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Assessing the potential of wildfires as a sustainable bioenergy opportunity

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Abstract

As the environmental and economic consequences of fossil-fuel use become clear, land is increasingly targeted as a source of bioenergy. We explore the potential for generating electricity from biomass vulnerable to fires as an ecologic and socioeconomic opportunity that can reduce the risk of greenhouse gas generation from wildfires and help to create incentives to preserve natural and seminatural vegetation and prevent its conversion to agriculture, including biofuel crops. On the basis of a global analysis of the energy generation and spatial distribution of fires, we show that between 2003 and 2010, global fires consumed ~8300 ± 592 PJ yr^{-1} of energy, equivalent to ~36–44% of the global electricity consumption in 2008 and >100% national consumption in 57 countries. Forests/woodlands, cultivated areas, shrublands, and grasslands contributed 53%, 19%, 16%, and 3.5% of the global energy released by fires. Although many agroecological, socioeconomic, and engineering challenges need to be overcome before diverting the energy lost in fires into more useable forms, done cautiously it could reconcile habitat preservation with economic yields in natural systems.

Keywords: bioelectricity, biomass burning, dry forests, fire radiative energy

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Introduction

In pace with declining fossil-fuel reserves and increasing concerns on global environmental deterioration, humans are trying to diversify and expand their sources of energy. Being the predominant energy source in preindustrial times, land ecosystems are gaining renewed attention as energy providers (Campbell *et al.*, 2009; Ohlrogge *et al.*, 2009; Richter *et al.*, 2009) at a challenging time in which the appropriation of food, fiber, and timber is already accounting for one quarter of their global net primary production (NPP) (Haberl *et al.*, 2007). Although biofuel crops receive increasing attention and government support, their expansion may compromise food production and provide questionable climate benefits (Fargione *et al.*, 2008; Searchinger *et al.*, 2008; Piñeiro *et al.*, 2009). New perspectives on which ecosystems should be targeted and how they should be managed to limit the trade-offs among energy generation, food production, and environmental protection are needed. Wildfires are an increasingly important pathway of energy release from land ecosystems, and here, we explore the magnitude and distribution of this energy flux and discuss its potential diversion to electricity generation and some of the associated environmental benefits and costs.

Globally, between 3.3 and 4.3 million km^{-2} of land, roughly the size of India, burn each year (Giglio *et al.*, 2010). These fires combust plant biomass and release particulate matter and greenhouse gasses, including the equivalent to 2 Pg C yr^{-1} of CO_2, CH_4, and N_2O, to the atmosphere (van der Werf *et al.*, 2010). They also disturb ecosystems and the services that they provide to society by triggering soil erosion, altering the hydrologic cycle, and, sometimes, destroying infrastructure (DeFries *et al.*, 2002; Hoffmann *et al.*, 2002, 2003; Mouillot & Field, 2005; Lohman *et al.*, 2007; van der Werf *et al.*, 2008). Throughout the history of life on Earth, fires have played a key role shaping plant adaptations, ecosystem composition and distribution (Bond *et al.*, 2005), and global biogeochemical cycles (Bergman *et al.*, 2004). Nowadays, however, in a world in which 75% of the ice-free land ecosystems are subjected to some type of management and use (Ellis & Ramankutty, 2008), their significance is very different. Wildfires today have

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increased their intensity, extent, and duration over many areas, favored by climate change and human activity (Kasischke *et al*., 1995; Skinner *et al*., 2006; Westerling *et al*., 2006, 2011; Tymstra *et al*., 2007; Flannigan *et al*., 2009; Liu *et al*., 2009; Le Page *et al*., 2010; Pechony & Shindell, 2010; Wotton *et al*., 2010). As a consequence, it is very likely that they have exceeded their 'natural' role as an ecologic and biogeochemical agent, becoming a new force of change in systems where they were uncommon before.

We propose that the controlled combustion for energy production, based on the diversion of biomass that would eventually burn in wildfires, provides an immediate opportunity to reduce fossil-fuel use and its associated greenhouse gas (GHG) emissions and satisfy the growing energy needs of some developing economies. The climatic benefits of this intervention not only involve replacing fossil fuels but also reducing other non-CO_2 gasses with high global warming potential, particularly carbon monoxide, and black carbon emissions, which are significant in wildfires, but avoidable under controlled combustion conditions (Crutzen & Andreae, 1990; Bond *et al*., 2005; Ramanathan *et al*. 2008). Furthermore, along with reducing net GHG emissions, biomass harvesting can provide economic returns that, ideally, can help maintain habitats vulnerable to agricultural expansion.

To explore the potential of this bioenergy alternative, we first quantify and map global energy release by wildfires and the corresponding fraction of the average NPP that burns in these fires. Next, we characterize wildfire energy release across biomes and identify countries where its partial allocation to electricity generation could satisfy a substantial portion of their electricity demand.

