

Evaluating greenhouse gas emissions inventories for agricultural burning using satellite observations of active fires

HSIAO-WEN LIN,^{1,5} YUFANG JIN,^{1,2} LOUIS GIGLIO,³ JONATHAN A. FOLEY,⁴ AND JAMES T. RANDERSON¹

¹Department of Earth System Science, 3242 Croul Hall, University of California, Irvine, California 92697 USA

²Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, California 90095 USA

³Department of Geography, University of Maryland, College Park, Maryland 20742 USA

⁴Institute on the Environment, University of Minnesota, St. Paul, Minnesota 55108 USA

Abstract. Fires in agricultural ecosystems emit greenhouse gases and aerosols that influence climate on multiple spatial and temporal scales. Annex 1 countries of the United Nations Framework Convention on Climate Change (UNFCCC), many of which ratified the Kyoto Protocol, are required to report emissions of CH₄ and N₂O from these fires annually. In this study, we evaluated several aspects of this reporting system, including the optimality of the crops targeted by the UNFCCC globally and within Annex 1 countries, and the consistency of emissions inventories among different countries. We also evaluated the success of individual countries in capturing interannual variability and long-term trends in agricultural fire activity. In our approach, we combined global high-resolution maps of crop harvest area and production, derived from satellite maps and ground-based census data, with Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) measurements of active fires. At a global scale, we found that adding ground nuts (e.g., peanuts), cocoa, cotton and oil palm, and removing potato, oats, rye, and pulse other from the list of 14 crops targeted by the UNFCCC increased the percentage of active fires covered by the reporting system by 9%. Optimization led to a different recommended list for Annex 1 countries, requiring the addition of sunflower, cotton, rapeseed, and alfalfa and the removal of beans, sugarcane, pulse others, and tuber-root others. Extending emissions reporting to all Annex 1 countries (from the current set of 19 countries) would increase the efficacy of the reporting system from 6% to 15%, and further including several non-Annex 1 countries (Argentina, Brazil, China, India, Indonesia, Thailand, Kazakhstan, Mexico, and Nigeria) would capture over 55% of active fires in croplands worldwide. Analyses of interannual trends from the United States and Australia showed the importance of both intensity of fire use and crop production in controlling year-to-year variations in agricultural fire emissions. Remote sensing provides an effective means for evaluating some aspects of the current UNFCCC emissions reporting system; and, if combined with census data, field experiments and expert opinion, has the potential to improve the robustness of the next generation inventory system.

Key words: agriculture; biomass burning; carbon dioxide (CO₂); climate treaty monitoring and verification; mitigation; radiative forcing; waste and residue.

INTRODUCTION

Covering ~12% of the earth's ice-free land surface, cropland ecosystems provide food, feed, fiber, and energy resources for humans and are a primary player in global environmental change (Foley et al. 2005, Ramankutty et al. 2008). Open field burning of agricultural biomass is a common land use practice in croplands that influences climate and air quality. The use of fire depends on the cropping system, harvesting technique, and cultural practice; examples include burning to rapidly remove the residue in multiple-season cropping systems (Prasad et al. 1999, Brye et al. 2006, Amuri and Brye 2008), pre-harvest burning in sugarcane

fields (Clay 2004), fertilizing the soil (Davidson et al. 2008), and managing weeds and disease (Prew et al. 1995, Smiley et al. 1996, Gallagher et al. 1999). Agriculture burning releases CH₄ and N₂O, precursors of O₃, and organic and black carbon aerosols into the atmosphere (Crutzen and Andreae 1990, Andreae and Merlet 2001, Yevich and Logan 2003). While burning in the field is thought to be CO₂ neutral due to carbon sequestration in the next cropping season, the other emitted gases and aerosols mentioned above alter atmospheric chemistry and radiative budgets and thus impact the climate (Forster et al. 2007). Agricultural burning also alters ecosystem carbon and nutrient budgets (Thompson 1992) and thus indirectly influences greenhouse gas emissions from soils (e.g., Robertson et al. 2000, Davidson et al. 2008). When aerosols from cropland burning are transported to higher latitudes (Stohl et al. 2007), deposition of black carbon on snow

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⁵ E-mail: hwlin@uci.edu

and sea ice decreases surface albedo and contributes to high-latitude warming (Flanner et al. 2007, Flanner et al. 2009).

Regulation of agricultural waste burning occurs at multiple levels of government, primarily with the aim of minimizing threats to air quality and human health. These include state- and country-level bans, especially within developed countries. Within the United States, for example, agricultural waste burning is managed by individual states to meet minimum air quality levels required by the Clean Air Act. Global efforts focusing on climate mitigation also take agricultural waste-burning emissions into consideration. Since 1994, the United Nations Framework Convention of Climate Change (UNFCCC) requires countries that ratified the convention to report national greenhouse gas (GHG) inventories, including CO₂, CH₄, N₂O, SF₆, hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). Within the UNFCCC reporting system, GHG emissions are divided into four sectors based on different types of human activity: energy; industrial processes and product use; agriculture, forestry, and other land use (AFOLU); and waste. Recommended guidelines for developing inventories for each sector, including approaches for combining activity data and emission factors, are described in the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidelines (IPCC 1996, 2000, 2006). Different tiers exist according to the complexity and the specificity of the methods used to retrieve emissions. In the agricultural waste-burning category of the AFOLU sector, the IPCC guidelines require information about crop productivity, the yield-to-residue ratio, the fraction of crop residue left on-site for burning, and emission factors for each crop type that are either default ("Tier 1"), country specific ("Tier 2"), or from field measurements ("Tier 3"). The current method used by most parties for agricultural waste-burning emissions is Tier 1 due to a lack of country-specific knowledge. There are also different reporting regulations for Annex 1 countries (developed countries) and non-Annex 1 countries (mostly developing countries). Annex 1 countries are required to report annually CH₄ and N₂O emissions from agricultural waste burning not only as a whole, but also for 14 major crop classes when applicable: wheat, rice, soybean, maize, beans, peas, sugarcane, barley, oats, rye, potato, and other cereal, tuber, and pulse crops. Lokupitiya and Paustian (2006) reviewed the agricultural categories within the AFOLU sector of the UNFCCC GHG inventory and found that the quality and information content was highly variable from country to country due to lack of updated parameters, overgeneralized use of emission factors, and other methodological problems. Similar issues likely exist with the agricultural waste-burning category because of the lack of systematic observations of key parameters, including the fraction of crop residues that are burned in the field. Our goal in this study was to examine the agricultural waste-burning

category, both in scope and in approach, using satellite-derived observations of active fire with the aim of finding ways to improve the reporting system.

Recent advances in remote-sensing products and crop data sets have improved our ability to study agricultural waste burning in a consistent way across different regions and countries and on multiple spatial scales. The Moderate-Resolution Imaging Spectroradiometer (MODIS) sensors on board NASA's Terra and Aqua satellites, for example, provide information about the global distribution of active fires (Justice et al. 2002, Giglio et al. 2006) and vegetation cover (Friedl et al. 2002) at a moderate spatial resolution. Studies using these products have identified regional and temporal patterns of agricultural fires, and show that fires occur consistently in some agricultural regions even though the use of fire in these areas is prohibited (Korontzi et al. 2006, McCarty et al. 2007). Geostationary satellites also provide important constraints on agricultural fires, including information about the diurnal cycle of fire activity, which may be subsequently used to estimate aerosol and ozone precursor emissions in forecasting models for air quality (Zhang et al. 2008, Yang et al. 2011). In parallel to satellite monitoring of fires, major efforts combining remote-sensing products with census-based data provide geographic information about the distribution of global agriculture, including crop types and yields, at a high spatial resolution (Monfreda et al. 2008, Ramankutty et al. 2008).

In this study, we combined MODIS active fire data with new crop data sets to evaluate the quality of the UNFCCC reporting system. We specifically examined four questions: (1) Is the current set of crop types targeted by the UNFCCC optimal for reporting agricultural waste burning? (2) How much burning occurs in countries that annually report their emissions to the UNFCCC? (3) Are agricultural waste-burning emissions inventories consistent among different reporting countries? (4) Are inventories for individual crop types consistent with the spatial and temporal distribution of active fires within countries? To answer this final question, we focused on three Annex 1 parties that regularly report their agricultural waste-burning emissions to the UNFCCC: Australia, the European Union, and the United States.

DATA SETS AND METHODS

Satellite-derived estimates of agricultural fires

We used MODIS active fire data to identify and assess spatial and temporal variations of agricultural burning. The MODIS sensors on board Aqua and Terra satellites detect actively burning fires with dedicated 3.9- μ m and 11.0- μ m fire channels, at a spatial resolution of 1 km, two times a day (at 01:30 and 13:30 hours for Aqua, and 10:30 and 22:30 hours for Terra; Giglio et al. 2003). Satellite-derived active-fire products provide a means to systematically monitor temporal and spatial patterns of fires in different ecosystems, including croplands (e.g.,

Korontzi et al. 2006, McCarty et al. 2007, 2009, Punia et al. 2008, Soja et al. 2009). Although the spatial resolution of the MODIS active fire product is 1 km at nadir (because of the spatial resolution of the infrared spectral bands), this product can detect actively burning fires that are much smaller in size, with the detection limit depending on fire temperature (Giglio et al. 2003).

A separate approach for measuring fire in agricultural areas is to quantify burned area using surface reflectance observation before and after the fire. For example, the Global Fire Emissions Database version 3 (GFED3) burned area, which is derived from 500-m MODIS surface reflectance, indicates that $\sim 1.3\%$ of global cropland area burned during 1997–2010 (Giglio et al. 2010). This is likely an underestimate of burned area in croplands because many agricultural field sizes (and fire sizes) are considerably smaller than the 25-ha area of a MODIS surface reflectance pixel, requiring specifically designed algorithms for this biome (McCarty et al. 2009). McCarty et al. (2009) developed a burned-area algorithm for agricultural fires in the United States, using field observations of fire perimeters (and plowed areas) for ground truth and regionally tuned thresholds for burned-area detection. In the McCarty et al. (2009) analysis, the amount of harvested area that was annually burned varied considerably among different states, with an annual total of ~ 1.3 Mha/yr. Compared to U.S. harvest area of ~ 140 Mha/yr, a little $< 1\%$ of the planted agricultural fields burned each year in the United States during 2003–2007. We are unaware of any similar product that has been developed for agricultural burning at a global scale. Here in our analysis of the UNFCCC agricultural fire emissions reporting system, we chose to use active fire products from MODIS because they provide systematic global coverage and because they enable the detection of small fires that are prevalent in this biome and below the detection limit of currently available global burned-area products.

