Estimates
 126 produced using sensitivities from 2005 are shown in green, 2007 in orange, 2008 in blue, and
 127 2009 in red. Dashed lines show corresponding July-October averages for each year. The plot
 128 shows the impact that application of different meteorological fields has on estimates of smoke
 129 exposure in Singapore. Of the five years, only 2006 is characterized by the simultaneous El Niño
 130 and positive Indian Ocean Dipole conditions similar to those in 2015.

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133 **6. Fire management strategies in Indonesia**

134 The rapid assessment framework demonstrated in this work would allow policy makers in
135 Indonesia to quickly identify the burning areas that are leading to the most severe air pollution in
136 populated areas downwind during extreme haze events. This information can then be used to
137 prioritize fire management efforts including land use management strategies to help mitigate the
138 domestic and transboundary smoke pollution resulting from these fires. However, implementing
139 effective fire management strategies on the ground in Indonesia is challenging. We summarize
140 here some of the difficulties currently facing effective fire management practices in Indonesia,
141 and, when relevant, how our adjoint approach may be implemented to help address some of these
142 issues.

143

144 *Regulating fires in smallholder farms vs. industrial plantations*

145 One major hurdle to effectively regulating fire activity in Indonesia is the heterogeneity
146 of the human activity landscape. For example, it is common for local communities and small
147 farmlands to be located immediately alongside, or even within, large scale industrial concessions
148 such as those for oil palm or timber, making the attribution of fire ignitions difficult (Cattau et al
149 2016, Gaveau et al 2016). Conflicting land tenure claims can even be a source of fire ignitions to
150 reclaim land, independent of any agricultural benefit (Dennis et al 2005). Additionally, while
151 the use of fire as a land management tool can perhaps be replaced by other alternative
152 approaches to slash-and-burn techniques on the large plantations, fire is often the only affordable
153 mechanism of land maintenance for small scale farmers (Tomich et al 1998, Palm et al 2004).
154 Certain land management practices outside of the burning season have been shown to help
155 reduce smoke emissions and the likelihood of escaped fires from small farms (Sahrajo and
156 Munoz 2005, Sahrajo 2011), but would require widespread efforts to incentivize the use of these
157 practices amongst local communities in order to matter for regional haze. Using the GEOS-Chem
158 adjoint to identify the burning areas contributing most severely to downwind pollution during
159 extreme haze events would help identify priority areas where developing economically feasible
160 alternative land clearing practices in small scale farms and settlements would most benefit local
161 and regional human health.

162

163 *Extinguishing fires in peatlands*

164 Another challenge to firefighting efforts in Indonesia is the difficulty involved with
165 actually extinguishing fires in peat, even with adequate resources. Because peat fires tend to burn
166 at low temperatures, they can smolder for many days to weeks or even months, undetected
167 within the subsurface peat layers (Turetsky et al 2015 and references therein). Due to this
168 smoldering tendency and to the variability in peat layer depth, which can range from inches to
169 tens of meters in some places, it is difficult for firefighters to know if the peat fires have been
170 completely extinguished. Subsurface peat fires can even migrate through the subsurface away
171 from their ignition source, reigniting weeks later in a completely different location (Rein 2009).
172 Identifying the areas contributing most to smoke downwind in near real time could help fire
173 management officials decide quickly where best to allocate their front line fire-fighting efforts
174 (e.g., trained personnel or helicopters for emergency water application) to better ensure that peat
175 fires in these areas have been fully extinguished. It would also guide the development of new
176 approaches for extinguishing peat fires when these traditional methods are ineffective (Byron
177 and Shepard 1998).

178 A better approach to reducing fires in peatlands would be to counteract the effects of
179 human degradation through peatland restoration (Jaenicke et al 2010). Peatland areas are
180 naturally resistant to fire due to their characteristically high moisture content (Turetsky et al 2015
181 and references therein). Though human activity has degraded much of the peatlands in Indonesia,
182 making these lands more fire-prone, efforts to restore peatlands to their natural fire-resistant state
183 are ongoing (Indriatmoko et al 2014). However, these restoration efforts face many of the
184 challenges common amongst conservation groups, such as a lack of funding and resources, and
185 limited participation from the public. Conservation efforts also rarely provide an obvious
186 economic benefit to the local communities, limiting their incentive to participate (Nicolas and
187 Beebe 1999, Chokkalingam et al 2007). Identifying the areas most important for regional haze
188 events would allow for more targeted efforts to restore degraded peatland and develop
189 sustainable partnerships with local communities in these high priority burning areas.

190

191 *Enforcing existing policies*

192 Lastly, effectively enforcing existing regulations related to illegal burning in Indonesia
193 has proven difficult (Jones 2006, Evers et al 2016). Insufficient enforcement of these regulations
194 during past extreme haze events has been attributed in part to inadequate planning and resource

195 availability arising from inefficient organization within the Indonesian government (Dennis et al
196 2005, Jones 2006 and references therein). In addition, many of the companies or individuals
197 accused of burning illegally escape with minimal punishment, providing no deterrent for getting
198 caught (Jones 2006). Complicating the issue further is the jurisdictional ambiguity surrounding
199 the enforcement of fire regulations; in many areas, fire use is regulated by both traditional
200 community laws and national regulations from the Indonesian government, which can be
201 contradictory (Byron and Shepard 1998, Dennis et al 2005, Gaveau et al 2016). The adjoint
202 method presented in this work would allow both state and local governments to prioritize the
203 allocation of police resources to those areas where enforcing the bans against illegal burning
204 would most effectively reduce damage to human health. Identifying the provinces where burning
205 is most important for regional air quality degradation would also highlight areas where the need
206 for cooperation between national and local governments on issues of fire regulation and
207 enforcement is paramount. Additionally, many large companies have pledged not to use fire for
208 land management to obtain certification from the Roundtable on Sustainable Palm Oil (RSPO;
209 <http://www.rspo.org/>), though policing such pledges is a challenge. The adjoint approach could
210 be used to both estimate the benefits to regional human health of no-burn pledges from
211 companies in particular provinces, as well as provide a means of accountability for companies
212 burning in the high priority areas most influencing regional air quality. Coupled with improved
213 spatial maps to reduce inconsistencies in land tenure claims ([http://blog.cifor.org/22534/new-
214 tech-better-map-on-tap-to-protect-indonesian-forests?fnl=en](http://blog.cifor.org/22534/new-tech-better-map-on-tap-to-protect-indonesian-forests?fnl=en)), the adjoint would be a powerful
215 tool for no-burning enforcement.

216

217 Extreme haze in Indonesia will likely continue to be an issue until the challenges
218 mentioned above are more fully addressed. However, the capability to pinpoint the areas most
219 affecting regional human health during extreme haze with our adjoint approach would help
220 stakeholders and policymakers prioritize the areas where fire management is most important for
221 domestic and regional air quality, increasing the precision and therefore the effectiveness with
222 which all these fire management strategies can be implemented.

223

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