Materials and methods

Fire radiative energy (FRE)

We estimated global radiative energy released by fires from January 2003 to December 2010 using the MOD and MYD14CMG fire products (Giglio *et al*., 2006) generated from the MODIS sensor collection 5 onboard Terra and Aqua platforms. This dataset integrates subdaily, 1 km^{-2} resolution data into monthly values for 0.5°×0.5° grid cells. Using a probabilistic characterization of fire density that avoids assumptions about fire duration, we calculated the FRE released (FRE, in MJ yr^{-1}) from any given cell as follows:

$$\mathrm{FRE}_{\mathrm{y,cell}} = \sum\nolimits_{i=1}^{i=12} \frac{\mathrm{Raw}_i}{\mathrm{Total}_i - \mathrm{Cloud}_i} \times \mathrm{sFRP}_i \times A_{\mathrm{cell}}$$

where i stands for month, Raw indicates the number 1 km^{-2} fire pixels observed by Aqua and Terra for that particular cell and month (pixels $cell^{-1}$ mo^{-1}), Total shows the number of pixels that were screened within a given cell during the month i (pixels $cell^{-1}$ mo^{-1}), and Cloud represents the number of cloudy pixels screened in the month i (Aqua + Terra) (pixels $cell^{-1}$ mo^{-1}). The first three terms of the equation yield a dimensionless index of fire density ranging from 0 to 1 for each cell and month. The term sFRP_i (specific radiative power per fire pixel in MW $pixel^{-1}$) corresponds to the fire radiative power values provided by the CMG dataset, which were estimated as the sum of the power release measured in all fire pixels' FRP divided by the number of fire pixels screened during a calendar month. The sFRPi values (MW $pixel^{-1}$) were transformed to energy per month (MJ mo^{-1} $pixel^{-1}$), and final values were scaled to the whole cell by considering the number of pixels per cell (A).

Sources of uncertainty in our FRE calculation would stem from biases in the estimates of the real number of fire pixels – due to limited sampling resulting from satellite orbits, cloud masking, and limitations in instruments and detection algorithms (Giglio *et al*., 2006) – and their average radiative power. For example, recent studies showed that improper background characterization may hamper cool fire detection (Schroeder *et al*., 2010), and sampling artifacts (i.e., 'Bow tie effect', Freeborn *et al*., 2011) may provide flawed FRP estimates. Our use of discrete MODIS observations to describe a continuous process assumed that the effectively observed pixels offer a reasonable representation of all pixels within any given cell and for any particular month. Similarly, we assumed that the sFRP values of the observed fire pixels were representative of those fire pixels that could have been obscured by clouds or missed by the satellite passes. To test the validity of our assumptions, we validated our methodology against the Global Fire Emissions Database v3 (van der Werf *et al*., 2010).

Total energy release and burned biomass

We assumed a ratio of total-to-radiative energy release from wildfires of 8.1 (radiative fraction = 12.3%), based on previously reported values of 18 MJ of total energy and 2.21 MJ of radiative energy per kg of biomass (Freeborn *et al*., 2007; Campbell *et al*., 2009). Nonradiative energy losses are attributable to conduction, convection, and vaporization, and other secondary processes (Wooster *et al*., 2005). We chose radiative energy rates of 2.21 MJ kg^{-1} (Freeborn *et al*., 2007) as opposed to alternative figures of 2.71MJ kg^{-1} (Wooster *et al*., 2005) because the former has been estimated for a wider variety of biomass types, including grasses, branches, twigs, and woody vegetation. Burned biomass was then calculated as the ratio between the total energy released by fires and the heating value of biomass (18 MJ kg^{-1}, Campbell *et al*., 2009). Average global NPP values were obtained from Imhoff *et al*. (2004) dataset. These authors used the CASA (Potter *et al*., 1993) carbon model driven by a global satellite-derived vegetation index (AVHRR-NDVI) and climate data obtained between 1982 and 1998 (Imhoff *et al*., 2004). CASA estimates NPP as a product of time-varying surface solar irradiance, NDVI computed from AVHRR sensor, a constant maximum light use efficiency modified by time-varying stress scalar terms for temperature and moisture effects. In turn, these stress scalar terms are calculated from the difference to optimal temperatures or from water deficits considering a land cover map produced by Hansen *et al.* (2000) and climatic and soil texture data taken from the International Satellite Land Surface Climatology Project, Initiative II (ISLSCP II, Hall *et al.*, 2005), and Zobler (1986), respectively. Therefore, fires or any other disturbance that reduce radiation interception by plants should be captured by this modeling approach.