To compare with cropland data available at a 5-min spatial resolution, we used Collection 5 of the Global Monthly Fire Location Product (MCD14ML; Giglio et al. 2006), which provides information about individual Aqua and Terra fire pixels. These products provide the geographic locations of fires (latitude and longitude coordinates) at the native resolution of the MODIS sensor thermal bands, which is ideal for comparing with the high spatial resolution of the crop data set, but has a limitation in that it does not include corrections for variability in the number of satellite overpasses or clouds. We used Aqua data as our primary data set for the analysis of spatial patterns because the overpass time for Aqua in early afternoon detected a much larger number of agricultural fires than the morning overpass from Terra (e.g., Giglio 2007, Mu et al. 2011). Prior to our analysis we screened the data set to remove active fires associated with gas wells, volcanoes, and industrial sources using a static hotspot database (Giglio et al. 2006). MCD14ML data sets are currently up to date;

here we chose a time span from 2003 to 2006 for Aqua to match the intervals of the publicly available UNFCCC GHGs inventories, and also to minimize the temporal offset with the crop harvest area data set that best represents the distribution of crops in the year 2000. Details of the latter two data sets are described in following sections.

We compared MODIS active fires with GFED3 emissions in cropland and grassland ecosystems and found that there was a monotonic increasing relationship between the number of active fire detections and emissions, particularly for areas with lower levels of fire activity (Appendix: Fig. A1). GFED3 emissions estimates were largely independent of active fire data during the MODIS era (van der Werf et al. 2010) since 500-m burned area observations (Giglio et al. 2010) were the primary driver of the biogeochemical model. In addition, the spatial distributions of annual mean active fires from Terra and GFED3 annual mean emissions during 2001–2006 were correlated at a $0.5^\circ \times 0.5^\circ$ resolution, across all ecosystems at a global scale ($r = 0.54$, $P < 0.0001$, $n = 16\,629$). For each grid cell through time, the mean correlation between monthly active fires from Terra and monthly GFED3 emissions was 0.60 ± 0.26 (mean \pm SD; calculated during a 72-month period for 11 653 grid cells with at least 10 months of active fire and emissions reports). These analyses support a key assumption in our analysis: that active fires detected by Terra and Aqua were closely related to cropland fire emissions.

Other independent work supporting a close relationship between active fires and emissions comes from studies of fire radiative power (FRP) and fire radiative energy (FRE). Past work on FRE indicates there is a linear relationship between FRE and biomass combusted, as derived from comparisons of ground-based experiments with multiple remote-sensing observations (e.g., Roberts et al. 2005, Wooster et al. 2005, Vermote et al. 2009). FRE and FRP have been used to estimate trace gas and aerosol emissions in the laboratory and also in regional remote-sensing studies (e.g., Wooster et al. 2005, Freeborn et al. 2008, Roberts et al. 2011). In areas with agricultural burning, the sum of MODIS active fire counts was found to be linearly related to the sum of MODIS FRP (Appendix: Fig. A2), indicating that that our use of MODIS active fires is closely related to FRP; and thus ultimately, emissions, drawing upon established relationships from the FRE literature.

The studies and analysis described in the previous paragraph provide evidence for a strong link between active fires and emissions. It is important to note, however, that this relationship is complex. The integration of FRP into FRE, for example, is influenced by many factors including the orbital characteristics, spatial resolution, and spectral characteristics of individual satellite sensors, cloud cover, fire behavior and duration, and active fire omission and commission errors (Wooster et al. 2005, Ichoku et al. 2008, Schroeder et al. 2008,

Boschetti and Roy 2009). In croplands, the relationship between active fire and emissions also may be sensitive to the size of individual fires (which may vary among different crop types and regionally specific field sizes) and management approaches that influence the time of day that fires are ignited by farmers.

Variability in the diurnal timing of burning could be an important issue for analysis of MODIS observations that provide samples only during one daytime and one nighttime overpass for each satellite. In this context, the broad similarities between the spatial and temporal distribution of agricultural fires observed by Terra and Aqua that have considerably different day overpass times (10:30 and 13:30 hours) suggested that our findings regarding optimization of the UNFCCC reporting system were robust. (Terra results are shown in the Appendix) Geostationary satellites, such as the Geostationary Operational Environmental Satellite (GOES), give invaluable information about the diurnal cycles of fires in different biomes (e.g., Mu et al. 2011), but with the current generation of spectrometers that have at best ~ 4 km spatial resolution for nadir (equatorial) viewing conditions, many small agricultural fires may go undetected, particularly those in mid- and high-latitude countries that are far from the geostationary sensor's sub-satellite point. Validation of GOES Wildfire Automated Biomass Burning Algorithm (WFABBA) and MODIS MOD14 active fire products over various land types show that MODIS performs as well as GOES with lower omission errors and similar commission errors for forest conversion and pasture maintenance fires in the Amazon, despite its less frequent temporal sampling (e.g., Schroeder et al. 2008, Hyer and Reid 2009).

Crop harvest area

We used the M3 (Madison-McGill-Minnesota) cropland data set developed by Ramankutty et al. (2008) and Monfreda et al. (2008). The M3 data set was constructed using a combination of agricultural areas identified by MODIS land cover (Friedl et al. 2002) and Global Land Cover 2000 (GLC2000) maps derived from the Satellite Pour l'Observation de la Terre (SPOT) VEGETATION sensor (Bartholome and Belward 2005), along with detailed agriculture census data from national and sub-national sources. Specifically, agricultural census data sources included national census data (Ramankutty et al. 2008), crop reports of the Food and Agriculture Organization of the United Nations (FAO), and numerous sub-national governmental data sets; in all, over 22 000 political units were analyzed with their census data. The data set included aggregated and individual crop harvest areas (as fraction of grid area) and yields (in metric tons of dry matter/ha) for 175 crop types at a 5-min \times 5-min (equivalent of roughly 9 km \times 9 km at the equator) spatial resolution. As far as we are aware, this is the highest spatial resolution crop data set (that resolves individual crop types and harvest areas)

available globally. These estimates were developed for the 2000 epoch using census data and reports from multiple years.

Attribution of active fires to different crop types

We aggregated MODIS active fire locations to annual sums at the 5-min spatial resolution of the M3 data set. The fraction of total crop harvest area to grid cell area was used to assign a component of the active fire annual sums to agricultural fires. In a second step, the agricultural fires were then attributed to different crop types within each grid cell based on the relative contribution of individual crop harvest areas to the total harvest area. This attribution approach assumed that different crop types within each grid cell had equal probabilities of burning, after taking into account differences in harvest area. In part because the M-3 harvest area data set was constructed from multiple years of agricultural statistics, very few 5-min grid cells were dominated by a single crop type. For example, $>50\%$ of all crop grid cells contained between 5–10 major crop types (Appendix: Fig. S3). To evaluate the effect of overlapping crop types on the attribution of active fires to individual crop types, we also estimated active fire densities using only grid cells where the primary crop type accounted for at least 30% of the total harvest area within each grid cell. Fire densities were similar for the major crop types analyzed here, did not change our recommendations regarding the optimization of the UNFCCC reporting system, and provided confidence that our attribution process was reasonable (see results shown in *Results: Optimal choice of crop types for emissions reporting*).

The active fires attributed to each crop type were then masked by political boundaries to obtain country-level values. The gridded national boundary data set was obtained from the Gridded Population of the World Project version 3 (GPWv3) data set produced by the Center for International Earth Science Information Network (CIESIN) at Columbia University (*available online*).⁶

UNFCCC emissions

GHG inventory data reports were acquired from the interactive online query system developed by the UNFCCC (*available online*).⁷ Within this reporting system, the emissions of CH₄ and N₂O from agricultural waste burning are aggregated into equivalent CO₂ emissions (CO₂eq emissions) using 100-year Global Warming Potentials. Dry-matter burned values are available only for Annex 1 countries. Reports were available online from 1990 through year 2008. Both the dry-matter and CO₂eq emissions products from the UNFCCC were used in this study. We used dry matter burned (Gg/yr) as a measure of greenhouse emissions

⁶ <http://sedac.ciesin.columbia.edu/gpw/analapps.jsp>

⁷ <http://unfccc.int/di/FlexibleQueries/>

from individual crops within Annex 1 countries, recognizing that there is some variability in emission factors for N_2O and CH_4 as a function of crop type (Aulakh et al. 1991). In our analysis, we compared mean annual emissions from 2003 to 2006 with Aqua active fires during the same period; these were the first three years for which a complete annual cycle of Aqua observations were available. We also compared mean annual emissions from 2001 to 2006 with active fires from Terra during this same interval; these were the first six years for which a complete annual cycle of Terra observations were available (and the period closest to the nominal year of the Monfreda et al. [2008] crop harvest area and production data set used in this study). Most non-Annex 1 countries reported agricultural waste-burning emissions infrequently; some of them had reported only once, immediately after they ratified the Convention in year 1994. We used annual emissions values closest to the MODIS era if emissions data were not available after 2000.

Analysis approach

To assess the optimality of the crops targeted in the reporting system, we aggregated crop types from the M3 data set into larger functional type categories used by the UNFCCC (see footnote of Table 1). We then sorted these categories according to the total number of satellite-derived active fires that were detected within the geographic areas of each crop. We performed these rankings separately at a global scale and for all Annex 1 countries and using both Aqua and Terra active fire data sets. In the context of these rankings, it is important to define what we mean by optimization. Here, we chose to rank crops (i.e., their suitability for inclusion on the UNFCCC list of targeted crops for agricultural burning) using the product of their total harvest area and per crop fire density (defined as the number of active fire pixels per unit of crop harvest area per year). This metric is probably suitable for considering how a change in the abundance of an individual crop (e.g., maize) influences global climate or for gauging whether a specific country's agricultural burning emissions are increasing or decreasing over time. This approach follows from the well-established IPCC Good Practice Guideline manuals that quantify the net climate impact of a particular human endeavor as the product of an activity level and the greenhouse gas production per unit of activity (i.e., an emission factor). It is important to note, however, that this optimization strategy is not appropriate for evaluating the atmospheric impact and cost effectiveness of individual mitigation projects. Sugarcane, for example, did not show up on our optimized list of crops for Annex 1 countries because of its small harvest area. However, because of the high intensity of fire use during sugarcane harvesting, projects targeting the management of this crop at local and regional scales may provide a cost-effective means for reducing emissions compared to other available mitigation strategies.

For our emissions analysis at a country level, active fires were aggregated for each country using the national boundary masks described in *Attribution of active fires to different crop types* in this section, and then compared with emissions reported by that country to the UNFCCC. As mentioned earlier, not all non-Annex 1 countries reported agricultural burning emissions, and those that have made reports in the past often do so infrequently. Therefore, we had to primarily focus our study on Annex 1 countries and some non-Annex 1 countries for which data were available. The objectives of this analysis were to identify whether Annex 1 countries under- or overreport their emissions relative to one another, and to identify emission levels expected for countries that have never reported their emissions. Argentina, Brazil, China, India, Indonesia, Thailand, Kazakhstan, Mexico, and Nigeria were important non-Annex 1 countries with large crop harvest areas; these countries were included in our analysis.

We also analyzed the temporal and spatial distribution of active fires within several different regions. For this analysis we chose three Annex 1 parties: Australia, the European Union, and the United States. Each of these parties had significant cropland extent and agricultural waste-burning emissions and also consistently submitted their reports to the UNFCCC. We compared country-level emissions reports for different crop types with active fire observations for these same crops from Aqua and Terra. We also examined if these countries had successfully represented the interannual variability of the emissions, by comparing year-to-year variations in UNFCCC annual emissions with variations in active fire measurements.

RESULTS

Spatial distribution of fires in croplands

During 2003–2006, there were 274 294 annual mean active fire detections by MODIS Aqua in croplands per year, or 9% of global total active fires. MODIS Terra detected 146 174 active fires per year in croplands during 2001–2006, accounting for 10% of total active fires. These estimates were similar to the 8–11% levels reported by Korontzi et al. (2006) using agricultural areas identified from the MODIS land cover product and Terra MODIS active fire products corrected by cloud cover.

Large numbers of agricultural fires occurred across Africa, Southeast Asia, and southern South America (Fig. 1a). In the northern extratropics, important fire regions included the Mississippi basin in the United States, Eastern Europe, and central Asia north of the Caspian and Aral Seas. Fires in croplands were not evenly distributed across the world, with active fire detections occurring more frequently in tropical ecosystems and in areas with lower levels of crop production (Fig. 2). Central and South America, Africa, and Southeast Asia accounted for ~75% of fires in croplands, but only 45% of harvest area, and 35% of

TABLE 1. Global statistics of harvest area and active fires detected by Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua for major crop types.

Crop types†	Active fires (fire counts/yr)‡	Global active fires (%)	Global harvest area (%)	Fire density ($\times 10^{-4}$ fire counts·ha ⁻¹ ·yr ⁻¹)
Crop types required by the United Nations Framework Convention on Climate Change (UNFCCC)				
Rice	37 169	13.6	12.5	2.4
Maize§	34 852	12.7	12.4	2.3
Wheat	28 719	10.5	17.2	1.4
Tuber-root other¶	23 073	8.4	2.4	7.8
Cereal other#	17 352	6.3	6.3	2.3
Soybean	9 898	3.6	6.1	1.3
Peas	7 650	2.8	2.4	2.6
Beans††	6 979	2.5	2.2	2.6
Sugarcane	5 988	2.2	1.6	3.0
Barley	5 395	2.0	4.5	1.0
<i>Potato</i>	2 261	0.8	1.6	1.2
<i>Oats</i>	1 735	0.6	1.1	1.3
<i>Rye</i>	694	0.3	0.8	0.7
<i>Pulse other</i> ‡‡	672	0.2	0.5	1.1
Sum	181 766	66.3	71.2	
Crop types optimized by Aqua				
Rice	37 169	13.6	12.5	2.4
Maize	34 852	12.7	12.4	2.3
Wheat	28 719	10.5	17.2	1.4
Tuber-root other	23 073	8.4	2.4	7.8
Cereal other	17 352	6.3	6.3	2.3
Soybean	9 898	3.6	6.1	1.3
Ground nuts §§	8 698	3.2	1.8	3.9
Peas	7 650	2.8	2.4	2.6
Cocoa	7 206	2.6	0.6	10.6
Cotton	7 179	2.6	2.5	2.4
Beans	6 979	2.5	2.2	2.6
Sugarcane	5 988	2.2	1.6	3.0
Barley	5 395	2.0	4.5	1.0
Oil palm	5 167	1.9	0.8	5.3
Sum	205 326	74.9	73.4	

† Crops were ranked by the number of active fires observed for each type from 2003 to 2006. To optimize the list according to the satellite observations, crop types in boldface need to be added and those in italic need to be removed. Active fires are shown as the mean during years 2003–2006. Global harvest area was 12 193 300 km².

‡ The numbers of active fires for individual crops in the tables may not sum to the global total because of rounding.

§ Includes maize for grain and maize for forage.

¶ Includes cassava, sweet potato, taro, yam, and yautia, but excludes potato.

Includes canary seed, fonio, millet, sorghum, sorghum for forage, and triticale, and excludes the major cereals rice, wheat, barley, oats, and rye.

|| Includes pea, chickpea, cowpea, and pigeon pea.

†† Includes beans and broadbeans.

‡‡ Includes bambara, lentil, lupin, and vetch, and excludes peas and beans.

§§ Peanuts.

global crop production. Annex 1 countries, which were located mainly in the Northern Hemisphere (except for Australia and New Zealand), accounted for 45% of both global crop harvest area and production, but only 15% of active fires. Within Annex 1 regions, Europe had the lowest amount of fire use per unit of crop production, accounting for ~2% of global agricultural fires, but over 15% of global crop production (Fig. 2). Central Asia (CEAS, including China) and Southeast Asia (SEAS, including India) had the highest percentages of crop area (22%) and crop production (21% and 16%) and intermediate levels of active fires (11% and 20%). In contrast, Northern Hemisphere Africa (NHAf) had <3% of global crop production, 8% of crop area, but ~30% of active fire detections (Fig. 2).

Fire use intensity, defined as the number of active fire detections per metric ton of crop production (from M3

crop yield data; Fig. 1b), was highly variable within and across countries, with regional hot spots across northern Kazakhstan, along the coast of Myanmar, in northern India near the border with Pakistan, and in many countries within Africa (Fig. 1c).

Optimal choice of crop types for emissions reporting

The 14 crop types targeted by the UNFCCC reporting requirements represented 71% of global harvest area and accounted for 66% of active fires in croplands globally (Table 1). A similar list of 14 crop classes derived solely from active fire detections by Aqua increased both the coverage of harvest area (by 2% to 73% of global harvest area) and the coverage of active fires (by 9% to 75% of active fires in global croplands). Parallel analyses with Terra MODIS are shown in the Appendix: Table A1. An optimized global set of crop types required the addition

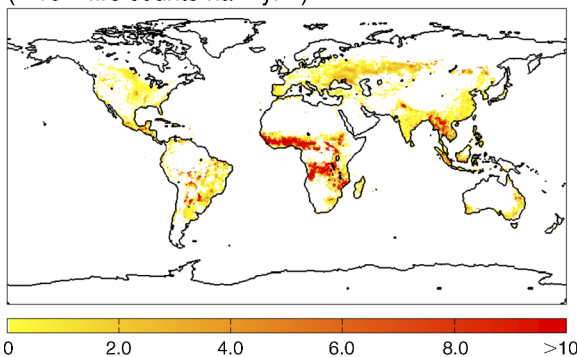
of ground nuts (e.g., peanuts and kerstings groundnuts), cocoa, cotton, and oil palm to the UNFCCC reporting list and removal of other pulse crops (i.e., pulse crops other than beans and peas, including bambara, lentil, lupin, and vetch), rye, potato, and oats. The latter crop types occupied $\sim 4\%$ of global harvest area, but $<2\%$ of global active fires. We note that mixed grass/legumes (defined as a mixture of grasses and legumes used for forage) were an important source of active fires, but that potential ambiguities exist with respect to reporting requirements. Emissions from this crop type may be reported within the “all other” crop functional type class in national inventories, or as a part of prescribed burning of savannas, which is another category in the AFLOU sector. If the inventories were extended to include the mixed grass/legumes crop type, we found that there would be an additional 3% increase in the active fires covered by the reporting system.

To assess possible effects resulting from the heterogeneity of crop cover in many grid cells, as mentioned in *Attribution of active fires to different crop types in the Methods*, we compared fire densities from Table 1 with fire densities calculated only from grid cells that had at least 30% of the harvest area associated with the primary crop type (and hence were “less heterogeneous”). Results from these less heterogeneous grid cells showed a similar ranking for fire densities of given crop types (Table 2). The list of satellite-optimized crop types for use the UNFCCC inventory was similar (data not shown). Hereafter we base our discussion on global results that covered all grids with the occurrence of a given crop type, as is in Table 1.

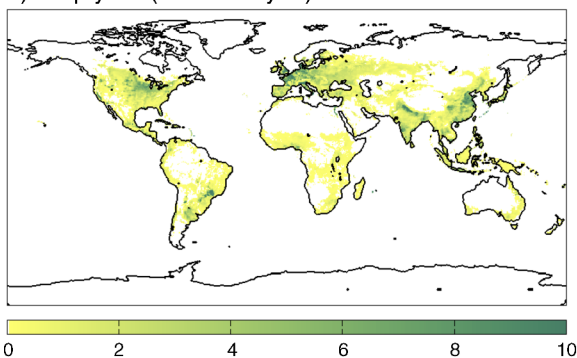
The top seven global crop types as ranked by MODIS Aqua fire counts were included in UNFCCC reporting system (Table 1). Rice, wheat, and maize were the three leading crop types with the largest harvest area and number of active fires, accounting for 42% of harvest area and 37% of agricultural fires globally. Rice and maize had intermediate levels of fire density, with wheat on the lower side among the crop types targeted for UNFCCC reporting. The maize crop class listed in Table 1 included both grain and forage components. Maize used for grain represented 90% of all maize and had a higher fire density (2.4×10^{-4} fire counts \cdot ha $^{-1}$ \cdot yr $^{-1}$) compared to that used for forage (1.0×10^{-4} fire counts \cdot ha $^{-1}$ \cdot yr $^{-1}$). Within the class “cereal other,” sorghum accounted for 63% of active fires and had a fire density of 2.8×10^{-4} fire counts \cdot ha $^{-1}$ \cdot yr $^{-1}$. Millet accounted for the other 34% active fires in this class (and had a fire density of 1.8×10^{-4} fire counts \cdot ha $^{-1}$ \cdot yr $^{-1}$). Cotton contributed to 2.5% of global harvest area and 2.6% of active fires in global croplands.