Spatial distribution of energy consumption and agricultural fires estimation

We assessed the spatial distribution of energy consumption globally as the product of population density and per capita energy consumption for each country. National population density data were obtained from the Gridded Population of the World Version 3 (GPWv3) (Center for International Earth Science Information Network (CIESIN), Columbia University; & Centro Internacional de Agricultura Tropical (CIAT), 2005), and the total energy consumption per capita and by country were calculated from data published by the International [6] Energy Agency (IEA) Statistics Division (2007). To estimate the amount of fires associated with agriculture, we overlapped the FRE map with the Global Land Cover (Arino *et al.*, 2008) vegetation classes aggregated to two classes (agricultural vs. other).

Results

The radiative energy released by fires from 2003 to 2010 averaged 8300 ± 562 PJ per year, combusting 1.8 ± 0.1 Pg C yr^{-1} dry mass or 3.2% of global annual NPP [7] (Fig. 1, see Supplementary Table 1). Africa and South America, with only 20% and 12% of total land surface area, were responsible for 48% and 24% of this energy release, respectively. In several areas of the globe – for instance sub-Saharan and tropical Africa, northern Australia, southern Russia, Kazakhstan, and southeast Asia – the amount of NPP burned in fires exceeds 20% and can be as much as 60% (Fig. 1b).

Fires in forests/woodlands/savannas, cultivated areas, shrublands, and grasslands contributed 53%, 19%, 16%, and 3.5% of the global energy release, consuming on average 2.4%, 1.9%, 4.8%, and 1.7% of NPP in those systems. The low fraction of grassland NPP consumed by fires may be due to their higher belowground allocation (Gower *et al.*, 1999; Saugier *et al.*, 2001; Chapin *et al.*, 2002), higher biomass turnover rates (e.g. Cebrian, 1999), and herbivore consumption (McNaughton *et al.*, 1989) as compared with forested ecosystems. Approximately 81% of the global fire energy release comes from areas dominated by natural vegetation, as suggested by land cover maps (Arino *et al.*, 2008). The amounts differed markedly by country, however; Australia and the Democratic Republic of the Congo had 90% and 93% of their fires under natural and seminatural vegetation, whereas >40% of the energy released by fires in India and China came from cultivated land. The human context left its imprint on fire energy release patterns, as suggested by contrasts within the same biome across political borders, such as those between Russia and China or Portugal and Spain (Fig. 1b).

Between 2003 and 2010, the average total energy annually released by fires equaled 14% of the total energy consumed by humans in 2008. In principle, if all of the biomass that fed these fires could be diverted to energy generation assuming an efficiency ranging from 33% to 40% conversion (efficiencies from the standard steam-Rankine cycle and conservative commercially mature power generation facilities, respectively, Jin *et al.*, 2009; Schiermeier *et al.*, 2008), the burned biomass would supply between 36% and 44% of the global electricity consumption in 2008 (Energy Information Administration, 2008).

Although many biophysical, socioeconomic, and technological factors limit the full capture of this bioenergy source, regions of greater opportunity can be identified. One important component is the geographic match between fire energy release and electricity demand (Fig. 1c), which can be assessed nationally. Among the top 12 countries of highest fire energy release, which accounted for 66% of the global total (Fig. 2), we identified three groups of countries that display contrasting ratios of this potential energy source to electricity consumption. In the first group of countries with ratios <0.2 (e.g., the United States), electricity generation with biomass could be locally important, but is unlikely to alter the national energy mix. In the second group (e.g., Argentina, Brazil, Australia, and Russia), ratios between 0.2 and 5 suggest a better opportunity to replace fossil fuels. Finally, countries with a ratio >5, such as most of the sub-Saharan African nations, have low electricity demand overall; in these countries, the bioenergy strategy that we describe may be most helpful in supplying energy for future economic growth.

Discussion

According to our analysis, fires consume ~3.2% of terrestrial NPP, producing considerable GHG emissions and generating ~8300 PJ of biomass energy release each year. Although the coarse vegetation classes that we [8] used do not allow a detailed quantification of the contribution of, for example, C4 grasses, at a global scale our values are consistent with, but slightly more conservative than, previously reported estimates in the literature. Our estimate of 1.8 Pg C of biomass burned annually is within the range of values reported as 2 Pg C yr^{-1} by