Tuber-root other was the fourth most important class of crops for active fires and had the highest fire density among the UNFCCC-reported crops. We found that cassava and yam were the two most important crop types within this class, accounting for 68% and 17%, respectively, of the total number of active fires. Cassava had a global harvest

a) Active fires in croplands
($\times 10^{-4}$ fire counts \cdot ha $^{-1}$ \cdot yr $^{-1}$)



b) Crop yield (tons \cdot ha $^{-1}$ \cdot yr $^{-1}$)



c) Fire use intensity ($\times 10^{-4}$ fire counts/ton)

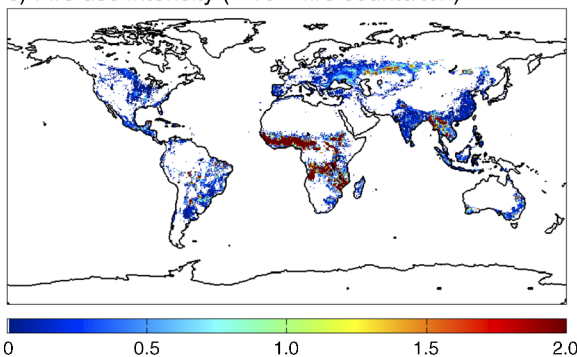


FIG. 1. Map of (a) Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) active fires, (b) crop yield (where “tons” are metric tons [1 metric ton = 1000 kg]), and (c) fire use intensity, averaged from 5-min grid cells within each 0.5° grid for better contrasts in global maps. The active fires are the mean values during 2003–2006. Crop yield is for the year 2000 from the M3 database (Madison-McGill-Minnesota cropland data set developed by Ramankutty et al. [2008] and Monfreda et al. [2008]). Fire use intensity was calculated as a ratio of active fires over crop production at a 5-min spatial resolution (and with units of active fire counts/metric ton), and then averaged over the 0.5° grid. Fire use intensity is a relative measure that is likely proportional to fire emissions per unit of crop biomass produced and is not directly comparable to estimates of fire return times derived from burned area.

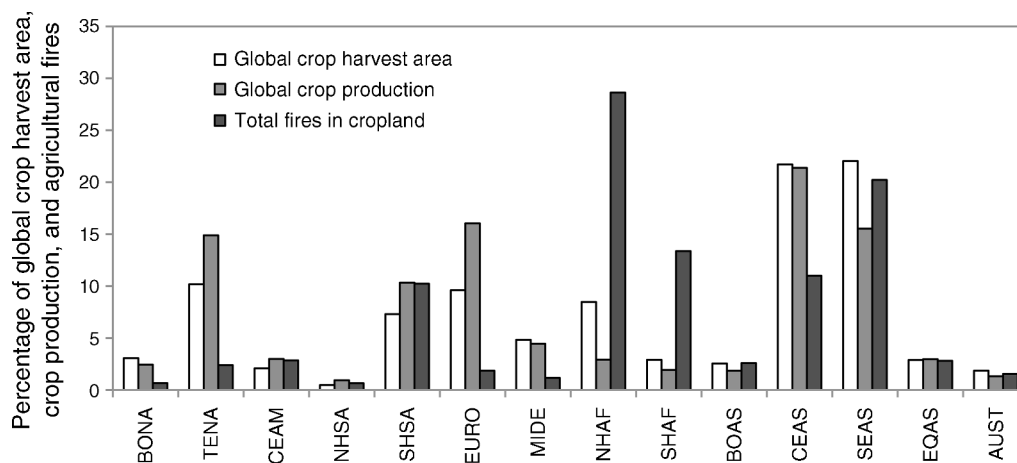


FIG. 2. Relative importance of fires in croplands, crop harvest areas, and crop production over 14 geographical regions in the world. Data shown are percentages of the global means during 2003–2006. Active fires were derived from Aqua MODIS. A map of the different regions is shown in the Appendix: Fig. A6. Region abbreviations are: BONA, boreal North America; TENA, temperate North America; CEAM, Central America; NHSA, northern hemisphere South America; SHSA, southern hemisphere South America; EURO, Europe; MIDE, Middle East; NHAf, northern hemisphere Africa; SHAF, southern hemisphere Africa; BOAS, boreal Asia; CEAS, central Asia; SEAS, Southeast Asia; EQAS, equatorial Asia; and AUST, Australia and Oceania.

area similar to potato and oats (1.2% of global crop area), but had a substantially higher fire density at 10.1×10^{-4} fire counts \cdot ha $^{-1}\cdot$ yr $^{-1}$. Yam accounted for only a small fraction of global harvest area (0.3%) but 1.4% of active fires, with a fire density of 10.8×10^{-4} fire counts \cdot ha $^{-1}\cdot$ yr $^{-1}$. Cassava is an important carbohydrate source in developing tropical countries, especially in tropical Africa (FAO 1997). It is

likely that the use of fire for other purposes in these regions, including deforestation, shifting cultivation, and pasture maintenance (Barbosa et al. 1999, Achard et al. 2002), contributed to the cassava active fire sums, given the complexity of land use that remains at the 5-min spatial resolution of the crop data set. Cocoa and oil palm also were found in tropical regions with substantial fire use, and

TABLE 2. Fire densities estimated only using grid cells where individual crop types accounted for at least 30% of the total harvest area.

Crop type†	Crop area that exists in grid cells that have >30% harvest area of this crop type (%)	Fire density ($\times 10^{-4}$ fire counts \cdot ha $^{-1}\cdot$ yr $^{-1}$)	Fire density from Table 1 ($\times 10^{-4}$ fire counts \cdot ha $^{-1}\cdot$ yr $^{-1}$)
Rice	75.5	2.3	2.4
Soybean	69.4	1.3	1.3
Cereal other	65.3	1.7	2.3
Wheat	61.2	1.7	1.4
Oil palm	49.3	3.0	5.3
Maize	49.2	2.1	2.3
Cocoa	44.3	16.4	10.6
Sugarcane	38.3	3.6	3.0
Cotton	34.9	1.3	2.4
Tuber-root other	30.7	12.3	7.8
Peas	22.3	7.7	2.6
Ground nuts	17.5	3.1	3.9
<i>Rye</i>	17.4	0.9	0.7
Barley	15.3	0.8	1.0
Beans	10.1	1.8	2.6
<i>Potato</i>	0.8	0.3	1.2
<i>Oats</i>	0.02	1.3	1.3
<i>Pulse other</i>	0.02	0.3	1.1

Notes: The list of crop types includes those on the original UNFCCC targeted list and new ones derived from the optimization using active fires. Together these crops account for 77% of harvest area globally. Active fire counts used for the calculation of fire density were from Aqua MODIS during 2003–2006.

† Crop types that should be added to the UNFCCC reporting list according to the Aqua observations shown in Table 1 are shown in boldface. Those targeted for removal to optimize the list are shown in italic. See the footnotes of Table 1 for more information about the specific crop types within major crop classes.

similarly, other land use activities probably influenced the fire densities reported here. We note that slash-and-burn agriculture has been a common land use activity in the humid tropics for many centuries (Hao and Liu 1994, Palm 2005), and this practice probably contributed to some of the high fire densities observed here in agricultural ecosystems in tropical regions (e.g., Fig. 1).

In this context, it is important to note that even if fire emissions do not originate from within the individual fields of the crops studied here, they may be closely connected to the management of these crops at a regional scale. Assuming these emissions can be separated from those associated with deforestation for the purposes of greenhouse gas inventories, they represent a valid target for climate mitigation programs. Over the last two decades, several projects have specifically investigated the sustainability of different agricultural management practices in tropical regions, including slash-and-burn agriculture, with respect to reducing greenhouse gas emissions and enhancing ecosystem function (Izac and Sanchez 2001, Palm et al. 2004, Davidson et al. 2008).

We performed a parallel optimization of crop types only considering agricultural areas in Annex 1 countries (Table 3), since annual emissions reporting for the UNFCCC is required only from Annex 1 countries. The optimal list of crops for this subset was similar to the optimal global list, but with several noticeable differences. Wheat had the most harvest area and the largest number of active fires in Annex 1 countries (accounting for 23% harvest area and 28% of active fires), followed by barley (9% of harvest area and 11% of active fires), and maize (13% harvest area and 8% of fires). Optimization of the list required the addition of sunflower, cotton, rapeseed, alfalfa, and the removal of pulse other, sugarcane, beans, and tuber-root other crop classes. These adjustments increased the efficacy of the reporting system from 64% to ~71% for coverage of active fires. Sugarcane had the highest fire density at 3.7×10^{-4} fire counts \cdot ha $^{-1}$ \cdot yr $^{-1}$ of any crop, but because of the low harvest area in Annex 1 regions as a whole (0.2%), it did not warrant inclusion on the optimized list. For many individual countries, however, including the United States and Australia, high fire densities and substantial harvest areas of sugarcane made this a significant crop and one important to include in the "crop other" emissions class in national inventories. If the agricultural-burning reporting system were extended to include the mixed grass/legumes crop type in Annex 1 areas, there would be an additional 17% increase in the efficacy of the reporting system.

Country-level evaluation

Annex 1 parties that provided annual reports to the UNFCCC accounted for 6% of active fires in global croplands as measured by Aqua (Fig. 3, Table 4). Within this set, the United States, Australia, and the European Union (EU-15) were key contributors,

together accounting for 5% of active fires in global croplands. Important non-reporting Annex 1 countries included the Russian Federation and the Ukraine that together were responsible for 8% of active fires in croplands globally. Canada also did not report open-field agricultural burning; however, it had ~3% of global harvest area, but less than 0.5% of global active fires in croplands. We also present data for important non-Annex 1 countries greater than 1% of global harvest area or greater than 1% of global active fires in croplands (Table 5). India, Nigeria, and Brazil were the top three countries and were responsible for over 25% of Aqua active fires in global agricultural areas (Table 5). China accounted for a substantially lower percentage of global active fires (3%) compared to its relatively high global percentage of harvest area (13%). Other important countries included Argentina, Indonesia, Thailand, Kazakhstan, and Mexico. If all Annex 1 countries reported their agricultural waste-burning emissions to the UNFCCC, the coverage of agricultural fires would increase from 6% to 15%. Further expanding reporting to include the top nine non-Annex 1 countries, the percentage would increase to 55% for MODIS Aqua and to 66% for MODIS Terra (Fig. 3, Table 5).