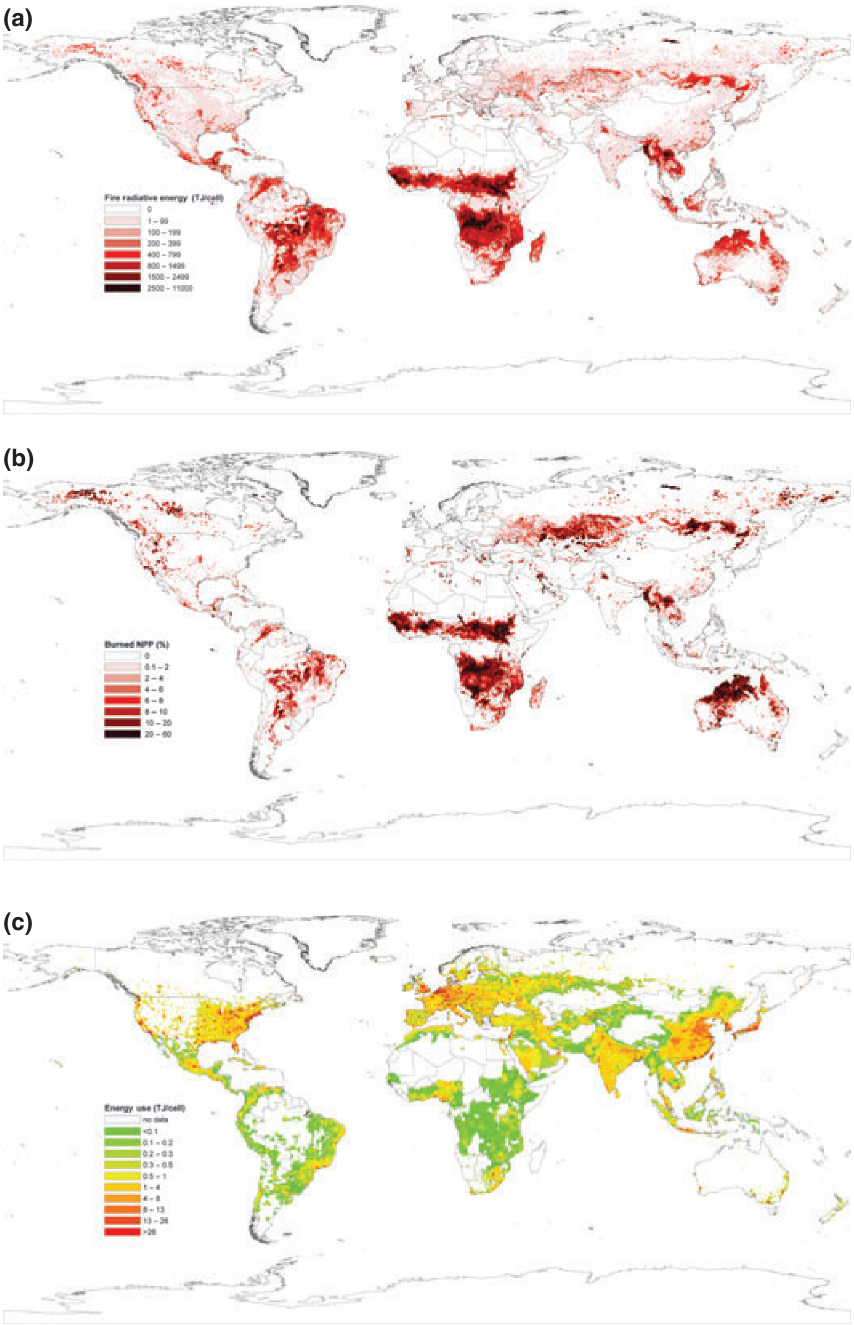

Fig. 1 Global distribution of wildfires and human energy consumption: (a) Radiative energy released by fires shown as the average energy flux (TJ yr^{-1}) per grid cell (0.5 by 0.5 degrees) estimated from the MOD14CMG product for the 2003–2010 period. (b) Percentage of mean net primary production (NPP) that burns in each grid cell to explain observed fire energy release rates (NPP values were obtained from the CASA model (Imhoff *et al.*, 2004)). (c) Energy use by humans (TJ yr^{-1}) per grid cell (0.5 by 0.5 degrees) based on the Gridded Population of the World (GPWv3) dataset and country-level estimates of per capita energy consumption from the International Energy Agency.

van der Werf *et al.* (2010) and 1.1 Pg C yr^{-1} by Haberl *et al.* (2007). We validated our estimates against the most recent and comprehensive fire database (Global Fire Emissions Database v.3), wherein fire emissions are derived from the combination of a biogeochemical model and remote sensing estimates of burned area, to estimate burnt biomass (van der Werf *et al.*, 2010). We [9] found a very good agreement (linear $r^2 = 0.9$, slope = 1.1, and y-intercept = −8) for 14 world regions and 7 years (2003–2009). In addition, we calculated the

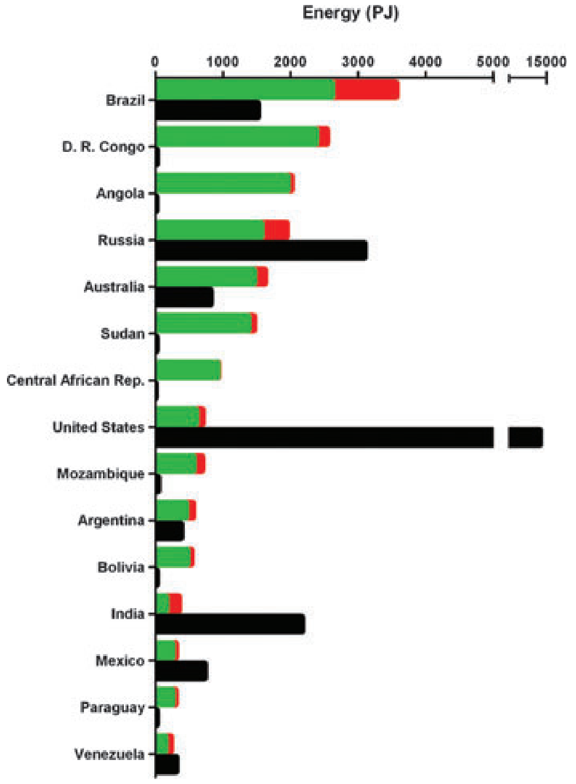

Fig. 2 Potential electricity supply through wildfire diversion vs. current electricity demand across nations. Estimates are based on fire energy release from agricultural (red) and nonagricultural fires (green) and current electricity consumption (black), assuming a conversion efficiency of 40%. Countries are sorted from highest to lowest fire energy released. Listed countries account for 66% of the total potential electricity. For 57 countries, this bioenergy source supply exceeds national electricity consumption.

correlation coefficient between our FRE estimate and the GFEDv.3 C emissions at a per pixel (0.5°×0.5°) basis for the 2003–2009 period, showing a correlation coefficient >0.6 in more than 60% of the pixels, suggesting that our simpler approach successfully captured spatial and temporal fire energy release patterns.

The land use context of wildfires, their long-term history, and their current geographic match with human energy consumption need to be considered in the discussion of electricity generation with biomass and its environmental and social opportunities. However, it is important to consider that the disruption of fire regimes on natural systems could have contrasting effects depending on their fire history, threatening those that have been shaped by long-term recurrent fires, but protecting those that suffer increasing burning in response to recent climate change or intensifying human ignition (Kasischke *et al.*, 1995; Skinner *et al.*, 2006; Westerling *et al.*, 2006, 2011; Tymstra *et al.*, 2007; Flannigan *et al.*, 2009; Liu *et al.*, 2009; Pausas & Keely, 2009; Pechony & Shindell, 2010; Wotton *et al.*, 2010).

A sustained and sustainable diversion of biomass from wildfires to electricity generation would require a careful categorization of fires capable of separating those that periodically affect (semi)natural vegetation (i.e. regime fires), from those that represent a one-time event associated with the clearing and replacement of (semi)natural vegetation by crops (i.e. clearing fires), and those involving the reduction in crop residues (i.e. agricultural fires). We here focused on 'regime fires' which may be the most attractive option for biomass diversion to electricity generation given that 'clearing fires' would offer a single event of biomass availability, in many cases undesirable for additional environmental reasons. 'Agricultural fires', in turn, demand a more detailed analysis because of the competing uses of the crop residues that they consume, which, besides bioenergy, include animal feed soil fertility maintenance through erosion control and soil organic carbon generation (Smil, 2005). According to one of the most recent global land use maps (Arino *et al.*, 2008) and our own fire distribution maps, natural and seminatural systems generated 81% of the global energy release by fires in the study period.

The geographic patterns of energy release by fires and electricity consumption by humans (Figs 1c and 2) reveal an overlap in some moderately developed countries, such as Brazil, Argentina, Russia, and Mexico, in which labor availability and harvesting costs could eventually make electricity generation with biomass feasible (Central Intelligence Agency, 2009). Although the most immediate opportunities for electricity generation using fire-prone biomass occur in these countries, Africa shows the largest potential. In the northern and southern fire belts of this continent (Fig. 1a), most countries currently have low electricity generation and rely on biomass to cover >75% of their national energy consumption (Malimbwi & Zahabu, 2010). **10** High urbanization rates in these countries have raised charcoal demands from an increasingly broader radius of rural areas (e.g. >400 km around Dakar and Dar es Salaam) (Luoga, 2000; Malimbwi & Zahabu, 2010), **11** making it a dominant source of rural income (Chidumayo *et al.*, 2001) and highlighting the already significant role of natural ecosystems as a major energy source in these developing economies.