We checked the consistency of reports among countries by comparing UNFCCC emissions with the percentage of global active fires in croplands measured within each country (Fig. 4). In this analysis, we often had to make comparisons with emissions from non-Annex 1 countries from various years during the 1990s due to incomplete reporting during the MODIS era (see the footnotes of Table 5). Relative to other countries, the ratio of active fires to reported emissions was high for Nigeria and low for Brazil. It is important to note, however, that these two countries submitted their emissions reports before 1995, and thus, there was a significant temporal mismatch with the Aqua satellite data. Other reported emissions from Annex 1 and non-Annex 1 countries showed reasonable agreement with the spatial distribution of active fires. Fig. 4b shows Annex 1 countries at a finer resolution. In Annex 1 countries, the UNFCCC-reported emissions and percentage of global active fires in croplands were significantly correlated ($r^2 = 0.79$, $n = 13$, $P < 0.001$), implying overall a moderately good consistency among countries in the methods used to estimate agricultural waste-burning emissions. Among individual Annex 1 countries, however, the ratio of active fires to reported emissions varied considerably, and was high for Australia and low for Japan. In future, these ratios may help to provide guidance in reducing reporting uncertainties within individual countries.

Within-country evaluations for select Annex 1 parties

We present case studies in this section for three important Annex 1 parties: the United States, Australia, and European Union (EU-15, hereafter as EU). Within the United States, maize was reported as the greatest

TABLE 3. Statistics of harvest area and MODIS Aqua active fires for major crop types for Annex 1 (A1) countries.

Crop types	Active fires (fire counts/yr)	A1 active fires (%)	A1 harvest area (%)	Fire density ($\times 10^{-4}$ fire counts \cdot ha $^{-1}$ \cdot yr $^{-1}$)
Crop types required by the UNFCCC				
Wheat	11 410	27.5	23.4	1.1
Barley	4 346	10.5	9.3	1.0
Maize	3 282	7.9	12.6	0.6
Soybean	1 556	3.8	7.2	0.5
Oats	1 506	3.6	2.6	1.3
Potato	1 064	2.6	2.2	1.1
Cereal other	821	2.0	1.8	1.0
Rye	642	1.5	1.9	0.7
Rice	489	1.2	0.9	1.3
Peas	440	1.1	1.1	0.9
<i>Pulse other</i>	411	1.0	0.7	1.3
<i>Sugarcane</i>	318	0.8	0.2	3.7
<i>Beans</i>	131	0.3	0.4	0.7
<i>Tuber-root other</i>	4	0.0	0.0	0.4
Sum	26 420	63.8	64.4	
Crop types optimized by Aqua				
Wheat	11 410	27.5	23.4	1.1
Barley	4 346	10.5	9.3	1.0
Maize	3 282	7.9	12.6	0.6
Sunflower	2 158	5.2	2.8	1.7
Soybean	1 556	3.8	7.2	0.5
Oats	1 506	3.6	2.6	1.3
Potato	1 064	2.6	2.2	1.1
Cereal other	821	2.0	1.8	1.0
Rye	642	1.5	1.9	0.7
Cotton	628	1.5	1.5	0.9
Rapeseed	620	1.5	2.4	0.6
Alfalfa	612	1.5	3.9	0.4
Rice	489	1.2	0.9	1.3
Peas	440	1.1	1.1	0.9
Sum	29 574	71.4	73.7	

contributor of dry matter burned, followed by soybean, wheat, rice, and sugarcane (Fig. 5a). MODIS active fires captured the major emitting groups of crops (soybean, maize, and wheat) and the minor ones of barley, rice, and sugarcane. The relative importance of the major crop types implied from the satellite observations of active fires, however, was different from that represented by the inventory. Wheat, for example, appeared to be underrepresented in the emissions inventory relative to soybean and maize. By ranking active fires within each country by crop type, we identified cotton, alfalfa, and orange as being at least as important in their contributions to total agricultural burning emissions in the United States as the minor group of crops that are currently targeted by the UNFCCC. Assuming that active fires were proportional to emissions, including these crops would increase the total reported emissions by the United States by 12% based on Aqua MODIS observations. If the inventory were extended to cover mixed grass/legumes, emissions would increase by an additional 11%.

Parallel analyses of Australia and the EU also showed discrepancies between the dry-matter emissions reported in the inventory compared to active fires detected by MODIS (Fig. 5b, c). Wheat was the most important

contributor based on both the emissions inventory and MODIS active fires, while both parties had higher relative contributions to emissions from rice agriculture than what would be inferred from MODIS. The UNFCCC list of crop types captured most agricultural waste burning for Australia, and optimizing the list by including cotton, grass for forage (this is different from the class of mixed grass/legumes), and rapeseed would increase the coverage of active fires by 10% (or 6.9% excluding the grass class). The EU reported a substantial amount of emissions in the "all others" class (452 Gg CO₂eq/yr), or ~80% of their total emissions inventory reported to the UNFCCC (Table 4). We omitted the "all others" class for Fig. 5c because of the differences in units of data available from UNFCCC online emissions database. It is difficult to convert the emissions reported in CO₂eq back into dry matter burned considering the mixed nature of this class. However, olive, grape, and forage other than alfalfa, cabbage, clover, and major grains ("forage other") were probably the main contributors to this class, as identified by MODIS active fires; other important crop classes with similar levels of active fires were sunflower, alfalfa, potato, cotton, oats, and rapeseed. Together, the "all others" crop class accounted for 57% of total active fires in the EU. For comparison,

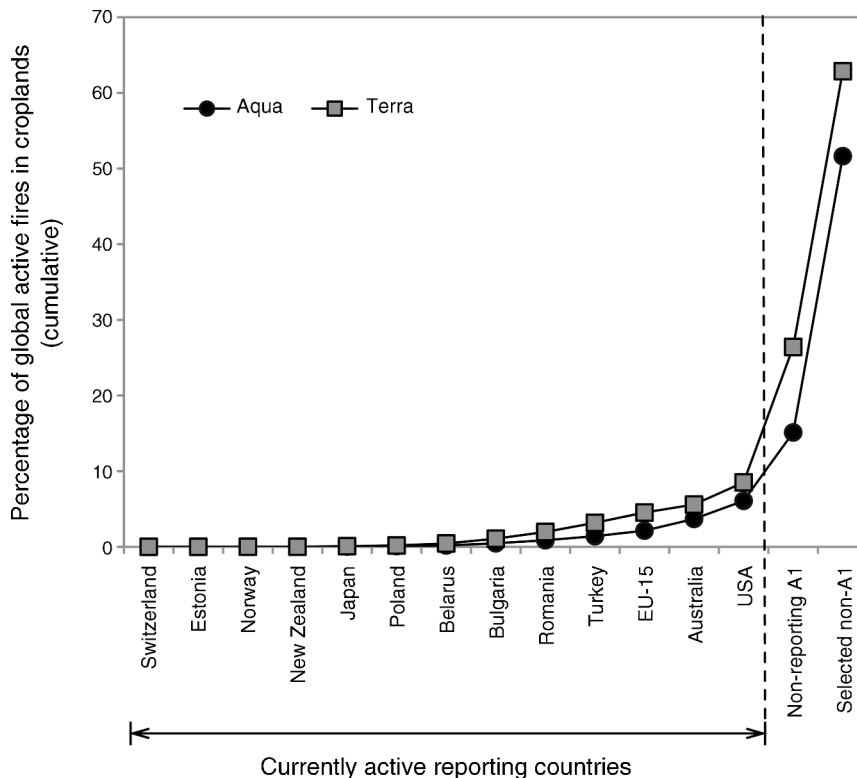


FIG. 3. The cumulative percentage of global active fires for reporting and non-reporting Annex 1 (A1) countries, and also for selected important non-Annex 1 countries. Non-reporting Annex 1 countries were: Canada, Croatia, Czech Republic, Hungary, Latvia, Lithuania, Russia, Slovakia, United Kingdom, and Ukraine. Selected non-Annex 1 countries were: Argentina, Brazil, China, India, Indonesia, Kazakhstan, Mexico, Nigeria, and Thailand.

Australia had 8 Gg CO₂eq reported as “all others” (not shown in Fig. 5b) or ~2% of total emissions. In contrast, the active fires in this class represented over 14% of total agricultural fires for Australia. The United States did not report any emissions for the “all others” class.

Interannual variability

Reported emissions from the United States, Australia, and the EU had different interannual trends compared to those derived from active fires (Fig. 6). To assess long-term trends, we analyzed Terra and Aqua MODIS active fires up to the year 2008 in this section. Dry matter burned from the UNFCCC inventory was less variable than that observed by MODIS. In the United States, for example, significant increases in active fires were observed for soybean ($P < 0.01$), maize ($P < 0.005$), and wheat ($P < 0.01$) over 2001–2008 (Fig. 6a). In contrast, the United States reported to the UNFCCC a nearly constant level of emissions among major crops during the same period (except for a small increase in emissions associated with maize). Given that crop production was relatively constant during 2001–2008 for wheat, soybean, sugarcane, and rice, the increase in fires observed for these crops was likely driven by management decisions to increase the intensity of fire use (Fig. 7a). The emissions inventory probably did not

capture these trends because it relied on the use of a time invariant conversion factor describing the fraction of crop residue burned in the field (U.S. EPA 2010). For wheat, much of the increase in active fires was concentrated in a few states, including Kansas and North Dakota. For soybean, much of the increase occurred along the banks of the Mississippi river, in the states of Arkansas, Tennessee, and Mississippi. The average rate of change in these hotspots was as high as 10–20% per year during 2001–2008. In contrast, for other important agricultural burning states within the United States, including California and Washington, active fire detections declined by 4% per year after 2003, mainly during the harvest season (October). These results suggest that efforts to limit agricultural emissions, including, for example, the burn permitting system in California implemented by the Air Resources Board in 2001 (*available online*)⁸ may have been successful in reducing emissions.

It is also important to note that the time series of active fires from Aqua (during 2003–2008) had similar patterns of interannual variability, but did not show the same magnitude of increases for corn and soybean during the latter part of the record (Appendix: Fig.

⁸ <http://www.arb.ca.gov/smp/smp.htm>

TABLE 4. Comparisons of annual reported emissions of crops required by the UNFCCC (mean \pm SD) from open-field agricultural burning and annual mean fire detections in croplands in Annex 1 countries.