Although significant and promising as a potential energy source, the massive use of fire-prone biomass from natural ecosystems introduces multiple technological and socioeconomic challenges, as well as likely trade-offs with other ecosystem services. The alteration of nutrient cycles brought by the replacement of *in situ* biomass burning with harvesting, removal, and *ex situ* combustion could lead to net nutrient losses and deterioration of soil fertility. This is particularly feasible for nonvolatile elements such as phosphorus and base cations, which would otherwise have remained in ashes after fires, their net removal could limit productivity in highly weathered or sandy soils. Harvesting schemes that leave nutrient-rich components such as leaves and bark in place or, logistically more challenging, return ashes back from power plants to the field could reduce this potential impact. Potential long-term change in biodiversity and pollinator abundance with reduced fire frequency is another front that needs further ecological study. Evidences from the large body of literature evaluating the effects of coarse woody debris extraction (a biomass component that will likely be eliminated under the management schemes proposed here) suggest mixed effects upon ecosystem services (e.g. MacNally *et al.*, 2002; Owens *et al.*, 2008). A recent study from an arid ecosystem concluded that coarse woody debris removal only showed transient negative effects on flower visitor abundance, whereas positive or nonsignificant effects were found for seed production of the dominant tree species, cover, richness, and composition of understory plants or soil properties (Vázquez *et al.*, 2012). Future research should also elucidate how electricity generation with native vegetation biomass could best be implemented to maximize the provision of other ecosystem goods and services for local people and societies and what mechanisms could warrant sustainable harvesting schemes.

Some challenging logistical and political issues emerge with the proposed energy generation approach. The distance of fire-prone areas to centers of energy consumption (Figs 1a and 1c) could impose constraints on the feasibility of large electricity generation plants. The location (distance, accessibility), type (woody vs. herbaceous, large vs. small wood), timing (harvest-regeneration periods, biomass moisture cycles), and density (harvestable mass per unit of area) of fire-prone biomass availability will determine the feasibility, design, and labor/equipment needs (Mahmoudi *et al.*, 2009). Energy consumption and road and electricity grid networks will define the type of generation method (Kumar *et al.*, 2003; Yagi & Nakata, 2011). Although here we propose capturing only the fraction of primary productivity that would otherwise be consumed by wildfires, it would be difficult to define the exact magnitude of that fraction and tempting to exceed it once the energy generation economy starts. Although suggesting a different perspective on bioenergy opportunities in land ecosystems, our proposal does not tackle the complex issue of environmental impacts and the development of management and regulation practices that could minimize them. That challenging task will require the application of ecologic, agronomic, and social knowledge under very different geographic contexts. Our increasing understanding of fire ecology, including recent fire prediction models (Preisler *et al.*, 2011), will aid in this process, yet it would be ultimately defined by the interaction of land managers, energy markets, and policy makers among other key stakeholders.

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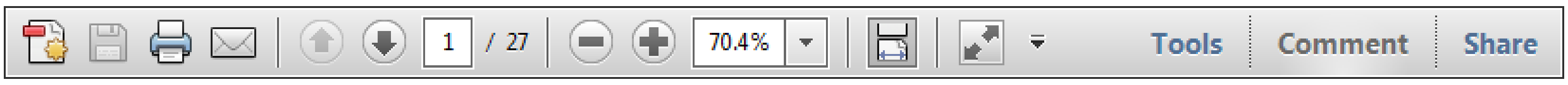
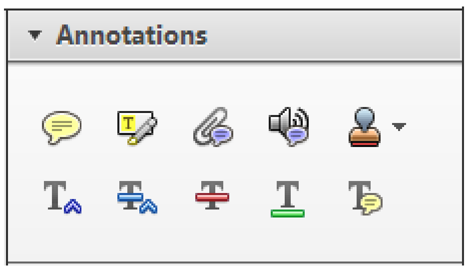
Required software to e-Annotate PDFs: Adobe Acrobat Professional or Adobe Reader (version 8.0 or above). (Note that this document uses screenshots from Adobe Reader X)
The latest version of Acrobat Reader can be downloaded for free at: http://get.adobe.com/reader/

Once you have Acrobat Reader open on your computer, click on the Comment tab at the right of the toolbar:



This will open up a panel down the right side of the document. The majority of tools you will use for annotating your proof will be in the Annotations section, pictured opposite. We've picked out some of these tools below:

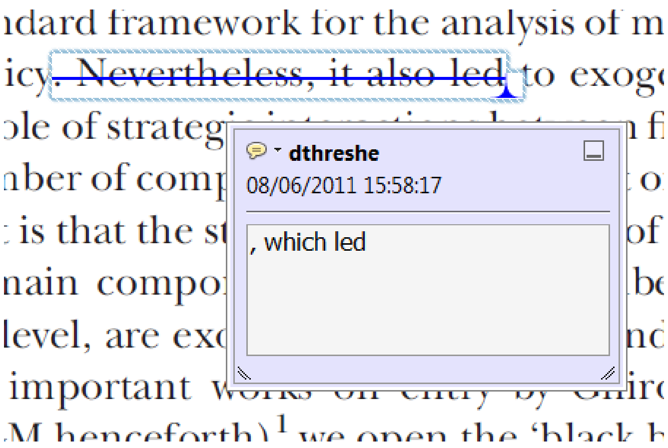


1. Replace (Ins) Tool – for replacing text.

Strikes a line through text and opens up a text box where replacement text can be entered.