Country†	Global harvest area (%)‡	UNFCCC emissions (Gg CO ₂ eq/yr)§	Detection by Aqua		Detection by Terra	
			Active fires (fire counts/yr)¶	All agricultural fires (%)	Active fires (fire counts/yr)#	All agricultural fires (%)
Australia	1.93	368.0 \pm 14.5	4 242	1.55	1 540	1.05
<i>Austria</i>	0.11	1.8 \pm 0.1	12	0.01	10	0.01
Belarus	0.51	8.7 \pm 0.5	239	0.09	390	0.27
<i>Belgium</i>	0.04	...	6	0.002	6	0.004
Bulgaria	0.27	32.6 \pm 2.6	776	0.28	918	0.63
Canada	2.88	...	1 331	0.49	969	0.66
Croatia	0.10	...	60	0.02	58	0.04
Czech Republic	0.22	...	10	0.004	15	0.01
<i>Denmark</i>	0.22	...	44	0.02	26	0.02
Estonia	0.06	4.0 \pm 0.3	7	0.003	6	0.004
EU-15	6.13	531.8 \pm 24.1	2 014	0.73	1 992	1.36
<i>Finland</i>	0.16	0.6 \pm 0.1	4	0.001	4	0.003
<i>France</i>	1.47	...	266	0.10	155	0.11
<i>Germany</i>	1.01	...	42	0.02	50	0.03
<i>Greece</i>	0.27	39.4 \pm 0.6	239	0.09	244	0.17
Hungary	0.40	...	230	0.08	271	0.19
<i>Ireland</i>	0.05
<i>Italy</i>	0.77	16.4 \pm 0.4	554	0.20	563	0.39
Japan	0.35	180.4 \pm 2.0	86	0.03	109	0.07
Latvia	0.07	...	15	0.005	27	0.02
Lithuania	0.20	...	68	0.02	48	0.03
<i>Netherlands</i>	0.07	...	15	0.01	6	0.004
New Zealand	0.04	22.5 \pm 2.9	13	0.005	4	0.003
Norway	0.05	7.8 \pm 0.9	9	0.003	7	0.005
Poland	1.01	40.7 \pm 1.2	141	0.05	131	0.09
<i>Portugal</i>	0.19	38.3 \pm 0.9	373	0.14	264	0.18
Romania	0.81	98.0 \pm 13.0	1 106	0.40	1 304	0.89
Russia	6.47	...	18 802	6.85	18 513	12.66
Slovakia	0.12	...	27	0.01	30	0.02
<i>Spain</i>	1.23	435.3 \pm 24.1	423	0.15	627	0.43
<i>Sweden</i>	0.19	...	4	0.002	7	0.005
Switzerland	0.04	13.9 \pm 0	2	0.001	3	0.002
Turkey	0.17	613.8 \pm 16.3	1 472	0.54	1 764	1.21
<i>UK</i>	0.48	...	32	0.01	29	0.02
Ukraine	2.28	...	4 219	1.54	6 164	4.22
USA	10.81	1292.4 \pm 30.9	6 572	2.40	4 285	2.93
Annex 1 sum	35.05	3214.7	41 440	15.11	38 549	26.37

† Countries in italic were members of European Union when the UNFCCC came into effect (EU-15). Their emissions were reported as a whole in the EU. Iceland, Liechtenstein, Luxembourg, Monaco, and Slovenia are Annex 1 countries but were not included in this table for their minimal harvest areas. Ellipses (...) indicate that no data are available.

‡ Global harvest area = 12 193 300 km².

§ UNFCCC emissions have units of CO₂eq. Dry-matter emissions were converted by individual countries into CO₂eq amounts based on emission factors and 100-year greenhouse warming potentials for CH₄ and N₂O.

¶ Mean values from 2003 to 2006.

Mean values from 2001 to 2006.

|| Emissions reported by members of the EU-15 individually were not summed in this total.

A4). One possible explanation is that there was an increase in burning that occurred primarily during mid-morning (during the time of the ~10:30 hour overpass of the Terra satellite). GOES and TRMM active fire products that provide information over the full diurnal cycle (e.g., Giglio 2007, Mu et al. 2011) may be particularly useful in future work for understanding the causes of these diverging trends. More detailed examination of diurnal observations of active fires from geostationary satellites may also help us to refine differences in the timing of crop burning over the course of day, which might vary as a function of crop type or region. The relative consistency of patterns of agricultural burning derived from Aqua and Terra

provide some confidence that diurnal patterns of burning among different crops do not widely diverge, and these estimates may be further refined using geostationary satellite observations.

Emissions and active fires in Australia (Figs. 6b and 7b) had a long-term downward trend, in contrast with that observed in the United States. Among the three different Annex 1 parties analyzed here, Australia had the highest values of fire use intensity for wheat. The interannual pattern of fire use intensity in wheat during 2001–2008 varied considerably and appeared to decrease in years following drought. For example, there was a severe drought in Australia that led to the drop in crop production during the 2002–2003 growing season for wheat (Australia

TABLE 5. Comparisons of annual reported emissions of crops required by the UNFCCC (mean \pm SD) from open-field agricultural burning and annual mean fire detections in croplands in selected non-Annex 1 countries (mostly developing countries).

Country	Global harvest area (%)	UNFCCC emissions (Gg CO ₂ eq/yr)	Detection by Aqua		Detection by Terra	
			Active fires (fire counts/yr)	All agricultural fires (%)	Active fires (fire counts/yr)	All agricultural fires (%)
Argentina	2.48	198.6	6 195	2.26	3 052	2.09
Brazil	4.10	4463.40 \pm 130.2	14 420	5.26	8 520	5.83
China	13.36	1 240.0	8 766	3.20	8 701	5.95
India	15.19	4 747.0	29 364	10.71	12 317	8.43
Indonesia	2.61	491.5	7 151	2.61	3 634	2.49
Kazakhstan	1.32	1 24.0 \pm 65.1	4 046	1.48	3 696	2.53
Mexico	1.41	44.9 \pm 1.7	4 403	1.61	3 567	2.44
Nigeria	3.05	942.7	25 821	9.41	9 794	6.70
Thailand	1.47	...	8 986	3.28	4 464	3.05
Non-Annex 1 sum	44.98	12 252.1	109 151	39.79	57 745	39.50
Total (Annex 1 + non-Annex 1)	80.04	15 466.8	150 592	54.90	96 294	65.88

Notes: Years of acquired emissions from selected non-Annex 1 countries: Argentina, year 2000; Brazil, mean of years 1990–1994; China, India, Nigeria, and Indonesia, year 1994; Kazakhstan, mean of years 2004–2005; Mexico, mean of years 2000 and 2002. Thailand did not report open-field burning in agricultural lands but had significant numbers of active fire detections in croplands and therefore was included here. UNFCCC emissions have units of CO₂eq. Dry-matter emissions were converted by individual countries into CO₂eq amounts based on emission factors and 100-year greenhouse warming potentials for CH₄ and N₂O. Ellipses (...) indicate that no data are available.

Bureau of Statistics 2003), and this appeared to be linked to a lower fire use intensity in 2003. As a consequence of the drought, it is possible that less residue was available for burning in the following year.

Emissions reported to the UNFCCC by the EU captured the decreasing trend of active fires through 2006 successfully (Fig. 6), even though crop production did not vary much during this period (Fig. 7). This indicates that other parameters in the EU inventory model, including the fraction of residue burned in agricultural fields, probably decreased. The largest decreases in active fires occurred in Romania and were mostly associated with wheat, and to a lesser extent, barley.

Country-level differences in UNFCCC reported emissions and active fires for individual crops

The EU had the lowest values of fire use intensity (active fires per unit crop production) as compared to the United States and Australia for wheat, oats, and barley (Fig. 7 and Appendix: Fig. A5). For wheat, the fire use intensity in the EU was threefold lower than in the United States and more than ninefold lower than in Australia as estimated using active fires from Terra. Thus, even though EU wheat production was approximately five times higher than in Australia, the number of active fires detected within this crop type was considerably lower (Fig. 6).

For the three parties, the ratio of UNFCCC-reported emissions to active fires for individual crops varied considerably, with large country-to-country differences for maize, wheat, and barley (Fig. 6). These differences were probably driven by different parameterizations of the forward inventory model used to estimate emissions (see the Discussion below), and may also reflect regional differences in the efficacy of active fires in detecting agricultural burning.

DISCUSSION

Implications for the current UNFCCC inventory system

The approach described by the IPCC Good Practice Guideline reports requires information on crop productivity and fire use activity to estimate agricultural waste-burning emissions. The emissions equation can be written as

$$E = P \times f_{r/c} \times f_{dm/r} \times f_{field} \times cc \quad (1)$$

where E is the total amount of emissions within a country (g dry biomass/yr), P is the crop production (metric tons/year), $f_{r/c}$ is the ratio that converts harvested crop mass into residue mass (unitless), $f_{dm/r}$ converts residue into dry matter (taking into account the water content of residue), f_{field} is the fraction of dry-matter residue in the field that is burned, and cc stands for the oxidized fraction, or combustion completeness of the dry-matter residue that is burned. E is then converted to CH₄ and N₂O emissions using crop-specific emission factors. Crop production (P) is well documented on a global level by the FAO, drawing on detailed census information provided by individual countries (e.g., Monfreda et al. 2008). The $f_{dm/r}$ value is also relatively well characterized for different crops. Therefore, primary sources of uncertainty for agricultural waste-burning emissions estimates come from $f_{r/c}$, which depends on crop type, f_{field} , which is regulated by agriculture practice and is, therefore, hard to quantify for individual countries, and cc that also may vary as a function of fuel moisture and agricultural practice. The IPCC Database on Greenhouse Gas Emission Factors (available online)⁹ provides default parameters for Eq. 1 only for a limited number of crop types (major cereal

⁹ <http://www.ipcc-nggip.iges.or.jp/EFDB/main.php>

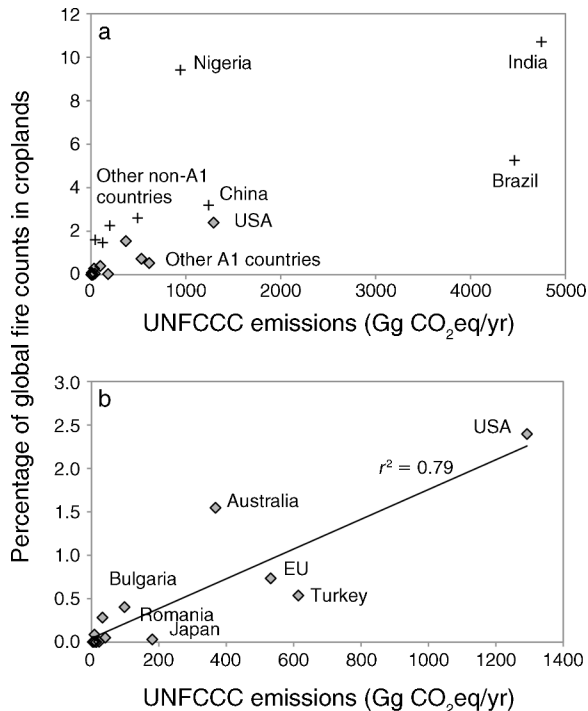


FIG. 4. Percentage of global active fires in croplands for years 2003–2006 from Aqua compared with United Nations Framework Convention on Climate Change (UNFCCC) inventories for agricultural waste-burning emissions for (a) currently reporting Annex 1 countries (diamonds) and selected non-Annex 1 countries that had submitted at least one agricultural emissions inventory (crosses) and (b) currently reporting Annex 1 countries. Note that the countries shown in panel (b) are a subset of those shown in panel (a). The relationship between reported emissions and satellite-measured active fires was significant for the full set of countries shown in panel (a) ($r^2 = 0.59$, $n = 22$, and $P < 0.001$) and the Annex 1 subset shown in panel (b) ($r^2 = 0.79$, $n = 13$, $P < 0.001$). The emissions of CH₄ and N₂O from agricultural waste-burning are aggregated into equivalent CO₂ emissions (CO₂eq emissions) using 100-year Global Warming Potentials.

crops, e.g., wheat, rice, and maize; and pulses, e.g., soybean, peas, and beans). Furthermore, even for the selected crop types, the emission factors database does not provide every parameter needed to estimate emissions. To fulfill the need for accurate emission reporting, many reporting Annex 1 countries have developed their own estimates of these parameters based on expert knowledge combined with country-specific field studies (e.g., U.S. EPA 2010).

The crop types targeted by the current UNFCCC reporting system appear to represent a compromise between the dominant crops contributing to production in both Annex 1 and non-Annex 1 countries. Some crop types, such as potato, oats, and rye, are only important in Annex 1 countries, while other crops like cassava (in the tuber-root other class) and sorghum (in cereal other) are more important in non-Annex 1 countries, as shown in Tables 1 and 3. Recently, several groups, including

the National Research Council (2010), have recommended extending annual reporting requirements to all countries (not just Annex 1) as a part of future climate agreements. In this context, an updated list of targeted crops developed specifically for different regions or groups of countries with similar biogeography may be the key to balancing reporting requirements (and thus costs) with efficient coverage. Optimized lists of crops derived from MODIS and other satellite observations have the potential to improve the reporting system in at least three different ways. First, they may allow for the design of regionally specific sets of crop types that maximize coverage of active fires and emissions. Second, they may allow countries to more efficiently invest limited resources on field studies targeting the most important agricultural waste-burning crop types to improve estimates of emissions parameters. Third, with detailed field information collected for a few key crops, the satellite observations may provide a means for scaling the different model parameters in Eq. 1 to less important or less studied crops, including for example the combined effect of f_{field} and cc .

Emissions of agricultural waste burning from current reporting Annex 1 countries were found to be broadly consistent with the active fires detected by satellites, suggesting that, for countries that currently report, the IPCC Good Practice Guideline approach generates a distribution of emissions that is internally consistent. An important caveat in this regard is that the relationship between reported emissions and active fires can vary considerably for individual sets of countries (Figs. 4 and 6). It also is important to note that only relative patterns can be derived from the analysis of active fire measurements and that systematic bias may exist as a consequence of uncertainties in several of the terms in Eq. 1. As the primary participants of the UNFCCC, reporting Annex 1 countries are not the main contributors of agricultural emissions, accounting for only 7% of total active fires in agricultural areas. Tables 4 and 5 show that parties accounting for the majority of emissions do not regularly report their emissions, including important Annex 1 countries and non-Annex 1 countries.

Agricultural waste-burning emissions are generally much smaller compared to those in energy or forestry sectors, and thus, compromises exist between increasing the reporting requirements for agricultural waste burning as compared with investment in improving other categories or sectors within the UNFCCC inventory. However, gains made in reducing agricultural fire emissions are likely to have immediate benefits for air quality, human health, and other ecosystem services (e.g., Laden et al. 2000, Tian et al. 2009), thus making it cost effective to target this category for emissions reductions. As demonstrated with our analysis, many aspects of the agricultural burning category can be evaluated using remote-sensing observations. Other categories within AFOLU are less amenable to evalu-

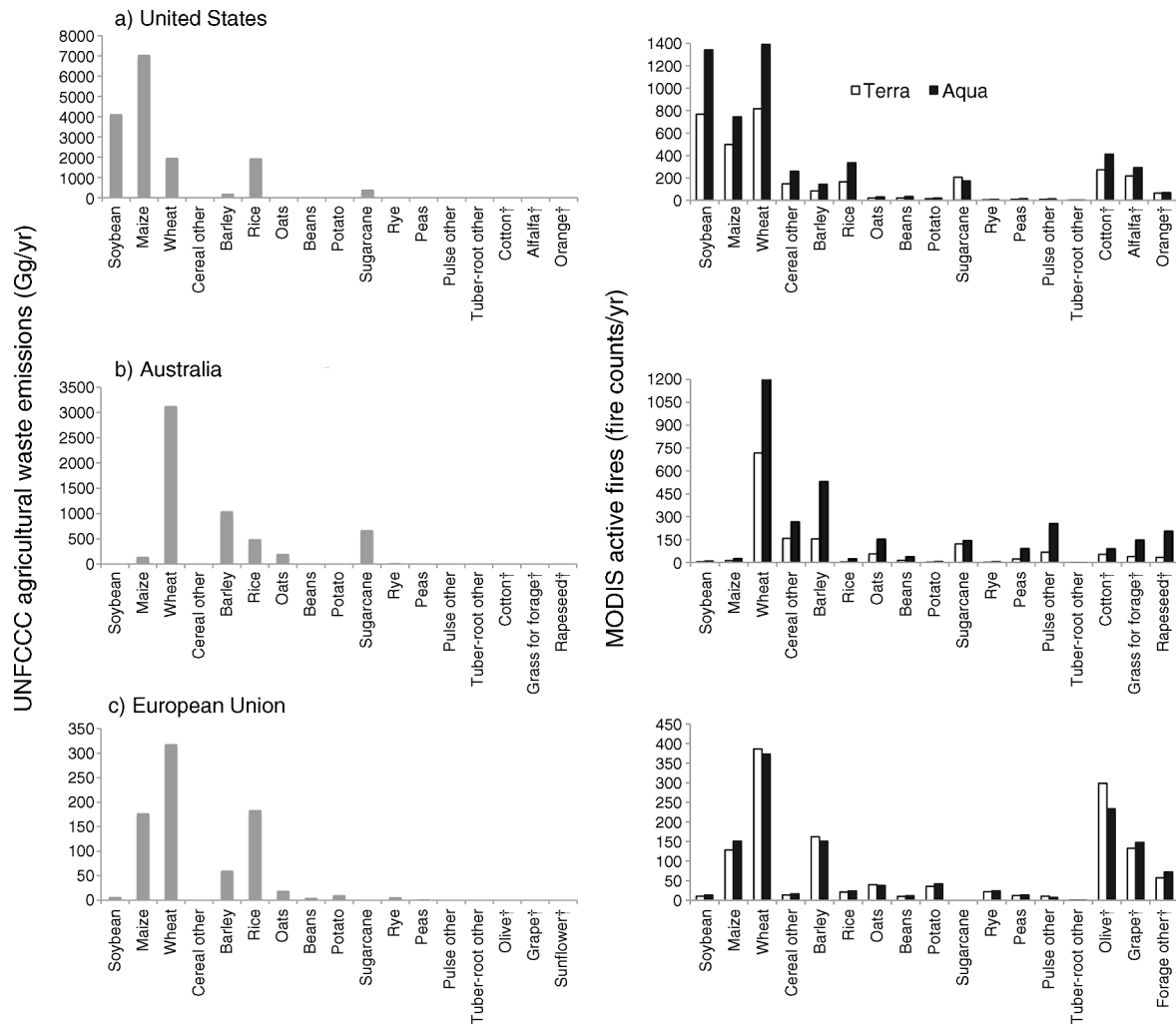


FIG. 5. Comparison of dry-matter burned emissions (Gg/yr) reported by (a) the United States, (b) Australia, and (c) the European Union (left panels) compared to the distribution of MODIS Aqua and Terra active fires within each region (right panels). Emissions were averaged over 2003–2006 to match the active fires from Aqua averaged over 2003–2006. Active fires from Terra were averaged over 2001–2006. Crop types shown with a dagger (†) are not on the UNFCCC recommend list, but are important in active fire rankings. The scale varies on the y-axis between the three regions. See the footnotes of Table 1 for more information about the specific crop types within major crop classes.

ation using remote sensing, including emissions from soils and changes in soil carbon stocks (NRC 2010). In this context, the quality of agricultural waste-burning emissions statistics, as evaluated using remote-sensing observations, may provide insight about the current condition of other components of the AFOLU inventory from a particular country, including categories that have higher levels of emissions. Crop production, for example, is a key driver of agricultural burning emissions (Eq. 1) and also is a key driver of other categories, such as combustion of biomass fuels in the energy sector and emissions of CH₄ from rice cultivation in the AFLOU sector. Active fire observations from MODIS and other geostationary and polar-orbiting satellites may therefore play an important role in monitoring compliance with the next climate treaty.