How to use it

- Highlight a word or sentence.
- Click on the Replace (Ins) icon in the Annotations section.
- Type the replacement text into the blue box that appears.



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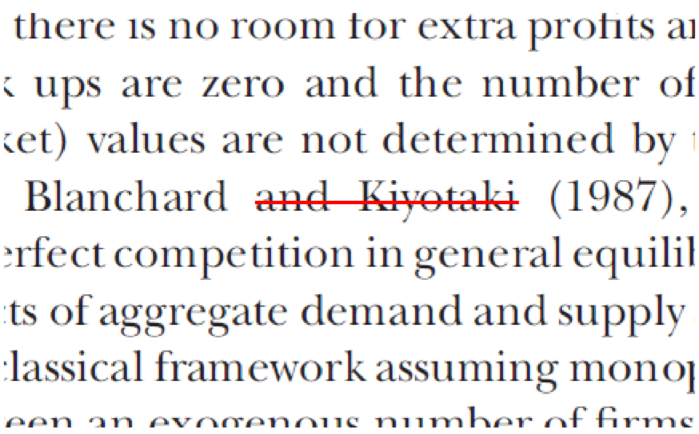
2. Strikethrough (Del) Tool – for deleting text.

Strikes a red line through text that is to be deleted.

How to use it

- Highlight a word or sentence.
- Click on the Strikethrough (Del) icon in the Annotations section.



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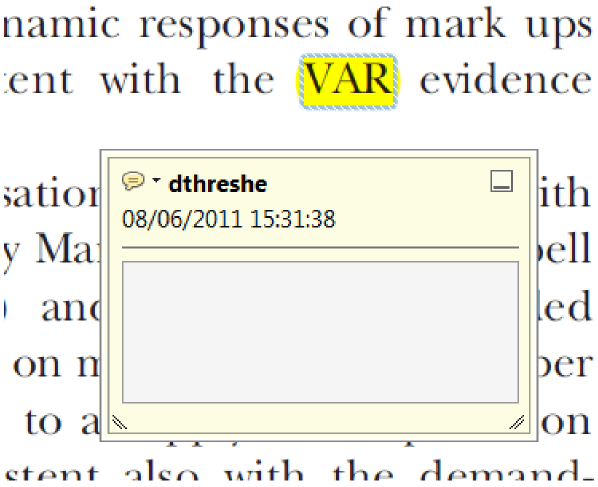
3. Add note to text Tool – for highlighting a section to be changed to bold or italic.

Highlights text in yellow and opens up a text box where comments can be entered.

How to use it

- Highlight the relevant section of text.
- Click on the Add note to text icon in the Annotations section.
- Type instruction on what should be changed regarding the text into the yellow box that appears.



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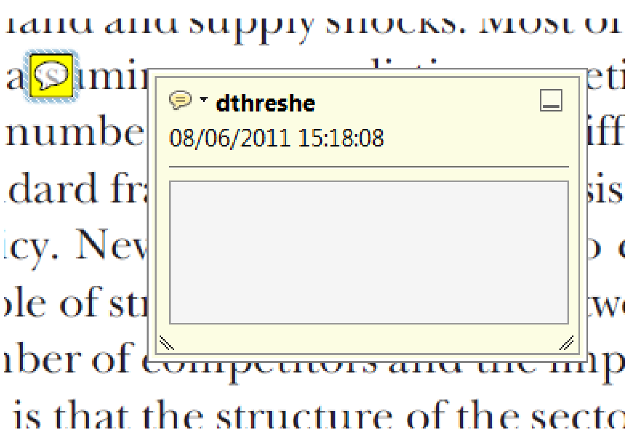
4. Add sticky note Tool – for making notes at specific points in the text.

Marks a point in the proof where a comment needs to be highlighted.

How to use it

- Click on the Add sticky note icon in the Annotations section.
- Click at the point in the proof where the comment should be inserted.
- Type the comment into the yellow box that appears.