Broader implications for managing agricultural ecosystems for climate

This study is one of the first to systematically quantify global variability in fire use as a function of major crop types and country, and as such provides several pieces of information that may be useful for the design of successful climate mitigation strategies involving agricultural burning. Crop yields were often similar within Annex 1 countries, but fire use intensity (fire counts per unit of crop yield) varied greatly. A good example is the difference between the United States and the EU (Fig. 7). The contrast of fire use intensity implies that there may be flexibility to reduce the impact of agricultural burning on climate with no apparent trade-off between management and yield for two biogeographically and culturally similar regions. Further work is needed to

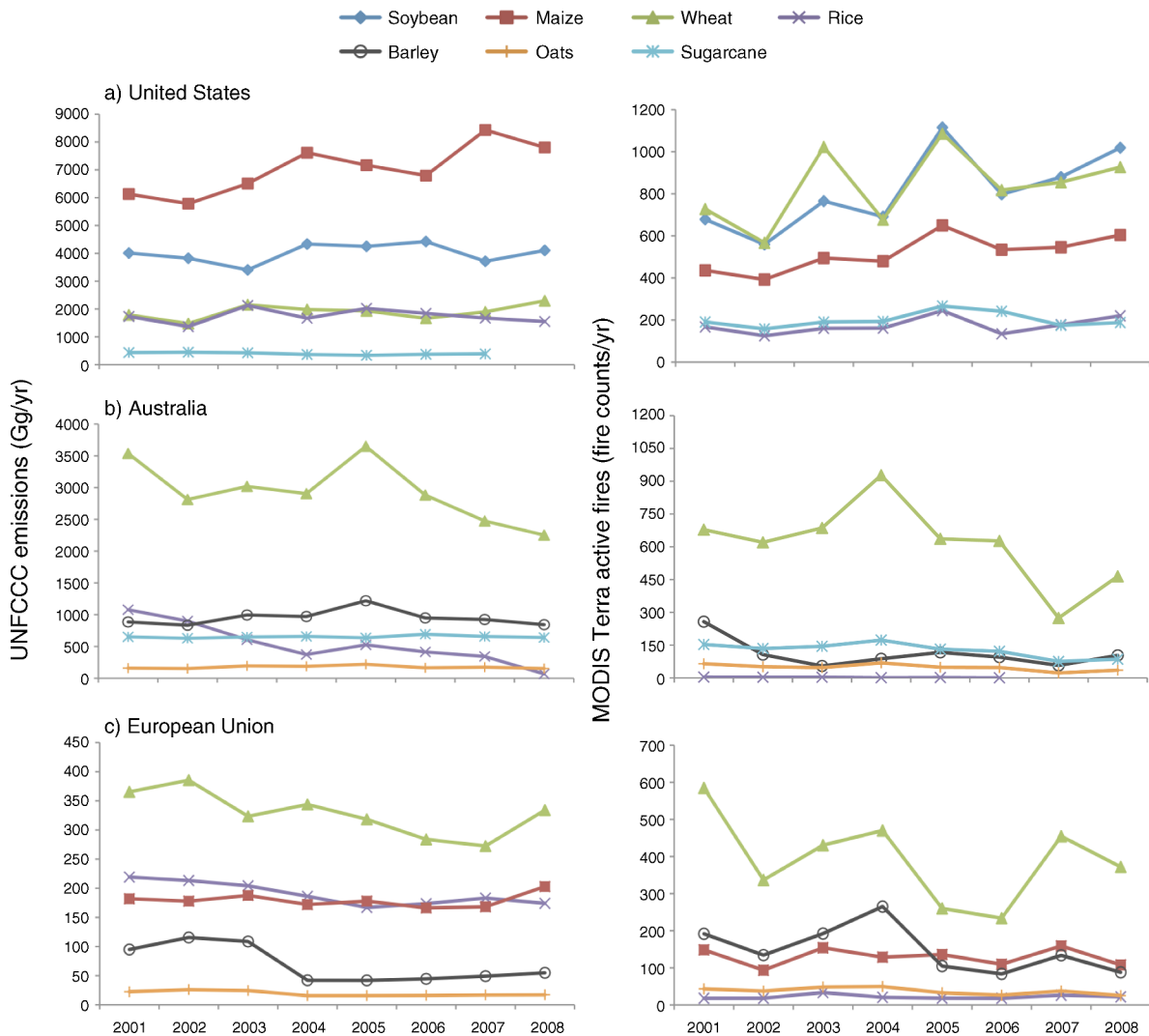


FIG. 6. Interannual variability of dry matter burned for major crop types reported to the UNFCCC by (a) the United States, (b) Australia, and (c) the European Union (left panels) compared to the time series of active fires from MODIS Terra in agricultural areas (right panels). The scale varies on the y-axis among the three regions. For crops in Australia, because the primary agricultural burning season was between September and May, we defined the annual reporting period for active fires as starting in July and ending in June.

quantify ecosystem services affected by agricultural fire management, but reducing the number of agricultural fires within many areas of the United States seems feasible and may allow for both climate and air quality benefits (e.g., Soja et al. 2009).

In Russia, Ukraine, and other countries in Eastern Europe and Central Asia (Fig. 1), use of fires in agroecosystems was extensive, with many of these fires occurring during spring and fall when snow and ice cover was present in downwind regions. Canadian agricultural fire use densities were considerably lower, suggesting that flexibility also may exist with respect to managing fires to optimize yields in northern high-latitude agricultural ecosystems. For these countries, the climate benefits of managing fires to reduce emissions

likely extend well beyond reducing the buildup of greenhouse gases currently targeted by the UNFCCC. Here, the primary climate benefit may be to reduce black carbon transport to arctic and boreal regions and thus the lowering of albedo in snow and ice covered regions (Warneke et al. 2010, Koch et al. 2011).

CONCLUSIONS

In this study, we evaluated multiple aspects of the UNFCCC reporting system for agricultural waste burning using MODIS active fires. To increase the global coverage of agricultural fires and the efficacy of the current reporting system, we developed optimal lists of crop types for reporting countries, both globally and for Annex 1 countries. We found that the list of crops

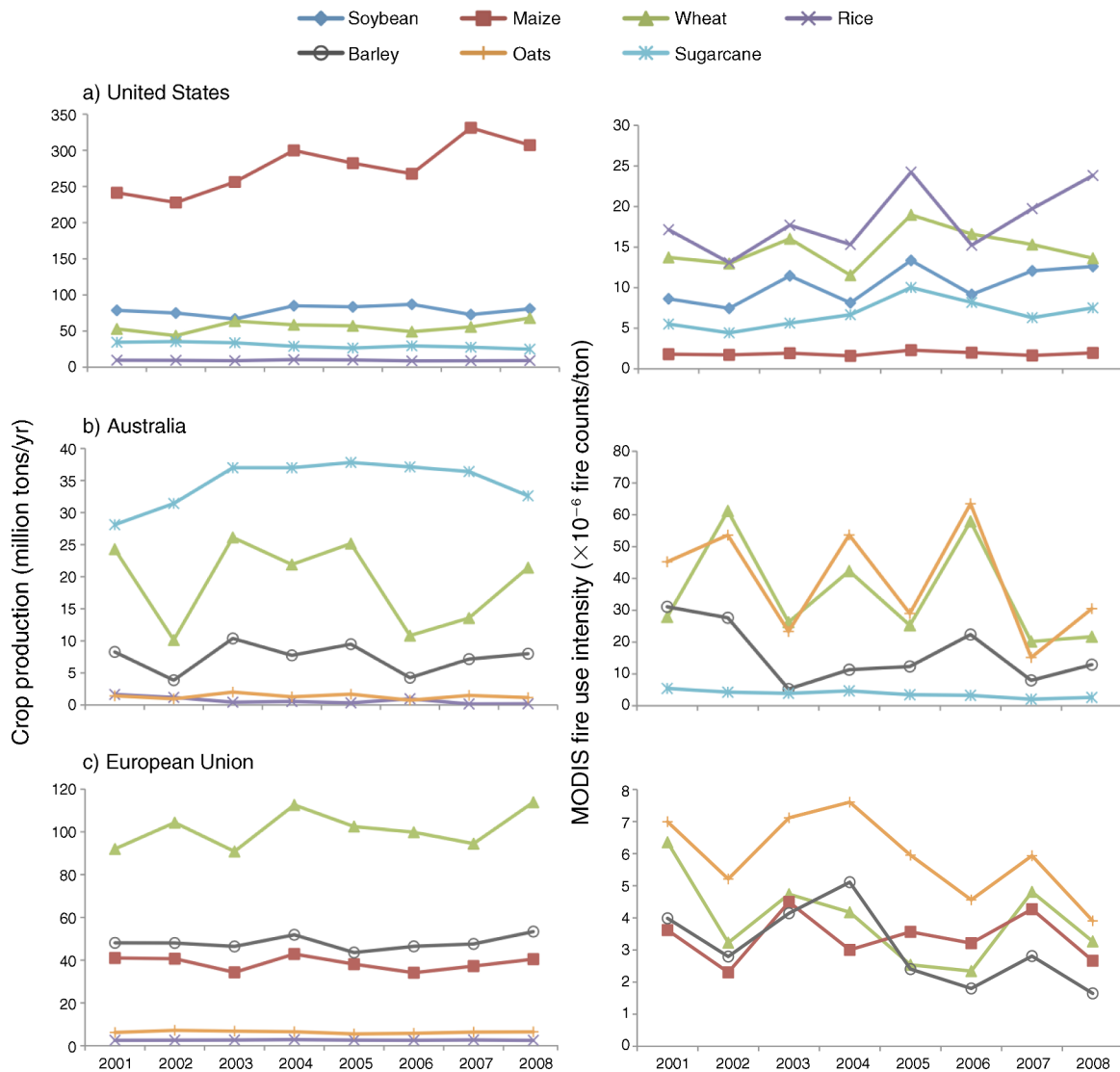


FIG. 7. Crop production (left panels) and normalized MODIS active fires by crop production (right panels) for (a) the United States, (b) Australia, and (c) the European Union. Production estimates for different crop types (millions of metric tons/year) were from the Food and Agriculture Organization of the United Nations (FAO). The scale varies on the y-axis among the three regions. For crops in Australia, because the primary agricultural burning season was between September and May, we defined the annual reporting period for active fires as starting in July and ending in June. Fires during this period are compared to FAO-reported crop yields during the calendar year that occurred at the onset of the active fire period. For example, July 2001–June 2002 active fire sums are compared with FAO estimates of crop yields from 2001.

currently targeted by the UNFCCC was not sufficient for capturing several important emitters, including cocoa, oil palm, cotton, and ground nuts at a global scale, and sunflower, rapeseed, cotton, and alfalfa for Annex 1 countries.

We also documented improvements to the reporting system that would occur if all Annex 1 countries reported their emissions and if reporting requirements were extended to non-Annex 1 countries. Reported emissions from some Annex 1 parties agreed well with long-term trends observed by MODIS, while emissions from other parties did not show the same level of

fidelity. Analyses of the United States and Australia showed the great importance of fire use as well as crop production in controlling the amount of emissions and the interannual variability of agricultural waste burning. More generally, this work demonstrates that remote sensing is an efficient tool for monitoring fire conditions in croplands at regional to global scales; if combined with census data, field experiments, and expert opinion, it has the potential to improve the quality of AFOLU inventories and the next generation of the UNFCCC greenhouse gas-reporting system.

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SUPPLEMENTAL MATERIAL

Appendix

Tables showing statistics of active fires and fire densities for major crops (supplementary to Tables 1 and 3); and figures of fire detection vs. emissions in croplands based on Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua and Global Fire Emissions Database version 3 (GFED3), of fire radiative power vs. active fire counts in Annex 1 and non-Annex 1 countries, of the number of major crop types in the grid cells of the crop data set used by this study, of time series of active fires and fire use intensities within major crop types of the United States, Australia, and the European Union (supplementary to Figs. 6 and 7); and a map of 14 GFED regions used in this study (*Ecological Archives* A022-070-A1).