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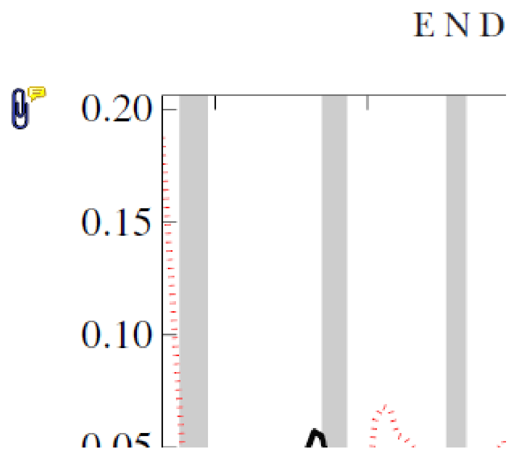
USING e-ANNOTATION TOOLS FOR ELECTRONIC PROOF CORRECTION

5. **Attach File** Tool – for inserting large amounts of text or replacement figures.

Inserts an icon linking to the attached file in the appropriate pace in the text.

How to use it

- Click on the Attach File icon in the Annotations section.
- Click on the proof to where you'd like the attached file to be linked.
- Select the file to be attached from your computer or network.
- Select the colour and type of icon that will appear in the proof. Click OK.

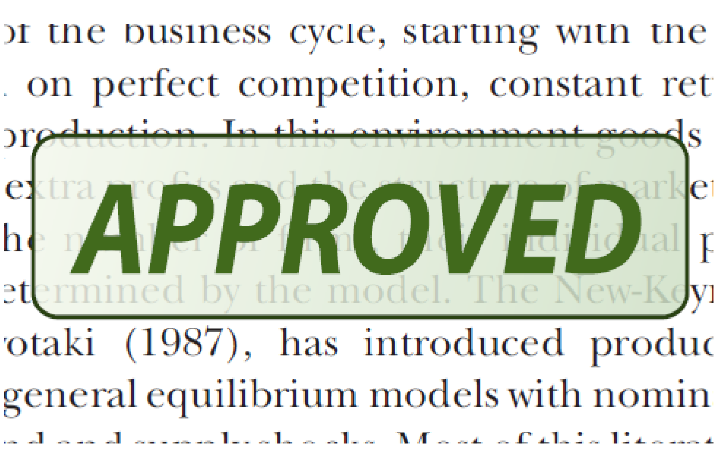


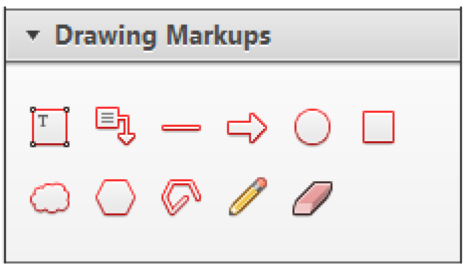
6. **Add stamp** Tool – for approving a proof if no corrections are required.

Inserts a selected stamp onto an appropriate place in the proof.

How to use it

- Click on the Add stamp icon in the Annotations section.
- Select the stamp you want to use. (The Approved stamp is usually available directly in the menu that appears).
- Click on the proof where you'd like the stamp to appear. (Where a proof is to be approved as it is, this would normally be on the first page).



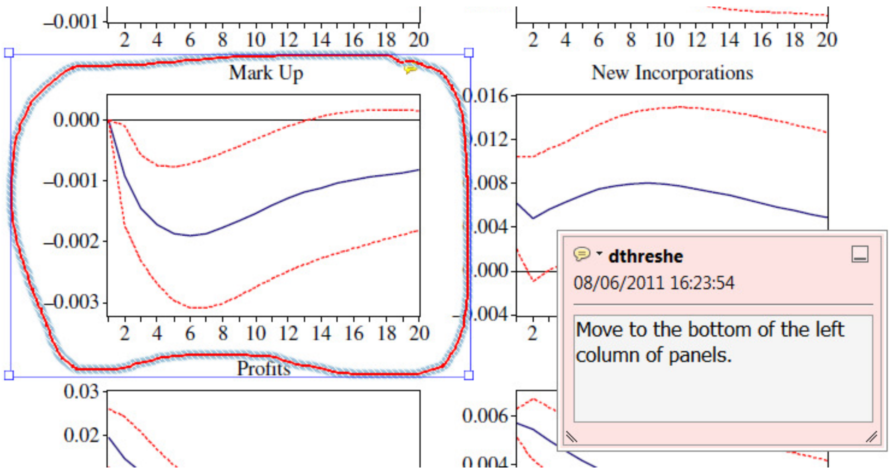


7. **Drawing Markups** Tools – for drawing shapes, lines and freeform annotations on proofs and commenting on these marks.

Allows shapes, lines and freeform annotations to be drawn on proofs and for comment to be made on these marks..

How to use it

- Click on one of the shapes in the Drawing Markups section.
- Click on the proof at the relevant point and draw the selected shape with the cursor.
- To add a comment to the drawn shape, move the cursor over the shape until an arrowhead appears.
- Double click on the shape and type any text in the red box that appears.



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Move to the bottom of the left column of panels.

For further information on how to annotate proofs, click on the **Help** menu to reveal a list of further options: